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Identifying Essential Epistemic Heuristics for Guiding Mechanistic Reasoning in Science Learning

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Mechanistic reasoning, or reasoning systematically through underlying factors and relationships that give rise to phenomena, is a powerful thinking strategy that allows one to explain and make predictions about phenomena. This article synthesizes and builds on existing frameworks to identify essential characteristics of students’ mechanistic reasoning across scientific content areas. We argue that these characteristics can be represented as epistemic heuristics, or ideas about how to direct one’s intellectual work, that implicitly guide mechanistic reasoning. We use this framework to characterize middle school students’ written explanatory accounts of two phenomena in different science content
areas using these heuristics. We demonstrate evidence of heuristics in students’ accounts and show that the use of the heuristics was related to but distinct from science content knowledge. We describe how the heuristics allowed us to characterize and compare the mechanistic sophistication of account construction across science content areas. This framework captures elements of a crosscutting practical epistemology that may support students in directing the construction of mechanistic accounts across content areas over time, and it allows us to characterize that progress.

Mechanistic reasoning, or reasoning systematically through the underlying factors and relationships that give rise to a phenomenon, is a valuable form of human thinking. Using mechanistic reasoning enables one to systematically explain and predict events in multiple areas of the world, including workplace and organizational dynamics (e.g., Senge & Sterman, 1992), environmental consequences of human decisions (e.g., Ben-Zvi-Assaraf & Orion, 2010), and emergent phenomena like traffic jams (e.g., Wilensky & Resnick, 1999). Mechanistic reasoning plays a particularly important role in constructing scientific explanations of natural phenomena. A mechanistic explanatory account moves beyond a pure description of a phenomenon by providing a theoretical account of the regularities behind these empirical observations. This theoretical dimension—proposing and reasoning through potential mechanisms—provides specific ideas that can be tested and evaluated (Darden & Craver, 2002; Nersessian, 1992a; Russ, Scherr, Hammer, & Mikeska, 2008). Because of its power to produce causal explanations and testable predictions, mechanistic reasoning is a hallmark of modern scientific work (Machamer, Darden, & Craver, 2000; Salmon, 1978).

As current reform efforts across education seek to bring disciplinary practices into kindergarten–Grade 12 classrooms, science education reforms—including A Framework for K-12 Science Education (National Research Council, 2012) and the Next Generation Science Standards (NGSS Lead States, 2013)—call for integrating causal, mechanistic thinking as a crosscutting concept into science instruction and for constructing and applying mechanistic accounts as part of building disciplinary knowledge (Lehrer & Schauble, 2006; Schauble, 1996). We define mechanistic reasoning in science contexts more specifically as a particular type of causal reasoning that involves the explanation of (a) the sequential stages, from input to output, of the underlying causal events leading to a phenomenon; and (b) how and why one or more factors behave to give rise to a phenomenon (Louca, Zacharia, & Constantinou, 2011; Machamer et al., 2000; Perkins & Grotzer, 2000; Russ et al., 2008; Springer & Keil, 1991).

When students are engaged in mechanistic reasoning as part of scientific knowledge-building practice, they are doing more than simply learning facts about mechanisms, such as the idea that losing heat can cause a substance to go
through a phase change. Instead, students are focused on investigating a question about a phenomenon that needs an explanation. In doing so, they are thinking through different possible mechanisms and testing to see which best accounts for the phenomenon. This reflects a key aspect of current science reforms: going beyond acquiring science facts and engaging in figuring out what is going on that underlies these facts (Schwarz, Passmore, & Reiser, 2017).

In this way, mechanistic reasoning can provide leverage for students to make progress in constructing explanations of phenomena. Learning to use mechanistic reasoning requires that students both recognize moments when mechanistic reasoning would be helpful and use it in a context in which their knowledge about science ideas is still developing. Supporting students in deciding whether and how to use mechanistic reasoning is an essential part of supporting their participation in explanatory knowledge-building work.

We were interested in understanding whether and how students get better at leveraging core aspects of mechanistic reasoning in constructing scientific accounts within and across science content areas. For instance, does learning to develop a mechanistic account in a chemistry unit give students any advantage when they begin an earth sciences unit? In order to answer this question, we needed to be able to look at students’ construction of scientific accounts in a comparable way across content areas (chemistry, physics, life sciences, and earth sciences) and over long time scales (3 years in middle school). In addition, we wanted to be able to answer this question through individual students’ written artifacts rather than through classroom discourse.

Several existing frameworks for mechanistic reasoning are each well suited for particular aspects of this task. Russ et al.’s (2008) framework for mechanistic reasoning in classroom discourse identifies important structural elements of scientific accounts. This framework emerged from work in closely related content area domains (particle physics and molecular biochemistry), so it was unclear how it might apply to dramatically different science content areas (e.g., ecology or geology). Hmelo-Silver and colleagues’ structure–behavior–function framework (e.g., Hmelo-Silver & Pfeffer, 2004) was designed to evaluate students’ accounts in complex systems environments, including ecology contexts, and it attends more explicitly to the function of a system as a whole than does Russ et al.’s framework. Finally, Wilensky and colleagues’ notion of thinking in levels (Wilensky & Resnick, 1999) has been a critical heuristic or strategy guiding students’ reasoning practices in our work. Although thinking about scalar levels is an important feature of systems thinking, it was unclear how it might play out in mechanistic reasoning.

Thus, this article proposes a framework synthesized across research on mechanistic reasoning and complex systems thinking that helps identify and analyze central epistemic aspects of mechanistic reasoning. More specifically,
the framework helps us characterize how students learn to recognize moments, decide to use, and then engage in reasoning about mechanisms across science content areas and in various forms of interaction, including classroom discourse and written accounts. In addition, this framework orients us to view mechanistic reasoning as an epistemic practice rather than as a set of structural components. We theorize that these central epistemic aspects are a form of practical epistemic knowledge in action (Sandoval, 2005, 2014)—ideas about mechanistic accounts that are not decontextualized, abstract definitions and rules but rather could serve as practical strategies used to guide knowledge-building work. We argue that this practical knowledge can support students in doing science rather than procedurally doing school (Jiménez-Aleixandre, Rodriguez, & Duschl, 2000) and that it can be leveraged to support teachers and students in engaging in productive scientific knowledge-building work. Thus, these strategies are part of students’ epistemologies-in-practice (Berland et al., 2016)—epistemic ideas that guide students’ knowledge-building work.

GUIDING QUESTIONS AND THE GOAL OF THE ARTICLE

This article presents the essential epistemic heuristics for mechanistic reasoning (EEHMR) framework. In alignment with Wilensky and colleagues’ notion of thinking in levels as an important complex systems thinking strategy, we propose that these elements of mechanistic reasoning are heuristics because they are patterned, strategy-like ways of engaging in knowledge-building activity. They are epistemic because they reflect ideas about how to build science knowledge and the form it should take. Finally, they are essential in that they are relevant across the breadth of science content areas. Describing and analyzing mechanistic reasoning in terms of essential epistemic heuristics is a departure from existing frameworks for mechanistic reasoning in that it simultaneously identifies the structure of the knowledge and hypothesizes its role in sensemaking.

In developing this framework, we were guided by two questions:

1. What essential epistemic heuristics can guide students’ mechanistic reasoning across science content area domains?
2. How do these heuristics align with and account for students’ construction of mechanistic accounts, specifically middle school students’ written explanatory accounts?

We address the first question by theorizing and synthesizing from the extant literature on mechanistic reasoning in conjunction with analyses of students’
model-based explanations of scientific phenomena that we collected in contextualized assessment tasks. We then address the second question by applying the framework to students’ constructed accounts in order to examine an epistemic dimension of students’ knowledge-building work.

GUIDING THEORETICAL COMMITMENTS

In theorizing about and looking for students’ use of epistemic heuristics in practice, our development of the EEHMR framework was informed by theoretical commitments about knowledge and learning. Guided by these commitments, we synthesize existing frameworks for capturing mechanistic reasoning (e.g., Hmelo-Silver & Pfeffer, 2004; Russ et al., 2008; van Mil, Boerwinkel, & Waarlo, 2013; Wilensky & Resnick, 1999), drawing on core epistemic components from each that allow us to identify and characterize some essential epistemic elements of mechanistic reasoning across scientific domains. In this section we highlight three commitments and their implications for guiding our work in order to clarify the distinctions in emphasis between existing frameworks and the one we propose.

Epistemic Heuristics Can Guide Students’ Decisions About When and How to Use Mechanistic Reasoning

The first commitment guiding our framework is that mechanistic reasoning is a powerful way of thinking that students can leverage as they are working to make sense of science phenomena. This commitment orients us to think about what guides mechanistic reasoning rather than what makes the resulting account structurally mechanistic. In particular, there are at least two important epistemic decisions that need to be made in the process of constructing mechanistic accounts: when a mechanistic explanation is needed, and how to go about constructing the account. In making these decisions, students draw on epistemic heuristics—pieces of strategy-like knowledge—to guide their reasoning.

We illustrate what using epistemic heuristics could look like with a vignette from a sixth-grade class’s discussion in which students were engaged in providing an account for a phenomenon. This vignette was synthesized from multiple

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1These data were collected across 5 years as part of studies examining students’ participation in science practices (Baek et al., 2011; Berland et al., 2016; Krist, 2016). The lesson during which this discussion took place was the first lesson of the sixth-grade Investigating and Questioning our World through Science and Technology Introduction to Chemistry unit (“How Can I Smell Things From a Distance?”; Krajcik et al., 2008, 2013).
classroom discourse examples that we have observed and collected from sixth-grade classrooms. We created this example based on our data that highlight the kinds of student reasoning moves involved in using epistemic heuristics. In this episode, students were trying to explain how they could smell peppermint across their classroom from a small bottle in one corner.

Before students entered the classroom, their teacher, Ms. D, had placed an opened bottle of peppermint extract in the front right corner of the room. A few minutes into class, Albert raised his hand and exclaimed, “Is it just me, or is there something minty in here!?”

Ms. D asked students to raise their hands if they could smell something minty. Students in the front righthand corner of the classroom had their hands up, forming a rough semicircle of people who could smell the peppermint. Two students insisted that the smell was coming from somewhere near the front or to the right, as that was who could smell it. They ran to the front to search for it, and they eventually found the bottle of peppermint extract.

Ms. D asked students how they thought they were able to smell the peppermint extract and why only some people could smell it. Several students shared ideas, with most converging on the idea that somehow the scent of the peppermint escaped from the bottle, spread out, and traveled around the room. A few minutes into this discussion, Michelle (who was seated in the back of the room) asked why the scent went to Albert and Josh but not to her:

Michelle: But why is it only in some places?
Ms. D: What do you mean?
Michelle: Like if it just escapes and travels everywhere, then how come like Albert could smell it, and Josh could smell it, but I can’t? Because we’re in the same room, with the same air. Like, there’s no wall in between or anything. If it’s going everywhere it should get here too.
Ms. D: So you’re saying, how come the scent went over by Albert, and it went over by Josh, but it didn’t get to you?
Michelle: Yeah. Like how does it know where to go?
Raul: Um, this is to Michelle. I think, I don’t think it knows. I think there has to be something else pushing it. Like, maybe an air current or an air vent or something.
Ms. D: Michelle, do you want to respond?
Michelle: Um. I kind of agree with Raul, but I kind of disagree? Like, it could be an air current pushing it, but then … wouldn’t it all go to one side?
Ms. D: What do you mean?
Michelle: Like, wouldn’t the air vent like always push it one direction? Because like, look at it [the vent in the ceiling]. It’s pointing all
one way. Like it would always push it over to Josh, and never towards Albert, so he would never be able to smell anything. But like, he did. So it didn’t just go over to Josh, it kind of went over there too, like at the same time.

Ahmad: But then how is it moving?
Ms. D: So, Michelle, do you have a different idea about how you think the scent is moving?
Michelle: Maybe like … maybe it’s not like pushing, but maybe the scent is like … attaching itself on the air particles and floating around with them. Like dust.
Ahmad: I’m kind of confused. What do you mean like dust?
Michelle: Like you know in a window when the sun comes in you can see the dust?
Students: Ohhhhhhhhh.
Michelle: Like that.
Ahmad: So the scent is like the dust. Just like floating around.
Michelle: Yeah, maybe. And then it’s just kind of random where it goes, but it takes a while, and that’s why it didn’t get to everyone yet. Just the people who were closer first.

In this example, students started with the idea that the scent from the peppermint bottle somehow had escaped from the bottle and was traveling around the room. This response was not satisfying to Michelle, however. She was confused by an aspect of the phenomenon she observed: Only some people had been able to smell the peppermint, even though everyone was in the same airspace with nothing blocking the scent. She pressed her classmates for a more in-depth explanation for exactly how the scent was moving around that would explain not only that the scent traveled but why it was near Albert and Josh but not near her.

Note that the students seemed to be searching for a mechanistic explanation. This is illustrated through Michelle’s confusion and subsequent press for an explanation about the distribution of the peppermint smell. When students recognized a need for a deeper explanation that fleshed out more of the step-by-step chain of cause and effect, they drew on heuristics about the kind of account that was appropriate and satisfying for what it was they were trying to explain. In this vignette, Michelle was not satisfied with a descriptive account of scent leaving the bottle and traveling around. She pressed for something deeper about how it was doing so.

Another important aspect of this vignette is how students went about constructing and evaluating a mechanistic account, illustrated in Raul and Michelle’s interactions. Raul responded to Michelle’s dissatisfaction with a candidate mechanism: He said that there had to be something else pushing the scent, and he suggested an air current from a vent in the room. Michelle
responded by imagining what would happen if that were true. In doing so, she noticed that the slats in the air vent in their classroom were all slanted the same way, so the air current from it would always be moving in the same direction—toward Josh. She was concerned that an air current from an air vent did not fully explain how both Josh and Albert could smell the mint at the same time.

We suggest that when students participate in cycles of proposing and evaluating mechanistic ideas, they draw on heuristics about how to go about constructing and evaluating a mechanistic account. In this vignette, Raul proposed a factor (air currents) that was not part of their descriptive account and a process (pushing the scent) by which that factor could give rise to the phenomenon they were trying to describe. Michelle then imagined how this factor and process would play out, checking to see whether it could fully give rise to the phenomenon at hand. When it could not, Michelle pointed out the problem. We suggest that these epistemic heuristics helped guide this process, even though the students lacked the specific disciplinary knowledge of the properties of gases and particle motion to develop a fully plausible causal account.

Our framework aims to articulate more specifically (a) some of the essential heuristics that students regularly use in response to these two important epistemic decisions about whether and how to construct mechanistic accounts and (b) how the use of these heuristics might show up within and across content areas and in both classroom discourse and written accounts. In focusing on the heuristics that guide key decisions rather than identifying the structure of the accounts, this framework takes on a different emphasis than existing frameworks for mechanistic reasoning, yet one that is also consistent with these frameworks. For example, the intervention that Vattam et al. (2011) designed to support students’ reasoning had a theorization about how students should go about constructing an account built into the design: They included a “Behavior” level visual representation as an “intermediate abstraction between structure and function” of a system (p. 68), with the implicit assumption that students should conceptually link how particular structures of entities can give rise, over time, to a system-level function. Our framework aims to make these implicit aspects explicit.

By naming only a few specific epistemic heuristics, we do not intend to diminish the messiness and complexity involved in mechanistic reasoning. This vignette demonstrates how mechanistic reasoning is neither clean cut nor linear. Instead, we are proposing core heuristics that we have observed across content areas as necessary components involved in building mechanistic accounts. It is in this sense that we call the heuristics we identify the “epistemic essentials” for doing the work of constructing mechanistic accounts.
Epistemic Heuristics Are Pieces of Implicit, Strategy-Like Knowledge That Guide Practice

The second guiding commitment involves the nature and ontology of epistemic heuristics. We propose that these heuristics are a form of strategic knowledge. Rather than viewing epistemic heuristics as explicit knowledge that students hold, we view them as an internalized discourse routine instantiated in practice (Forman & Ford, 2014; Thompson, Windschitl, & Braaten, 2013). Classroom communities, particularly science classrooms, use particular forms of language and discourse that carry with them particular norms and epistemological assumptions (Gee, 2014; Kelly, 2007). Students and teachers in the classroom community negotiate the various discourses and their related assumptions present in the classroom, such as whether students are sharing ideas, whether they are arguing to figure something out, or whether the teacher is providing information and answers (e.g., Berland & Hammer, 2012). In this way, various epistemological stances, aims, and commitments (Chinn, Buckland, & Samarakunhavan, 2011; Hammer & Elby, 2002) emerge and are negotiated through talk and interaction in context (Wickman, 2004).

Our choice of terminology emphasizes our view of epistemic cognition as being situated in practice (Berland et al., 2016; Kelly, 2011; Östman & Wickman, 2014). We use heuristics to emphasize that we are identifying patterned ways of engaging in knowledge-building activity that reflect underlying, implicit understandings about the disciplinary knowledge and knowledge-building practices that are expected and appropriate in context. That is, these heuristics help guide the explanation process in generally helpful directions, helping to generate plausible ideas even in the face of lacking knowledge about specific mechanisms that would explain the phenomenon (such as how particles behave). We posit that it is through discursive and interactional classroom processes and routines that students can come to understand that particular discourse cues in context are asking for a response of a particular nature (e.g., mechanistic). They are picking up on and responding to the epistemic frames, and the related discourse routines that these frames cue, that are used consistently in their classroom context (Hammer, Elby, Scherr, & Redish, 2005; Scherr & Hammer, 2009).

However, we also use the term heuristics to signal something more specific than the epistemic frames typically described in the literature (e.g., memorizing things vs. sensemaking; Elby & Hammer, 2010; Rosenberg, Hammer, & Phelan, 2006). We are describing a particular aspect of the sensemaking of doing science—a part of doing science that recognizes mechanistic explanations as an important structure for scientific accounts (Kapon, 2017). We think of these heuristics as akin to Collins and Ferguson’s (1993) notion of an epistemic game, or a set of implicit rules to follow in order to flesh out a mechanism. It is important to note
that we argue that knowledge of epistemic heuristics, or the specific rules of this particular epistemic game, need not necessarily be explicit. Many students may be able to draw on this knowledge implicitly: picking up on a discourse routine, imitating it, and using it to do similar kinds of work (including answering written assessment items asking them to explain phenomena in different content areas; the relationship between heuristics situated in practice and those evident in written work is discussed in more detail in the Assessment Item Development and Administration section). Thus, we view a student’s decision that a mechanistic response is appropriate to be an implicit recognition of an epistemic frame in context and subsequent implementation of a discourse routine.

Mechanistic Sophistication as a Descriptor of Process and Structure Rather Than a Descriptor of Content Knowledge

The third guiding commitment is that particular epistemic heuristics guide the building of sophisticated mechanistic accounts. In deciding what counts as a more sophisticated mechanistic account, we follow Russ et al. (2008), who identified the mechanisticness as a descriptor of the structure of the account rather than a descriptor of the particular knowledge elements that the account contains. The implications of this are that an account can be structurally mechanistic (e.g., explain how and why a phenomenon occurs based on proposed underlying processes) but canonically incorrect. For example, Michelle’s account of scent traveling by “attaching itself on the air particles and floating around with them,” perhaps elaborated to include the idea that the scent particles and air particles attract like magnets when they get close enough to each other, is structurally mechanistic, even though it is not scientifically accurate. Undoubtedly these dimensions are related; Kapon (2017) argued for these, along with framing, as dimensions of a multidimensional framework for characterizing sensemaking. In this article, we aim to characterize the sophistication of students’ accounts based on the extent to which they are structurally mechanistic.

Our framework depends largely on Russ and colleagues’ (2008) characterizations for identifying the structural components of a mechanistic account, with adaptations made to address particular problems that arose in attempting to compare the sophistication of students’ mechanistic reasoning across science content areas. To address these problems, we drew on Wilensky and colleagues’ notion of thinking in levels (Jacobson & Wilensky, 2006; Wilensky & Resnick, 1999) and on Hmelo-Silver and colleagues’ description of system states that result from combinations of behaviors in

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2 We acknowledge that Wilensky and colleagues’ work and Hmelo-Silver and colleagues’ work come from very different theoretical traditions with respect to complex systems thinking (Yoon, 2018). We are focusing on these specific perspectives because they have been instrumental in supporting our thinking about mechanistic reasoning.
complex systems playing out over time (Hmelo-Silver, Marathe, & Liu, 2007; Hmelo-Silver & Pfeffer, 2004) to transform Russ et al.’s structural components into heuristics. We describe these transformations in more detail after the presentation of our framework.

We posit that the epistemic heuristics in our framework are the essential pieces that students carry with them and use across content areas that guide and direct the work of fleshing out a specific mechanism. When we describe mechanistic sophistication, we refer to the degree to which a response includes evidence of alignment with developing a causal explanatory account. The more essential elements or heuristics it contains, the more sophisticated the mechanistic process evident within the response.

We also acknowledge that other structural forms of scientific accounts have led philosophers of science to disagree that causal mechanisms are the gold standard of scientific explanation. These include accounts that identify and draw on loose coupling of events and functional equivalence to more fully explain evolutionary advantage (Simon, 1977); accounts involving feedback loops, such as those involved in homeostasis, that require considering the state of the system as causing a subsequent cascade of interactions (Bechtel, 2011; Moshman & Tarricone, 2016); and accounts of distributed and decentralized causality that require connecting together seemingly unrelated events or causal chains in complex ways (Grotzer, Derbiszewska, & Solis, 2017). Although the framework presented here is not explicitly designed to capture this breadth of forms, we consider the three epistemic heuristics presented here to be epistemic essentials, critical foundations for constructing mechanistic accounts. They are likely not sufficient for describing all complex phenomena. We encourage the continued refinement and elaboration of this framework to advance the field.

PROCESS FOR FRAMEWORK DEVELOPMENT AND VALIDATION

The development of this framework occurred in two phases. First, as part of a larger research project focused on identifying and characterizing students’ epistemologies-in-practice (see Berland et al., 2016), we developed draft rubrics for capturing the nature of the accounts that students constructed in science class (Scientific Practices Research Group, 2015). In parallel, we conducted a literature review of mechanistic reasoning drawing from science studies, psychology, and education. We then compared the literature to identify candidate heuristics related to reasoning mechanistically. This synthesis resulted in an initial draft of this framework.

Second, we developed assessment items (revised iteratively based on the data and frameworks) that asked students to provide written explanatory accounts of phenomena. Students’ responses contained indicators of the epistemic heuristics they (tacitly) drew on to construct a scientific account during the task. More detail about the design of these items is provided in the next section.
We collected responses from 1,837 students in 31 teachers’ classrooms from eight schools in three states for 12 middle school science units that were part of the Investigating and Questioning our World through Science and Technology curriculum (Krajcik, Reiser, Sutherland, & Fortus, 2013). To develop and revise the framework, we began by analyzing students’ responses to items developed for a sixth-grade chemistry unit focused on the mechanisms of particle motion that give rise to the behavior of gases. After a round of revisions, we then applied the framework to responses to sixth-grade biology items that focused on mechanisms related to population dynamics. We revised the framework as needed, then reanalyzed the chemistry items. The resulting framework is presented here. In this article, we present data from these two units. We have since used this framework to analyze responses from the 10 remaining Investigating and Questioning our World through Science and Technology units.

We assessed both face validity and construct validity of this framework. In assessing face validity, we wanted to ensure that the heuristics we identified were relevant for mechanistic reasoning in that they were associated with higher quality scientific accounts. To assess this relationship, a team of external evaluators recruited science faculty members to complete a ranking task in order to confirm that our characterization aligned with the ways in which scientists generally evaluate the quality of scientific reasoning (Esch & Smith, 2016). Each faculty member scientist (two chemists and two biologists) received two 8-item sets of student responses within his or her respective domain of expertise and was asked to rank them based on the quality of the reasoning. The external evaluation team then compared the scientists’ rankings to our scoring of these same items. The scientists agreed or moderately agreed with our scoring for all 32 chemistry responses and for 27 of the 32 biology responses. The five biology responses for which the scientists strongly disagreed with our rankings were items that we had ranked as low mechanistic sophistication and the scientists had ranked highly, typically because they were giving credit for implicit elements in their responses that our scoring required to be present explicitly. Overall, this external evaluation suggested that our framework was generally in alignment with, and sometimes more conservative than, scientists’ intuitive rankings of the quality of scientific reasoning.

In assessing content validity, we aimed to determine whether our framework captured epistemic aspects of reasoning consistent with the literature on epistemologies. In particular, we drew on a resources perspective (Hammer & Elby, 2002, 2003; Louca, Elby, Hammer, & Kagey, 2004) that conceives of epistemologies as multifaceted and context dependent and thus relevant for guiding the

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3We were less concerned with content validity with respect to mechanistic reasoning because we drew on these literatures heavily in developing our framework, which contains components from multiple existing frameworks. Therefore, it did not make sense to do comparative coding.
nature of students’ work (e.g., Sandoval, 2005, 2014). This perspective suggests that traces of the epistemic ideas guiding students’ work should be visible in the products of that work. To verify that we were identifying epistemic aspects of students’ explanation-construction process, we selected incorrect or noncanonical responses that attempted to explain how and why something occurred. We characterized these responses using our framework to ensure that they would receive a nonzero score for mechanistic sophistication. This ensured that we could see evidence of highly mechanistic, but canonically incorrect, responses that would be considered mechanistically sophisticated according to our framework.

Assessment Item Development and Administration

To develop and refine this framework, we used pre- and postunit assessments from sixth-grade content areas in chemistry (particle model of matter) and biology (ecosystems). Students taking these assessments were part of a larger study investigating their participation in scientific practices. Their classrooms were in eight different schools in three different Midwestern states (five in Illinois, one in Michigan, and two in Ohio). The schools all used curriculum materials designed to engage students in scientific practices through project-based learning (Baek, Schwarz, Chen, Hokayem, & Zhan, 2011; Krajcik, McNeill, & Reiser, 2008; Krajcik et al., 2013). We designed all pre- and postunit assessment items across content areas to include three features:

1. **A core mechanism from the unit.** Each item focused on a core mechanism that students worked out during the unit. For example, the strawberries item in Table 1 focused on the mechanism for phase changes.

2. **A familiar but new cover story.** After selecting the core mechanism from the unit, we selected a phenomenon that students had not discussed extensively in the unit, according to the curriculum materials. We developed two cover stories for each core mechanism and counterbalanced the cover stories. For example, the companion cover story for strawberries was a similar story about candle wax hardening on a birthday cake. A student who received the strawberries item on the pretest received the candles item on the posttest.

3. **A comparison highlighting where to dig in, or what to focus on in the explanation.** We built in a comparison, either over time or between two nearly similar phenomena, to highlight the aspects of the phenomenon in need of explanation. For example, the strawberries item highlighted a comparison over time of the state of the chocolate.

We selected these three features to intentionally simplify and reduce the focal phenomena in a way that framed the questions as contexts in which mechanistic reasoning would be useful. Doing this ensured that we would obtain responses that
could be analyzed for epistemic heuristics. However, we acknowledge that by focusing our assessment questions, we limited the kinds of reasoning in which students were likely to engage. For example, our questions made it unlikely that students needed to reason about distant causes or multiple interacting mechanisms. Thus, our framework does not take into account the presence or absence of such types of reasoning in analyzing students’ responses.

We also note the tensions inherent in using assessment data to make claims about epistemic heuristics. In particular, there is tension between viewing epistemic heuristics as situated, social, and context dependent and our method of identifying them in an individual assessment task. We know that the assumptions and expectations that students bring to assessments are different from those that they bring to their classroom discussions or small-group work activities. Thus, the kinds of epistemic heuristics these data illustrate are contextualized to these assessments. For example, students are more likely to view the kind of answer they should provide on an end-of-unit test to be a final-form one rather than viewing the assessment task as an opportunity to play with ideas. As a result, we were not likely to see heuristics related to in-process evaluations and decisions about how well an idea works. In addition, removing the social context may have limited our access to heuristics students may leverage in negotiating the social dynamics involved in account construction.

At the same time, these assessments do allow access to what students perceive is an acceptable kind of account in response to a low-stakes assessment item. Accordingly, we designed the questions to reflect how and why questions that paralleled those in the

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**TABLE 1**

**Mechanistic Reasoning Assessment Items**

<table>
<thead>
<tr>
<th>Sixth-Grade Chemistry: Strawberries</th>
<th>Sixth-Grade Biology: Squirrels</th>
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<tbody>
<tr>
<td>Elise and Fred helped their mom make chocolate covered strawberries. They dipped the strawberries in melted chocolate and placed them on the counter. The melted chocolate hardened on the strawberries after a while. [Draw a model (diagram)/Construct a scientific explanation] that answers the question “How and why did the melted chocolate harden on the strawberries?”</td>
<td>For a long time, red squirrels were the main type of squirrel in the United Kingdom. However, in the late 19th century, gray squirrels from North America entered the country. The gray squirrels spread rapidly throughout the country and replaced the red squirrels in many parts of the UK. Today, more than 2.5 million gray squirrels live in the UK compared to only 160,000 red squirrels. Both types of squirrels eat nuts, insects, and berries. Only gray squirrels can eat acorns.[Draw a model (diagram)/Construct a scientific explanation] that answers the question “How and why did the red squirrel population go down in the late 19th century?”</td>
</tr>
</tbody>
</table>

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*Note. At the time of each administration, half of the students received the item with a modeling stem and the other half received the explanation stem. UK = United Kingdom.*
curriculum units, using the kinds of language and phrasing teachers and students had typically used. In this way, we hoped that the questions would cue a similar kind of frame with respect to the nature of the account as students had been working on in class.

In presenting our findings, we focus on two assessment items: the strawberries and squirrels items (see Table 1). All students in our study ($n = 805$) completed these items in sixth grade (mostly in years 2012–2013). Students completed the strawberries item in January (pre) and March (post) and the squirrels item in March (pre) and May (post). In total, we had 514 responses to strawberries items and 384 responses to squirrels items. Because of the counterbalancing of cover stories, we expected to receive one response to each of these items per student participating in the study (a total of 805 responses per item). Missing data were the result of student absences and/or specific teachers or class periods not completing the pre- or posttest. In particular, three sixth-grade teachers either did not enact the biology unit (and therefore did not administer the pre- and posttests for that unit) or did not enact enough of the unit to build one of the core ideas (e.g., less than one third of the lessons) and therefore opted not to administer the posttest.

**EEHMR ACROSS SCIENCE DOMAINS**

The goal for this framework was to identify the epistemic heuristics evident in students’ work that indicated whether and how they decided to engage in reasoning about mechanisms: Did students utilize the epistemic essentials to indicate that they were working to construct explanatory accounts? If so, in what ways did they do this?

Here we describe the three essential epistemic heuristics that make up our framework: (a) considering what occurs at the scalar level below the level of the observed phenomenon, (b) identifying and characterizing the relevant elements at that lower level, and (c) coordinating those elements over space and/or time to see whether and how they give rise to the observed phenomenon. These three elements are illustrated in Figure 1. In this section, we describe each of these heuristics and consider how they are evident in both physical and life sciences contexts.

**Thinking Across Scalar Levels**

The first epistemic heuristic essential to mechanistic reasoning is that students think across scalar levels. Most definitions of mechanistic reasoning (e.g., Grotzer & Perkins, 2000; Machamer et al., 2000) use the term *underlying* to describe the kinds of things that must be identified and characterized in order to
explain a target phenomenon. We argue that explaining a phenomenon by identifying the underlying causes involves thinking at least one scalar level below the level of the target phenomenon. For example, in an explanation of how and why the melted chocolate hardened on the strawberry, the observable phenomenon in question is at the level of substances and mixtures. In order to explain this phenomenon, students need to move down to the molecular level and consider the relevant interactions and properties of molecules that could lead to a phase change.

Thinking across scalar levels is a nontrivial task. Especially for younger children, identifying that there is a nonvisible entity, such as that water is actually made up of smaller pieces called molecules, is an important step in doing mechanistic reasoning (Schwarz et al., 2009). In addition, many phenomena are emergent, or not immediately obvious or intuitive from the interactions and behaviors of the underlying entities (Jacobson & Wilensky, 2006; Perkins & Grotzer, 2000). Wilensky and colleagues have advocated for thinking in levels as key to building explanations: being able to move between an emergent phenomenon, such as evaporation, and an agent level, such as that of water particles and their individual behaviors and properties (first described in Wilensky & Resnick, 1999). In addition, they have argued that levels slippage, or conflating the behaviors and properties of agents at one level with those at a different scalar level, underlies many errors in student reasoning (e.g., Levy & Wilensky, 2009; Sengupta & Wilensky, 2009; Wilensky & Reisman, 2006). Building from this work, we identify this strategy—considering what is going on at the scalar level below the level of the observed phenomenon—as an important epistemic heuristic guiding students’ construction of mechanistic accounts.
Another form of thinking across levels occurs when abstract or nonmaterial factors are involved, such as energy or forces. These abstract factors often came about from the need to invent a theoretical entity, such as electrons, to fully explain phenomena scientifically (Brown, 2012; Nersessian, 1992b). Some of these entities, such as energy, are theoretical but measurable in indirect ways. Keeping track of them helps provide explanations for what is going on in the world. Thus, students may also bring in theoretical or abstract entities that are not necessarily at a scalar level below but are also not directly observable in the phenomenon itself. Identifying these abstract entities requires similar epistemic work in that it requires students to move across degrees of abstractness in identifying and representing causal factors.

The format of our assessment items asked students to explain (rather than predict) phenomena, and it intentionally simplified the contexts of the phenomena in order to focus their attention on a particular mechanistic aspect. Therefore, in these items we looked for students to move to the scalar level below that of the phenomenon in order to explain it mechanistically. This is also a partial description of the kinds of conceptual work that students may need to do in less bounded contexts. For example, contexts that attempt to engage students in more complex reasoning about dynamic systems often require moving to scalar levels above that of the aggregate phenomenon (e.g., Witherington’s, 2011, description of homeostasis) or looking for causal connections that are at the same scalar level but distantly related to the phenomenon, and therefore it is not immediately obvious that or how they are involved in the causal story (e.g., Grotzer et al.’s, 2013, description of students explaining how lawn fertilizer affected fish die-off). We leave open to further investigation when and how moving up or laterally across scalar levels is a relevant epistemic heuristic and how that kind of reasoning relates to the mechanistic reasoning we describe here.

Identifying and Unpacking Relevant Factors

Once students move down to a lower scalar level or consider abstract factors, they have to figure out what is there and how it behaves. The second epistemic heuristic essential to mechanistic reasoning involves this process. Students need to identify and use “properties, entities and rules introduced that are not part of the surface situation but account for it” (Grotzer & Perkins, 2000, p. 5). Identifying what is happening there is not necessarily intuitive. Doing so requires not only having some degree of specialized disciplinary knowledge but also recognizing which elements are relevant given the specifics of the phenomena in question.
Understandably, this is where much existing work characterizing mechanistic reasoning focuses. We diverge briefly from elaborating this heuristic to discuss examples from the literature that have characterized work on mechanisms in contexts at very different scalar levels. We focus here on the physical sciences, which often involve nonvisible entities, and on ecological phenomena in the life sciences, which do not. Although these examples draw on different frameworks and use different language to characterize students’ mechanistic reasoning, we draw parallels in order to identify epistemic similarities in relevant thinking processes.

**Entities, Properties, and Rules in the Physical Sciences.** Often students must identify and use nonvisible entities such as particles to describe the interactions and relationships that give rise to physical phenomena. For example, in mechanistic reasoning about how and why water condenses on a cold ice pack, the aggregate (i.e., visible) phenomenon is at the level of substances and materials. Students must move down a scalar level, to the molecular level, and identify air particles and water vapor particles as key entities. They then must also identify properties of those entities, such as the relative temperatures of the ice pack, the air, and water vapor. They then have to figure out what those particles are doing and how they behave, generally by identifying rules or principles such as “Colder particles move more slowly” or “Air and water vapor particles are always moving.” Identifying entities, properties, and rules are important pieces of students’ mechanistic reasoning in process (Russ et al., 2008), including inventing or theorizing entities if they are not easily observable (e.g., Wilkerson-Jerde, Gravel, & Macrander, 2015).

Phenomena in the physical sciences do not all involve nonvisible entities. These phenomena can also involve visible entities, often involving objects such as carts on a ramp or simple machines. Mechanistic explanations for these types of object systems involve decomposing the system into its (visible) object components (e.g., naming specific structures) and identifying the relevant properties or rules associated with those objects, such as noting that the slope matters or describing a relationship such as higher slopes seem to make a cart go faster. Then, similar to phenomena with nonvisible entities, students must coordinate interactions between these objects, properties, and rules and keep track of the aggregating effects of interactions between objects. For example, as a cart moves down a ramp, the slope of the ramp affects the cart’s velocity. Within this system, students must identify the slope of the ramp, the position of the cart,
and the cart’s velocity (as well as gravity, an abstract factor) as relevant properties affecting the cart’s motion. They then must unpack these factors by identifying how they matter: As the cart continues moving down the ramp, the velocity continues increasing because of the continuous pull of gravity (e.g., Bolger, Kobiela, Weinberg, & Lehrer, 2012; Louca et al., 2011).

In both cases, the critical work required to develop mechanistic accounts in these physical science contexts involves identifying entities and properties of those entities, characterizing the behaviors of those entities, and characterizing the impact of interactions between entities on the properties of those entities. This is true for phenomena involving both visible and nonvisible entities. However, these examples also are all sufficiently explained by articulating how individual entities are interacting with one another at the lower scalar level. This is often not the case in other areas of science, especially in the life sciences involving population-level or ecosystems phenomena. We discuss next how examples of mechanistic accounts from these fields have been described in the literature in order to elaborate epistemic parallels to mechanistic accounts in the physical sciences.

Entities, Properties, and Rules in the Life Sciences. Most literature characterizes student learning about ecosystems as complex systems thinking rather than mechanistic reasoning. Although there are multiple ways of framing complex systems thinking (see Yoon, 2018, for a recent synthesis), a number of components across these perspectives are considered central to complex systems thinking. Specifically relevant for this article is that complex systems thinking involves integrating across multiple (visible) levels (Hmelo-Silver & Azevedo, 2006; Jacobson & Wilensky, 2006) and considering multiple causal relationships (Grotzer & Basca, 2003) in order to explain a target phenomenon. We draw on one particular framework, the structure–behavior–function framework (Hmelo-Silver & Pfeffer, 2004; Vattam et al., 2011), to draw epistemic parallels between ecosystems examples and the physical sciences examples. Empirical work derived from this framework helps to highlight the essential work that students do when constructing mechanistic accounts at an underlying scalar level when that underlying level is still visible.

When explaining ecological phenomena such as changes in squirrel populations (a cover story from our assessment items) or new plants in a garden patch (Manz, 2012), the causal entities are often themselves entity-behavior relationships. In each of these ecosystem-level examples, the entities are individual organisms: an individual squirrel or an individual seed. The properties of these entities are often their behaviors, such as “Gray squirrels eat berries, insects, and acorns.” In the physical systems discussed above, playing out these kinds of behaviors and interactions is key to explaining the mechanism. However, in
these ecological contexts, characterizing these entity-behavior relationships is really only identifying the structure of the ecosystem (Vattam et al., 2011). To explain the dynamics of or changes in that ecosystem, students need to play out and coordinate the behaviors and interactions of multiple entity-behavior relationships.

In other words, rather than taking an individual entity (e.g., a squirrel) as the causal unit, reasoning about ecological phenomena requires considering the entity and its behavior as a single factor—which Tretter, Jones, Andre, Negishi, and Minogue (2006, p. 286) called “unitizing.” An example of a unitized entity-behavior relationship is “Gray squirrels eat acorns and berries.” Entity-behavior relationships can also involve spatiotemporal relationships that include ideas such as “Plants produce seeds” and “Seeds grow into new plants” (as described by Manz, 2012). These unitized relationships and properties then become the entities that students use to reason about causality.

Treating entity-behavior relationships, or the structures of a system, as unitized entities allows us to identify some parallels to mechanistic reasoning in phenomena at smaller scalar levels. In both cases, students follow this second epistemic heuristic: identifying and characterizing relevant elements at a scalar level below that of the target phenomenon. However, depending on the content area, the nature of the elements differs. In the physical sciences, these elements are often individual entities or agents, whereas in the life sciences the elements are often unitized relationships between agents and properties. Thus, we use the term factor to refer generally to the relevant elements at the scalar level below that of the aggregate phenomenon. Similarly, we refer generally to the intellectual work involved in characterizing the relevant properties, rules, and behaviors of factors as unpacking those factors.

We acknowledge that in collapsing some distinctions between individual agents, their properties, and their organizations we are ignoring important aspects of the diversity and complexity involved in mechanistic reasoning. In addition, we are glossing over several key difficulties in complex systems thinking, such as the centrality of emergence (Jacobson, 2001) and the importance of reasoning about system states in addition to structures and processes (Yoon, Goh, & Park, 2018). This is not because we think these aspects are unimportant or irrelevant to students’ epistemic work or to mechanistic reasoning. However, as this framework aims to identify epistemic essentials, we have collapsed important differences in order to identify broad patterns of epistemic activity that characterize mechanistic reasoning across content areas.
Linking to Coordinate Relationships Over Time and/or Space

Finally, the third heuristic essential to mechanistic reasoning involves checking how well the underlying mechanisms fit the observed phenomenon. Once students have identified and characterized the relevant entities, properties, and rules, they then must play out and coordinate these relationships, developing a chain of causes and effects as they occur over time and/or space. In order to fully account for the phenomenon, part of the coordination involves connecting those effects back up to the phenomenon at the original scalar level. For example, does a model in which warmer particles end up farther apart from one another explain how someone can smell something faster when it is hot outside?

In this way, the work of engaging in mechanistic reasoning is a form of model-based reasoning. A model consists of “elements, relations, operations, and rules governing interactions that are expressed using external notation systems” (Lesh & Doerr, 2003, p. 10). Cognitively speaking, the expression of these ideas—the elements, relations, operations, and rules—comes from (or is part of the process of simultaneously coconstructing) a model that explains the phenomenon. Thus, the cognitive work involved in this portion of mechanistic reasoning involves constructing and playing out these models of the elements and relationships of underlying features, often over time or across physical space, to see how they then link back up or give rise to the phenomenon in question (Passmore, Gouvea, & Giere, 2014). This characterization is similar to Hmelo-Silver and Azevedo’s (2006) description of system states and Russ et al.’s (2008) description of chaining. However, in addition to the temporality of the sequences, we emphasize the vertical linking across scalar levels involved in playing out an explanation. Because the nature of the entities differs between content areas, we again consider what this linking looks like in the context of the same examples in the physical sciences and the life sciences.

**Linking in the Physical Sciences.** In an example described by Wilkerson-Jerde et al. (2015), a pair of students invented a particle-like entity (an oogtom) to represent how an odor traveled. After agreeing on the properties and rules for oogtoms, the students played out the effects of those properties and rules on the aggregate phenomenon, supported by a computer simulation. They noted that a smell died down after a while and decided that the person smelling the odor consumed the oogtoms when they hit her. This linking—moving back and forth between playing out the interactions and behaviors of the oogtoms at the particle level and the aggregate effect of those interactions and behaviors at the observable substance level—allowed for rich inquiry into the mechanisms at play and helped the students explore explanations for the key aggregate effects.
**Linking in the Life Sciences.** Similarly, in explaining ecological phenomena, students must coordinate one or more entity-behavior relationships with various properties of those relationships and how they might aggregate over time in order to explain what Vattam et al. (2011) called the function of the system, or the system-level outcomes. For example, the ecological system in the forests of England that are home to squirrels includes system-level properties like the amount of food and the number of each type of squirrel. These properties cycle back and affect the entity-behavior relationships: When additional squirrels are added, they eat the food, so the total amount of food available decreases; when squirrels do not have food, they die, so the number of squirrels decreases. This cyclical behavior can be visualized as a series of snapshots of system states that describe the properties of the system at any given moment (Vattam et al., 2011). Engaging in mechanistic reasoning about these types of phenomena involves coordinating entity-behavior relationships or properties with system states into a chain-like sequence of events, connecting several interactions together over space or time. Ultimately, explaining how and why the red squirrel population decreased involves playing out the effects of a competitive relationship for food between individual red and gray squirrels and how that relationship affects or gives rise to the system-level outcomes—in this case, a drop in the relative size of the population of red squirrels after the gray squirrels started competing for food.

In each example, playing out conjectured models of the entities, properties, behaviors, and relationships over space and/or time is a critical component of mechanistic reasoning. This third heuristic supports the construction of mechanistic explanatory accounts, rather than simply the characterization of mechanisms, by constructing a causal chain to reflect how the unpacked factors give rise to the observed phenomenon. This heuristic involves linking back up from the interactions at the underlying level to the level of the target phenomenon and investigating whether the entities, properties, behaviors, and relationships fully account for the observed phenomenon.

**COMPARING THE ESSENTIAL EPISTEMIC HEURISTICS FRAMEWORK WITH ELEMENTS OF MECHANISTIC REASONING FROM RUSS ET AL. (2008)**

We now briefly revisit how the three heuristics in our EEHMR framework compare with Russ et al.’s (2008) framework, to which our framework is most similar but differs in a few critical ways. These differences reflect two challenges that arose when we attempted to compare the sophistication of students’ mechanistic accounts across science content areas. In response to
these challenges, our framework organizes the elements identified in the Russ et al. framework differently, as displayed in Table 2.

One difference in organization involved collapsing some of Russ et al.’s identification codes. We collapsed these categories as we compared students’ responses and found that slight differences in question prompts emphasized different elements. For example, in the strawberries item from the sixth-grade chemistry unit and in a question that asked how and why students could smell popcorn from across the room (also from the sixth-grade chemistry unit), the identification of a chocolate or popcorn particle as an entity was critical to the explanation (Russ et al.’s code of identifying entities; see Table 2). However, in one context a property of that entity was critical (the change in temperature and its effect on chocolate particles), whereas in the other the organization of entities was critical (the spatial organization of popcorn particles in space and over time). In other question contexts, we explicitly stated the relevant entity in the question prompt. In those cases, the work students had to do was to reason through the effects of properties of entities, the organization of entities, or both. In addition, regardless of the type of element students were reasoning about, the work they were doing with these elements reflected the same goal: identifying a key feature necessary for explaining the phenomenon.

In response, we collapsed the codes of identifying entities, identifying properties of entities, and identifying organization of entities into one category: identifying factors (see Table 2). We maintained identifying activities as an important distinct category that represented a shift we noticed in pilot responses between simply naming a factor (the chocolate got colder) and actually thinking about how it might play out (e.g., how does the change in

<table>
<thead>
<tr>
<th>Russ et al.’s Code</th>
<th>Our Code(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Describing the target phenomenon</td>
<td>Not included; already identified in question prompts</td>
</tr>
<tr>
<td>Identifying setup conditions</td>
<td>Identifying factors (distinctions maintained within individual coding guides)</td>
</tr>
<tr>
<td>Identifying entities</td>
<td>Unpacking factors</td>
</tr>
<tr>
<td>Identifying properties of entities</td>
<td>Multiple levels: consider the scalar level below</td>
</tr>
<tr>
<td>Identifying organization of entities</td>
<td>Linking: connecting interactions to the scalar level above</td>
</tr>
<tr>
<td>Identifying activities</td>
<td></td>
</tr>
<tr>
<td>Chaining: backward and forward</td>
<td></td>
</tr>
</tbody>
</table>

TABLE 2
temperature affect particle motion?). So that it could be applied regardless of
the type of factor identified, we called it unpacking factors.

Another difference in organization involved additional specification
around Russ et al.’s chaining code. As we compared responses across
science content areas, the chaining code was not specific enough to be
able to help us differentiate variation in how students were talking about
the mechanisms. For example, in the context of the squirrels item, one could
count a gray squirrel as an entity. A relevant property of this entity is that it
can eat berries, insects, nuts, and acorns. Its relevant activities are eating,
reproducing, and dying. One could also consider it to be chaining if one
connected the availability of an additional food source (acorns) to squirrels’
ability to eat them and not die.

We initially coded students’ responses to the squirrels item this way, but
almost every student received scores for a fully mechanistic account despite
large differences in the intuitive quality of students’ mechanistic accounts. In
particular, some students attended to only the activities of individual squir-
rels and their survival or death within one generation, whereas others
recognized this as a cyclical process occurring across multiple generations,
a biologically important difference (Mayr, 1961). So although chaining
together activities in sequential steps was a sufficient characterization in
our chemistry and physics contexts, this coding did not necessarily disam-
biguate responses in this ecology context, making it an inaccurate way to
compare the quality of the mechanisms in students’ responses across these
content areas.

Instead, we noted that we were less interested in the sequential chaining
of activities of an individual squirrel, such as “A red squirrel can’t eat
acorns, so it can’t find food, so it dies.” We were much more interested in
a student’s chaining that connected those individual behaviors back to the
dynamics of the squirrel population: “When gray squirrels survive, they can
reproduce, leading to more and more squirrels, until eventually there are
more gray squirrels than red.” As we examined this difference and compared
it to similar differences in chaining in physical sciences and in earth
systems, we recognized that the differentiation was about scalar levels. In
the first type of chaining, the student remains at the same scalar level: that
of individual squirrels and their individual actions. In the second example of
chaining, the student moves back up to the scalar level of populations,
linking together how individual squirrel actions contribute to aggregate
population dynamics. This second response was also more akin to linking
together how molecular actions and interactions contribute to aggregate
phenomena such as evaporation.
To better capture this distinction in a parallel way across science content areas, we reframed chaining as activity requiring moving across scalar levels. Accordingly, rather than coding for chaining, we coded for multiple levels (i.e., Did they move to the scalar level below?) and linking (i.e., Did they connect how underlying interactions gave rise to the aggregate phenomenon?).

APPLICATION OF THE FRAMEWORK TO STUDENTS’ MECHANISTIC ACCOUNTS IN CHEMISTRY AND ECOLOGY

In this section, we address our second question—How do these heuristics align with and account for students’ construction of mechanistic accounts?—by applying the epistemic heuristics to characterize sixth-grade students’ accounts in response to our strawberries and squirrels items. In doing so, we are looking to characterize students’ sophistication with respect to the process of constructing mechanistic accounts: whether students utilize the essential epistemic heuristics and in what ways.

TABLE 3
Summary of Essential Epistemic Heuristics for Mechanistic Reasoning

<table>
<thead>
<tr>
<th>Heuristic</th>
<th>Use Across Science Content Areas</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heuristic 1: Multiple scalar levels</td>
<td></td>
</tr>
<tr>
<td>Considering the scalar level below that of the observed phenomenon</td>
<td></td>
</tr>
<tr>
<td>• Concrete entities, such as particles</td>
<td></td>
</tr>
<tr>
<td>• Abstract entities, such as energy</td>
<td></td>
</tr>
<tr>
<td>Heuristic 2a: Identifying factors</td>
<td></td>
</tr>
<tr>
<td>Identifying the things that need to be reasoned about</td>
<td></td>
</tr>
<tr>
<td>• Entities, either concrete or abstract</td>
<td></td>
</tr>
<tr>
<td>• System relationships, made up of entities and behaviors</td>
<td></td>
</tr>
<tr>
<td>• Properties of entities or of systems</td>
<td></td>
</tr>
<tr>
<td>Heuristic 2b: Unpacking factors</td>
<td></td>
</tr>
<tr>
<td>Characterizing the factors’ behaviors, interactions, and effects</td>
<td></td>
</tr>
<tr>
<td>• System transitions: the effect of system relationships on system properties</td>
<td></td>
</tr>
<tr>
<td>• Bounded effects: the differential effect of properties on entity behavior or on system relationships</td>
<td></td>
</tr>
<tr>
<td>• Connections between observed phenomenon and factors at the level below</td>
<td></td>
</tr>
<tr>
<td>• Aggregating connections over time and/or space</td>
<td></td>
</tr>
<tr>
<td>Heuristic 3: Linking</td>
<td></td>
</tr>
<tr>
<td>Coordinating how the unpacked factors give rise to the observed phenomenon</td>
<td></td>
</tr>
</tbody>
</table>

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Indicators of the Use of Epistemic Heuristics in Students’ Accounts

To illustrate the indicators of each epistemic heuristic in students’ accounts, we use two student-generated examples. The indicators are summarized in Table 3, and the student examples are displayed in Table 4.

Heuristic 1: Thinking Across Scalar Levels. To identify whether students were considering multiple levels while constructing their accounts, we looked to see whether students described an element of the phenomenon at
the scalar level below that of the observed phenomenon or whether they used an abstract factor to account for some aspect of the phenomenon. The majority of responses considered multiple levels for the strawberries and squirrels items. Prototypical responses for each item are displayed in the top half of Table 4. For strawberries, responses that considered multiple levels contained entities like molecules, particles, or dots in their diagrams, which indicated that students were thinking about smaller parts that might make up chocolate. For squirrels, responses that considered multiple levels discussed what individual squirrels did or were like rather than only considering interactions and relationships at the population level. In contrast to these responses, the student responses in the bottom half of Table 4 did not consider either a factor at the level below or an abstract factor.

Heuristic 2: Identifying and Unpacking Factors. This heuristic involves identifying the things that need to be reasoned about and then doing the reasoning about how they act or behave. It is at this step that content knowledge is most valuable and the nature of students’ reasoning work varies most drastically based on the specific context. Thus, to determine what counted as evidence that students had identified and unpacked factors, we drew heavily on the previously described literature about mechanistic reasoning in the physical and life sciences. We used this synthesis to generate the general categories that could count as factors and what it would mean to unpack them. Depending on the scalar level of the phenomenon, these could include the following:

1. Entities, either concrete (e.g., particles) or abstract (e.g., energy)
2. System relationships, made up of entities + behaviors (e.g., red and gray squirrels both eat berries and acorns, competition)
3. Properties of entities or of systems (e.g., chocolate particles start warm and lose heat/energy over time; with more squirrels, there is a food shortage)

We considered simply naming or mentioning any one of these factors to be evidence that the student had identified that factor. We then looked to see whether students had unpacked the identified factors: Did they describe why they matter or how they work in order to produce the target phenomenon? Depending on the identified factor, students could unpack the following:

1. Behaviors and interactions between entities (e.g., particles bounce around and collide with one another)
2. System transitions: the effect of system relationships on system properties (e.g., because both kinds of squirrels eat the same kind of food, they are competing for a limited resource)

3. Bounded effects: the differential effect of properties on entity behavior or on system relationships (e.g., when there is a food shortage, gray squirrels can resort to eating acorns and still survive while red squirrels will die)

In order to illustrate these possibilities, we use two highly complex student responses that identified and unpacked both canonical factors (as described in Table 5) to explain each of the phenomena:

1. The molecules cooled. When the molecules were hot they slid past each other and could take the shape of their container. But when they
cooled, the molecules got together and started to vibrate. The liquid chocolate got hard and it cooled into a solid. (Student G)

2. Grey squirrels eat the same things the red squirrels eat. Grey squirrels can also eat acorns, but red squirrels can’t. The grey squirrel will eat all the red squirrels food, and eat acorns and survive. Since red squirrels can’t eat acorns, and their food is gone, they won’t survive. (Student R)

The strawberries response first identifies the change in temperature as a causal factor: “The molecules cooled” (key property, underlined). It also identifies the process as a phase change by naming the hardened chocolate as a solid “the liquid chocolate got hard and it cooled into a solid” (key entity, in italics). For this response, the unpacking of the factors (indicated in bold text) is done together, as the behaviors of the chocolate molecules during each phase change are linked to the change in temperature: “When the molecules were hot they slid past each other … but when they cooled, the molecules got together and started to vibrate.”

Similarly, the squirrels response identifies and unpacks two factors. This response first identifies the competitive relationship (“Grey squirrels eat the same things the red squirrels eat”; key system relationship, in italics) and then identifies the competitive advantage (“Grey squirrels can also eat acorns, but red squirrels can’t”; key property of the system, underlined). It then unpacks the consequences of the competitive relationship by indicating that the red squirrels’ food is gone, and without food they cannot survive. It also unpacks the consequences of the competitive advantage: Gray squirrels will survive because they can eat acorns, whereas red squirrels will not survive.

These responses are similar in many ways. Both of these responses identify the process that is happening (a phase change and competition). We include this naming as a factor both because it is an important part of sensemaking (placing this phenomenon in a category of type of thing) and because it often passes as an acceptable school answer. Why did the chocolate harden on the strawberry? “Because it went through a phase change.” Why did the red squirrel population decrease? “Because of competition.” Both of these responses then go a step beyond this to unpack what was going on during that process. For strawberries, the response moves down to discuss at a microlevel how the chocolate “molecules” were behaving in a way that explains the macrolevel change: when hot they slid past each other, and that allowed them to take the shape of their container, but as they cooled, they got together and started to vibrate, which made them a solid. Similarly, for squirrels, the student moves down from a population level to an individual organism level to discuss how the competitive relationship would play out in the behavior of individual squirrels and how that would affect the system: They would eat all of the food and there would be a
food shortage. Both responses also consider another factor: a change in temperature or a competitive advantage. They similarly play out the consequences of this factor in their responses.

Clearly these are not perfect, scientifically accurate responses; some non-canonical ideas are mentioned in the responses. The strawberries response does not explain why the chocolate particles cooled down; it just assumes that they did. The response also assumes that the particles would know to get together and start vibrating as they cooled down. Similarly, the squirrels response assumes that the gray squirrels are eating all of the red squirrels’ food before even mentioning the competitive advantage. This again could be indicative of a deterministic understanding of the system or an attribution of agency to a central causal being (in this case, gray squirrels) rather than a view of the relationship as dynamic and recognizing that both red and gray squirrels would be experiencing the effects of the food shortage. We know that students do tend to view complex systems this way and that this kind of reasoning may become problematic as they try to explain more and more complex phenomena. This is an important concern, and our coding scheme does not differentiate between these types of responses. However, these responses are still more mechanistic than the following responses, which each only identifies one factor (indicated with italicized text):

1. As atoms cool down, they begin to harden. The room’s temperature was cooler than the melted chocolates so naturally the chocolate would harden as the atoms that make up the chocolate cooled down. (Student N)
2. The red squirrel’s population went down because the grey squirrels ate the same food. So that’s why the red squirrel population went down. (Student O)

These responses both identify a key causal factor. However, they do little more than provide a typical school answer, such as “Because of competition.”

**Heuristic 3: Linking.** The final heuristic involves coordinating the unpacked behaviors and interactions over space and/or time in order to link those interactions at the lower level to the aggregate phenomenon. We considered students’ attempts to explicitly make connections between the mechanism level and the phenomenon level to be evidence of linking. This was often most evident in the structure of students’ writing. Some key indicators of that relationship are terms like eventually, the cycle continues, after a while, as (e.g., “as it cools”), from ___ to ____, and so on.

Table 6 displays responses to the strawberries and squirrels items that considered multiple levels and identified and unpacked at least one factor, but
### TABLE 6
Linked Versus Nonlinked Responses

<table>
<thead>
<tr>
<th>linked Responses</th>
<th>linked Responses</th>
<th>linked Responses</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strawberries</td>
<td>The melted chocolate hardened on the strawberries because when the chocolate melted, it was very hot. The counter is much colder than the melted chocolate so as soon as the melted chocolate touched the counter, the speed of the molecules decreased greatly. After awhile, the molecules got cold enough so that the melted chocolate turned back into a solid chocolate. (Student E)</td>
<td></td>
</tr>
<tr>
<td>Squirrels</td>
<td>The red squirrel population went down because on the food chain gray squirrels can eat 4 different foods but red squirrels only can eat 3 foods. The population went down because the gray squirrels had more food options to survive off of so their population could get bigger and because red ones only have 3 choices of food so they ran out of food and starved. (Student F)</td>
<td></td>
</tr>
</tbody>
</table>

![Diagram of food chain]
**Strawberries**

The molecules cooled. When the molecules were hot they slid past each other and *could take the shape of their container*. But when they cooled, the molecules got together and started to vibrate. (Student G)

**Squirrels**

Because gray squirrels eat the same things red squirrels do, there is less for red squirrels, so they die off. Even though red squirrels eat some of gray squirrels' food, gray squirrels still have acorns to themselves. (Student H)

*Note*. Prose linking the underlying level to the aggregate level is italicized and bolded. Prose setting up or concluding the account as linked to the aggregate level is italicized and underlined. Indicators of considering interactions over space and/or time are bolded and underlined. We looked for at least two of these features to consider a response linked.
one response to each item linked while the other did not. We see that each of these responses identified and unpacked at least one factor at the level below the aggregate phenomenon. But the linked responses closed the loop on their mechanistic account by considering how the interactions that they were unpacking related to the aggregate phenomenon and accounted for that phenomenon. Some of these responses (e.g., Student E) included multiple instances of linking—the student was continuously linking the underlying entity interactions back to the aggregate phenomenon. This seems to indicate what we would expect about what the process of constructing a mechanistic account would look like in discourse: an iterative looping of these three heuristics as an inquiry process, testing out possible factor interactions and effects and identifying areas in need of further explanation.

How Each Heuristic Contributes to Mechanistic Sophistication

Now that we have identified indicators of students’ use of the epistemic heuristics, we demonstrate how they allow us to differentiate the mechanistic sophistication of students’ accounts. Here we discuss how each heuristic provides a dimension of sophistication.

**Heuristic 1 Acts as a Doorway to Mechanistic Reasoning.** The first heuristic—considering entities at the scalar level below that of the target phenomenon—serves as a gatekeeper heuristic for mechanistic reasoning. Without considering multiple levels, students will not (by definition) be able to construct a mechanistic account. Another way to think about considering multiple levels is as a productive heuristic for starting to investigate a phenomenon. For example, a class working to explain how and why the chocolate hardened on the strawberry could use this heuristic to develop initial models by asking what chocolate is made of, what is going on inside of it as it is hardening, or how they imagine the chocolate is interacting with the strawberry or air to make it cool down. In this way, use of this heuristic provides a doorway into reasoning about mechanisms.

**Heuristic 2 Differentiates the Complexity of the Explanatory Process.** Identifying and unpacking factors that give rise to the target phenomenon is the core of constructing a mechanistic account. We use evidence of this second heuristic to differentiate between responses that only identify factors and responses that unpack them. For example, we see that all three responses in Table 7 identified a competitive relationship between gray and red squirrels (shown in italicized text). However, only Student J unpacked that factor by playing out the consequences of
that competitive relationship (shown in bold italicized text in Table 7). Similarly, both Students I and K identified the competitive advantage for gray squirrels (shown in underlined text in Table 7). However, only Student K unpacked that factor by indicating that “there’s more\(^5\) acorns and food for them” (shown in bold underlined text in Table 7).

In addition to differentiating between responses that only identify factors and responses that actually use them (as described earlier), use of this heuristic can differentiate between degrees of complexity of mechanistic responses in a way that is similar to existing frameworks on mechanistic reasoning.

**Heuristic 3 Provides Quality of Accounting for the Phenomenon.** The third heuristic, linking, is the best indicator that students are working to build coherent accounts that fully explain the phenomenon. Through doing the linking, students may be better able to notice logical gaps or inconsistencies in how the processes unpacked using Heuristic 2 lead to the aggregate phenomenon. If such gaps or inconsistencies exist, students may be able to reengage in a more focused way to identify additional factors or processes that give rise to the phenomenon. We consider the linked responses to demonstrate students’ thinking about how the mechanistic interactions gave rise to the aggregate phenomenon. These linked accounts provide some evidence that students were using these heuristics to explain the phenomenon rather than to demonstrate their content knowledge.

\(^5\)Here we chose to interpret the idea of more food as an indication that gray squirrels have more food options available, not a greater quantity of food as a result of a decreased amount available to red squirrels as a result of competition.
Taken together, these three heuristics offer three progressive dimensions on which we can differentiate the mechanistic sophistication of students’ account construction process.

The Use of Heuristics Even Without Correct Content Knowledge

Finally, it is important to demonstrate that these indicators are capturing some element of students’ epistemologies rather than only their increased understanding of the content knowledge. We repeatedly saw examples in which students identified and used noncanonical factors to construct fairly well-developed mechanistic accounts. For example, a student described how “heat waves” that were trapped inside the chocolate were able to escape or transfer out when the chocolate touched the strawberry and the air. Using noncanonical factors (such as heat waves) to explain the phenomenon is evidence that the student used the heuristic of dropping down to the scalar level below: The students knew that he or she had to explain how and why but was not sure what the factors at the level below were, so the student drew on his or her everyday knowledge to construct a scientific account. Table 5 lists a sampling of noncanonical factors that we observed students identifying and using in their accounts.

When students considered noncanonical factors at a level below that of the observed phenomenon in their responses to our items, they often drew on familiar but abstract everyday ideas and mechanized them, or gave them a form and function that they then used to reason through an explanatory process. For example, Table 8 shows Student L’s response that used air pressure, which we considered to be an abstract factor for students at this level. Although this is not a canonically accepted explanation for phase changes under normal atmospheric conditions, this student considered an abstract element not immediately visible as a component of the phenomenon. The student then described what the factor was doing—pushing down on the chocolate—and the consequence of that behavior: making the chocolate stick onto the strawberry. Similarly, Student M attributed the decrease in the red squirrel population to individual squirrels moving away from an area with lots of acorns to an area with more plants that they could eat.

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6In upper elementary and middle school, students typically begin with an understanding of temperature as that of a property of a substance: It is a number on a thermometer rather than an emergent property of the amount of kinetic energy of a substance’s particles. Students also begin by thinking of pressure as a push, more akin to an intuitive understanding of a force, rather than something measurable and related to particle interactions.
<table>
<thead>
<tr>
<th>Strawberries</th>
<th>Squirrels</th>
</tr>
</thead>
<tbody>
<tr>
<td>It hardened like that because the air made <strong>pressure</strong>, <em>pushing down on the chocolate</em>, making the chocolate stick/harden onto the strawberry. (Student L)</td>
<td>We have a lot of acorns and if the <strong>red squirrels don’t eat acorns</strong> then they <strong>moved somewhere with more plants</strong>. (Student M)</td>
</tr>
</tbody>
</table>

*Note.* Noncanonical factors are indicated in bold. Unpacking of those factors is in bold italics.
In both examples, students moved to a scalar level below, identified and unpacked at least one causal factor, and linked that unpacking back up to explain the aggregate phenomenon. Though these examples were relatively rare in the overall data set, we consider these mechanistic uses of noncanonical factors as evidence that drawing on these epistemic heuristics can help students propose a possible mechanistic account that can then be explored and tested. Being able to identify these epistemic heuristics, even in instances in which students are not drawing on canonical content knowledge, suggests that this analysis may be detecting epistemological efforts of students’ activity.

DISCUSSION AND IMPLICATIONS

This article proposed the EEHMR framework for identifying and characterizing students’ mechanistic reasoning as a form of practical epistemic knowledge in action (Sandoval, 2005, 2014) in middle school students’ work across scientific content areas. We applied this framework to examples from student assessment responses to illustrate these components. The three essential heuristics in the framework offer three progressive dimensions on which we can differentiate the mechanistic sophistication of students’ accounts with respect to their process for constructing mechanistic accounts. We argued that this knowledge can support students in doing substantive work to develop science knowledge rather than superficially recalling information, and it may be leveraged to support teachers and students in engaging in productive scientific knowledge-building work. In this section, we discuss the implications and possibilities for supporting students’ engagement in mechanistic reasoning across content areas.

Our analysis of students’ written work indicated that the three epistemic heuristics in our framework were evident in students’ accounts of phenomena in the strawberries and squirrels items, even in responses with noncanonical mechanisms. We argued that these three heuristics may be part of what students learn when constructing accounts of scientific phenomena.

This framework enables us to begin to identify some epistemic dimensions of students’ practical work constructing mechanistic accounts. This dimension is intimately interwoven with the social, material, and conceptual dimensions of science practice (Duschl, 2008; Stroupe, 2014). At the same time, we have shown here that our framework is capturing something related to, but distinct from, knowledge about specific mechanisms.

If we want students to move beyond simply learning that scientific answers provide mechanistic accounts, they need to learn to draw on these epistemic heuristics as part of their regular classroom practice. We propose that these
heuristics are knowledge that embodies both ideas and action and that they do real work for students in guiding their practice (Louca et al., 2004; Sandoval, 2005). As students utilize these heuristics from context to context, we expect it to be messy. Students will likely not construct as complex mechanistic accounts at the beginning of Unit 2 as they did at the end of Unit 1, for example. But they will also construct more complex accounts at the beginning of Unit 2 than they did at the beginning of Unit 1. This proposition is one that we are continuing to test and explore in students’ responses across 3 years.

Being able to see these epistemic heuristics in students’ work is valuable both theoretically and practically. First, it helps clarify understanding of how mechanism is a crosscutting concept in science (National Research Council, 2012; NGSS Lead States, 2013). Note that articulating the heuristics as practical epistemic knowledge that guides students’ work demonstrates that mechanism is not just a crosscutting declarative idea or conceptual theme across multiple content areas. Mechanistic reasoning is a crosscutting form of thinking across multiple scientific practices. As a heuristic, it can help students guide decision making, evaluation, and reflection as they are building and testing scientific ideas. When students use these heuristics, they are doing so in a way that requires that they develop and use (mental) models, especially when playing out relationships across space and time. Attempting to unpack how a particular entity behaves likely requires asking (mechanistic) questions, designing and carrying out investigations, and analyzing and interpreting how those empirical data translate to the model-based explanation. Finally, the act of constructing the account—particularly the use of the heuristic for linking—requires students to consider the audience to whom they are communicating their account. In this sense, using these three general heuristics for constructing mechanistic accounts cuts across multiple scientific practices in that it requires bringing them together in a coherent way.

Second, identifying students’ use of these general epistemic heuristics helps us to identify and characterize students’ epistemic development both microgenetically and longitudinally. To this point, studies looking at students’ epistemological development have been able to characterize that their epistemic ideas change over time (e.g., Lederman, Abd-El-Khalick, Bell, & Schwartz, 2002; Smith, Maclin, Houghton, & Hennessey, 2000) but have not been able to characterize much about the processes by which students’ epistemic ideas develop. As called for by Sandoval (2014), we can begin to answer questions about the how of epistemic development by examining how students’ use of these epistemic heuristics, and others like them, changes over both short and long periods of time. In addition, the three epistemic heuristics presented here provide a guideline for the nature of what students may be learning as epistemologies-in-practice.
Finally, these epistemic heuristics provide practical fodder for supporting students in better developing mechanistic accounts. They may become practical tools for beginning to explore a phenomenon. For example, when trying to explain how and why a nail rusted after being left outside for a week, a teacher might prompt students to look at the scalar level below the phenomenon and think about what might be going on with the molecules. In contrast, when trying to explain how and why the volcanoes on Iceland formed, a teacher might prompt students to think about different kinds of earth materials and how they might be interacting with one another as a part of an earth system. Whether there are ways of predicting the intersection of epistemic heuristics and the details of the content knowledge is an open theoretical question that warrants future work.

We conclude with some notes of caution and with related recommendations for continued research. As we have underscored above, the heuristics we propose here are essentials for mechanistic reasoning in that they are of fundamental importance, but they are not comprehensive. We have ignored much of the complexity and difficulty in doing mechanistic reasoning (e.g., Hmelo-Silver & Azevedo, 2006; Perkins & Grotzer, 2005). In addition, these emergent or aggregate effects are often the result of interactions between two or more related components (Hmelo-Silver & Azevedo, 2006). Our simplified question contexts intentionally removed those kinds of interactions, making this process easier. However, these three heuristics are likely insufficient to fully guide students’ work in constructing more complex mechanistic explanatory accounts. On a related note, complex phenomena are often dynamically emergent rather than the outcome of linear mechanistic processes (Bechtel, 2011; Grotzer et al., 2013; Jacobson & Wilensky, 2006). The epistemic essentials framework does not account for the kinds of heuristics guiding reasoning about feedback loops and other dynamic complex systems mechanisms. Research on these problem contexts should continue to investigate the strategies and rules of thumb that guide students in moving across scalar levels to construct complex, nonlinear mechanistic accounts.

Another note of caution comes in using this framework to support classroom practice. We do not suggest that students should fill out worksheets labeled “Consider the level below,” “Identify and unpack factors,” and “Link back to target phenomenon.” Such an approach would fall into the “double-edged sword” of scaffolding (Berland et al., 2016, p. 1104), and it would quickly turn into an act of doing the lesson by turning what should be a process into an end in and of itself (Jiménez-Aleixandre et al., 2000). Instead, we want students to be using these heuristics flexibly and iteratively, as a strategy for developing a mechanistic account. Our framework is also limited in that it is derived from students’ written assessments that target a particular mechanism for a
contrasting phenomenon rather than analyses of classroom practice. We emphasize in-practice studies as an important direction for future research: What does it look like in classrooms when student work is guided by these epistemic heuristics? And how can teachers support student learning of these heuristics in a meaningful way?

The heuristics in our framework support the how of students’ work. They allow us to characterize how students go about constructing a mechanistic account once they have decided that doing so would be productive. As this research moves into explorations of classroom practice, close examination of when and why students choose to build mechanistic accounts is an important avenue for continued characterization of epistemic heuristics. For example, when do students spontaneously begin searching for mechanisms? What kinds of phenomena, questions, or concerns prompt them to do so? And how do students decide that the depth or clarity of a mechanistic account is sufficient? Examining students’ classroom activity and their reflections on it is an important step in further elaborating students’ use of heuristics for when and why to pursue construction of mechanistic accounts in the first place.

Considering how teachers can support student learning of these heuristics raises questions about how students learn to use them. Although we propose that these heuristics might emerge through routines in interaction and become internalized or made explicit over time, an important question becomes how and at what point, if at all, these kinds of epistemic heuristics should be made explicit to students. One could imagine that the explicit articulation of productive guidelines for investigating phenomena could be an effective support, especially for students who do not tend to identify with the activities of science—or of schooling (e.g., Carlone, Huan-Frank, & Webb, 2011). However, unless these guidelines are made explicit as they emerge from student activity and are articulated by students themselves (e.g., Manz, 2016; Ryu & Sandoval, 2012), they could easily become dogmatic and rote. Future work is needed to examine the kinds of resources and rationales that students bring to the process of constructing mechanistic accounts that could be built on to deepen students’ epistemic work.

In summary, we provide these general epistemic heuristics for constructing mechanistic accounts as a theoretical proposal for what students learn as they develop epistemologies for science; they are a template for future work identifying other epistemological resources relevant for meaningful science (and other subject area) learning, and they are potential leverage points for supporting rich engagement in scientific practices. We propose them in order to aid in analyzing students’ practice and to develop tools for supporting teaching and learning that engage students in mechanistic reasoning.
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