It's Okay to be Wrong: Recognizing Mechanistic Reasoning During Student Inquiry

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Abstract: Recent reforms in science education place emphasis on engaging students in inquiry similar to that of research scientists. In their attempt to assess this goal, many educators and researchers evaluate student inquiry based on how well their conceptual understanding aligns with canonical knowledge. Such assessments fail to recognize other more valuable aspects of inquiry. We assert that mechanistic reasoning, shown by the history and philosophy of science literatures to be vital in the construction of scientific knowledge, is a more appropriate dimension along which to measure the quality of inquiry. We present a coding scheme designed to identify this reasoning and use it to analyze a discussion among second grade students about why juice boxes collapse when you suck on their straws. Assessing their mechanistic reasoning in this way reveals a value and sophistication that is obscured by current measures of conceptual correctness.

Introduction

The concept of 'inquiry' is central in the primary documents of the current science education reform movement *(The National Science Education Standards* (National Research Council, 1996) and *Science for All Americans* (American Association for the Advancement of Science, 1993)). In them, inquiry is viewed as both the normal activity of scientists and what reformers want students to do in science classrooms.

Given its prominence in science reform, educators and researchers quite reasonably want to assess the quality of students' inquiry. However, much of the research evaluates student inquiry based upon tests of conceptual understanding (e.g. Lee and Songer, 2003; Marx et al, 2004). We find such assessments problematic because they fail to recognize aspects of inquiry that are ultimately more valuable than correctness. One such aspect, mechanistic reasoning, is shown by the history and philosophy of science literatures to be vital in the construction of scientific knowledge. We believe students doing inquiry should engage in mechanistic reasoning. In this work we use a framework for identifying mechanistic reasoning to reveal valuable aspects of student inquiry overlooked by much current research.

The following explanation given by a first grade student for why seeds will not grow in sand provides a rich example of the type of mechanistic reasoning we consider valuable.

Teacher: And so that seed in the sand?
Elisabeth: Is just left alone without the s- the water that helps it grow in soil. Because the soil is like hard and the water is like, pssshhh, blocked. Like with all those sticks and stuff- it's real hard so the water won't get through. But in sand since usually sand will be blown away not sticks into the sand- it's easy that it's not blocked so it just goes—shhhhhhwweeee. (Motions with both hands water flowing down.)

Elisabeth reasons (mechanistically) that since water falls straight through sand, the seed is left alone and cannot get the water it needs to grow. It would be inappropriate to disregard Elisabeth's inquiry merely because her final conclusion about seed growth is wrong. The nature of her sophisticated thinking still warrants attention that the framework we present here is intended to provide.

This example demonstrates that assessing students based on how well their conceptual understanding aligns with canonical concepts may misrepresent their inquiry. As above, it might give an impoverished view of good inquiry that arrives at incorrect conclusions. Alternatively, it might judge inquiry highly in instances when the students provided correct answers they do not understand. Such judgments assume (perhaps tacitly) that if students do inquiry well they'll get the right answer. However, the history of science is full of examples where eminent scientists arrived at conclusions later judged incorrect (Darden, 1998). Good scientific inquiry does not guarantee true knowledge - either historically or in the classroom.

The use of mechanisms to construct new knowledge about the physical world provided the foundation for the Scientific Revolution (Westfall, 1986). Prior to that time, natural phenomena were explained by appealing to occult powers that mediated matter, itself possessing both life and perception. With the rise of modern science as we know it today, scientists like Descartes, Galileo, and Newton began grounding their explanations in mechanisms involving inert matter in motion. Their use of mechanistic explanations as a means of understanding and describing natural phenomena allowed for significant advances in scientific knowledge. Even today, searching for and articulating mechanisms for natural phenomenon is central to science (Machamer, Darden, and Craven, 2000; Glennan, 2000; Thagard, 1998).

Given the role of mechanistic reasoning in modern science, we argue assessments of student inquiry must be attentive to it. Here, we use a coding scheme based in the mechanism literature from the philosophy of science to assess the quality of a discussion among a group of second grade students and their teacher about why the sides of a juice box move inward when they suck on the straw. For our purpose mechanism is defined as "entities and activities organized such that they are productive of regular changes from start or set-up to finish or termination conditions." (Machamer et al., 2000). In what follows we describe the coding scheme, its foundation, and how it was used to analyze the student discussion.

Characterizing Mechanistic Reasoning: A Coding Scheme

We briefly review Machamer et al.'s (2000) mechanism framework and provide descriptions of the coding scheme based on it we use to recognize mechanistic reasoning. This coding scheme is appropriate in settings where students are describing their reasoning. To date it has been used to code both student discussions (Russ et al., in preparation) and written work. Below we provide code examples from the discussion highlighted in the introduction – first graders discussing seed growth in sand.

Describing Target Phenomenon

Scientists may either begin with knowledge of the phenomenon and then inquire into the mechanism that produces it; or they may describe phenomena as predictions based on their prior knowledge of entities and activities. The phenomena scientists identify are stable, regular and reliably produced because the mechanisms that underlie them "work always or for the most part in the same way under the same conditions." (Machamer et. al, 2000) Given that formulating mechanistic accounts in science requires clear description of the phenomena, we look for moments when students state/demonstrate the particular phenomenon or result they are trying to explain. Such comments are coded as "Describing Target Phenomenon." For example, a student saying "I think that seeds will not grow in sand." describes the target phenomenon he hopes to explain.

Set-up Conditions

Scientists' goal "in establishing and displaying mechanism is to show how one stage produces the next, and so on." (Machamer, 2004) Set-up conditions are descriptions of the organizations (spatial and temporal) among entities and activities that begin the regular changes of the mechanism that produce the phenomenon. This aspect of Machamer et al.'s (2000) framework lends itself readily to a coding scheme - we can identify utterances in a transcript when students identify particular enabling conditions of the environment that must be met at the beginning in order for the mechanism to run. Such comments are coded as "Set-Up Conditions." For example, a student saying "But if you have [the seed in] a cup, it could just be like protected." is suggesting a set of starting conditions to use in their explanations.

Identifying Entities

Scientists recognize that one component of mechanistic descriptions are entities - the things (or objects) that play roles in producing the phenomenon. Physicists may consider electrons (entity) pushing on one another while biologists may talk about restriction enzymes (entity) cutting DNA. Since it is important for students to articulate objects that affect the outcome of the phenomenon, we code such comments as "Identifying Entities" even if the entity has been previously identified. For example, a student says "[I]f you put a seed in the sand it won't grow because there's no food for the plant" recognizes the necessary entity of food.

Identifying Activities

Along with knowing the entities in a mechanism, scientists also need to know the relevant activities. Activities are the components of mechanisms that produce change – they are types of causes. Most generally, activities are "the various doings in which these entities engage." (Craver and Darden, 2001) Given that activities are a major component of mechanisms, students who articulate the actions and interactions that occur among the entities are coded as "Identifying Activities." We use this code whenever students describe the things that entities "do" that cause changes in the surrounding entities, even if it has been previously identified. For example, a student saying "[T]he sand… sucks *UP* the water, like keeps it to itself, like takes the water away from the seed." identifies the sand can suck up water and keep it away from the seed.

Identifying Properties of Entities

Isolating the relevant properties of the entities is a vital part of scientific discovery. Often, scientists pare down the number of variables they need to consider by neglecting surface features of entities that do not affect the mechanism. When coding for "Identifying Properties of Entities," we look for students who articulate general properties of entities that are necessary for this particular mechanism to run. For example, a student describes the properties of sand and soil by saying, "When I pick up sand it easily kind of goes through my fingers really fast but when I do with soil it really does not do that."

Identifying Organization of Entities

In science, there are many phenomenon for which the mere presence of the necessary entities is insufficient for the mechanism to run. Rather, in order for a specific mechanism to take place, "Entities often must be appropriately located, structured, and oriented." (Machamer et al., 2000) When students identify where entities are located spatially and how they are organized, we code their comments as "Identifying Organization of Entities." For example, a student saying "Because if the water is going through… the water is going near the bottom and if it's going near the bottom, it's not near the seed it's by the top." identifies an important spatial organization between the water and the seed.

Chaining: Backward or Forward

A general reasoning strategy that aids the discovery and articulation of mechanisms involves using knowledge about the causal structure of the world to make claims about what must have happened previously to bring about the current state of things (backward) or what will happen next given that certain entities or activities are present now (forward). We code both types of reasoning as "Chaining" and use the following criteria to help us understand it as forward or backward.

By knowing the general properties of entities involved, much to be said about the activities that must have produced them. Similarly, "characteristic features of an activity may provide clues as to the entities that engaged in it." (Darden and Craver, 2002) Such comments answer the questions "What activities could have given rise to entities with these properties?" or "What entities were necessary in order for this activity to have occurred?" As with backward chaining, the general properties of entities can also speak to the activities in which they can engage, and the occurrence of an activity can indicate the entities it might produce. These comments answer the question "What activities could these entities with these properties be expected to engage in?" or "If this activity occurred, what would I changes would I expect in the surrounding entities and their properties?" For example, a student (forward) chains when he says "I think [the seed] would grow because, because the water goes through [the sand], and if if the water goes through [the seed] might receive some water."

Hierarchy of Codes

The codes above are sequentially arranged based both on our intuitions about scientific sophistication and on the conjecture that information gained by the lower level reasoning is needed in higher level reasoning. Describing phenomenon (with varying detail) including starting conditions is a basic skill of scientific inquiry, and thus these codes fall first in the hierarchy. After initially considering the physical situation, students can speculate about which entities or activities may play a role in the mechanism. When the entities have been identified, their relevant properties and organization can be explored. Finally, backward and forward chaining involve using information about the components already established to construct a step-by-step story for the mechanism runs. These final two codes seem (both intuitively and experientially) to be the most difficult and sophisticated.

Additional support for this arrangement comes from Metz's (1991) work on student explanations of sets of gears. She identifies three developmental phases of explanation that coincide with our hierarchy of mechanistic reasoning - "(a) function of the object as explanation, (b) connections as explanation, (c) mechanistic explanation."

In associating causality with the function of an object, the youngest students are identifying entities in the mechanism. By attending to connections, students are considering properties and organization of entities. Finally, what Metz calls the mechanistic phase of the oldest children is equivalent to our identification of activities and subsequent forward and backward chaining. Given that Metz observed 3-year-olds constructing connections explanations that were nascent versions of mechanistic reasoning, it is not unreasonable that we would find instances of the mechanism codes described above in school science discussions.

Context for Analysis

We apply the mechanism framework to a discussion between seven second graders and a science teaching specialist about why juice boxes collapse when you suck on the straw. These students met occasionally with this teacher throughout the year for enrichment sessions. Since he did not have to cover the standard county curriculum in this context, the teacher was free to choose topics based on what he thought would engage the students. This topic was chosen because the teacher speculated the students would have productive intuitions about it based in their experience.

Inter-rater Reliability

Both authors coded each student line on a transcript of the class discussion. In cases where a speaking student was interrupted by the teacher or another student we coded each line separately, but considered the student's adjacent lines when interpreting the meaning. This is particularly relevant when students use indexical words like "this" or "that". Codes are not mutually exclusive, so one line of transcript can have multiple codes. It is also possible for a line to receive no codes.

We evaluated inter-rater reliability in two ways. First, we checked for agreement among the 'codability' of lines. That is, do the researchers agree about which lines are examples of mechanistic reasoning and which are not. We obtained high inter-rater reliability, 93%, which indicates the coding scheme is very reliable at recognizing statements that are relevant to mechanistic reasoning. Second, for each mutually coded line we checked whether the highest codes agreed so as to assess how reliable the coding scheme is for identifying the most sophisticated aspect of each comment. This measure is important given that we are making claims about the overall sophistication of student reasoning. Our inter-rater reliability on this measure was 74% before discussion and 97% after. Our discussion revealed that low initial agreement did not result from difficulties with the coding scheme itself, but rather from differing interpretations of student meaning that were resolved with discussion. Interpretation discrepancies arose from the ambiguity inherent in second graders' language and our decisions about whether or not to interpret some statements based on adjacent comments.

Student Mechanistic Explanations

During the discussion the students presented three possible explanations for the phenomenon - only one of which is correct when judged against the physics canon. Below we provide an account of two of the explanations, one right and one wrong, including excerpts from the student discussion. We then use these particular examples of dialog to show how the coding scheme was implemented and what work the mechanism framework can do in terms of revealing valuable aspects of student reasoning.

Incorrect Explanation: A Push From the Inside the Juice Box

Three of the students focused on the role of the air and/or juice inside the juice box. In one form of this 'inside pusher' model, one student suggested the juice inside the box pushes out on all the sides of the box. Another student suggested that the air inside the juice box actively blows out or pushes against the sides of the box, holding the box in its "normal" shape. Thus whenever juice or air is removed from the box, there is no longer anything pushing from the inside to hold the box out, so the sides cave in. Some students articulated that the amount the sides of the box cave in is related to the amount of air left inside the box. While some of these students merely did not mention the air outside, others explicitly asserted that air outside the box is irrelevant to the box caving in.

For example, Erin explained her reasoning by discussing the role of the air inside the juice box.

Erin: I think because since you sucked out the air, it's like, it caves in because there's not any air so it has no, nothing's pushing it in from the inside to make it like [?flat] -
Teacher: Like this?
Erin: - like its normal shape. Yeah.
Teacher: Nothing's inside there so -
Erin: There's not much, not as much is inside so it's, it, there's not mu, as much pushing out so it caves in.
Teacher: Oh. So you mean right now there's air in there pushing out to make it the box shape.
Erin: I think so.
Teacher: And then what happens when I suck? What's -
Erin: You take some of the air out so -
Teacher: - and so why should the sides. (Side comment to another student.) Why should the sides then cave in? I mean, is there anything pushing –
Erin: No –
Teacher: - the outside in?
Erin: - there's nothing pushing.
Teacher: There's nothing pushing.
Erin: So when –
Teacher: Nothing pushing where, on the inside or the outside?
Erin: Inside.

Should we discount Erin's explanation of the phenomenon solely because her inquiry lacks conceptual understanding of air pressure? Certainly not! How do we account for its value? Although Erin's answer is incomplete (she explicitly rejects the idea of the air outside pushing on the box), her reasoning is mechanistic. She begins by identifying the starting conditions – the sides of the box are in their "normal shape." She then describes a relevant entity – the air inside the box – that pushes out (activity) on the sides holding the box in its starting conditions. Erin forward chains and claims that when the air that was pushing out on the box from the inside is removed, the box collapses. The inferences she makes in her forward chaining are all plausible based on her everyday experiences (for example with balloons). It is her ability to forward chain from activities to entity properties using her intuitions that makes her model valuable even though it is incorrect.

Correct Explanation: An Imbalance of Pushes from Inside and Out

Only one student in the class gives a correct explanation for why the juice box caves in – noting that both the air inside and outside the box contribute. He states a 'tug-of-war' model - air inside actively pushes to hold the sides out while the air outside pushes in. When air from the inside is removed, the amount of air (and thus the push) on the inside and outside are no longer equal, so the box collapses.

Hunter: Um. What I was thinking was when it's empty there's air inside -
Teacher: Okay.
Hunter: - and if you suck up, and there's like air pushing on the sides. And there's air pushing on the inside, there's air pushing on the sides to keep them out. And outside, um there's air pushing on the outside. [?And it -]
Teacher: Pushing. So the air outside is pushing which way?
Hunter: Um it's, um the sides in.
Teacher: Pushing the sides in. And then -
Hunter: And then [??when we took] some of the air out it won't be equal so, um, the sides start to [?cave/get] in.
Teacher: Equal. That sounds like a math term. What do you mean by that?
Hunter: Um.
Teacher: What's not equal?
Hunter: They both um, the amount of air is the same.
Teacher: By the amount the same you mean on the inside and on the outside?
Hunter: Yeah.

Should we say that Hunter is doing good inquiry solely because he gets the correct answer? Again we say "No!" He does give a correct explanation, but even more importantly he gives a mechanistic explanation. Hunter begins by giving the starting conditions and entities that are important to his explanation of the phenomenon - the juice box begins filled with air. He also identifies where that air is located – inside the box - and what activities air engages in – pushing. In a similar way he describes another relevant entity, its location, and its activity – the air outside pushes the box in. Hunter then forward chains, laying out a causal sequence of events that follow from one another based on the entities, activities, and properties he has asserted – sucking on the straw removes air from inside the box, which causes an imbalance of the in and out pushes. Since the inward push is now greater the box caves in. It is this forward chaining that marks Hunter's explanation as highly mechanistic. To assess his response based solely on his conceptual understanding misses the sophistication of his reasoning.

Discussion: The Quality of Mechanistic Inquiry

These two excerpts demonstrate how we use the mechanism coding scheme to assess student inquiry rather than assessing with conceptual standards. Particularly notable is that our assessment of these two explanations identifies similar sophistication in the reasoning used, despite the fact that judged against canonical knowledge one is wrong and the other is correct.

In the discussion students rarely engage in discourse at the lowest levels of the coding scheme – describing target phenomenon and articulating starting conditions. One reason we don't observe the lowest levels is that the students have already established the "What" of the question and quickly move onto the "How." We observe that for them it is insufficient to just make observations; they must also consider what causes the phenomenon. This in itself is quite sophisticated. It is likely that the teacher's role in soliciting these types of explanations is significant. While not the focus of this paper it is an important dimension that should be explored in future work.

Even more importantly, during moments of especially sophisticated inquiry students use the highest level of mechanistic reasoning - forward and backward chaining. They move beyond naming relevant components and use their physical intuitions about what kinds of things can happen to construct plausible explanations. We believe this strategy of using ideas about the entities and activities in one step of the mechanism to reason about another step is the hallmark of quality mechanistic inquiry. It is the students' use of forward and backward chaining to construct their explanations that leads us to assess their inquiry so highly.

We suspect that higher level mechanistic reasoning like that used by these students is the kind of thinking that contributes to the progress of science. Forward and backward chaining allows scientists (and students) to assess hypotheses by pursuing the implications of an idea to a place where they can be empirically tested. Similarly, it helps students trace and evaluate the individual steps of rival hypotheses to identify inappropriate conclusions and ultimately decide among them. Finally, its reliance on physical intuition encourages students to search for explanations that are plausible when judged against their knowledge from everyday experience.

In this work, we assert that evaluating students based on conceptual understanding gives an impoverished view of their scientific inquiry. We present mechanistic reasoning as another dimension along which to measure the quality of inquiry. Assessing mechanistic reasoning allows us to observe student sophistication in areas that the history and philosophy of science have shown to be valuable for understanding science, even more valuable than immediately obtaining a correct answer.

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