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DEFINING LEARNING PROGRESSIONS FOR SCIENTIFIC INQUIRY

Most learning progressions, while acknowledging the importance of inquiry, focus on students' movement toward canonical understandings. In addition, many progressions depict students' steady progress through conceptual attainments. Our work is alternative in two ways. First, we focus on students' progress in scientific inquiry as a primary goal in itself, to be assessed in its own right rather than by the proxy of canonical correctness. Second, we expect progress to be episodic, that students' engagement in inquiry will vary by situation. In this paper, we illustrate our theoretical framework by outlining an example analysis in terms of one aspect of inquiry—coherence seeking. We also address some of the benefits and challenges to defining a learning progression for inquiry.

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Theoretical Framework

Motivation for Defining a Learning Progression in Inquiry

While science education has systematically emphasized students' arrival at canonically correct understandings, the field has yet to achieve a systematic emphasis on inquiry, despite years of awareness of its importance. Learning progressions, or "the successively more sophisticated ways of thinking about a topic," however, offer an opportunity for the field to again focus on authentic scientific practice (Duschl, Schweingruber, & Shouse, 2007, p. 214). In particular, it is these "more sophisticated ways of thinking" that are the focus of our learning progression in inquiry.

Drawing upon the work by Hammer, Russ, Mikeska, and Scherr (2008), we define scientific inquiry as "trying to form coherent, mechanistic accounts of phenomena" (p. 150). Because inquiry is at the heart of authentic scientific practice, we argue that the development of a learning progression in inquiry—where the primary objective is developing more sophisticated inquiry practices, rather than correct canonical understandings—is essential. For example, in their work on learning progressions for scientific modeling, Schwarz et al. (2008) focus not "on learning of specific scientific models" but instead "on how the practice of modeling itself improves" (p. 9). Similarly, we argue that in order to make inquiry an educational goal in and of itself, the lower and upper anchors of an inquiry learning progression should be defined by engagement in inquiry practices rather than by scientifically accepted understandings. Importantly, we are not implying that inquiry can or should occur in the absence of content. Our approach to learning progressions emphasizes that while inquiry is a primary goal of science education, it only really occurs when students are genuinely reasoning about phenomena.

Resources and Framing

Researchers in science and mathematics education have interpreted student reasoning and performance in terms of phenomenological (diSessa, 1993) and epistemological (Hammer, 1994; Hammer & Elby, 2002) resources. In this view, the basic cognitive structure for interpreting student reasoning is not a robust "theory" or "conception", but "mini-generalizations from experience whose activation depends sensitively on context" (Hammer & Elby, p. 95). There is some evidence to suggest that the kinds of resources students draw upon when reasoning about a situation depend largely on their framing of the activity (Louca, Elby, Hammer & Kagey, 2004; Hammer, Elby, Scherr & Redish, 2005). For example, children can and do reason mechanistically, but often they do not apply mechanistic reasoning in situations when a scientist would consider it appropriate (Abrams, Southerland & Cummins, 2001; Newton & Newton, 2000).

We find two implications of the resources perspective especially appealing: first, it suggests an alternative to a linear, stage-based description of progression; and second, it helps us recognize productive student thinking that might otherwise be dismissed as inconsistent with scientifically accepted understandings. In particular, the resources perspective allows us to to investigate the *situations* in which students engage in inquiry practices.

Conceptualizing Progress in Terms of Resources and Framing

For our work on learning progressions, we define progress as more stable engagement in inquiry practices over a wider variety of contexts. By more stable, we mean both more frequently and more sustained. For example, we might expect students to reason mechanistically only fleetingly at first, but progress into seeking mechanistic accounts even when none are apparent. And by context, we refer not only to the content about which students are reasoning, but also the social settings in which they reason. We might expect students to challenge claims from authoritative sources, for example, only after they more stably engage in evaluating the claims of their peers.

In considering how such a progression might occur, we again draw on the resources perspective and the view of learning "not as the acquisition or formation of a cognitive object, but rather as a cognitive *state* the learner enters or forms at the moment, involving the activation of multiple resources" (Hammer et al., 2005, p. 93). From this perspective on learning, we see progress in inquiry occurring in at least two ways. First, students may begin to change their expectations about "what it means to do science," that is, their framing of science activities. These changes in expectations may allow students to activate and coordinate previously latent resources for pursuing coherent, mechanistic accounts of phenomena. Second, students may develop and refine resources for reasoning about natural phenomena. The process by which development and refinement of resources occurs is beyond the scope of this work, but is addressed by Redish (2004) and Hammer et al. (2005), among others.

In both of these cases, we conceptualize the progress as occurring episodically, rather than steadily and linearly. We see this approach as complementary to levels-based approaches, with the unique strength of accounting for the context sensitivity of students' reasoning. More specifically, while a students' apparent "relapse" to less sophisticated inquiry practices poses a challenge to strict levels-based approaches, the resources view anticipates and accounts for such variation in students' inquiry practices.

Grain Size for Characterizing a Learning Progression in Inquiry

Other work on inquiry learning progressions has focused on one or more scientific practices, including modeling (Schwarz et al., 2008) and the construction of scientific accounts (Covitt, Gunckel, & Anderson, 2009; Mohan, Chen, & Anderson, in press). Similarly, we take the grain size of our learning progression to be a single aspect of inquiry, such as mechanistic reasoning, modeling, and coherence seeking. We then use classroom data to build descriptions of changes in the nature of students' engagement in these aspects of inquiry over the course of instruction, while acknowledging that progress in one aspect of inquiry may be inextricably linked to progress in others.

Our immediate focus, however, is to identify examples of student engagement in a given aspect of inquiry, identify the conditions under which the engagement occurred, and interpret students' activity in terms of smaller grain-sized components. From this work, we eventually hope to describe examples of resources and their origins, as well as propose an example learning progression in scientific inquiry.

Coherence Seeking as Part of a Learning Progression in Inquiry

To illustrate our approach to defining a learning progression in inquiry, we focus on one aspect of inquiry—coherence seeking: scientists seek accounts of phenomena that cohere in the sense that the set of ideas and information taken to be true are mutually consistent and supportive. Although coherence seeking is not typically identified in education research as a component of inquiry, work by Thagard (1989) and others (Ranney & Schank, 1998; Ranney & Thagard, 1988; Thagard & Nowak, 1988) suggests that coherence plays a central role in scientific theory selection. Drawing on this literature, we identify at least two distinct but related roles that coherence plays in scientific inquiry. First, coherence is an aspect of a mature scientific theory, explanation, or model. Second, *seeking coherence* is an aspect of sophisticated scientific reasoning. Therefore, in considering progress, we must attend to the ways students seek coherence as well as to the coherence of the ideas they produce. While work by Schank and Ranney (1992) and others (Sandoval, 2003; Vosniadou & Brewer, 1992) have focused on assessing the coherence of students' ideas, we focus on students' coherence-seeking behaviors.

For the purposes of our work, we tentatively define two key aspects of coherence seeking: looking for consistency between elements and looking for meaningful relations between elements. What constitutes an element depends on the context, but in general the term refers to one idea, claim, or piece of data within a larger discussion, argument, or explanation.

Drawing primarily on research on students' epistemologies of science, we argue that students possess resources for seeking coherence, and that they can activate these resources under certain circumstances. For example, Sandoval (2003) found that high school students, with the help of technological scaffolds, can attend to the causal coherence of explanations. Work by Smith, Maclin, Houghton, and Hennessey (2000) suggests that even elementary students are able to "recognize inconsistency in the thoughts of others" and identify consistency as one "criteria for acceptance of ideas" (p. 364). In defining a learning progression for scientific inquiry, we must consider how these and other coherence-seeking behaviors develop into part of a more sophisticated practice of scientific inquiry.

Importantly, we are not claiming that a learning progression in inquiry is defined solely by progress in coherence seeking. Mechanistic reasoning, modeling, and a host of other practices are central to forming "coherent, mechanistic accounts of phenomena" (Hammer et al., 2008, p.

150). We use coherence seeking primarily to illustrate our theoretical framework for a learning progression in inquiry, as well as to bring to light challenges of this framework.

Methods

Participants and Data Collection

In this paper we illustrate our approach to characterizing learning progressions in inquiry using data collected during an NSF-funded research project, "Learning Progressions for Scientific Inquiry: A Model Implementation in the Context of Energy" (NSF DRL 0732233). This project has three major goals: (1) to devise learning progressions for students and teachers for scientific inquiry; (2) to develop model materials and strategies for elementary and middle school curriculum and teacher professional development; and (3) to study how students and teachers learn using the curriculum and professional development materials. We are currently completing the first year of implementation and data collection.

For this project, eight participating elementary and middle school teachers attended a week-long summer workshop where they engaged in scientific inquiry activities and interpreted video of students reasoning about scientific phenomena. Teachers also continue to participate in biweekly meetings designed to help them attend to student thinking and promote inquiry practices. During the school year, each teacher spends approximately 20 classroom hours using curricular materials developed as part of the project. The curriculum modules seek to promote scientific inquiry practices in the context of a different scientific discipline for each grade level—motion (third and fourth grade), electric circuits (fourth grade), earth science (fifth grade), and ecology (sixth grade)—each with opportunities for ideas about energy to emerge. Video, field notes, and artifacts are collected from professional development meetings, workshops, classroom implementations of curriculum modules, and additional classroom episodes at the discretion of the teacher. These serve as the primary sources of data for our development of student—and teacher—learning progressions. Here, we report video data collected in the elementary classrooms during the implementation of our curricular modules.

Analysis

In identifying examples of coherence seeking, we review classroom video and student artifacts looking for evidence both of students seeking *consistency* between ideas and seeking *meaningful relations* between ideas. Examples of evidence include identifying an inconsistency, offering a reconciliation for an inconsistency, or articulating a relationship between ideas. Our preliminary coding scheme, along with illustrative examples from classroom transcripts, is included in Tables 1 and 2.

The Beginnings of a Learning Progression in Coherence Seeking

Evidence of Coherence Seeking in One Elementary Classroom

As previously mentioned, our curriculum modules are designed to allow students to pursue coherent, mechanistic accounts of various phenomena. In the case of our fifth grade module, students reason about phenomena related to the water cycle, such as the apparent "disappearance" of a puddle over the course of a day. During implementation of this module, one of our fifth grade teachers, Ms. M, poses the following question to her students:

> "[This morning] there were clouds and now there aren't clouds. Where did the clouds go?"

One of her students, Raphael, replies that he thinks "clouds need a cold environment" because a flight attendant told him that if a plane window opened, everyone would turn into a "block of ice." Upon further questioning, Raphael also agrees that high clouds are "probably [made of] ice." Just as Ms. M is about to move on to another student, Raphael exclaims "Oh! I have an idea." He continues:

> Raphael: Uh, well I think that uh when the sun comes up, the- it pushes the clouds down and that's the morning and uh they turn into fog. And they go and they form puddles. And then when the sun gets really hot, uh hotter, like later in the afternoon, the puddles evaporate. And that's, and the clouds are connected to the fog and the water and the sun, evaporation.

Ms. M recognizes that Raphael has made "connections" between clouds, the topic of the day's discussion, and puddles, the previous days' discussion topic:

> Ms. M: Okay, so there's some, now you're bringing back in what we talked about yesterday. There's some connection with all of this.
>
> Raphael: Yeah, the ice, because they're [clouds] made of ice, ice can melt. And since they're so close to uh, the sun, the sun will push em down because and then they'll turn into fog and they'll, they'll melt and then the water that's left will go into the puddles and the sun will evaporate the puddles later on in the afternoon.

In Raphael's responses we see evidence of coherence seeking in the form of *looking for meaningful connections* between phenomena. In particular, Raphael spontaneously identifies *temporal relations* between phenomena the class had been discussing over the course of two days—cloud movement, fog and puddle formation, and evaporation. He also describes a describes a *cause and effect relationship* between the sun, melting clouds, and fog formation. Drawing on text comprehension literature, we identify these two types of relationships, namely causal and temporal, as central to coherence seeking (Trabasso, Secco, & Van Den Broek, 1984). We also note that Raphael's description of fog formation is evidence of another aspect of inquiry, mechanistic reasoning (Russ, 2006).

The next day, in another instance of coherence seeking, Raphael interrupts a conversation about lightning to ask about clouds:

> Raphael: And also, I know this is kind of off our main question but, I just thought like since the the clouds are so high, high up and it's cold, and the sun, and they're closer to the sun than we are, why is it cold?

Again, we see evidence of Raphael seeking coherence, only this time it is in the form of *looking for consistency*. More specifically, Raphael *identifies an inconsistency between two pieces of information*: clouds are closer to the sun and clouds are cold. From a resources perspective, we interpret Raphael's statement as indicative of his activation of the p-prim "closer means stronger," or closer means warmer, which here serves as a resource for reasoning about clouds' temperature relative to their distance from the sun (Hammer, 1996, p. 102). A series of students attempt to *offer reconciliations for the inconsistency* through arguments about the angle of the sun's rays and the density of the atmosphere. Raphael finds these reconciliations unsatisfactory and systematically rejects them.

> Louis: Um, actually, might [be] because the atmosphere and the cloud cover um that it won't be—that it could get cold. And um, the sun probably isn't right where we are at that point. It could be somewhere else around the Earth.
>
> Raphael: Yeah but they're [clouds] still freezing. And it's still freezing above the Earth with or without the clouds. (Louis: okay) So why? I mean cuz the sun is right there closer and we still have the hottest days when the clouds are sitting up there freezing.

Louis *offers a reconciliation*, namely, that the coldness could be caused by cloud cover or location of the sun. Although he considers the reconciliation Louis has offered, Raphael still does not think the inconsistency is settled. We interpret Raphael's question "So why?" as a continued *request for reconciliation*, and evidence that he is still engaged in coherence seeking. Toward the end of the conversation, another student, Jake, *identifies an inconsistency* related to the one Raphael identified. He brings the inconsistency to the attention of the class:

> Jake: Well in space, even if you're facing the sun it's freezing. Why do you think that? It's closer to the sun.

Again, we interpret Jake's question in terms of his activating the *closer means stronger* p-prim, and in this case it serves as a resource for identifying another inconsistency similar to Raphael's. No students offer reconciliations for Jake's question, and the conversation moves on to other topics.

Characterizing Progress in Coherence Seeking

Raphael engages in the activity of coherence seeking in that he identifies meaningful (temporal and causal) relationships between phenomena, identifies an inconsistency between two ideas, and requests a reconciliation for those inconsistencies. In the spirit of a learning progression in inquiry, we hope Raphael will become more sophisticated in his practice of coherence seeking over the course of instruction. In other words, he will more stably seek coherence in a wider variety of contexts.

As Raphael becomes more stable in seeking coherence, we might expect him to draw attention to inconsistencies more often, and let fewer contradictions get by "unnoticed" in the classroom, and continue to push for reconciliation despite barriers to doing so. Likewise, he may show evidence of identifying temporal and causal relations between phenomena more often. In another form of progression, however, we expect Raphael to attend to coherence in a wider variety of situations.

For instance, he might identify inconsistencies not only during a class discussion, but also during experiments or while working on his own. He might also attend to different kinds of relations among ideas depending, among other things, on the topic being investigated. For example, while reasoning about clouds and related phenomena, Raphael appears to reason using cause and effect and temporal relationships. In another content area, however, like ecology, we might also expect Raphael to consider part-to-whole relationships. In fact, one route we are pursuing in our analysis is to identify if and when students attend to these different types of relations as they proceed through our toy car, electricity, water cycle, and ecology modules.

Challenges to Student Progress in Coherence Seeking

Although we have evidence both from our classroom video and from the literature (Sandoval, 2003; Smith et al., 2000) that students can and do engage in activities that we are calling coherence-seeking, we also theorize that students' engagement in these behaviors is initially unstable and highly context-sensitive. One of our important tasks in developing a learning progression in inquiry, therefore, is to identify contexts in which students do or do not seek coherence. What features of situations tend to cue coherence seeking? What tend to inhibit it? While our work is largely theoretical at this point, we do anticipate that finding evidence of student progress in coherence seeking will be more likely in instances where students' ideas are central to classroom activity. For that reason, we have focused our professional development with our participating teachers around the idea of *responsive teaching*, where student ideas guide instruction. We have also designed our curriculum modules to allow ample opportunities for students share, debate, and refine their ideas. One of our project goals is to study in what ways responsive teaching and our curriculum modules facilitate not only coherence seeking, but other aspects of inquiry as well.

Concluding Points

In this paper, we argue for the development of an inquiry learning progression that takes as a primary objective students' development of more sophisticated inquiry practices. We outline a framework for defining an inquiry learning progression in terms of students' more stable engagement in inquiry practices as they reason about phenomena, using coherence seeking as an example. While our work offers an alternative way to conceptualize and define learning progressions, it also raises challenging questions. One of our immediate challenges is to develop empirical approaches to describing a learning progression that is episodic in nature.

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Table 1
Evidence of Coherence Seeking in Terms of Looking for Consistency

Student Behavior	Example from Classroom Data
Identify an inconsistency between: · Two or more pieces of information · A claim, prediction, or explanation and two or more pieces of information	*"...how could a magnet have electricity in it because, isn't a magnet metal too? sort of? If it had electricity in it, it would go out. Because once electricity hits metal it goes, it keeps going in the metal until it goes—until there's no other metal on to for it to travel through and then it goes out."* The student identifies an inconsistency between two pieces of information (electricity goes through metals, magnets are metal) and another student's claim that magnets have electricity in them.
Request reconciliation of an inconsistency	*"...since the the clouds are so high, high up and it's cold, and the sun, and they're closer to the sun than we are, why is it cold?"* The student requests reconciliation for the inconsistency of clouds being cold when they are "closer to the sun."
Offer a reconciliation of an inconsistency	A student finds that, contrary to his prediction, the asphalt from which a puddle evaporated is cooler than the surrounding asphalt. He offers a reconciliation: *" I think the water kind of acted like a cover for the asphalt for a few moments. So it, so that it, so this [asphalt] started to heat up, so it was like putting a cover over this so this doesn't heat up as fast..."*
Devise a hypothetical situation involving a contradiction	*"...what happens if lightning struck the top of a tire with the rim in it? Like what would happen because that ha—the rim is metal and if it struck the top of it, would it reflect off because you have metal under the rubber so?"* The student sets up a hypothetical situation with the implicit contradiction that electricity behaves differently in rubber and metal.
Indicate that a result or observation is unexpected	*"You know what's probably really interesting…you would think that, let's say that three inches evaporated in five minutes…then wouldn't you think that the six inches would evaporate in ten minutes?"* The student indicates surprise regarding an observation about puddle evaporation times.

Table 2
Evidence of Coherence Seeking in Terms of Looking for Meaningful Relations

Student Behavior	Example from Classroom Data
Identify a relationship between ideas, for example: · cause and effect · part-to-whole · category and example · temporal/chain of events	*"...She said that it was heat coming up. Me and Robert were thinking maybe it's like um cause and effect. Heat is the cause and the water vapor is the effect."* Students are debating what the "stuff" is that they see rising from an evaporating puddle—steam, water vapor, or heat. As part of her argument for why the "stuff" is not heat, the student identifies a cause and effect relationship between heat and water vapor.
Identify an unexplained phenomenon	*"...if they [clouds] need to get rid of their energy and it turns into electricity, why does that only happen in certain areas?...Some areas they have like storms and rain and uh everyday. Um, why does that not happen here?"* The student recognizes that another student's idea (that clouds have to get rid of energy) does not explain why some places are stormier than others.
Request a relationship between ideas	A teacher puzzles over a student's comments about rocks, wondering what relationship the student sees between a piece of a rock and the larger rock: *But I also want to know, what is the relationship between what she's thinking is a slice of the rock? What's the relationship of the smaller piece to the larger piece, like, what is her interpretation of what it should be? Would they both look the same? What is the relationship between the two?*
Offer a reconciliation for an inconsistency	A student finds that, contrary to his prediction, the asphalt from which a puddle evaporated is cooler than the surrounding asphalt. He offers a reconciliation for the inconsistency: *"You know what I think it is. I think the water kind of acted like a cover for the asphalt for a few moments. So it, so that it, so this started to heat up, so it was like putting a cover over this so this doesn't heat up as fast as this. And then taking the cover off."* In particular, the reconciliation indicates a causal relationship between water cover and asphalt temperature.