What is this thing called sensemaking? A theoretical framework for how physics students resolve inconsistencies in understanding

By

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There's an old Viking saying that roughly translates to

> *Friendship is built*
> *when people can share*
> *their ideas with one another.*
> *Nothing is worse than fickleness;*
> *friends don't just tell friends what they want to hear* (Håvamål, verse 124)[1]

There were many people who helped me on this journey, with whom I shared ideas, exchanged critical feedback, and built friendships.

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[1] Or, in the original Icelandic:
Sifjum er þá blandat
hverr er segja ræðr
einum allan hug
alt er betra
en sé brigðum at vera
era sá vinr öðrum, er vilt eitt segir

ABSTRACT

Students often emerge from introductory physics courses with a feeling that the concepts they have learned do not make sense. In recent years, science education researchers have begun to attend to this type of problem by studying the ways in which students make sense of science concepts. However, although many researchers agree intuitively on what sensemaking looks like, the literature on sensemaking is both theoretically fragmented and provides few guidelines for how to encourage and support the process.

In this dissertation, I address this challenge by proposing a theoretical framework to describe students' sensemaking processes. I base this framework both on the science education research literature on sensemaking and on a series of video-recorded cognitive, clinical interviews conducted with introductory physics students enrolled in a course on electricity and magnetism. Using the science education research literature on sensemaking as well as a cognitivist, dynamic network model of mind as a theoretical lens, I first propose a coherent definition of sensemaking. Then, using this definition I analyze the sensemaking processes of these introductory physics students during episodes when they work to articulate and resolve gaps or inconsistencies in their understanding.

Based on the students' framing, gestures, and dialogue I argue that the process of sensemaking unfolds in a distinct way, which we can describe as an epistemic game in which students first build a framework of knowledge, then identify a gap or inconsistency in that framework, iteratively build an explanation to resolve the gap or inconsistency, and (sometimes) successfully resolve it. I further argue that their entry into the sensemaking frame is facilitated by a specific question, which is in turn motivated by a gap or inconsistency in knowledge that I call the vexation point. I also investigate the results of sensemaking, arguing that students may use the technique of conceptual blending to both “defragment" their knowledge and resolve their vexation points.

Chapter 1: What is this Thing Called Sensemaking?

INTRODUCTION

Mrs. J., an AP physics teacher, was deftly wrapping up her lesson on Newton's 3rd Law, commonly known as the law of "equal and opposite forces." She felt the lesson had been both thorough and successful: after providing the class with a detailed definition and description of the principle, she had walked them through several relevant examples, such as collisions between cars of different masses, showing in each case numerous pieces of evidence that the law held. As the class filed out of the room a bewildered-looking student, Marco, approached her, saying "Excuse me, Mrs. J., I don't quite know how to ask this. I understand that what you said in today's class is true, at least mathematically, but I just don't get it. If a car crashes into a semi it'll be crushed and the semi will be fine, but Newton's 3rd law says that the forces on the two are equal. How can this be the case? It just doesn't make sense!"

Mrs. J. was flummoxed. What did Marco mean when he said "it just doesn't make sense?" She had quite clearly shown him that it was true, complete with the equations of motion, clear diagrams of the forces at work, and even graphs of actual measured forces from real collisions. She patiently pulled up her notes on the subject and walked the student through the argument again, but by the end of the interaction he still seemed unsatisfied. Mrs. J., too, felt frustrated; she didn't quite understand what didn't make sense to Marco, nor did she understand how to help him.

Many of us have, at one point or another in our learning lives, been either Mrs. J. or Marco. There have been times when ideas have not made sense to us, and when we have not been able to help them make sense to our students. However, despite our extensive experience of the feeling, what we mean when we talk about ideas "making sense" is fairly nebulous and intuitive, and for that reason, elusive.

In recent years, science education researchers have begun to try to pin down "sensemaking" by documenting and analyzing cases of students engaged in the process of making sense of science. While the term *sensemaking* has been commonly used as early as the 1980s in fields such as organizational research (Dervin, 1983), artificial intelligence (Klein & Moon, 2006), and symposia on decision making (Leedom, 2001), it has more recently become a fast-growing topic of science education research. In fact, since 2007, the total number of publications mentioning the term sensemaking (or sense-making/sense making) has nearly doubled across three major science education journals, *Science Education*, the *Journal of Research in Science Teaching*, and the *International Journal of Science Education*, with 326 such publications occurring between 2007-2017, compared to 169 publications during the previous ten years and only 41 before that.

However, despite this increased interest in sensemaking research, the field remains divided on what, in fact, we even mean by sensemaking. Its recent rise in use makes it a relatively new theoretical construct in the science education research literature. As a result, and as with any newer construct, there is not yet widespread theoretical agreement on its nature and scope. Although there have been some recent attempts to create overarching frameworks of sensemaking (Ford, 2012; Kapon, 2016), the science education literature on the subject remains fragmented. Moreover, there is a great deal of overlap between prior theoretical constructs and frameworks in science education (such as *knowledge integration*, *epistemological frames*, *analogical reasoning*, etc.) and what is now being called sensemaking.

This lack of theoretical clarity is a problem—a problem for researchers, for instructors, and for students. As science education researchers, part of our job is to characterize and understand what students are doing when they are learning science, and sensemaking is almost certainly a crucial part of that process. However, we have yet to assemble a coherent picture of what sensemaking actually entails. How can we study sensemaking if we don't even have a clear definition of what it is? How can instructors like Mrs. J. support students in sensemaking if they haven't delineated what students are actually doing when sensemaking? And how can we ultimately help students like Marco come to recognize it in themselves if we cannot put words to the term?

In what follows, we address these issues by presenting a theoretical definition for sensemaking synthesized from the science education research literature. We begin by illustrating the phenomenon of sensemaking using two prototypical excerpts that we suspect, despite being separated by 100 years of scholarship, will both resonate with readers. We then present our definition and justify it using three main strands of literature that have described and studied sensemaking. We illustrate the utility of this definition by showing how it can distinguish sensemaking from other more general phenomena like *thinking*, *explaining*, and *arguing*, and conclude by exploring the theoretical and pedagogical implications of this description.

MOTIVATION FOR A COHERENT THEORY OF SENSEMAKING

While the body of science education research on sensemaking has grown in recent years, one might reasonably wonder, “why study it in the first place?” In reviewing the literature on sensemaking, we have found three primary reasons that researchers are interested in this view of science learning. First, researchers have argued that sensemaking promotes “deep” learning, allowing students to more easily build connections between the new and existing knowledge and encouraging interest in the subject or task (Chin & Brown, 2000; Danielak, Gupta, & Elby, 2014; Scardamalia & Bereiter, 1992). Second, and relatedly, researchers have argued that when students make sense of ideas it facilitates the process of transferring those ideas to new and different domains (Kapon & DiSessa, 2012; Nokes-Malach & Mestre, 2013; Ruibal-Villasenor et al., 2007). Third, sensemaking is essential to the way that scientists and engineers construct knowledge, and so researchers have argued that promoting it in the science classroom can bring “school science” more in line with disciplinary practices (Danielak et al., 2014; Feynman, 1999; Ford, 2012).

However, the theory of sensemaking is fragmented. For example, here are a few explicit definitions or descriptions of sensemaking drawn from the science education literature:

- “The process of explaining observed phenomena through coordination of theory and evidence.” (Crowder, 1996, p. 174)

- “Pursuing a deep understanding that integrates formalisms, concepts, and everyday or intuitive thinking.” (Danielak et al., 2014, p. 9)

- "The goal of sensemaking focuses more on generating or understanding a claim than challenging it, whereas the goal of persuasion is more coercive and it occurs when the focus is more about critiquing the posited claim." (Berland & Reiser, 2011, p. 193)

- "Behaviors associated with sense making include making connections to the real world or lived experience, coordinating multiple representations, considering the reasonableness of solutions, and treating the problem as a sensible one to solve." (Chen, Irving, & Sayre, 2013, p. 2)

- "Employing scientific ideas and models in the way described above involves a complex process of sensemaking in which a learner constructs and reconstructs a series of self-explanations that evolve, change, replace one another, or merge into a new self-explanation. It is assumed here that the evolution of self-explanations involves an ongoing tacit evolution of their relative soundness." (Kapon, 2016, p. 2)

In addition to these, there are many other descriptions of similar phenomena that use other theoretical terms, such as *knowledge integration* (Linn & Songer, 1993), *argumentation* (Berland & Reiser, 2009), or *a storytelling frame* (Rosenberg, Hammer, & Phelan, 2006). How can all of these definitions and descriptions be talking about the same phenomenon? And with such a fragmented theoretical description, how can science educators who aim to support sensemaking decide which approach to use in their classrooms?

DESCRIBING SENSEMAKING

With such fragmented literature on sensemaking, before we tackle the theoretical construct we need to be sure we have basic agreement on what the phenomenon itself looks like. So, what is sensemaking? Or, to rephrase the question, when people are sensemaking, what are they doing?

Dewey, “How we Think" (1910)

In Chapter 6 of John Dewey’s *How We Think* (1910) he describes a case of what he calls reflective experience, or reflection upon an observation. While he didn’t use the term, we characterize his description as a clear example of what is now referred to as *sensemaking*. Says Dewey,

> Projecting nearly horizontally from the upper deck of the ferryboat on which I daily cross the river, is a long white pole, bearing a gilded ball at its tip. It suggested a flagpole when I first saw it; its color, shape, and gilded ball agreed with this idea, and these reasons seemed to justify me in this belief. But soon difficulties presented themselves. The pole was nearly horizontal, an unusual position for a flagpole; in the next place, there was no pulley, ring, or cord by which to attach a flag; finally, there were elsewhere two vertical staffs from which flags were occasionally flown. It seemed probable that the pole was not there for flag-flying.
>
> I then tried to imagine all possible purposes of such a pole, and to consider for which of these it was best suited: (a) Possibly it was an ornament. But as all the ferryboats and even the tugboats carried like poles, this hypothesis was rejected. (b) Possibly it was the terminal of a wireless telegraph. But the same considerations made this improbable. Besides, the more natural place for such a terminal would be the highest part of the boat, on top of the pilot house. (c) Its purpose might be to point out the direction in which the boat is moving.
>
> In support of this conclusion, I discovered that the pole was lower than the pilot house, so that the steersman could easily see it. Moreover, the tip was enough higher than the base, so that, from the pilot's position, it must appear to project far out in front of the boat. Moreover, the pilot being near the front of the boat, he would need some such guide as to its direction. Tugboats would also need poles for such a purpose. This hypothesis was so

> much more probable than the others that I accepted it. I formed the conclusion that the pole was set up for the purpose of showing the pilot the direction in which the boat pointed, to enable him to steer correctly.

We suspect many readers would agree that Dewey's account represents prototypical sensemaking of the sort we want to see students engage in in our science classes. He has noticed something inconsistent with his understanding of the world, and is trying to find some way to resolve it. In order to achieve this resolution he builds an explanation, which bridges the gap between the anomalous observation or idea, the thing that doesn't "make sense," and what he otherwise knows to be true.

Fleshing out Dewey's process in this excerpt gives us some hints as to what sensemaking entails. Specifically, in Dewey's case the process begins with something he suspects or knows (or accepts) should be true, but doesn't understand; he has noticed a long white pole with a gold ball on the top which juts off the front of a ferryboat, but he doesn't know why it is there. It clearly must serve some function on the boat, but he doesn't know what that function is. In other words, he has found something that doesn't make sense, an observation that doesn't fit with what he otherwise knows and observes about the world. So, Dewey decides that he is going to make sense of this anomaly, that he will figure out why this pole is there.

Dewey does not stop with merely identifying this inconsistency; the next step in his sensemaking process is to start coming up with ideas for why it would be the case. He has plenty of ideas and experiences to draw on, including his observations of boats, flagpoles, and telegraphs. So, Dewey tries out different ways of connecting this observation to what he knows about the world: maybe it's a flagpole? He brings in other knowledge of flagpoles, but then finds inconsistencies, such as key pieces of flagpoles that are missing and the fact that there are other poles on the boat already used for flying flags. He considers several other ideas—ornaments and radio antennae—and in each case he tries connecting that idea to his understanding of boats until he finds inconsistencies. Finally, he proposes that the pole might point in the direction the boat is moving; he connects this to several other observations and ideas of the ferryboat, finds no major inconsistencies, and settles on that explanation.

Hutchison and Hammer (2010)

In the above example, Dewey described his own individual, recollected thought process about an everyday question. Possibly as a result, the process he describes is highly rational and linear. For contrast, we now examine a raw, collaborative example of scientific sensemaking in which students are making sense in real time rather than reconstructing previous thinking.

In this transcript excerpt from Hutchison and Hammer (2010, p. 513-514), three pre-service science teachers are trying to understand why certain things float in water and others sink. Earlier in the conversation, the class has discussed the fact that a solid copper cylinder will sink but apples and Styrofoam will float. They have proposed that perhaps this has something to do with pockets of air in the material. This line of questioning kicks off the following conversation, in which two students try to reconcile whether the floating behavior is, in fact, due to pockets of air or a more general property, density:

Bekah: I kind of have an idea. This thing is aluminum, right? (*holds up a solid aluminum block*)

Teacher: Yep.

Bekah: So what if we took a piece of aluminum foil and put it in there. (*points to a large beaker with water in it*) That, does aluminum foil have air in it? Like I would think it would float. So then I think that depending on whether or not she thinks it'll float, I remember back in class when we talked about this, like mass over volume, and if it's less than the density of water it's going to float, so no matter what the object is, it depends how big it is, and (inaudible), so I don't think air is really a big factor.

Teacher: So Bekah, you're, and you wrote this in your daily sheet, you're arguing for air is not a factor, the density is the important thing.

Bekah: Yeah.

Teacher: Okay

Bekah: I just think air, I'm sure it has, like it doesn't hurt it, but it had to (*inaudible*)

Katie: Maybe air affects the density then.

Rachel: I was just going to say that it seems like it's really the same thing. We're just calling it air and she's calling it density. Just like, if you (*inaudible*)

Katie: I mean maybe the atoms, if you take the Styrofoam, it's (*she picks up a piece of Styrofoam and looks closely at it*)

Rachel: I don't really know so much about density, but it's not that, I don't think [Styrofoam is] that dense.

Teacher: So if, if there's a lot of air pockets kind of mixed in with the material then it would be less dense.

Katie: Yeah.

Rachel: Right.

Katie: Because air is the, okay, density is the absence of air. Like the more dense an object is the less air it has.

Teacher: The less air there is, okay.

Katie: So maybe they work together in that way.

In this example, the class is trying to address a gap in their knowledge: they know some things float and others sink, but they don't know why. In the process, they've encountered an inconsistency in the explanatory framework they've developed: things were thought to float because they have pockets of air inside them, but a crumpled ball of aluminum foil floats even though metallic aluminum doesn't have much air inside it. Bekah builds on this explanation by drawing a connection between floating and a term she'd heard before, density, which she describes as mass over volume. However, Katie and Rachel, bringing in their knowledge of Styrofoam, suggest that perhaps pockets of air actually contribute to density, concluding that an object's density is inversely related to the amount of air it contains, and thereby returning to the original explanation.

Katie, Rachel and Bekah's process of sensemaking is similar in many ways to Dewey's; the students have identified an anomaly, something they realize they don't fully understand (why certain objects sink and others float). They know that there must be a reason, but that reason remains a mystery—it doesn't make sense. However, the preservice teachers have a great deal of experience with sinking and floating objects to draw on in order to explain this phenomenon. When the excerpt starts, they are already building an explanation out of connected ideas (air pockets, density). As they build the explanation, they encounter inconsistencies, but they try to reconcile them by modifying their explanation to take them into account. While they don't come to a conclusion in this transcript, their *process* of trying to connect this anomaly to what they otherwise understand is similar to that described by Dewey above.

A Proposed Definition of Sensemaking

Although Dewey's example was originally meant to illustrate "reflective thinking," we argue—and believe most readers would agree—it can also be thought of as an episode of sensemaking. The modern example from the science education literature has been explicitly labeled as sensemaking. Together, we can use these two examples to begin to define what sensemaking means and looks like.

Based on these two examples, as well as the science education literature on the subject which we describe in the remainder of this article, we propose that *sensemaking* is a dynamic process of building an explanation in order to "figure something out"—to ascertain the mechanism underlying a phenomenon in order to resolve a gap or inconsistency in one's knowledge. One builds this explanation out of a mix of prior knowledge and formal knowledge by iteratively proposing and connecting up different ideas on the subject. One also simultaneously checks that those connections and ideas are coherent, both with one another and with other ideas in one's knowledge system.

Is this definition consistent with the above two examples that we intuitively consider sensemaking? Sensemaking, according to this definition, begins when something is puzzling or unexpected, there is some gap in existing knowledge, individual facts or ideas conflict with one another, or some combination of these. What is that pole? And what's the deal with a floating aluminum foil ball? This part of the sensemaking process is also consistent with Marco's experience in the opening vignette. He knows that when a car collides with a semi-truck, the car gets crushed, but Newton's third law says they exert equal forces on each other. The latter piece of information seems inconsistent the former, doesn't make sense; it is, as some researchers have called it, "anomalous data" (Chinn & Brewer, 1993).

Once one has decided something needs explaining, the next step in the sensemaking process is to start throwing out ideas for why it would be the case. The first things that come to Dewey's mind are that the object could be a flagpole, or possibly an ornament or radio antenna. For the pre-service teachers, it is air and density. Some researchers have called this process "shopping for ideas" (Hammer & Zee, 2006) or "mode-skimming" (Sherin, Krakowski, & Lee, 2012); Dewey calls it "cultivation of a variety of alternative suggestions" (p. 75). It's essentially a process of brainstorming possible ideas related to the phenomenon, which act as the seeds of the explanation that resolve the anomaly. They then throw out related ideas or beliefs, and connect them together into a chain of ideas. As this chain gets assembled, they check that these ideas are consistent (Hammer & Zee, 2006; Kapon, 2016; Rosenberg et al., 2006), both with the explanation as a whole and with other ideas that may not necessarily be directly useful in building the explanation, but which they otherwise believe to be true. By the end of this process, if their sensemaking is successful, they end up with a coherent explanation that fills in the gap in knowledge or resolves the inconsistency—at this point, things "make sense."

There are of course many ways this basic process of identifying a gap, shopping for related ideas, and then piecing them together into coherent explanation could be complicated and complexified during sensemaking. First, this simple process is likely repeated over and over—the process is iterative and non-linear. Second, some of the ideas that emerge in this process may be inconsistent with the explanation as a whole, and as such students must either modify their explanation, reject it, or reject the idea. Third, students may end up with several competing explanation for the same phenomena. In these cases, they may have to decide between them, or merge them into a single explanation.

In order for a definition to be useful it must cover not only the two examples above, but must also be applicable to the broader science education literature on sensemaking. So, in the remainder of this article, we summarize three primary theoretical descriptions of sensemaking from the science education research literature and show how this definition covers and incorporates each. These three descriptions, which we refer to as three primary “strands” of sensemaking research, each conceptualize sensemaking in a different way: as a stance towards science learning, a cognitive process, and a distinct discourse practice. We then show how this definition can be used to differentiate sensemaking from other, broader theoretical constructs such as *thinking, explaining, learning, argumentation,* and *modeling,* and conclude by considering the implications of this definition for future research on sensemaking in science education.

APPROACHES TO DESCRIBING SENSEMAKING IN SCIENCE EDUCATION

Sensemaking as a Stance Towards Science Learning

Some science education researchers have conceptualized sensemaking as a stance, or approach, that people take to science learning. To describe this stance, researchers have used the theoretical construct of *framing,* a term borrowed from the sociology, linguistics, and psychology literature, referring to the expectations that individuals or groups of people bring to an activity—that is, how they answer the question “what’s going on here?” (Tannen, 1993). In school settings, however, most of the tasks students engage in are focused on knowledge and learning, so educational researchers have coined the term *epistemological frames,* or e-frames, to describe the approaches that students take to learning-based activities (Bing & Redish, 2009; Hammer, Elby, Scherr, & Redish, 2005; Hutchison & Hammer, 2010; Scherr & Hammer, 2009).

Based on this research, students framing their activity as sensemaking view their task as building a new explanation for something unknown or not understood—to "figure something out"—using their own ideas, intuitions, and experiences (Hutchison & Hammer, 2010; Kapon, 2016; Rosenberg et al., 2006). The way students involved in this sensemaking e-frame answer the question "what is going on here?" is different from several other ways students might approach science learning. For example, researchers have described other frames in which students see their jobs as memorizing and reproducing scientifically correct pieces of information, or as collecting and ordering information into lists (Rosenberg et al., 2006), trying to get the right answer to a problem through the quickest, easiest method they can find (Chen et al., 2013), or joking and being "off-task" (Scherr & Hammer, 2009). Thus, researchers often define the sensemaking e-frame in contrast to these other possible stances toward science learning.

In science, students explore not just *what* things happen in the world but also *how* and *why* they work—the mechanisms behind phenomena (Braaten & Windschitl, 2011). This stance therefore also typically involves some component of mechanistic reasoning (Kapon, 2016; Russ, Coffey, Hammer, & Hutchison, 2009; Russ, Scherr, Hammer, & Mikeska, 2008), in which students describe physical phenomena using a combination of visible and invisible entities, their properties and actions, how those entities are organized relative to one another, and how this organization changes with time. For example, a mechanistic explanation of why heat moves from hot to cold objects would include reference to atoms (the entities) which are bonded together and therefore jostle one another (the actions). This jostling causes kinetic energy to move through the system (organization changing with time), which we perceive as an object getting warmer (the physical phenomenon). Articulating this type of mechanism, as the class does in Hutchison and Hammer's example, is often a key step to "figuring out" an unknown phenomenon and is therefore a key component to the set of expectations that makes up the sensemaking frame.

Fundamental to the theory of sensemaking as an e-frame is the assumption that frames are dynamic—people shift in and out of them, often very fluidly and quickly. For example, a student might be framing her physics homework as a rote exercise one moment, but in the next moment a particularly interesting or meaningful problem might shift her framing to interested speculation. In accordance with this theory, researchers have observed students who frame their activity as sensemaking shifting in and out of that frame very rapidly, although teachers can also deliberately shift that framing with small, carefully-calibrated nudges (Rosenberg et al., 2006).

Collaboration adds even more dynamicity: when students collaborate, their group-level frame is built of individuals' frames, which means that the different individual frames and interactions may shift the group framing, potentially moving the activity closer or further from sensemaking (Irving, Martinuk, & Sayre, 2013; Scherr & Hammer, 2009). Student frames may even interfere with one another (Tannen, 1993), and so students may have to align their individual frames in order to progress in their task, either by positioning certain members of the group as "sources" and "listeners" or by negotiating and co-constructing a shared frame (van de Sande & Greeno, 2012).

Frames are not completely dynamic, however; researchers have observed that they can be stable for longer periods of time, such minutes or even hours (Rosenberg et al., 2006). Furthermore, if students regularly use a sensemaking frame, that frame may become their go-to approach to science learning, or even a way of interacting with the world more generally. For example, Danielak, Gupta, and Elby (2014) provide a case study of a just such student, Michael, a high-achieving engineering student who placed high value on understanding the concepts presented in his courses but struggled when that approach to science learning conflicted with the dominant approach in his classes. Michael ultimately felt marginalized by a class culture that did not support his sensemaking, to the point that he felt the need to compromise on that approach and considered leaving his engineering program.

In summary, the "stance" strand of sensemaking research is defined by the underlying factors that influence sensemaking: students' goals, expectations, and framing. Our proposed definition explicitly incorporates the sensemaking stance in two ways: first, it highlights the goal or purpose of sensemaking, which is to "figure something out." This is critical because it distinguishes the goal of sensemaking (Berland & Reiser, 2009) from other activities like answer-making (Chen et al., 2013; Maloney, 2015) in which students' goal is to produce a canonically correct answer, regardless of whether it fits with their understanding. Second, this stance is dynamic—students are likely shift between the sensemaking frame and other frames multiple times during a single class period or even in a single discussion—and so our definition foregrounds this dynamism.

Both Dewey (1910) and Hutchison and Hammer (2010) provide clear examples of sensemaking as a stance in their respective works. Hutchison and Hammer explicitly state that their students were in a sensemaking frame, and we see evidence of this in both the students' attempts to figure out why the observed sinking and floating behavior was happening, and the fact that they never consulted an authority to answer their question. That is, at no time did they either do an internet search on the mechanism or ask their teacher; rather, they tried to ascertain the mechanism themselves, through their discussion. The authors also point out that this frame was dynamic: shortly after the excerpt ended, the class shifted away from the sensemaking frame. Similarly, Dewey focused his example on intuiting the underlying purpose of the mysterious pole. He could easily have resolved his question by simply asking the boat's pilot, but instead, he "tried to imagine all possible purposes of such a pole."

Together, these descriptions of sensemaking as a stance towards science learning excel at demarking the boundaries of sensemaking: that is, they show when students switch into or out of the sensemaking frame, and/or how this frame affects other areas of their lives. However, what do students actually do while they are in this frame?

Sensemaking as a Cognitive Process

A second way science education researchers have conceptualized sensemaking is as a specific type of cognitive process. Researchers using this conceptualization focus their analysis on the types of knowledge that people use to make sense of science.

Across all theoretical frameworks, it seems to be universally accepted that sensemaking is based on prior knowledge (e.g., Kapon, 2016; Rosenberg et al., 2006; Warren, Ballenger, Ogonowski, Rosebery, & Hudicourt-Barnes, 2001). That is to say, when sensemaking we fit new knowledge into our existing knowledge frameworks, which are built out of ideas that we've learned or gathered from our experiences. However, especially when learning science, we often have to make sense of unfamiliar, abstract, or complex concepts, and these concepts may not be directly related to our prior knowledge—in fact, they may even conflict. So, this area of research aims to understand how we gather, integrate, and use such concepts when sensemaking.

One rich line of research focused on sensemaking as a cognitive process is built on the theory of *knowledge integration* (Chiu & Linn, 2011; Linn, 1995; Linn & Eylon, 2000; Linn &

Songer, 1993; Shen & Linn, 2011). According to this theory of science learning, students come to science classes full of partially or fully-assembled mental models of how the world works. In order to learn science, students have to assimilate and integrate new, scientific models into their existing frameworks. Knowledge integration is a process in which students articulate their mental models, consider new models, compare their current models to the new models, and ideally integrate the two. Within this theory, sensemaking is seen as the part of the process in which a student iteratively compares and integrates parts of the new model with their articulated mental model (Chi, de Leeuw, Chiu, & LaVancher, 1994; Shen & Linn, 2011). In practice, researchers have argued that students facilitate this integration by generating explanations for themselves, also called *self-explanations* (Berthold et al., 2009; Chi et al., 1994; Kapon, 2016).

A second line of research relies on a specific theory of cognitive structure, the *resources* model of cognition or Knowledge in Pieces (KiP, DiSessa, 1993). The KiP framework describes knowledge as being built out of many "pieces" of intuitive knowledge, or *resources* (Hammer et al., 2005), which we abstract from our daily experiences. Specific types of resources have been hypothesized to constitute thinking at a variety of levels, including physical intuition (DiSessa, 1993), mathematical understanding (Sherin, 2006), higher-level or abstract concepts (Kapon & DiSessa, 2012) and epistemology (Hammer & Elby, 2002). Researchers suggest these resources network or connect to one another, over and over, and the particular connections in different contexts give rise to our ideas for how the world works (Hammer et al., 2005; Sherin et al., 2012). From this perspective, gaps or inconsistencies in knowledge can be thought of as either missing connections or missing resources, and sensemaking is the process of iteratively activating and (re)connecting various resources to resolve this type of gap or inconsistency (Clark, 2006).

Scientific models can be represented in many ways (equations, graphs, pictures, etc.), and so another way in which people make sense of, or integrate, science knowledge is by coordinating multiple representations. A particular representation of a scientific phenomenon carries some information or meaning, but it may hide other essential information about the system being represented. So, in order to fully understand unfamiliar or confusing scientific ideas one may have to draw from and unpack several different representational forms, such as mathematical formalism (Gupta & Elby, 2011; Sherin, 2006), ontological classifications (Chi, Roscoe, Slotta, Roy, & Chase, 2012; Chi, Slotta, & De Leeuw, 1994; Gupta, Elby, & Conlin, 2014), graphs and pictorial representations (Berthold et al., 2009; Chiu & Linn, 2013; Gire & Price, 2014; Linn, 1995; Manz, 2012), or even gesture-based representations (Crowder, 1996; Flood et al., 2015; Manogue, Gire, & Roundy, 2014). Sensemaking therefore involves extracting and connecting up essential features of these types of representations in order to incorporate the represented model into one's knowledge framework.

Research shows there are a variety of ways people could go about the actual connection and integration of their ideas during sensemaking. For example, students may use analogies, metaphors, or conceptual blends to facilitate connections between their prior knowledge and new science ideas (e.g., Brewe, 2011; Clement, 1993; Podolefsky & Finkelstein, 2007). Students may also use the linguistic affordances of analogies or metaphors to classify certain abstract concepts, thus connecting them to other concepts in the same ontological category (Brookes & Etkina, 2009; Jeppsson, Haglund, Amin, & Strömdahl, 2013), although some researchers have also suggested that these connections can cause trouble for students if they place concepts into the wrong category (Chi & Slotta, 1993; Slotta, 2011). Regardless, analogies and metaphors are a primary way in which students create the requisite connections between the information that doesn't "make sense" and one's knowledge framework (Wong, 1993).

To summarize, the cognitive process strand is defined by the sources of knowledge that students draw on, and what they do with it. Our definition explicitly incorporates that strand in two ways: first, it foregrounds the role of prior knowledge and experience in sensemaking, highlighting the fact that sensemaking involves a mix of formal and prior knowledge. This is critical to distinguish sensemaking from activities like "cutting and pasting" (Rosenberg et al., 2006) in which students are drawing on and manipulating formal facts and terminology with little regard to their actual meaning. Such behavior is unlikely to result in the students making any sense of a subject, and so should not be considered sensemaking. Second, it explicitly mentions the iterative way in which students construct knowledge by connect their ideas together (Sherin et al., 2012), which is also key to the process since it distinguishes sensemaking from cases in which students reflexively recall or produce an answer. In such cases students are unlikely to notice any gap or inconsistency in understanding—something that "doesn't make sense"—which would disqualify the activity as sensemaking.

By viewing sensemaking as a cognitive process, we can gain new insights on the examples described by Hutchison and Hammer (2010) and Dewey (1910). In Dewey's case, the role of prior knowledge in the process is clear: Dewey is building his explanation out of everything he knows and recalls about ferryboats. Furthermore, he clearly lays out the connections he draws between the different ideas, connecting his idea that "its purpose might be to point out the direction in which the boat is moving" to his observation that the pole was lower than the pilot house but was angled upwards and his realization that the pilot likely needs some sort of guide to determine the boat's direction. In Hutchison and Hammer's example, we similarly see that all of the examples the class discusses (apples, aluminum foil, Styrofoam) are grounded in the students' everyday experiences and prior knowledge. The transcript also illustrates how the class iteratively try to connect and reconnect their ideas about density to the presence or absence of air pockets, for example with Rachel asserting "We're just calling it air and she's calling it density," and Katie later suggesting that "density is the absence of air."

This strand of research, together with the description of sensemaking as a stance, are both focused on modeling the cognitive factors that underlie sensemaking. However, as Hutchison and Hammer show, sensemaking is also something that one can observe people doing in science classrooms and everyday life—sensemaking is also collaborative and communicative. What defines this kind of collaboration?

Sensemaking as a Discourse Practice

The final way science education researchers have described sensemaking is as a particular style of communication and interaction, a form of collaborative discourse (Berland & Reiser, 2009; Crowder, 1996; Ford, 2012).

One of the richest areas of science education research on student discourse related to sensemaking is *argumentation*. From this perspective, sensemaking is an integral part of the process of learning science through building and defending arguments. Here, argumentation doesn't just mean "arguing" in the colloquial sense (trying to win an argument by convincing someone else you're right). While argumentation research generally focuses on how students construct arguments out of claims and evidence, argumentation researchers use the term *argument* broadly—it encompasses not only ways of persuading, but also ways in which people make claims, construct explanations, and articulate their ideas, all of which are seen as key to sensemaking (Berland & Reiser, 2009).

Some researchers studying sensemaking through argumentation go one step further and define *sensemaking* as a distinct goal that students may have during discussions, which they contrast with *persuasion.* The goal of persuasion focuses on “winning” an argument, convincing someone else of your claim. Sensemaking, on the other hand, is focused more on constructing claims and explanations. Where persuasion is competitive, sensemaking is collaborative; students “arguing” in this style are trying to build an explanation together, and while they may critique each others’ arguments they are doing so to make their explanation stronger, not to “win.” (Berland & Reiser, 2011; McNeill & Krajcik, 2008; Naylor, Keogh, & Downing, 2007; Osborne & Patterson, 2011).

The goal of sensemaking, or constructing claims and explanations, can further be broken down into two iterative sub-processes: *construction* and *critique* (Ford 2012). According to this theory, when people are sensemaking they are building an explanation by repeatedly coordinating (connecting) pieces evidence to back up a claim, and/or constructing a warrant that links this evidence to the claim. This aspect of sensemaking, *construction*, is essentially the connection process described in the cognitive process strand. But one needs to check that explanation to make sure all of the connected pieces are coherent with one another, and that the explanation holds together. Researchers have called this aspect of the sensemaking process *critique* (Ford, 2012).

Whether it’s being done collaboratively or individually, sensemaking always involves this dialogue between construction and critique. People may fluidly shift into these roles during collaborative sensemaking discussions, or a single person may use different mental “voices” for construction and critique (Ford, 2012), as Dewey illustrates. However, from the perspective of argumentation research this dialogic process of coherence-seeking (Sikorski & Hammer, 2017) is inherent to sensemaking.

In order to explain scientific phenomena, students may have to draw on and use advanced scientific concepts or terminology; however, the sensemaking literature generally agrees that a key part of sensemaking is building and communicating these explanations in their own words or language (Ash, 2004; Hutchison & Hammer, 2010; Rosenberg et al., 2006; Warren et al., 2001). In other words, when students build explanations out of terminology that they don't understand, researchers have argued that they are not, in fact, sensemaking since their goal is more likely to satisfy the teacher's or assignment's expectations than to build an explanation that is meaningful to them (Berland et al., 2015; Berland & Hammer, 2012). This requirement can also be tied to the dialogic processes of construction and critique, since it is difficult to either build off of or critique another's reasoning if you don't understand what they are saying.

In summary, the discourse practice strand is defined by the ways in which communication facilitates and supports sensemaking. Our definition explicitly incorporates this strand by acknowledging the role of critique and coherence in sensemaking. This contribution is critical because sensemaking, by its nature, must involve some judgments as to whether or not an explanation does in fact "make sense." Critiques, as we have defined them, provide a mechanism for those judgments, as does the criteria of coherence. However, while such discourse practices are clearly social in nature, we do not include this aspect of sensemaking in our definition because these discursive practices can also occur inside the minds of individuals (Ford, 2012).

The discourse practice dimension of sensemaking is clearly visible in both Dewey's (1910) and Hutchison and Hammer's (2010) examples. Dewey's example of individual sensemaking illustrates the way one can use mental construction and critique “voices” to make sure the explanation is coherent. For example, he proposes that the mysterious object might be a flagpole, ornament, or telegraph terminal, but critiques and rejects all three notions on the grounds that they do not fit with other things he knows to be true about ferryboats and tugboats. Hutchison and Hammer similarly show how the students constructed and critiqued each others’ ideas in a social environment: for example, Bekah opens with a critique of the notion that sinking and floating can be attributed to air pockets in an object’s material, and the class spends the rest of the excerpt trying to achieve coherence between the concept of density and their proposed mechanism of air pockets in materials. This example also shows how sensemaking explanations can be built out of a mix of everyday language and formal terminology: the students in the example, while questioning and critiquing one another, are clearly focused on articulating their ideas in their own words, for example rephrasing the term density as “the absence of air” or “a lot of air pockets kind of mixed in with the material.”

Overlap Between the Strands

Although we’ve presented these areas of sensemaking research as distinct, they can and do overlap significantly with one another. For example, although it’s a discourse practice, argumentation has also been described as a specific frame that students can take to science learning (Berland & Hammer, 2012). Similarly, mechanistic reasoning has been conceived of a form of discourse, with its own discourse-analytic framework (Russ et al., 2008). Knowledge integration requires one to compare and contrast the features of one’s own mental models with those of established scientific models; thus, in the process of knowledge integration, students must both articulate their models and create arguments for how they compare to the establishment, which is essentially the argumentation duality of construction/critique (Berland & Reiser, 2011; Ford, 2012; Shen & Linn, 2011). All in all, each of these areas of sensemaking research either touches on or overlaps with the others. This is to be expected, however, since all of these theoretical descriptions are focused on the same phenomenon, sensemaking.

At the same time, each of these areas of research, at its core, addresses a different but complimentary aspect of that phenomenon. *Stance-based descriptions* address the overall approaches people take to science learning, their attitudes or frames. From a cognitive perspective, these frames denote the regions of mental "space" they draw on when learning science, essentially the boundary conditions for how they approach science learning. *Cognitive processes* describe specifically what happens within this mental space—how students use or modify their mental models and prior knowledge through interactions with established models or representations. *Discourse practices* describe how this manifests in the science classroom at an observable level—that is, what students can actually be seen to be doing when they are sensemaking.

We suspect that readers may see other ways to categorize this set of science education literature; we ourselves can imagine a number of possibilities. However, the categorization presented here is particularly useful for two reasons: first, as we have shown, this structure highlights key aspects of the processes described in the two intuitive examples of sensemaking. Second, and perhaps more importantly, using our theoretical definition of sensemaking and this categorization structure, we can begin to tease apart and distinguish sensemaking from other different but related theoretical constructs.

DISCUSSION: DIFFERENTIATING SENSEMAKING FROM OTHER "GOOD" THINGS TO DO WHEN LEARNING SCIENCE

Integrating existing definitions of sensemaking with the intuitions gleaned from unpacking prototypical examples of sensemaking is, in some sense, an attempt to develop a grand unified theory of sensemaking. One concern with such an approach, however—especially one that brings together constructs from the literature as disparate as framing, argumentation, and knowledge integration—is that everything will become sensemaking. If every activity that is "good" for science learning falls under the umbrella of sensemaking, then having a precise theoretical definition of it becomes superfluous. The power of a definition is in its ability to tease apart subtle differences to unpack the phenomena at work.

Sensemaking and Thinking

One might reasonably ask whether our definition of sensemaking is any different from the more general act of *thinking*. The three strands of sensemaking research above allow us to make these distinctions. For example, "thinking" isn't restricted to a specific stance. Every frame describes some sort of "thinking"—rote memorization/recall is a kind of thinking, but it's a different way of thinking than sensemaking. Furthermore, knowledge integration, or working with multiple representations, is not strictly necessary for "thinking," broadly defined; one can "think" with only one representation, or without integrating any new models into one's existing knowledge frameworks. Within argumentation, "construction" and "critique" are considered specific ways of thinking, typically constrained to sensemaking or argument building: that is to say, there are many areas of life and ways of thinking in which critique is unwanted or unnecessary.

Sensemaking and Learning

To say that learning is an incredibly complex and diversified process would be an understatement. We would argue sensemaking is a form of learning, but that there are also many ways to learn that do not involve sensemaking. For example, memorization, or learning by muscle memory (either physical or metaphorical) need not involve explicitly "figuring something out" and so would not be considered sensemaking by our definition due to a lack of sensemaking framing, but would certainly be considered a type of learning. From a discourse perspective, science students who have build an explanation out of overly complex terminology and can recall it at will have certainly learned something—perhaps at a very surface level, but they have learned. However, according to both our definition and the discourse practice strand, said students have not engaged in sensemaking. Furthermore, it's entirely possible to learn many things without ever critiquing them. Finally, from a cognitive process perspective, it's well documented that students can learn about phenomena or scientific models without integrating them into their understanding (i.e., Case & Gunstone, 2003; Chin & Brown, 2000; Hammer, 1989).

Sensemaking and Explaining

The Next Generation Science Standards define constructing explanations as one of the central practices for science learning. Specifically, explanations are "accounts that link scientific theory with scientific observations of phenomena" (NRC, 2012, p. 67). Reiser, Berland, and

Kenyon (2012) further articulate how students must construct the causal chain of reasoning from evidence to the claim of how or why a phenomenon happens, and then compare and critique that chain of reasoning with others. Is sensemaking, then, just equivalent to explaining?

Based on our definition of sensemaking, we would argue no. Sensemaking involves building new knowledge or forging new connections between existing knowledge, whereas explanations can be generated without the need for any new knowledge or connections. From a stance or framing perspective, explanations show up in many different frames, and those frames do not necessarily have to be focused on "figuring things out." A parent, for example, who is trying to explain why the sky is blue to their child may be reciting and elaborating a remembered explanation, but if in the process they aren't "figuring out" anything new they are not sensemaking. From the perspective of sensemaking as a cognitive process, students who already have a pre-assembled mental model often don't need to make sense of anything new in order to generate explanations from that model (Crowder, 1996; Flood et al., 2015). And, from an argumentation or activity-based perspective, explanation is a broader category of activity that need not involve the elements that characterize sensemaking, like critique or mechanistic reasoning. An explanation can easily be constructed with little need for plausible mechanisms or critiques, instead providing a straightforward, "correct" answer with no need for further elaboration ("the sky is blue because of the way light scatters").

Sensemaking and Argumentation

As discussed in the discourse process strand, there is a great deal of overlap between research on argumentation and research on sensemaking. This research has established that sensemaking includes elements of argumentation, but that argumentation extends well beyond sensemaking. For example, Berland and Hammer (2012) have argued that sensemaking is one of the possible goals or frames for argumentation, but that there are others, including *persuasion* and *authority* (e.g., when a teacher controls the interaction). So, when students are engaging in argumentation they may certainly be in a sensemaking frame, but argumentation also encompasses other framings than sensemaking. Zooming in on these frames, from a cognitive process perspective, students who are trying to persuade each other are not necessarily building or integrating new knowledge. They may simply be trying to find new ways to express the knowledge they already have. Students who are sensemaking, however, are trying to build new knowledge, by critiquing and strengthening their explanations.

Sensemaking and Modeling

Of all of our considered science learning activities, modeling has the greatest overlap with sensemaking. Models, as defined by Schwarz et al. (2009), are "specialized representations that embody aspects of mechanism, causality, or function to illustrate, explain, and predict phenomena. Working with scientific models involves constructing and using models, as well as evaluating and revising them" (Schwarz et al., 2009, p. 634).

This definition clearly has elements from each of our strands of sensemaking literature: the purpose of modeling is to explain a phenomenon—to figure it out—by drawing on and using a variety of different representations. One also evaluates and revises the model as it's being built. However, we see two major distinctions between modeling and sensemaking. First, modeling involves creating a distinct final product (the model, in whatever form it takes) that is meant to be used by people other than its creator. That is, the goal of modeling is simultaneously to figure something out and to represent it in some way for further use. In sensemaking, the goal is just to figure something out—representation may play a part, but it's not a core aspect of the process. Second, we see sensemaking and modeling as taking place on different scales, at different grain sizes. Sensemaking is dynamic—people slip in and out of it, potentially minute-to-minute. Modeling is a conceptualized as a formalized activity, one of the NGSS core practices (NRC, 2012), and it takes place over longer time scales (hours, days, or weeks).

In summary, we are not claiming that sensemaking is completely separable or incompatible from any of these activities. Instead, we are claiming that sensemaking is a specific instance or approach to each, but that each in some way extends beyond sensemaking. Thus, for example, we would expect to see sensemaking to greater or lesser degrees in classrooms that emphasize explaining, argumentation, or modeling. The degree to which we would expect sensemaking, however, would depend on which aspect of that activity they emphasize—i.e., in a classroom focused on explanation, are you emphasizing the process of building new explanations or just that students need to have explanations readily at hand?

CONCLUSION

In this article, we have proposed a definition of sensemaking to address the previously fragmented theoretical nature of the concept in the literature. Based on our organization of the science education research literature, we define sensemaking as a dynamic process of building an explanation in order to resolve a gap or inconsistency in knowledge. These explanations are built in one's own words, through an iterative process of construction and critique. Cognitively, when students are sensemaking they are building and refining their mental models, and they draw from and connect up multiple different representations and external explanations as they do so.

Sensemaking also constitutes a certain stance toward science learning, defined by the goal of trying to "figure something out," which may differ from the approaches students might otherwise take (memorization and recall, or focusing on getting right answers).

We see this definition as contributing to the field of science education research both theoretically and pedagogically. First, theoretically, this definition of sensemaking *unifies* different strands of sensemaking research. This unification highlights similarities within and across these strands, which otherwise might be considered separate. For example, within the *cognitive process* strand, research on self-explanations and knowledge integration have, until now, generally been considered separate domains, but we are arguing that both address a similar aspect of sensemaking. Across strands, we are arguing that research on subjects like framing and knowledge integration are complimentary in subject, even if they differ in their approach to that subject. By creating these connections we can highlight the tacit, shared assumptions that researchers bring to their study of sensemaking, which may encourage collaboration and cross-pollination between different strands of research.

Furthermore, by bringing together these diverse areas of research, we can highlight the differences in their approaches, thereby promoting greater communication—cross talk—between them. That is to say, a unified definition of sensemaking allows us to have explicit conversations about the different approaches researchers take to studying sensemaking, conversations that wouldn't be possible without bringing this research together. These conversations can highlight the affordances or constraints of particular approaches, differences in theoretical or conceptual frameworks—for example, the type of "thing" they consider sensemaking to be (a frame? An activity?)—as well as the places and ways in which they would expect to find sensemaking happening.

Our second theoretical contribution is that this definition of sensemaking allows us to *distinguish* it from other areas of practice and research. We have argued that this definition allows researchers to distinguish sensemaking from more general phenomena, such as "thinking," "learning," and several scientific practices. But it also allows us to distinguish phenomena which some might label as sensemaking but either don't fit with the rest of the existing literature (Ibrahim & Rebello, 2012; Karelina & Etkina, 2007; Lippmann Kung & Linder, 2007) or which address one small sub-process of the larger-scale sensemaking activity (Nokes-Malach & Mestre, 2013). That is, in saying what sensemaking *is,* we also articulate what it is *not.* This, in turn, helps science educators to determine how to isolate and study sensemaking, specifically, in their research and practice.

Our third theoretical contribution is that this unification of the science education research on sensemaking *highlights the blank spaces in that research*, both for individual researchers and for the field as a whole. For individual researchers, this description of sensemaking highlights aspects of the phenomenon that they might be missing in their definitions or research approaches. For example, a researcher taking a framing-based perspective might be missing aspects of the ways students are integrating different representations, or how students are constructing and critiquing explanations. While no research method can take every aspect of a phenomenon into account, a precise definition of sensemaking allows researchers to make informed choices about where they should spend their focus.

For the field of science education as a whole, this definition also highlights spaces that have yet to be studied—future avenues of sensemaking research. For example, as we have delved into the sensemaking literature, we have noticed several trends, which raise their own questions:

1. Most of the work on sensemaking has been in isolated episodes, so how does sensemaking change over time, especially in science courses that are taught so that each week's material builds on the prior week?

2. What specific strategies do students use, when they are sensemaking, to build their explanations, and why do they use those particular strategies?

3. When do people really feel like something finally "clicks" or makes sense? Is there a threshold? That is, how many connections do they need, and do those connections have to be causal for people to feel that they make sense?

In addition to our theoretical contributions, this definition also has some pedagogical consequences. First, this definition allows us to provide some resolution to the question posed in our opening vignette: how could a teacher like Mrs. J. handle a student like Marco who believes what she says but feels that the ideas "just don't make sense?" Based on our definition, we would argue that Marco is clearly well on the road to sensemaking: he's in a frame of trying to "figure it out," he's identified a conflict in his knowledge (some aspects of collisions between cars and semi-trucks don't seem to fit with the principles Mrs. J. has outlined), and he seems to have plenty of prior knowledge to draw on. So, how should she respond? We suggest that the difficulty that Marco is having could be diagnosed as *not enough connections.* That is, the principles don't yet make sense to Marco because he hasn't yet connected enough of his experiences to the formal principles Mrs. J. has just finished teaching.

While not necessarily satisfactory, this hypothesis would suggest that one approach Mrs. J. could take would be to check back with Marco after he's had time to "digest" the ideas, to discuss them with friends and work through them in homework problems, and see if Marco's feeling persists. However, this approach would necessitate that Marco remain in the sensemaking frame after he's left the classroom. While some students are certainly dedicated to sensemaking (especially if, like the student in Danielak et al.'s 2014 case study, sensemaking is their go-to approach for science learning), such frames are often fleeting and difficult to maintain. So, more immediately, Mrs. J. could endeavor to outline some potential connections for Marco in the form of a plausible mechanistic explanation that connects what Marco knows (cars get crushed in collisions with semi trucks) with the formal principle (Newton's 3rd law). Perhaps something along the lines of "the forces are equal and opposite, but the *results* of those forces are different. A car has a much smaller mass, so it has a much stronger response to that force than a truck. It's like how a few adults can push a car in neutral down the road, but those same adults would not be able to push the truck."

Thinking beyond the case of Marco, this coherent description of sensemaking allows us to design targeted interventions, tools, and teaching methods to address it. Similar to how teaching methods based on argumentation (Berland & Reiser, 2009), framing (Elby, 2001), and Knowledge Integration (Linn, 1995) could not have come about without those theories first being precisely defined and articulated, we are arguing that the first step in developing teaching methods focused on sensemaking is to define it. We therefore hope this definition will give rise to design principles which will allow us to create new teaching tools, understand the mechanisms for how new and existing tools work, and highlight the affordances and constraints of particular tools and approaches.

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Chapter 2: The Sensemaking Game

INTRODUCTION

As physics instructors, we all want our students to make sense of the ideas they encounter in our courses. And, for good reason; sensemaking has been shown to help students both build new knowledge and create connections within the knowledge they already have (Gire, Manogue, Rebello, Engelhardt, & Singh, 2012; Gupta & Elby, 2011; Hutchison & Hammer, 2010). The process of sensemaking also helps students to achieve coherence between their everyday understanding and their formal physics knowledge, keeping them from mentally "walling off" physics from the "real world" (Danielak, Gupta, & Elby, 2014; Hammer, 1989; Sikorski & Hammer, 2017). Furthermore, students who aim to make sense of physics, viewing it as a set of interconnected principles rather than a jumble of equations, are well on their way to an expert-like epistemology of physics (Adams et al., 2006; Bing & Redish, 2012; E. Redish, Saul, & Steinberg, 1998).

Physics education researchers have had little trouble locating examples of sensemaking to analyze. Numerous studies have documented snapshots of student sensemaking (e.g., Danielak, Gupta, & Elby, 2014; Gupta & Elby, 2011; Hutchison & Hammer, 2010; Kapon, 2016), providing an ever-growing list of the hallmarks of this process. However, though the research literature provides many ways to identify sensemaking, *eliciting* and *sustaining* it are an entirely different matter. We are able to recognize sensemaking as it is happening, yes, but we do not yet know how to reliably make it occur, or how it proceeds once it has begun.

This is a problem because if properly harnessed, sensemaking has the potential be another powerful tool in our pedagogical toolbox. We could for example use it to design curricula and learning environments, similar to other approaches based on principles like guided inquiry (Etkina, Karelina, & Ruibal-Villasenor, 2008; Karelina & Etkina, 2007), active learning (Potter et al., 2014; E. F. Redish, Saul, & Steinberg, 1997), epistemology (Adams et al., 2006; Elby, 2001; Hammer & Elby, 2003), modeling (Brewe, 2008; Brewe, Kramer, & O'Brien, 2009; Chabay & Sherwood, 2011), and analogical scaffolding (Clement, 1993; Podolefsky & Finkelstein, 2007). However, if we have not mapped the process—if we do not know how it begins, proceeds, and ends—it will be difficult to build into physics courses.

Our present study aims to address this problem by characterizing and describing the complete process of sensemaking, from beginning to end. Using a case study from a series of cognitive clinical interviews meant to prime and capture episodes of sensemaking, we argue that sensemaking is a distinct, bounded process which unfolds in a characteristic way. We then describe this process using the same theoretical machinery used elsewhere in PER to describe other varieties of student inquiry, the epistemic games framework, and further use this framework to tease out the parameters of the sensemaking "game."

LITERATURE REVIEW AND THEORETICAL FRAMEWORK

What is Sensemaking?

There is a substantial amount of science education research literature that aims to define and characterize scientific sensemaking. Elsewhere (Chapter 1 Ref), we have argued that this body of literature, when taken as a whole, conceptualizes sensemaking in three different ways: as a stance or frame towards science learning, a cognitive process, and a discourse practice.

Generally speaking, *framing* is a term borrowed from the sociology, linguistics, and psychology literature, referring to how individuals or groups of people answer the question "what's going on here?" (Scherr & Hammer, 2009; Tannen, 1993). From a framing perspective, sensemaking is a way in which students approach science learning, which is characterized by trying to "figure something out" using one's prior knowledge. That is to say, when students are sensemaking their "task" is to build an explanation based on their understanding of the world, rather than to find a formally correct answer or ask an authority figure to provide that answer (Danielak et al., 2014; Hutchison & Hammer, 2010; Kapon, 2016; Rosenberg, Hammer, & Phelan, 2006).

From a cognitive process perspective, sensemaking is a way in which students construct new knowledge by building connections to and within their prior knowledge. When making sense of a new science concept, these connections may be facilitated when students create links between different types of scientific representations for that concept, such as mathematical formalism (Gupta & Elby, 2011; Sherin, 2006), ontological classifications (Chi & Slotta, 1993; Dreyfus et al., 2014; Gupta, Elby, & Conlin, 2014; Gupta, Hammer, & Redish, 2010), graphs and pictorial representations (Christensen & Thompson, 2012; Gire & Price, 2013; Ivanjek, Susac, Planinic, Andrasevic, & Milin-Sipus, 2016), and gesture-based representations (Manogue, Gire, & Roundy, 2014; Scherr, Close, McKagan, & Vokos, 2012). Mapping techniques like analogies, metaphors, or conceptual blends may also help to facilitate cognitive connections between prior knowledge and new science ideas (e.g., Brewe, 2011; Clement, 1993; Podolefsky & Finkelstein, 2007).

These two descriptions of sensemaking overlap, somewhat, in that both commonly draw on a cognitive, constructivist theory of learning called the resources framework. The resources framework (Hammer, 2000; Hammer, Elby, Scherr, & Redish, 2005; E. F. Redish, 2003) is a theory of mind that describes knowledge as being built out of many "pieces" (commonly called *resources*), which we extract from our daily experiences. Resources are theorized to be tiny, compact bits of knowledge and intuition, which are commonly applicable across many contexts. Researchers often model these resources as being arranged in an interconnected network. Within this network, particular resources are activated based on cues from one's experience and environment. These active resources then cue (or activate) other resources, which cue still other resources, and so on (E. F. Redish, 2014; Sherin, Krakowski, & Lee, 2012).

Within the resources framework, we can think of students' "ideas" as clustered sets of resources that all get activated together. When students build connections between different ideas, they are activating and adding additional resources to this network. Student frames, from this perspective, are then subsets of resources that are reliably cued together (Hammer et al., 2005; Rosenberg et al., 2006; Sherin et al., 2012).

While this model may seem highly theoretical, it has direct consequences for how we think about and study sensemaking. For example, according to this theory the resource cuing process is highly dynamic—it happens frequently, and on very short timescales (on the order of fractions of a second). Consequentially, we would expect that both the cognitive process of connection building and the resultant shifts in student framing would be equally dynamic.

Additionally, according to this theory one's context plays an important role in cuing resources: a person working on a particular task (say, splitting a restaurant check) may activate very different sets of resources depending on the context of that task (as an exercise in a math class vs. in an actual restaurant, for example). These active resources, in turn, determine how they will approach that task. This, then, suggests that sensemaking may require specific cues to arise—we cannot expect it to occur spontaneously—and that these cues may vary from student to student.

In contrast to these two cognitivist descriptions of sensemaking, researchers have also conceptualized sensemaking in a third way, as a particular form of argumentative discourse (Berland & Reiser, 2009, 2011; Ford, 2012). From this perspective, sensemaking is a mode of dialogue in which students articulate and strengthen explanations, similar to the way in which one articulates and supports a claim in an argument. However, researchers have proposed that the goal of sensemaking is to strengthen claims and improve their explanatory power rather than to persuade others or "win" the "argument" (Berland & Reiser, 2009, 2011). As students construct their explanations, they engage in an iterative process of building off of each others' ideas, critiquing those ideas and connections, and (especially in science) describing the mechanisms underlying the phenomena being explained (Ford, 2012; Kapon, 2016; Russ, Scherr, Hammer, & Mikeska, 2008).

Affordances and drawbacks of these descriptions

Together, these three descriptions provide a thorough characterization of the features of sensemaking—that is, they outline the hallmarks of the process, which one could use to identify it. However, though this literature describes the features of sensemaking, it does not show us the trajectory of that process; in other words, even with this body of literature we are still left to wonder how the sensemaking process unfolds in practice.

This question presents a problem for researchers interested in studying sensemaking and educators who wish to support it. In order to study and support something we have to know, not just how to recognize it, but also how it behaves—the starting points, ending points, and what happens in between.

To use a related example, in order to support students in physics problem solving, it is not enough to just recognize when students are solving problems or the features of different solution approaches; we also have to understand the complete process of solving a problem, from start to finish. By taking this holistic view, we gain greater perspective on the different approaches students may take, their potential strengths and pitfalls, and their uses in different parts of a physics course. In a similar way, we feel that a full characterization of the sensemaking process would give us greater insight into that process than the hallmarks alone.

Our present study is focused on investigating and characterizing the full process of sensemaking for just this reason. To facilitate this description, we are drawing on a theoretical framework specifically designed to describe different processes of inquiry, the *epistemic games* framework.

Epistemic Games and Sensemaking

The Epistemic Games Framework. Epistemic games (or e-games) are a theory designed to describe how people in different fields carry out investigations or inquiry. The theory was originally proposed by Collins and Ferguson (1993) in order to specifically understand how scientists and historians guide their processes of inquiry, but has since been commonly used in the field of Physics Education Research to describe how students and professors approach structured tasks like problem-solving (Chen, Irving, & Sayre, 2013; Kustusch, Roundy, Dray, & Manogue, 2014; Tuminaro & Redish, 2007). As the name suggests, the theory draws an analogy between strategies that people use in investigation and some of the features of games (broadly defined) such as rules, legal moves, and beginning/ending conditions.

Epistemic games have certain key features that define them as a theoretical construct. Each epistemic game has a certain *target epistemic form* (form of knowledge), or “target structure” that it is meant to produce—producing this target structure is how one completes or “wins” the game. For example, when students play the “answer-making game” (Chen et al., 2013) their goal is to get the “right answer” to a posed problem. Within this game, the epistemic form (type of knowledge they’re trying to produce) is a correct numerical or symbolic answer.

Epistemic forms are typically constrained in some way, and these *constraints* help define the “rules” of the particular epistemic game, i.e., what one is and isn’t allowed to do. In the above-mentioned answer-making game, we could imagine constraints like the fact that there is only a single right answer, and that this answer has to be expressible in a short, compact form (a number or equation, rather than a 10-page essay).

The epistemic forms and constraints essentially define the parameters of the game. But, Collins and Ferguson further argue that e-games have three other general characteristics that determine how one actually “plays” the game. These include entry conditions, moves within a game, and opportunities to transfer to another game.

A game’s *entry condition* is the set of circumstances that “kick off” that game. Often an entry condition may be an explicit prompt or question; the answer-making game, for example, seems to be commonly played in response to multiple-choice or short-answer physics problems (Chen et al., 2013). However, other games might have a more nebulous set of entry conditions, like an experience, feeling, or perceived need for a tool—for example, Tuminaro and Redish (2007) describe the *pictorial analysis game*, in which students try to create a representation of a physical system (like a circuit diagram) in order to specify the relationships between the elements in that system. Such a game need not be kicked off by a formal prompt or question; instead, the entry condition could be a feeling of puzzlement over how a certain circuit functions.

Moves are the set of actions one is allowed to perform while playing a game. For example, when playing the answer-making game, some possible moves include "try to remember the result," "choose and justify an intuitive answer," and "do some math." Each of these is a possible approach for getting from the entry condition to the target epistemic form, and they may be chained together in various ways; e.g., if a student remembers the result they finish the game in one step, but if they can't they may have to resort to additional moves (Chen et al., 2013).

Sometimes certain moves are not allowed in the current game, which may necessitate *transferring to another game*. For example, a student playing the answer-making game might choose to draw a picture in order to try to justify an intuitive answer. As they are drawing that picture, their task shifts to creating a representation of the system, which constitutes a new epistemic form and thus a new e-game (the *pictorial analysis game*, in fact) with its own set of constraints, entry conditions, moves, and possibilities for transfer. Once the picture is complete, they would then transfer back to the answer-making game and use the picture as a source of additional moves within that game.

For the sake of clarity, we summarize these features in **Table 1** below:

Feature	Description	Example (from the answer-making e-game)
Target epistemic form	The "goal" or knowledge structure one creates by "playing" the game	A numeric or symbolic correct answer to a posed problem
Constraints	The "rules" of the game	• There is only one right answer • The answer comes in a short, compact form
Entry conditions	The circumstances that "kick off" the game	Being assigned a multiple-choice or short answer physics problem
Moves	The most common activities within the game, that help one to create the target epistemic form	• Try to remember the result • Choose and justify an intuitive answer • Do some math
Transfers	Moves that change the e-game to another commonly played e-game	• Drawing a picture (pictorial analysis e-game)

Table 1: Features of epistemic games

Epistemic Games Applied to Sensemaking. How does the epistemic games framework help us to study sensemaking? First, the framework is designed to not just describe different processes of inquiry, but to tease apart their underlying mechanisms—how and why people use them. The entry conditions and target epistemic forms, for example, tell us the conditions that begin and end these inquiry processes. The moves then show us how people get from beginning to end, and the constraints and transfers show us ways in which the process might either end prematurely or be put temporarily on "hold." By delineating these factors for sensemaking, we can see how all of the previously mentioned hallmarks of sensemaking synergize into a full, useful process of knowledge construction.

Second, e-games impose a measure of analytic uniformity on the sensemaking process. As shown in the literature, people use many different strategies when sensemaking, like analogies, drawing and augmenting pictures, ontological classification, etc. By describing sensemaking as an e-game, we can compare the different moves that students use, the order in which they do those moves, and look for patterns within different instances of the game. This also puts sensemaking on a similar footing to other explicitly non-sensemaking games like answer-making or rote application of equations, so that we can see how students might transfer from one to the other.

The epistemic games framework has already been briefly applied to the study of sensemaking in other work focused on physics problems solving. Specifically, Tuminaro, in his thesis (Tuminaro, 2004) and an associated paper (Tuminaro & Redish, 2007), described six e-games he observed students playing while solving physics problems. He then grouped these games under three general categories of student framing: *qualitative sensemaking*, *quantitative sensemaking*, and *rote equation-chasing.*

Within this analysis, Tuminaro positioned sensemaking, as we use the term, within a specific frame and epistemic game (the "qualitative sensemaking frame," and "physical mechanism game" respectively). However, his research was not concerned primarily with sensemaking—instead, he focused on how introductory physics students used math in when solving tutorial problems. For this reason, the "physical mechanism game" that he describes is fairly short and cursory—he describes the game as an activity in which "students attempt to construct a physically coherent and descriptive story based on their intuitive sense of physical mechanism" (Tuminaro & Redish, 2007, p. 7), which involves two steps: "build a causal story" and "evaluate story."

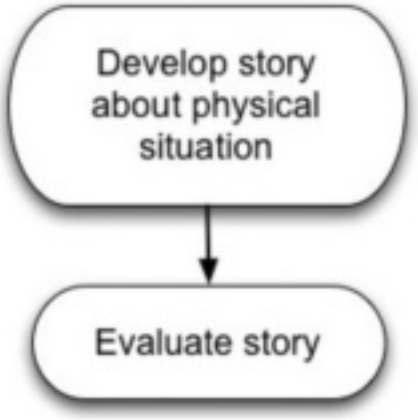

Figure 1: Tuminaro & Redish's *Physical Mechanism* epistemic game

In this paper we build off of Tuminaro's work, elaborating on this "physical mechanism game" and fleshing it out into a more theoretically "thick" description, which we refer to as the *sensemaking epistemic game*. Based on this goal, our primary research questions are as follows:

1. What are the parameters of the sensemaking epistemic game?
2. How does this game progress once it begins?

METHODS: CAPTURING AND ANALYZING SENSEMAKING

Participants and Data Collection

In order to understand how sensemaking unfolds, we aimed to compare students' sensemaking processes across multiple groups of students over numerous episodes. The present study featured students from an introductory, algebra-based, undergraduate physics course at a major Midwestern university. The course was the second in the algebra-based sequence for non-majors, focusing on electricity and magnetism.

Based on the conceptual dynamics described by the resources framework, the first author, in consultation with the second author, designed and conducted clinical interviews (Ginsburg, 1981; Russ, Lee, & Sherin, 2012) with students from this course, in order to try to prime them into sensemaking and document the strategies they used once underway. Clinical interviewing is a flexible methodology in which the interviewer aims to understand and respond to a subject's thinking. The interviewer prepares a set of carefully-developed prompts designed to elicit specific aspects of student thinking (in this case, sensemaking/explanation building); however, they are also free to ask new follow-up questions as necessary, which gave us the flexibility to pursue lines of reasoning that seemed rich in potential sensemaking.

Building off of the argumentation-based sensemaking literature (Berland & Reiser, 2009, 2011), we chose to interview students in pairs, in order to encourage dialogue and critiques between the students. During recruitment, we requested that participants find a friend in the class before contacting us to enroll in the study, in the hopes that friends would be more comfortable critiquing one another's reasoning. In total we had 9 pairs enroll in the study. We interviewed each pair 5 times throughout the semester, paying each student $15 per interview to ensure that they would return. Every pair completed the full set of 5 interviews, except for one pair who were unable to complete the final interview. We video and audio-recorded all interviews, which typically lasted 45 minutes to an hour, resulting in about 42 hours of video data.

Each interview protocol was designed to encourage students to make sense of physical phenomena, either hypothetical (thought experiments) or actual physical demonstrations that they were free to play with. Students were assured that the researchers were only interested in their reasoning, not right or wrong answers. All interviews opened with the interviewer asking students to "talk about what they had been learning in class," both to establish rapport and to prime participants into thinking about recent physics concepts (essentially, bringing these concepts to the forefront of their minds). Thereafter, the interviewer would ask various questions related to a phenomenon that could be explained with specific electricity and magnetism concepts such as electric forces, electric fields, electric potential, and current.

The interviews included a range of tasks designed to encourage students to build these explanations. For example, one of the thought experiments from the electric forces interview used the following prompt:

> *During a thunderstorm, you and a friend wisely decide to take shelter in your car, which you've parked in an open-air parking lot. As you're waiting, lightning strikes the car. However, besides being a little bit jolted the loud noise and bright flash, you both feel totally fine. After the storm has passed, you feel like getting out to stretch your legs, but your friend yells "Stop!" and warns you not to the surface of the car as you get out, because you might still get electrocuted. Do you believe your friend? Why or why not?*

Other thought experiments asked them questions like "what would the safest place be to grab an electric eel?" and "is it actually necessary to stand clear from someone when using a defibrillator on them?" In every case, prompts were designed to allow many possible lines of reasoning without any obvious right or wrong answer, but to also require students to make a definitive choice (e.g., step out of the car or not, grab the eel at the head, the middle, or tail, etc.).

Demonstrations included picking up scraps of paper with a charged rod, assembling circuits from lightbulbs and resistors, and investigating interactions between charged pieces of scotch tape. In contrast to the thought experiments, students playing with the demonstrations were typically simply asked to "talk about what you're seeing and what you think it means," with the interviewer asking clarification questions and follow up questions regarding ideas students brought up.

Throughout the interviews, students were frequently asked to draw representations of what they were imagining was happening, and were provided with large sheets of paper and markers for that purpose. This not only helped students to articulate and clarify their thinking, but also prompted them to create and revise various representations of the phenomena under discussion. The interviewer also deliberately left various props strewn around the table, such as colored stress balls, to be spontaneously picked up and used in explanations. Sometimes the interviewer would himself pick up one of the props and use it to gesture during prompts, normalizing this behavior and priming students to do the same.

Data Analysis

Phase 1: Selecting student groups and reducing the data. After data collection was completed, the first author reviewed the entire data corpus, in audio form, noting compelling moments that seemed rich in sensemaking. Based on this cursory analysis, he then engaged in repeated intensity sampling (Creswell, 2007) in which he pared down the dataset to a selection of episodes that seemed to be richest in sensemaking. Here, the goal was not to extract every possible episode of sensemaking from the dataset, but rather to get a sample of the episodes that seemed most likely to include sensemaking, which could then be analyzed and compared with one another.

From the full dataset, the first author began by choosing two sequences of 5 interviews (10 interviews in total) from the two groups who seemed most prone to sensemaking. He then transcribed all 10 of these interviews in full, creating analytic memos as he did so on the general trajectories of the interviews and episodes or quotes that seemed particularly compelling.

Phase 2: Identifying episodes of sensemaking. Next, the first author reviewed these 10 transcribed interviews and extracted episodes that seemed to have an abundance of the above-mentioned hallmarks of sensemaking. Each interview typically yielded 1 or 2 episodes, for a total of 19 episodes across all 10 interviews. He reviewed these episodes in greater detail, taking additional notes on what happened line-by-line in order to get a feel for the students' reasoning, and comparing student behavior, gesture, and dialogue to the above-mentioned hallmarks of sensemaking to confirm that they did, in fact, fit with the process described in that literature.

He then reviewed a subset of these episodes a second time, analyzing and coding each utterance across two dimensions, based on features of sensemaking from the science education research literature:

1. **Framing:** Russ et al. (2012) proposed three categories of student framing in clinical interviews: *inquiry,* in which the students' task is to construct an explanation in response to a question posed by the interviewer; *oral examination,* in which the students' task is to produce a correct answer in a clear and concise fashion; and *expert interview,* in which the students' see their task as discussing their own thinking or prior knowledge on a subject. He identified these three categories based on students' framing behaviors, summarized in Table 2.

2. **Dialogue:** Based on Ford (2012), he coded for lines in which students were either engaging in *construction* (building an explanation) or *critique* (criticizing or questioning the explanation).

These dimensions, along with their behavioral and dialogic markers, are summarized in Table 2 below:

Analytic Dimension	Category	Behavioral/Discourse Markers
Framing	Inquiry	• Long pauses in speech • Restarts during explanation • Little eye-contact • Frequent gesturing
	Oral Examination	• Lack of hedging language • Eye contact with interviewer • Limited use of gesture • Use of scientific vocabulary
	Expert Interview	• Lack of hesitation • Eye contact with interviewer • Frequent gesturing • Use of colloquial terminology
Discourse and Argumentation	Construction	• Students build off or augment each other's explanations
	Critique	• Students question or criticize each other's explanations

Table 2: Analytic dimensions, categories, and behavioral/discourse markers used in our analysis

Phase 3: Selecting and unpacking a specific case. Using these categories, the first author then looked for patterns across these analytical dimensions within the analyzed episodes. It quickly became apparent that these episodes all seemed to unfold in a distinct way, which was both consistent with the sensemaking literature and also fit with the characteristics of the epistemic games framework. Based on this observation, he coded for key features of epistemic games as described by Collins and Ferguson (1993) and later used by Tuminaro and Redish (2007). These codes provided the general parameters of the sensemaking epistemic game.

In summary, we used a case study approach to derive the parameters of the sensemaking epistemic game from episodes in our data corpus. This approach is both consistent with that used by other epistemic games research in PER (Chen et al., 2013; Kustusch et al., 2014; Tuminaro & Redish, 2007) and is, we feel, suitable for our study goals. Case studies are useful for developing plausible existence arguments and to identify the underlying mechanisms for behavioral phenomena (Creswell, 2013; Lising & Elby, 2005); since our focus is on identifying and describing how the sensemaking process unfolds, we feel this methodology is appropriate.

Since we used a case study methodology for our analysis, we are taking a similar approach in our presentation of the sensemaking game: in what follows, we describe this game using a first-person account of a sensemaking episode from the data corpus. Tor (the “I” in the case) performed the interview. This presentation is different than that used in other physics education research on epistemic games (Chen et al., 2013; Kustusch et al., 2014; Tuminaro & Redish, 2007). However, as well as being a faithful presentation of our analysis, we use this approach for two additional reasons: first, the sensemaking epistemic game unfolds over longer timescales than other games in the literature, most of which were sufficiently short that they could be illustrated in a few lines of transcript. For that reason, we feel that a full case description is necessary to see the entirety of the game. Second, unlike most other games in the literature which have a relatively small number of moves, the sensemaking game by its nature has an extremely large number, and we feel that the moves we describe are more compelling when viewed within the narrative structure of the game as a whole.

The episode comes from a circuits-based interview (the third in the sequence of 5) with two students, Ruth and Emma. We chose this particular episode because is “prototypical” of our analyzed episodes, in that it is brief but it illustrates the essential structure of this game (the entry condition and epistemic form), as well as several moves and a brief transfer.

Ruth and Emma were good friends, and both were biology majors. Both had previously taken the prerequisite algebra-based mechanics course, and Ruth additionally had at least a semester of high school physics. The pair were enthusiastic about discussing and improving their understanding of physics; in this episode, they displayed that enthusiasm during a discussion in which they articulated and resolved a perceived inconsistency in the behavior of parallel circuits.

A CASE OF SENSEMAKING

Setting up for sensemaking

In general, we have found that the sensemaking game is preceded by some broad discussion of the topic at hand. In this case, that discussion focused on current in series and parallel circuits.

At about 40 minutes in to the interview, I had provided Ruth and Emma with a powered circuit board, various resistors and wire segments, several lightbulbs, and a challenge: construct two circuits, one to make a lightbulb shine as brightly as possible and the other to make it shine as dimly as possible while still being visible. As they did this, I asked them to explain their thinking.

To make the bulb shine brightly, Ruth and Emma chose to construct a parallel circuit out of the three lightbulbs provided. Based on this choice, I asked them to talk about their understanding of the difference between current in a series vs. parallel circuit, specifically how the current coming out of the power supply would compare between the two. This prompted Emma to recall Kirchoff's current rule:

342 **T:** So, what does that say about the current now? Like, if we looked at the current coming right out of this power source before it starts splitting, so what does that say about the current here, with these 3 bulbs like this, versus the current that you had when they were all sort of in one line?

343 **E:** Yeah, so this *{Emma points at wire coming out of battery}* is I_{total}, and then it's like *{Emma gestures to circuit branches}* I_1, I_2, I_3. And I_1, I_2, I_3 is equal to I_{total}, and then they all become I_{total} again right before they go in [to the battery].

In response, I clarified my question, asking the pair to compare the total current in a series circuit to that of a parallel circuit.

344 **T:** But, I guess I'm asking, like, if you compared I_{total} now to the I_{total} you had before in the series circuit, when—

345 **E:** It should be the same.

At this point, the students have not yet begun sensemaking—they are not trying to "figure something out," focusing, rather, on recalling facts about circuits to answer my interviewing questions. The ease with which they responded, along with the formal terminology they used (such as the I_1, I_2, I_3 from Kirchoff's current rule) indicate that they are in the oral exam frame. Their "task," in other words, seems to be to produce clear, concise, correct answers to my posed questions (Russ et al., 2012).

In the process, however, the students have also assembled (or, more likely, re-assembled) a framework of knowledge in response to these interview prompts. That is, the pair have laid out their initial ideas on the phenomenon at hand (parallel circuits), including the notion that current splits and recombines, and that the total current should be the same regardless of the way in which the circuit is constructed. This framework is dynamic, in that it was assembled in the moment and the pair will likely only use it for a short time before moving on to other ideas.

However, despite being short-lived, we argue that this framework sets them up for sensemaking by both directing their attention to these specific circuit features and giving them a framework within which they can notice a gap or inconsistency in knowledge.

Transition into sensemaking

Next, the students transitioned from assembling a knowledge framework to articulating and addressing a specific inconsistency within that framework. They began by discussing Emma's statement that the current would be the same in parallel and series circuits, trying to decide if that is, in fact, true:

346 **R:** Well, this is like that question on the, on the homework. It, like, on the quiz last week where it's like 'how do you make it...' (E: Yeah) I mean it, you're dealing with the same... (E: Current, no?) Like, if we have 3 lightbulbs... No, okay, that's not how we said it. Yeah, I think the total current will ultimately be the same? *{whispers} V equals I R…*

347 **E:** So, is it the voltage that, like, creates the l—like, the voltage has a better say on like what the light is than the current? Must be.

348 **R:** Yeah. The current is just the, the flow. (E: Yeah) Whereas the voltage is what actually makes the light glow.

After some more discussion, the pair tried calculating the net currents in the two types of circuits and found two dramatically different numbers. This result prompted a strong reaction:

363 **R:** Oh, that's counter-intuitive, yeah.

364 **E:** Yeah, that sucks. That’s super counter-intuitive. Why would a current be bigger, just coming out of the volt—out of the battery?

365 **R:** Because it's the same…

366 **E:** No, but you know, okay, like, subjectively, there's just, okay, ignore everything past this. *{Emma puts her hand over the circuit}* Coming out of the battery, why wouldn't it be the same current to begin with? In the s—you know what I mean?

Based on their investigation, Emma has noticed an inconsistency in her understanding: batteries send more current through parallel circuits than series circuits, but this behavior feels counter intuitive to her. That is, she seems to feel that power sources shouldn’t change their behavior depending on what’s attached to them, but their calculations indicate that this is exactly what happens. The pair spent the remainder of the episode looking for some way to resolve this inconsistency.

There is a transition here in the students’ dialogue and framing. Initially, during the period when they were discussing and calculating current throughout the different circuits, their framing matched what Russ et al. called an inquiry frame: the two spoke slowly, hesitantly, staring off into space or at their circuit board. Dialogically, they were building off of or augmenting each others’ statements, not critiquing each others’ reasoning or answering interviewer questions. Essentially, they seemed to be trying to brainstorm what they knew about series and parallel circuits, “dredging up” knowledge on the subject from sources like homework and quiz questions.

At the point where Emma verbalized her question (line 366), however, we see their dialogue and framing begin to shift: both students become more animated, turn toward each other, make more frequent eye contact, begin to speak more fluidly, and use more gestures. Their hesitancy drops away. Rather than simply building off of each other's ideas, their dialogue starts to become more argumentative (as we see from Emma's critique in line 366).

Figure 2: Student body position and gaze before (left) and after (right) the frame shift

These framing behaviors do not fit neatly with any of the three categories described by Russ et al. (2012): the pair seem to be more confident (rather than hesitant and uncertain, as with the inquiry frame), but they are speaking to each other, not the interviewer (as would be expected from both the oral exam frame and the expert interview frame). However, their "task" also seems to shift, from trying to remember what they know about circuits to trying to resolve the inconsistency Emma pointed out. This goal, of building an explanation based on one's understanding of the world is consistent with that described in the sensemaking literature (Danielak et al., 2014; Hutchison & Hammer, 2010; Kapon, 2016; Rosenberg et al., 2006). Additionally, the critical shift in the pair's dialogue is consistent with the argumentative nature of sensemaking (Berland & Reiser, 2009; Ford, 2012). So, this transition, we argue, marks the students' entry into a new frame, which we call the sensemaking frame.

For analytic clarity, we summarize the framing behaviors associated with this new sensemaking frame below:

Analytic Dimension	Category	Behavioral/Discourse Markers
Framing	Sensemaking	• Fluid speech, lack of hesitation/restarts or hedging language • Eye contact (with each other) • Frequent gesturing

As we will show in the next section, the pair's shift goes beyond just framing behaviors: Emma and Ruth have, we claim, begun playing the sensemaking epistemic game. Since this transition occurs around the moment when Emma articulates her question in line 366, we consider this question to be the **entry condition** into the game.

Playing the Sensemaking Game

Having transitioned into a sensemaking frame and entered into the sensemaking game, the students now began to build an explanation to resolve this inconsistency. The episode continued as Ruth responded to Emma's question, "why wouldn't it be the same current to begin with?":

367 **R:** Because here the resistance is smaller. Because the equivalent resistance is, is 1 over four plus four plus fou—whatever we said that each resis—three plus three plus three. And so, since, or it's like a third plus a third plus a third.

368 **E:** But then it's one over that number.

369 **R:** But then, exactly, but that number is still smaller than the resistance when they're in series with each other.

370 **E:** I know, but what I'm saying is like if you just have a circuit, *{Emma draws a small circuit}* the current coming out right away, right? *{Emma draws an arrow coming out of*

the battery} Before you're looking at anything here, whether it's parallel or in series, why wouldn't that current be the same?

371 **R:** Because there's less resistance—

372 **E:** But it hasn't approached the resistance yet.

373 **R:** But I think it just knows.

374 **E:** It just knows?

Here, Ruth and Emma are in the midst of playing the sensemaking game. Looking at the structure of their conversation, the pair are now engaged in a cyclical process of iteratively building an explanation that resolves Emma's inconsistency.

This explanation, we propose, is the **epistemic form** of the sensemaking game, the end-product that the pair are trying to produce. But Emma isn't satisfied with just any explanation—she seems to have certain requirements, certain points the explanation has to address, as we see from her reactions in lines 370 and 374. Mathematical arguments seem to be insufficient for her, as are teleological explanations ("It just knows"). As each argument or explanation is rejected, Emma returns to her question, which drives the pair into their next cycle of construction and critique.

Ruth and Emma's behavior and body language in this segment remain consistent with the sensemaking framing behaviors described above. The pair are animated, making eye contact with each other, with gestures and turns of talk coming in quick succession. Their dialogue has also fully shifted into the cycles of construction and critique which researchers have argued is characteristic of sensemaking (Berland & Reiser, 2009; Ford, 2012). From a framing perspective, their task or goal seems to be to build an explanation that achieves coherence (Sikorski &

Hammer, 2017) between what Emma thinks should be true (batteries can't "know" how much current they should send to the circuit) and what they have observed.

In this segment, we also see several **moves** from the sensemaking game, recurring tactics that the students use to get one step closer to the target epistemic form. In line 367, we see Ruth *assigning values* to illustrate her point that the equivalent resistance is smaller. While she could have just left her argument at "the equivalent resistance is smaller," she goes one step further and actually assigns numbers to that resistance to flesh out her claim. In line 370 we see Emma *refining her question* in response to Ruth's proposed solution, setting up her critique in line 372 that the equivalent resistance shouldn't play a role because the current coming out of the battery hasn't "approached" this resistance.

Since the pair had not yet provided a satisfactory resolution to Emma's inconsistency, the discussion continued with Ruth elaborating on her claim that the battery "just knows":

375 **R:** It kno—like it, it's like, this voltage is stuck, and so it can't change how many volts are being put out, so the only—and it can't change what resistors are out and what orientation. So it can only change this current. It can only decide how fa—er, how, yeah, how much it, charge can move in,

376 **E:** Right, I understand that, once it [the current] gets to like this node. *{Emma points to the first junction}* But I don't get how it [the battery] would know what's coming [further down the circuit] from here. You know what I'm saying?

Here, again, we see Emma refining her question (line 376). This refinement was a consistent pattern across the episode; even as the pair tried to address the inconsistency mathematically ("the equivalent resistance is…"), teleologically ("it just knows"), and (in the next segment) mechanistically, they continually returned to Emma's question, which acted as the starting point for each cycle of dialogue. This, we posit, is evidence that the initial question was more than just an entry condition into sensemaking game: it also acted as a recurring move throughout the game, which Emma successfully used to critique Ruth's explanations.

Resolving the inconsistency

After playing the sensemaking game for several minutes, the pair had yet to resolve Emma's inconsistency. So, what was Emma looking for? The discussion continued:

377 **R:** I think it's just that charges are everywhere. But no, I, I see what you're saying, but I also don't think we're seeing it from that perspective.

378 **E:** Yeah, I guess I'm also, yeah, I guess I'm also thinking about it as, like, the charge starts right here, but really it's like always all moving. Yeah.

Here, Emma seemed to be signaling that Ruth's explanation resolved her inconsistency. To confirm this hypothesis, I pressed them to explain what they had established:

379 **T:** So, could you say more about that? Like, uh, Ruth, you said like there's charge everywhere here. So how would that—

380 **R:** Well, like, if we think about it, we don't have, like, when we have a circuit put together, and the minute we put the lightbulb in, it turns *{snaps fingers}* on. Like, er, that, that, immediately after we put the lightbulb in, it turns on, so it's not like 'oh, it's [the current] starting from here, and then it's going—and once it gets here then it'll turn it on and keep moving.' It's the fact that because this wire is connected, there's charges all over, and so even though they're, the current is what's driving the charge around, there's already charge built up in here, so by the time I put it in, that, it starts everything moving. So the second everything starts moving, I'm gonna get, there's gonna be things moving here, here, here, everywhere.

381 **E:** Yeah. That's what I was missing. Is that, like, I can't think of this as independent from everything else. 'Cause it's already going, so it's like, it's not that this charge doesn't know about this charge already, it's just that these charges have alr—like, it's going so fast that this charge is already going.

Based on this elaboration and Emma’s explicit statement “that’s what I was missing,” it seems that Emma was looking for a mechanistic explanation (Russ et al., 2008) that would align their mathematical results her intuitive understanding of circuits (batteries can’t “tell” what they’re hooked up to). For her, the notion that “charges are everywhere” throughout the circuit made that connection, achieving coherence and filling in what she was “missing." This explanation, then, was the **epistemic form** she was looking for, and once they’d constructed it they completed the sensemaking game.

The pair’s framing cues during this segment confirm that they had finished the sensemaking game. We see one more transition in framing immediately after the students settled on a resolution and I pressed them to explain their conclusion, in line 379. Where before they were in an animated discussion, exchanging quick bursts of dialogue, they now turned to me, the interviewer, and spoke authoritatively, explaining the conclusion they had come to. As they did so, their framing shifted to what Russ et al. called the expert interview frame as shown in Figure 3: they turned to face me, the interviewer, speaking fluidly and authoritatively, with frequent gestures. Their "task" seemed to have shifted to transmitting the knowledge they had constructed to the interviewer. This shift supports our claim that the pair had completed the sensemaking game and were now moving on to a different game or task.

Figure 3: Student body position and gaze in the sensemaking frame (left) vs. the expert interview frame (right)

THE SENSEMAKING EPISTEMIC GAME DESCRIBED

Building on this case study, we can now begin to unpack the features of the sensemaking epistemic game. To do so, we first outline the trajectory of the game—how it unfolds in general terms—and then flesh out this description with the individual characteristics of the game drawn from both Ruth and Emma's case and other relevant cases in our data corpus.

Trajectory of the Sensemaking Epistemic Game

Looking at the episode as a whole, we can see that Ruth and Emma's sensemaking unfolded in a distinct way, which we summarize in Figure 4:

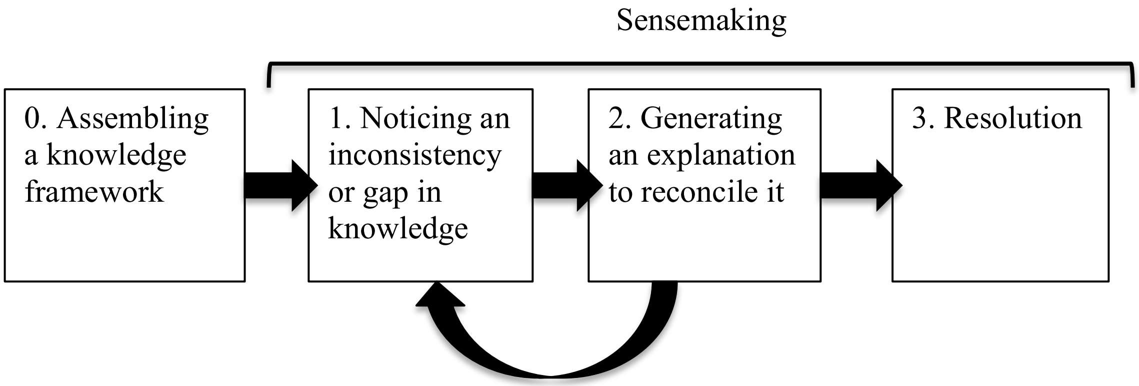

Figure 4: Students' trajectory through the process of sensemaking

Based on Emma and Ruth's trajectory through this episode (which was exemplary of that observed in other episodes of sensemaking) we propose the following model of this sensemaking process:

Step 0, Assembling a knowledge framework: Before sensemaking begins, students assemble an initial knowledge framework, drawing on and priming their prior knowledge on a particular subject. This knowledge framework is dynamic, in that it is assembled (or re-assembled) in the moment in response to contextual cues, like a prompt or question posed by the interviewer. For example, in the case above, Ruth and Emma were drawing on their knowledge of voltage drops in series and parallel circuits, Kirchoff's rules for electric current, their intuition that net current will be the same for series and parallel circuits, and (likely) other bits of circuits knowledge like Ohm's law. This process of activation is a necessary precursor to sensemaking, in that the students are unlikely to notice a gap or inconsistency in their understanding until they have assembled said framework.

Step 1, Noticing a gap or inconsistency: Next, as they are assembling this framework, one of the students notices an inconsistency or gap in their knowledge. In the case above, this happened in line 366, when Emma articulated her question "Coming out of the battery, why wouldn't it be the same current to begin with?" This question precipitates a shift in framing, from *brainstorming* to *sensemaking*, and thus acts as the entry condition to the sensemaking epistemic game.

Step 2, Generating an explanation: Once a student has identified a gap/inconsistency, they begin to iteratively build and rebuild an explanation to resolve the inconsistency or bridge the gap. During this period of explanation-building, the students in our data corpus would exhibit most, if not all, of the characteristics of sensemaking described in the previous chapter, such as cycles of construction and critique (Ford, 2012), mechanistic reasoning (Kapon, 2016; Russ et al., 2008), mapping across different representations (Berthold, Eysink, & Renkl, 2009; Crowder, 1996; Gire & Price, 2013; Gupta & Elby, 2011), and analogy-building (Jeppsson, Haglund, Amin, & Strömdahl, 2013; Podolefsky & Finkelstein, 2007).

Step 3, Resolution: During the final step, students will sometimes successfully build an explanation that resolves this gap or inconsistency. Other times they give up out of frustration or exhaustion. Either way, the sensemaking game ends, and the students move on to further sensemaking or other activities.

This model allows us to describe the general trajectory of sensemaking. However, it does not help us define the parameters or "rules" of the activity, the features that actually drive the process. So, to flesh out this description we now use the epistemic games framework to detail the parameters of the game.

Parameters of the Sensemaking Epistemic Game

Epistemic form and Entry conditions. In the sensemaking epistemic game, students are trying to construct an explanation that bridges a gap or resolves an inconsistency in knowledge. This explanation is the target epistemic form for the game.

In this regard, the game we are describing quite similar to Tuminaro's "Physical Mechanism" e-game, in which students "attempt to construct a physically coherent and descriptive story based on their intuitive sense of physical mechanism" (Tuminaro & Redish, 2007, p. 7). However, the e-game we are describing goes beyond physical mechanisms; while many of the examples from our dataset featured students building causal stories and describing physical mechanisms, gaps/inconsistencies in knowledge come in a wide variety of forms so the e-game could also conceivably be used to make sense of more abstract bodies of knowledge like complex mathematical functions (e.g., trying to understand the physical meaning of a mathematical construct like Curl, or the use and meaning behind Green's functions).

The first articulation of this gap or inconsistency acts as the entry condition into the sensemaking e-game. We see evidence of this in the frame shift that happens before/after the initial articulation of Emma's inconsistency, when the pair shift from "brainstorming" to "sensemaking." This shift marks the transition between the students' initial discussion and the actual “game” of sensemaking. This shift was also consistent across all of the examples of sensemaking we analyzed.

Moves. The sensemaking game has certain moves that seem common across our analyzed groups. Since the goal of the game is to build an explanation, these moves are intended to advance the explanation by drawing on knowledge from a variety of sources and/or critiquing aspects of the explanation. For example, in our presented case Emma repeatedly *refined her question*, thereby narrowing the scope of the explanation, and Ruth at one point assigned values to a mathematical argument in order to illustrate her point.

Because of the brevity of the case above, as well as the abstractness of the material, we were only able to identify these two moves from that case; however, in addition to these two moves, we have gathered illustrative examples of five other common moves from our data corpus in the table below:

Move	Description	Example
Assigning Values	Students assign specific values to a physical quantity to elaborate on their explanation	“Because the equivalent resistance is, is 1 over four plus four plus fou— whatever we said that each resis— three plus three plus three.”
Refining the Question	Students change or refine the initial question to advance or critique an explanation	“What I'm saying is like if you just have a circuit, the current coming out right away, right? Before you're looking at anything here, whether it's parallel or in series, why wouldn't that current be the same?”
Appealing to reality	Students use the plausibility of an event to build or critique the explanation	“I guess you don't ever hear about cars being struck where they have to, like, de-charge the car.”
Appealing to common-sense knowledge	Students use common-sense knowledge to build or critique the explanation	“The safest place to be in a lightning storm is in your car with the window cracked open.”
Appealing to authority	Students look to authority to help them build or critique the explanation	“Uh, you're not gonna tell us the answer either, right? Will you tell us the answer at the end, 'cause this is really gonna bother me. We can google it.”
Appealing to past experience	Students use a personal experience to build or critique the explanation	“But, like, when I put in the dryer sheet… I'm not saying it eliminates all the static, but there's a significantly less amount of static from that sheet, and scientifically proven by my laundry experience.”
Building an analogy	Students use an analogy to build or critique the explanation	“it's like when you touch, you walk on the carpet and touch the doorknob, you're transferring charge.”

Table 3: Moves from the sensemaking epistemic game

To be clear, these were just some of the recurring moves we observed in our recorded instances of the sensemaking game. This is not an exhaustive list—there will certainly be additional moves in this game, used by other students playing the game in different settings. Our goal here is not to catalogue all of the possible moves of the sensemaking game; rather, we are simply trying to illustrate the types of moves that students may use when playing this game.

Other epistemic games analyses outline the particular order in which their moves are used (Chen et al., 2013; Kustusch et al., 2014; Tuminaro & Redish, 2007). However, the sensemaking game is less prescriptive than e-games focused on mathematical problem solving, in which students are proceeding towards a single correct answer. When building explanations, there are a wide variety of conclusions students can come to and an even wider variety of approaches students can take, since there are many different resources and knowledge bodies they can draw on to build those explanations. In practice, this meant that no two groups ever used the same set of moves, even when they had identified similar inconsistencies in knowledge. Therefore, we see little reason in trying to directly map the order in which students used these moves.

Constraints. Identifying constraints presents a major analytical difficulty: how do you determine what is not allowed in a game? This difficulty is perhaps why none of the other studies of epistemic games in the literature discuss the constraints of the games they present.

The easiest way to figure out when something is a "rule" is to look for cases in which that rule is broken; so, ideally, one would look for cases in which students started sensemaking and then ended prematurely, and then examine the factors that caused that premature end. However, this kind of analysis was outside of the scope of our study: we were focused on collecting and characterizing as many positive instances of sensemaking as possible, and so we were not looking for cases in which sensemaking ended prematurely.

Therefore, although we do not have direct evidence of constraint violation, we can speculate at some of the constraints based on the descriptions and characterizations of sensemaking in the science education literature. These constraints, we propose, represent some of the "rules" of sensemaking—if they are violated, we would hypothesize that the activity in question is either not sensemaking (i.e., some other activity like answer-making) or, if that violation happens during the game, it might bring a premature end to the game.

1. Sensemaking is a **discussion in which students contribute their ideas**. Sensemaking not a lecture, or a one-way transfer of information (Berland & Reiser, 2009; Danielak, Gupta, & Elby, 2014; Ford, 2012; Hutchison & Hammer, 2010). Thus, one constraint on sensemaking is that it must be a two-way discussion, and the game would end if one student completely takes over the conversation, turning it into a monologue.

2. Sensemaking happens around a topic/idea that **one has not already made sense of yet** (Crowder, 1996). Thus, the sensemaking game would end (or, perhaps never start at all) if it is on a topic one participant already feels completely knowledgeable about.

3. Sensemaking **involves colloquial talk/definitions, not just formal terminology** (Hutchison & Hammer, 2010; Rosenberg et al., 2006). Thus, the sensemaking game would end if students simply revert to citing formal definitions, rather than discussing their own ideas.

4. Sensemaking **requires one to question/critique the explanation** (Ford, 2012). Thus, the sensemaking game would end if students refused to critique one another's reasoning.

5. Sensemaking **involves multi-step reasoning or a chain of reasoning.** (Russ, Coffey, Hammer, & Hutchison, 2009; Russ et al., 2008) Sensemaking is not just a single answer—that's answer-making, as described by Chen, Irving, & Sayre (2013). If a student identifies an inconsistency/gap in knowledge and another student resolves it with a short, one-sentence answer, then the sensemaking game has ended before it has begun.

6. Within the sensemaking game, achieving the final epistemic form **requires a feeling of satisfaction** (Kapon, 2016; Kapon & Parnafes, 2014). That is, for the sensemaking game to resolve successfully, students must feel confident in that resolution.

Again, we are not claiming that this list of constraints is exhaustive, nor that it necessarily covers all of the possible variations for this game. Different students and different groups had different approaches to the sensemaking game, and although there were patterns across the groups we examined, there are almost certainly other constraints students might impose when playing this game. However, we feel that this limited number of constraints and moves is acceptable for our initial description of the game, since our purpose is more to use this theoretical machinery to describe the general parameters of the activity—the ways students get in and stay in the sensemaking game—than to specify the ways they proceed while they're playing it (the moves they make).

Transfers. During the sensemaking game, students will sometimes briefly **transfer to other games** described in the literature. For example, at one point in the case above, Ruth briefly transitions to the Mapping Mathematics to Meaning game (Tuminaro & Redish, 2007):

367 **R:** Because here the resistance is smaller. Because the equivalent resistance is, is 1 over four plus four plus fou—whatever we said that each resis—three plus three plus three. And so, since, or it's like a third plus a third plus a third.

368 **E:** But then it's one over that number.

369 **R:** But then, exactly, but that number is still smaller than the resistance when they're in series with each other.

According to Tuminaro, in this game students "develop a conceptual story corresponding to a particular physics equation" (Tuminaro & Redish, 2007, p.020101-6). In accordance with this game, Ruth seems to be trying to explicate the target concept of *equivalent resistance* using an equation that relates this circuit's equivalent resistance to the individual resistances of the light bulbs in their parallel circuit ($1/R_{eq} = 1/R_1 + 1/R_2 + 1/R_3$).

In our data corpus we saw examples of students transferring to several other games described in the literature including the Pictorial Analysis game (in which they drew and augmented pictures to clarify their thinking) and Mapping Meaning to Mathematics (in which they translated their physical understanding into an equation, then manipulated that equation to progress their understanding of the system; Tuminaro & Redish, 2007). Additionally, we saw evidence of other activities that seemed to be epistemic game-like, but which have not yet been discussed in the research literature, such *empirical verification* (in which students take measurements from a physical system, like the voltage in a circuit, in order to verify a prediction).

Occasionally, there would even be cases in which the students would recursively transfer to another instance of the sensemaking game itself. This usually happened when the students, in the course of their explanation-building, stumbled on a key piece of the explanation that they hadn't yet made sense of. This, in turn, caused them to articulate a new gap or inconsistency in knowledge, which they would try to resolve before returning to their original explanation (transferring back to the original instance of the sensemaking e-game).

DISCUSSION: USEFULNESS OF THE EPISTEMIC GAMES DESCRPTION

What does this description of sensemaking buy us? We argue that an epistemic games-based description of sensemaking has several advantages over either a theoretical definition of sensemaking or a list of the hallmarks of the process. First, it emphasizes that sensemaking is not just a nebulous type of reasoning or "way of thinking"—instead, sensemaking is a separable, defined activity, with boundaries and transitions that can be analytically identified. From an e-games perspective, sensemaking is a distinct approach to knowledge construction, with its own goal and rules.

Second, and relatedly, this description brings additional theoretical clarity to this process, allowing us to distinguish it from other theories and practices in science education. For example, explanation building is one of the key practices of the NGSS framework (NGSS Lead States, 2013), and as illustrated in the case above, sensemaking involves a great deal of explanation building. Does that mean the two are one-and-the same? In other words, if we want our students to engage in sensemaking, is it sufficient to simply encourage them to explain physical phenomena, as the NGSS recommends?

Based on this epistemic games description of sensemaking, we would argue no. Although sensemaking involves explanation building, the type of explanation matters, as does the student motivation for building the explanation. That is, to be playing the sensemaking game, the students' explanations need to have both the target epistemic form and the entry condition associated with that game.

As a case in point, here is an example of another explanation from our data corpus, in which a student, Jake, describes how batteries charge and discharge:

> *Now we're working on like charging and discharging, So, the comparison that we use is a balloon. And, when you're charging this battery, um, it's like, you have like blow up a balloon. And when you start off blowing up the balloon it like charg—it like fills up quicker. And then as it gets bigger and bigger it starts to like take a little bit longer to fill it up more because it has less, like, available area to put the air into there. So it's kind of like this,* [a battery] *too; as you charge it up it's like, um, it starts off very quick, and then it starts to like plateau at the top. And then it reaches a max, like, right there. Once it reaches that max it can't get any higher. And then, um, the same thing with discharging it,* [the battery] *it's like imagine if you like untied the balloon, the balloon, the air would flow—flow really quickly, but then it'll eventually just kind of like dissipate to a lower amount and just kind of stop. And that's charging and discharging a battery. (J&L2, line 22)*

Jake is clearly building an explanation, but we would claim that he is not, in fact, sensemaking because this explanation does not have the features of the sensemaking epistemic game. First, there is no identifiable gap or inconsistency in knowledge here; in fact, Jake seems to be quite confident in his understanding, and is using this explanation to communicate that understanding. Thus, this activity has a different type of target epistemic form than that seen in the sensemaking game—Jake's explanation is built to illustrate a point, rather than resolve an inconsistency. The lack of a gap or inconsistency in knowledge also means there is no entry point into the sensemaking game here. And, supporting this analysis, we note that this explanation lacks other hallmarks of sensemaking like critiques, a stance of "figuring things out," or connections between different representations.

To put this difference in simpler terms, the sensemaking game is used to construct understanding, to make new conceptual connections. Explanations can serve not only this function, but also many others, like describing or illustrating a concept one already understands.

However, although we see sensemaking as a vehicle for building new knowledge, we also wish to be cautious in our estimation of the strength, scale, or endurance of the new conceptual connections formed while sensemaking. Sensemaking is described in the science education research literature as a dynamic process (Gupta & Elby, 2011; Hutchison & Hammer, 2010; Rosenberg et al., 2006)—that is, it takes place over short time periods (Ruth and Emma's case took a little over 7 minutes in total) and students may or may not re-assemble these same conceptual connections during subsequent conversations. This is not to say the process isn't valuable; rather, it suggests that students may have to engage in consistent, repeated sensemaking over a long period of time to build larger-scale, more stable cognitive connections.

CONCLUSION AND IMPLICATIONS

To summarize, we are arguing that sensemaking is a process in which students assemble an initial knowledge framework, identify a gap or inconsistency in that framework, iteratively build an explanation to resolve the gap/inconsistency, and (hopefully) arrive at a resolution. Along the way, there are numerous moves the students can use to construct the explanation, as well as constraints or “rules” that regulate the process.

To be clear, ours is an initial description of this game, based on a limited set of episodes. We mean it to be a foundation on which others can build future studies to flesh out the details of the game. However, even in its present form we can use it to glean insights on how learning environments can support sensemaking and how researchers might elicit and analyze sensemaking in future studies.

There has already been some research on the features of sensemaking-focused learning environments. Turpen and Finkelstein (2010), in their investigation of clicker question use during peer instruction, observed that a classroom focused on sensemaking has the following norms: low-stakes grading practices; an instructor who consistently and explicitly emphasizes sensemaking or reasoning; significant opportunities for students to build explanations and discuss physical reasoning in small-group formats and whole-class discussions; and frequent opportunities for the instructor to model scientific discourse (p. 020123-16).

Our description of sensemaking builds on this research by providing a framework to understand why these norms work. Based on our model, we argue that each norm is meant, in some way, to help guide students through the different steps of the sensemaking process. Clicker questions provide students with initial prompts, which prime them to assemble their initial knowledge frameworks. When they notice gaps or inconsistencies in these frameworks, the low stakes grading practices give students the time, space, and permission to pursue and resolve them. The remaining norms (focus on explanation-building, opportunities for discussion of physical reasoning, and modeling of scientific discourse) then explicitly support students in building their explanations.

These norms were derived from observations of classrooms that happened to support sensemaking; with our model of sensemaking, however, we can go one step further and propose more specific, targeted suggestions for how to engineer learning environments to support the process. For example, we predict that sensemaking-focused prompts will be most effective if they are open-ended and explainable from multiple conceptual angles; for example, a question like "if you charge up a capacitor, then disconnect it from a circuit and pull apart the plates, the voltage increases. Why does this happen?" can be explained in multiple ways (using the mathematical definition of capacitance, conservation of energy, electric fields, or a "height" analogy for voltage). These multiple explanatory paths give students room to articulate and address inconsistencies between the different approaches. One might even explicitly encourage students to consider the different paths to the answer by asking a follow up question like "how many different ways can you explain this behavior? Are they all coherent with one another?"

Additionally, with regard to the entry condition to the sensemaking game, we have noticed that students must engage in a certain amount of metacognitive reflection to pin down and articulate their gaps/inconsistencies in knowledge. So, instructors who wish to support the sensemaking game may want to explicitly address and encourage this kind of metacognitive practice in their courses.

Beyond specific guidelines for learning environments, we can also use this model to situate sensemaking within the science education curricular ecology—that is, we can use it to decide where to best leverage sensemaking in a course. Based on our observations, sensemaking is a process that is especially useful for helping students “debug” or “defragment” knowledge they have already gained, as Emma and Ruth did in the case presented above. This means that to help students make sense of specific physics concepts, we may want to engineer our courses to “nudge” students towards sensemaking after have already encountered said concepts at least once (e.g. from a pre-lecture video or during a whole-class meeting). Sensemaking may also be useful for students who are learning concepts for the first time; however, we suggest caution in pushing students to make sense of material the first time they encounter it, as this may put students who have already had exposure to the material (and thus can more readily situate it within their knowledge frameworks) at an advantage.

For researchers, these guidelines on supporting sensemaking in the classroom may also apply when eliciting sensemaking in more controlled environments like interview settings. However, this model also provides both suggestions and open questions for future sensemaking research. For starters, if the sensemaking game does, indeed, begin with a gap or inconsistency in knowledge, this raises the question of what kinds of gaps or inconsistencies are most effective at kicking off sensemaking? At the other end of the spectrum, once students have successfully completed the sensemaking game, researchers may investigate which types of explanations students find most effective for resolution. Emma, in the case above, seemed to be looking for a mechanistic explanation rather than a mathematical one—was this preference unusual, or is it common across students? And while students are in the midst of the game, what other moves might they use? Are particular moves used more often than others, and which other epistemic games do students commonly transfer to while they are sensemaking? By investigating these questions, we propose that we can both flesh out the sensemaking game and better understand how to fine-tune our learning environments to support sensemaking.

In conclusion, we believe that sensemaking holds great promise as a design principle for physics education. However, to unlock that potential, we must characterize the process—not just in descriptive terms, but also establishing *how* and *why* it happens. In this study, we have taken a first step in documenting the process, beginning to end, and teasing out some of the factors that drive it. We look forward to seeing the ways in which this theory will be further refined, how it may be built into physics curricula, and the many interesting explanations students will generate as they are sensemaking.

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Chapter 3: Vexation Points in Sensemaking; Knowing What You Don't Know

I don't know, something about that in my mind just didn't seem right.

(Jake, interview 4)

INTRODUCTION

In many ways, learning science is a process of learning to make sense of the world. When a student curiously plays with a magnet and an iron nail (Cavicchi, 1997), or observes an empty soda can crushed by atmospheric pressure, or sees a Ping-Pong ball suspended in a moving column of air, we hope that they will be driven to figure out some way to understand and explain what they're seeing. Many of the skills and concepts taught in science classes, from conservation of energy to Punnett squares, are meant to help them in this process. By learning to make sense of phenomena in the classroom, we hope that we can prepare them to make sense of unfamiliar, complex, or seemingly inconsistent scientific phenomena later in their lives, like genetic diseases or climate change (Dewey, 1910; Lambert & Rose, 1996; Ryghaug, Holtan Sorensen, & Naess, 2011).

However, students do not always engage in sensemaking to the degree that we, as instructors, would wish for. If prompting sensemaking were simply a matter of showing students interesting examples and demonstrations, our jobs would be easy. But there is more to sensemaking than just observation; as any teacher who has ever shown off their all-time favorite demo can attest, sometimes students seem driven to make sense of phenomena, while other times they seem to casually blow by.

So, why does this happen? What goes on between the act of observing something unexpected and the act of making sense of it? Why do students sometimes become captivated by a question or phenomenon, desperate to explain and understand it, and other times ignore it completely?

In this paper, we examine the process of sensemaking to try to understand how it comes about. Using a pair of parallel case studies, we delve into the moments when students identify what it is that "doesn't seem right" to them and articulate it as a question or statement of uncertainty. By focusing in on these moments, we aim to show how these types of questions or statements of uncertainty echo throughout their subsequent conversations, helping them to persist in the process.

LITERATURE REVIEW AND THEORETICAL FRAMEWORK

Hallmarks of Sensemaking

In recent years, sensemaking has become a topic of increasing interest in the science education research literature. As the body of sensemaking literature has grown, three different strands of research have emerged on the subject, each conceptualizing sensemaking in a slightly different way. First, sensemaking has been described as a cognitive process in which students create connections to and within their everyday knowledge by building analogies and mapping across different representations of phenomena (Brewe, 2011; Chiu & Linn, 2013; Clement, 1993; Crowder, 1996; Gupta & Elby, 2011; Manogue, Gire, & Roundy, 2014). Second, sensemaking has been studied as an argumentative discourse practice in which students construct and critique explanations (Berland & Reiser, 2009, 2011; Ford, 2012) and describe the mechanisms underlying phenomena (Kapon, 2016; Russ, Scherr, Hammer, & Mikeska, 2008). Third, sensemaking has been viewed as a generalized stance or framing students take toward science learning, in which they try to "figure something out" based on prior knowledge instead of formal concepts or terminology (Danielak, Gupta, & Elby, 2014; Hutchison & Hammer, 2010; Kapon, 2016; Rosenberg, Hammer, & Phelan, 2006). In this work, we explicitly draw on this third strand of the sensemaking literature, viewing sensemaking as an epistemological frame.

Generally speaking, *framing* is a term borrowed from the sociology, linguistics, and psychology literature, referring to how individuals or groups of people answer the question "what's going on here?" (Scherr & Hammer, 2009; Tannen, 1993). Based on that theory, students in a sensemaking frame view their "task" as building an explanation based on things they already know to be true, rather than trying to find a particular canonically correct answer or asking an authority figure to answer the question for them (Hutchison & Hammer, 2010; Kapon, 2016; Rosenberg et al., 2006).

Researchers identify student framing using both verbal and non-verbal cues. For example, Russ, Lee, and Sherin (2012) identify three different frames that students may take in clinical interview settings, based on the students' gestures, body positions, gaze, and verbal factors like volume and clarity, pacing, or use of hedging language. These frames include "inquiry" (in which students try to construct an explanation), "oral examination" (in which they try to produce the "right answer") and "expert interview" (in which they talk authoritatively about what they know). However, such analyses are complicated by the fact that frames are also usually tacit; that is, students often seem to have difficulty identifying their own framings in the moment, and so one usually has to carefully examine how students are behaving in order to infer these frames (Berland et al., 2015; Russ et al., 2012)

This conceptualization of sensemaking is strongly tied to the *resources* theoretical framework, which we also adopt for this study. The resources framework (Hammer, 2000; Hammer, Elby, Scherr, & Redish, 2005; Redish, 2003) is a cognitivist theory of knowledge that describes knowledge as being built out of many "pieces" (commonly called *resources*), which we abstract from our daily experiences. Resources are theorized to be tiny, compact bits of knowledge and intuition, which are commonly applicable across many contexts.

Researchers often model these resources as being arranged in an interconnected network. Within this network, particular resources are activated based on cues from one's experience and environment. These active resources cue (or activate) other resources, which cue still other resources, and so on (Redish, 2014; Sherin, Krakowski, & Lee, 2012). From this perspective, students' "ideas" are clustered sets of resources that all get activated together. The specifics of one's context plays an important role in cuing resources: a person working on a particular task (say, splitting a restaurant bill) may activate very different sets of resources depending on the context of that task (as an exercise in a math class vs. in an actual restaurant, for example), which in turn determines how they will approach that task.

The resource cuing process is highly dynamic, which is to say it happens frequently and on very short timescales (on the order of fractions of a second). However, the theory also predicts that groups of resources may be consistently cued en masse, especially if they are regularly cued together over time—these subsets are known *coherences* (Rosenberg et al., 2006), *modes* (Sherin et al., 2012), or *frames* (Hammer et al., 2005).

Thus, from this perspective, the sensemaking frame is composed of a particular set of resources, and the frame is therefore dynamic and unstable—we would expect students to shift in and out of this frame, minute-to-minute. So, students may only be sensemaking for a short time (a few minutes) before they shift to another task or approach to science learning. Over time, however, certain students may develop an affinity for the sensemaking frame, leading them to engage in sensemaking even when that frame isn't supported in their learning environment (Danielak et al., 2014).

Theoretical framework for sensemaking. Together, this body of literature provides a detailed picture of the hallmarks of sensemaking. Based on this literature, to recognize sensemaking, one might ask the following questions: are students trying to "figure out" something, or are they trying come up with a canonically correct answer? Are they building an explanation out of their prior knowledge? Is the explanation linking together multiple ideas and/or representations? Are they critiquing aspects of this explanation? If the answers to most or all of the questions is yes, the students are probably sensemaking.

However, while this body of literature has thoroughly described the hallmarks of sensemaking, it has not yet situated this activity within a larger context. That is to say, this body of literature has established what sensemaking *is* and what it looks like, but has not focused on describing the underlying factors that help to drive this process. In this paper, we examine this issue head-on, characterizing some of the factors that underlie sensemaking.

Elsewhere (Chapter 2), we have taken initial steps in this direction by proposing a theoretical model for the sensemaking process. There, we described it as an epistemic game, and provided both the features of this game and its trajectory, supported by initial evidence drawn from an episode of sensemaking in an interview-based setting:

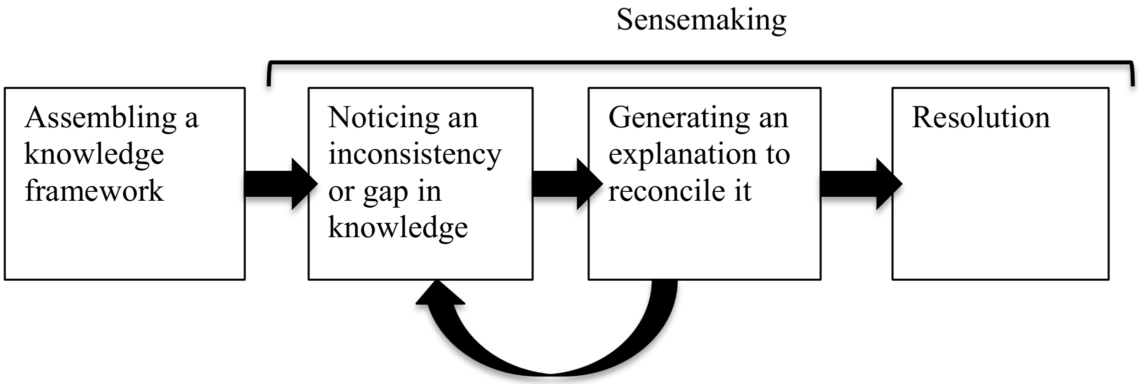

Figure 1: Model for the process of sensemaking

This model provides us with a framework to describe how sensemaking unfolds, in general terms, and also narrows our analytical focus: within this description, there is a critical step in the sensemaking process (Step 2) in which students notice an inconsistency or gap in their knowledge and express it as a statement of uncertainty or a question—that is, they articulate what it is they don't know. In this study, we investigate this step in-depth, looking at the role this gap or inconsistency plays in the ongoing sensemaking process. Since this step is often characterized by student questioning, we draw heavily on the science education literature on question-asking for our analysis.

Question-asking in inquiry and sensemaking

It may be intuitively obvious that questions are related to scientific inquiry, learning, and sensemaking. However, there has been a great deal of research that delves into the role, nature, and function of questions in formal science learning, especially in K-12 settings, and this research has shown that question-asking is a skill that is well worth developing as a science learner. Question-asking promotes deep learning (Chin & Brown, 2002), as well as material retention, independence, and is a disciplinarily authentic skill in science (Harper, Etkina, & Lin, 2003). *Asking questions and defining models* is also a core practice of the Next Generation Science Standards (NGSS Lead States, 2013).

Most studies of sensemaking have used overarching questions to prompt students to engage in the process. For example, Berland and Reiser (2011) based their investigation around a unit on invasive species in which the students were asked to explain, based on provided data, which species was invasive. Hutchison and Hammer (2010) highlighted episodes of sensemaking in which students tried to answer the question of why some materials always float, while others sink/float depending on their shape. And Kapon (2016) presented an example of students trying to explain why a bottle would shrink when all of the air is pumped out of it.

Based on this trend of overarching questions, as well as our sensemaking framework, we conjecture that questions serve a critical role in initiating the sensemaking process. The science education literature on questioning provides at least three additional reasons to suspect this is the case.

First, researchers have argued that questions drive students through the process of inquiry. That is to say, meaningful questions push one to progressively build and refine explanations. As these explanations develop, they expose previously unnoticed ambiguity in the phenomena and uncertainties in interpretation, which bring about new questions (Cavicchi, 1997; Chin & Brown, 2002; Chin & Chia, 2004). This is especially true for explanations that are explicitly built to further one’s own understanding, often called self-explanations (Vanlehn, Jones, & Chi, 1992). Since sensemaking is a form of inquiry, albeit one with specific hallmarks and which unfolds in a specific way, we would expect that questions would be important to sensemaking.

Second, question-asking and sensemaking are both motivated by gaps or inconsistencies in knowledge. Theoretically, researchers have argued that in order to generate a question one has to “know what you don’t know” (Miyake & Norman, 1979) which, in turn, means one has to have built a framework knowledge to see the gaps in the first place (Chin & Osborne, 2008; Vanlehn et al., 1992). Building on this theory, Phillips, Watkins, and Hammer (2017) argue that the act of identifying a gap or inconsistency in knowledge and formulating it as a question is a critical part of the inquiry process. They refer to this process of articulation as *problematizing*, and argue that it is both a key part of student inquiry and an extremely challenging endeavor (Phillips, Watkins, & Hammer, 2017). Empirically, Harper, Etkina, Lin (2003) found a direct relationship between depth of questions asked by introductory physics students and prior conceptual knowledge. In a similar way, we have argued elsewhere (Chapter 2) that sensemaking is a process of building explanations to resolve gaps or inconsistencies in knowledge; based on this similarity we suspect the two processes are likely connected.

Third, there is an affective dimension to both sensemaking and question-asking. When sensemaking, there is an undeniable joy in “figuring things out” (Feynman, 1999) and several researchers have written about the way in which a successful resolution to the sensemaking process is marked by an affective, or emotional, response, sometimes characterized as an "ah-ha” moment (Luke D. Conlin, 2013; Luke David Conlin, 2012; Gopnik, 2000). There is also an affective dimension to question-asking—that is, certain questions “feel” compelling, which researchers have argued is a key aspect of their role in inquiry. For example, Jaber and Hammer (2015, 2016) have characterized this feeling of unease or vexation as “epistemic affect,” or one’s feelings towards one’s own knowledge. Epistemic affect can be both negative (i.e., the frustration of realizing you don’t understand something) or positive (i.e., the pleasure of the ah-ha moment), but either way these emotions are entangled with the experience of doing science. In fact, in that work the authors go one step further, arguing that epistemic affect is a key factor in both students' dispositions *towards* science and their experiences *during* scientific inquiry. These similarities lead us to suspect that sensemaking and question-asking are interrelated.

While we have been referring to questions in the abstract, not all questions are created equal: there are different kinds of questions, and some may be more aligned with sensemaking than others. For example, by analyzing the specific questions students ask, researchers have found that questions can be at different cognitive levels. Many studies of question-asking distinguish between factual or text-based questions and knowledge-based or "wonderment questions." *Fact-based* or *text-based* questions tend to be at low cognitive levels, answerable by recalling facts. In contrast, *knowledge-based questions* tend to be on a higher cognitive order: they "focused on explanations and causes instead of facts, and required more integration of complex and divergent information from multiple sources." (Chin & Osborne, 2008).

This is not to imply that certain students only ask particular levels of questions: individual students may ask questions at a variety of different levels depending on several factors, such as their level of interest in a subject, their prior knowledge, and the environment they're in (Chin & Osborne, 2008; Scardamalia & Bereiter, 1992). However, multiple studies have found that factual questions (and low-level questions in general) tend to be more prevalent in traditional classrooms, though this finding comes with the caveat that student questions as a whole tend to be scarce (Chin & Osborne, 2008; Commeyras, 1995; Graesser & Person, 1994). Although they are rarer, knowledge-based questions tend to be more useful and valuable for learning because they drive students to construct explanations. These results lead us to suspect that knowledge-based questions, in particular, may be especially associated with sensemaking.

Based on these initial conjectures, in this paper we explore the relationship between questioning and sensemaking in depth. Building off of the question-asking literature in science education and using the construct of framing, in this article we aim to investigate the moment in sensemaking in which the students identify and articulate a gap or inconsistency in their knowledge, and the types of questions they use to do so. Thus, our research question is as follows:

1. What roles do questions play in the sensemaking process?

METHODS

Data Collection

The data for this research comes from our study on sensemaking, in which we aimed to collect multiple episodes of sensemaking across multiple students/groups of students and across longer time periods than previously seen in the literature. Our study took place with students from an introductory, algebra-based undergraduate physics course at a major Midwestern university. The course was the second in the algebra-based sequence for non-majors, focusing on electricity and magnetism.

We chose to do semi-structured cognitive, clinical interviews with students from this course (Ginsburg, 1981; Russ et al., 2012), in order to try to prime them into sensemaking and document the strategies they used to do so. Clinical interviewing is a flexible methodology in which the interviewer aims to understand and respond to a subject’s thinking. The interviewer goes into the interview with a set of carefully-developed prompts designed to elicit specific aspects or modes of student thinking (in this case, sensemaking). However, because we chose to make our interviews semi-structured, the interviewer was also free to ask follow-up questions as appropriate, which gave us the flexibility to pursue lines of reasoning that seemed reach in potential sensemaking. The first author (Odden) conducted all interviews.

Based on recommendations from the argumentation-based sensemaking literature (Berland & Reiser, 2009, 2011; Ford, 2012), we chose to interview students in pairs, in order to encourage dialogue and critique between the students. During recruitment, we requested students find a friend in the class before contacting us to enroll in the study, in the hopes that friends would be more comfortable critiquing one another's reasoning. In total we had 9 pairs enroll in the study. Each pair was interviewed 5 times throughout the semester, except for one pair who were unable to complete the final interview. We video and audio-recorded all interviews, which typically lasted 45 minutes to an hour, resulting in about 42 hours of video data.

Each interview protocol was designed to encourage students to build explanations for physical phenomena related to the electricity and magnetism topics covered in the course, such as forces between electric charges, electric fields, and circuits. The phenomena were either hypothetical (thought experiments) or actual physical demonstrations that students were free to play with. For example, both of cases presented below happened in response to a particular thought experiment used early in the interview sequence, the "lightning car." The prompt goes like this:

> *During a thunderstorm, you and a friend wisely decide to take shelter in your car, which you've parked in an open-air parking lot. As you are waiting out the storm, lightning strikes the car. However, besides being a little bit shaken up by the loud noise and bright flash, you both feel totally fine. After the storm has passed, you feel like getting out to stretch your legs, but as you reach for the door to get out your friend yells "Stop!" and warns you that leaving the car might be dangerous. Do you believe your friend? Why or why not?*[2]

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[2] For those interested in what would actually happen in this situation, our understanding is that the passengers inside the car would be safe because the amount of charge delivered by a lightning strike is so powerful that it would melt through or explode the tires, allowing the metal wheel wells to touch the ground and grounding the car. If there was any remaining charge on the car, we suspect that the rain from the thunderstorm would carry it away.

Our original goal with this prompt was to encourage the students to discuss electric fields (the prompt was used in an interview focused on electric fields) but it turned out to be more productive for kicking off discussions about conductors/insulators, induction, static/sparks, and moving charges.

In order to help students feel comfortable expressing their ideas, they were assured at the beginning of the interviews that the researchers were only interested in their reasoning, not right or wrong answers. Students were asked to clarify their thinking by drawing representations of what they were imagining was happening, and were provided with large sheets of paper and markers for that purpose. This not only helped students to articulate their ideas to the interviewer and one another, but also prompted them to create and modify multiple types of representations of the phenomena under discussion. The interviewer also deliberately left various props strewn around the table, such as colored stress balls, to be spontaneously picked up and used in explanations. Sometimes the interviewer would himself pick up one of the props and use it during prompts, potentially priming students to do the same.

Data Analysis

Phase 1: Initial Data Reduction. After data collection was completed, the first author reviewed the entire data corpus in audio form, noting moments that seemed rich in sensemaking based on the hallmarks described in the literature, such as extended explanations (Kapon, 2016), argumentation (Berland & Reiser, 2009; Ford, 2012), mechanistic reasoning (Russ et al., 2008), and connections between different types of representations (Crowder, 1996; Gire & Price, 2013). Building on this cursory analysis, he then engaged in repeated intensity sampling (Creswell, 2007), choosing two set of 5 interviews (10 interviews in total), from two groups who seemed especially prone to sensemaking, for primary analysis. He transcribed all 10 interviews in full, taking additional notes as he did so on the general trajectories of the interviews and episodes or quotes that seemed particularly compelling and sensemaking-rich.

Phase 2: Identifying Shifts in Framing. Next, the first author reviewed these 10 transcribed interviews and extracted specific episodes of what felt intuitively like sensemaking from each. Interviews typically yielded 1 or 2 episodes lasting 5-15 minutes each, for a total of 19 episodes across all 10 interviews. He reviewed these episodes in greater detail, creating analytic memos (Bailey, 2006) on what happened line-by-line in order to get a feel for the students' reasoning. The first author next reviewed a subset of these episodes (7 in total) a second time, analyzing and coding student framing in each line using the 3 categories described by Russ et al. (2012):

3. **Inquiry:** in this frame, the students see their task as constructing an explanation in response to a question posed by the interviewer
4. **Oral examination:** in this frame, the students see their task as producing a correct answer to a prompt or question in a clear and concise fashion
5. **Expert interview:** in this frame, the students' see their task as discussing their own thinking or prior knowledge on a subject, positioning themselves as an authority on that subject

As the first author analyzed these cases, however, he found that the *inquiry* category was insufficient to describe the students' framing every time they were building an explanation—that is to say, sometimes they seemed to be building an explanation in a different way than Russ et al. describe, focused more on assembling existing, prior knowledge than building new knowledge. So, he split *Inquiry* into two different framing categories, *brainstorming* and *sensemaking*:

6. **Brainstorming:** in this frame, students are trying to construct an explanation in response to a question by remembering or "dredging up" their prior knowledge on a subject. This is similar to what Hammer & Zee (2006) have called "shopping for ideas," or what Sherin et al., (2012) have called "mode skimming"

7. **Sensemaking:** in this frame, students are trying to collaboratively build an explanation in response to a perceived gap or inconsistency in knowledge (Chapter 1; Kapon, 2016)

After analyzing these interviews according to these framing dimensions, we began to notice that there was a critical, transitional moment in students' framing, in which they moved from expert interview, oral examination, or brainstorming to sensemaking. This transition seemed to be accompanied by a verbalized question or statement of uncertainty. Once we had identified this transition, we specifically focused our analysis on the role that this question or statement of uncertainty played in the process of sensemaking.

Phase 3: Selection of cases to illustrate the role of questions in sensemaking. Since we aim to describe the role of questions in sensemaking, we have used a case-study approach for both our final round of analysis and our data presentation. Case studies are useful for developing plausible existence arguments and to identify the underlying mechanisms for behavioral phenomena (Creswell, 2013; Lising & Elby, 2005). We therefore feel that a case study approach is suitable for the kind of microgenetic analysis (Opfer & Siegler, 2004; Schoenfeld, Smith, & Arcavi, 1993) required to see the roles that questions play in sensemaking.

The particular episodes we've chosen to highlight here come from parallel sequences of interviews with two pairs of students, Ruth/Emma and Jake/Liam (pseudonyms). In both pairs the students were good friends with one another, and all four students were enrolled in the same course. We chose these episodes, in particular, because both featured the same initial prompt, the "lightning car" thought experiment presented above; however, in responding to this prompt, the groups revealed interesting similarities and differences in both the natures and functions of the questions they used while sensemaking.

THE ROLE OF QUESTIONS IN SENSEMAKING

In what follows we use these two cases to illustrate three essential features of questions in sensemaking. First, drawing on our theoretical framework for sensemaking, we set up the case studies by showing how the students transitioned into a sensemaking frame during moments when they articulated a question or statement of uncertainty. We then show how the students continually cycled back to their questions throughout their sensemaking episodes, and argue that this behavior, as well as the students' affective response when re-articulating their questions, means that questions serve a key function in driving students through the sensemaking process. Finally, we analyze the specific conversational functions of the students' questions, and use those functions to argue that these types of questions also stabilize the sensemaking frame.

Initial questions and transitions into the sensemaking frame

The sensemaking literature suggests that the sensemaking frame is dynamic and that there will be noticeable shifts when students begin and end sensemaking (Danielak et al., 2014; Gupta & Elby, 2011; Hutchison & Hammer, 2010; Tuminaro & Redish, 2007). In our two cases, we see an initial frame shift when the students enter into sensemaking, marked by distinctive discursive and behavioral features including an articulated question or statement of uncertainty. To set up our analysis of the role of questions in sensemaking, we describe these questions and transitions below.

Jake and Liam's initial question. We begin with Jake and Liam's case. After the interviewer posed the "lightning car" prompt, Jake and Liam began by drawing the car, lightning, and the resulting charge distribution immediately after the lightning strike. As they drew, they reasoned that the lightning deposits a large amount of negative charge on the car, which spreads out over the conductive body, but that the people inside will probably be safe analogous to how airplane passengers remain safe even though large amounts of static builds up on flying airplanes (an example their professor had discussed in an early lecture). However, they also reasoned that the lightning's charge would remain stuck on the body car, unable to leave because of the rubber tires preventing it from moving to the ground.

Having sketched out this scenario, the two began to try to answer the question at the end of the prompt: is it safe to leave the car? They reasoned that as the charge spreads out throughout the car, it will gather in the car's "pointy parts," analogous to the static discharge wicks on airplane wings (again, discussed during lecture). Focusing specifically on the door handle mentioned in the prompt, they reasoned that because the door handle isn’t one of these “pointy bits” the person inside the car would at least be safe in grabbing that handle. However, this idea led them to a question: how does charge ever leave the car?

177 **J:** Oh, okay, so, *{J taps on the drawing of the car}* conductor—uh, this is a really, like, it's a really big surface, so the electrons (L: so they'll spread out) are gonna like spread out across, like this. *{J draws negative charges all across the surface}* And, because there's like, like the door handle of our car isn't like a point, it's not gonna like build up right there, where like a shock's gonna come off of it. Because remember, like the airplane wings has (L: yeah) these like little, like, points there *{J draws an airplane wing with little spikes coming off and little lightning bolts coming off the spikes}* and that's were like the shocks come off. So there's nowhere on the car that's like a big point like that. So, it's not gonna shock you when you reach for the door handle because there's not enough, like, electrical, electr—uh, like a negative electric charge that, uh, create a shock. (silence, 14s)

178 **L:** I think that makes sense.

179 **J:** I just don't know how you get rid of this.

180 **L:** Yeah, like does your car just stay charged until it gets grounded?

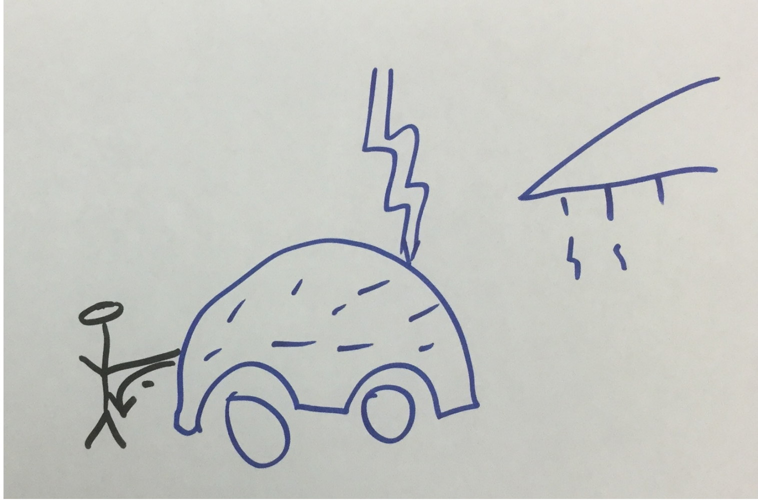

Figure 2: Jake and Liam's drawing of the "lightning car" scenario, with the analogous airplane wing on the right side

So far, Liam and Jake have progressed through first two steps in the sensemaking process. In response to the prompt, the pair have laid out their initial ideas about key aspects the system, such as the negative charge from the lightning and the conductive properties of the car body. The ideas they used to build their explanation constitute their (currently activated) knowledge framework. In the course of this explanation, Jake has articulated a key question: "I just don't know how you get rid of this [charge]" (line 179).

During this segment, there's a noticeable shift the pair's body position, gaze, and dialogue, indicating a shift in framing. Specifically, before Jake's question in line 179 both students were speaking slowly, hesitantly, with many restarts, all while staring at the paper. After the question they turned to each other and made eye contact. Their dialogue shifted, becoming more rapid and responsive. In terms of the modified coding scheme based on Russ et al. (2012), the pair appears to have shifted from "brainstorming" to sensemaking.

Figure 3: Jake & Liam’s body position and gaze before/after frame shift

This frame shift seems to be centered around Jake’s question in line 179. This is not coincidental: Jake’s question, we argue, determined both the topic and “task” of their conversation going forward. That is, Jake’s statement “I don't know how you'd get rid of this charge” focused the pair’s attention on a specific aspect of the physical situation they were analyzing, the free charge trapped on the surface of the car. In that way, it set the topic of their conversation. But, by pointing out an unresolved point in their explanation, the utterance also set Jake and Liam’s goal for the episode, to generate an explanation for how the charge would leave the car. They spent the rest of the episode in this endeavor.

This type of transition point, marked by a question or statement of uncertainty, was common across all analyzed episodes of sensemaking from the data corpus. Drawing on the science education literature on question-asking, we propose that these types of questions/statements of uncertainty indicate gaps or inconsistencies in the students’ knowledge (Chin & Osborne, 2008; Harper et al., 2003; Vanlehn et al., 1992). From a resources perspective, if we think of one’s knowledge as consisting of a huge number of individual resources—compact “bits” of knowledge, which network together to form a framework—then this kind of statement indicates that the student has noticed either a set of “bits” that are missing from their locally constructed framework or a group of “bits” that they previously associated but has now realize are inconsistent with one another. To be clear, we are not saying this gap existed before the interview and/or will persist afterwards. In fact, we assume it likely will not. However, in this moment, they have identified the gap.

What is the inconsistency or gap in knowledge underlying Jake’s question? Based on Jake’s wording in line 179, it appears that he believed, intuitively, that the car would become de-charged at some point, but didn’t see a mechanism for how that would happen. Liam agreed (line 180). So, this statement seems to be both an expression of that conflict and a question about how it would happen.

Ruth and Emma’s initial question. Ruth and Emma were given the same prompt, and their reasoning initially followed a similar trajectory to Jake and Liam’s: they determined that the lightning would deposit a large amount of charge on the body of the car, and that this charge would remain trapped there because of the insulating tires. They further reasoned that this large amount of charge would make it unsafe for someone to exit the car because, by leaving the car, they would give the charge a path to ground. This chain of reasoning led Ruth and Emma to the same inconsistency that Jake and Liam articulated: how would the charge leave the car?

258 **R:** …that's why your friend's worried, because, if it's still around the car

259 **E:** Excess around the car, as soon as, if you touch the metal—

260 **R:** You're gonna shock (E: yourself), you're gonna absorb the shock. (E: Yeah) But I don't know—if it's been a while, I don't know if that shock, like dissipitates [sic]? Whatever that word is.

261 **E:** Disperses, yeah. Well, it's can't. Where would it go?

262 **R:** Well, it's a conductor.

263 **E:** Yeah, but the rubber is the thing that's touching it, and the rubber can't do that.

264 **R:** But it's open air.

265 **E:** Yeah, but wouldn't you see, like, sparks or something?

266 **R:** But it's a, I mean, if it's on the ground, what takes away charges when it's grounded?

267 **E:** Wait, how are they ever gonna get out of the car!?

268 **R:** People get out of the car. That's the thing. So he can't—unless like you need to wait, like, an hour.

Like in Jake and Liam's episode above, at this point Ruth and Emma have progressed through the first two stages of the sensemaking process. The pair began by laying out their initial ideas on the topic of the prompt. As they did so, they noticed an inconsistency (line 260/261): it seems like people should be able to leave the car (as Ruth explicitly states in line 268) but that intuition conflicted with their explanation about charges being trapped on the car's body. After articulating this inconsistency, the pair launched into an explanation to try to resolve it.

Similar to the previous case, there is a noticeable frame shift here, centered around the question in line 260/261. Before this question both Ruth and Emma were speaking slowly and hesitantly, with frequent restarts, while staring off into space. They seemed to be in an "inquiry frame," (Russ et al., 2012) in which their goal was to "dredge up" their initial ideas about what would happen and use them construct an initial explanation. Because they were brainstorming the general scenario, they hadn't yet focused on any particular gap or inconsistency—that is, they hadn't yet encountered anything that in particular that didn't "make sense." At line 259-260 there's a noticeable shift in their dialogue: their speech pacing picked up, they made eye contact with one another, their speech became less hesitant and more fluid, and they began to critique one another (e.g., lines 261, 263, 265), all markers of the sensemaking frame.

Figure 4: Ruth and Emma's body position and gaze before/after frame shift

Similar to Jake and Liam's case, this shift illustrates how the initial articulation of the gap or inconsistency in knowledge marks the transition into sensemaking. That is, Emma's question set the pair's "task" and topic of discussion. Before the question, they were brainstorming what they knew about the physical system; after, they began to try to figure out how it would be possible for someone in this situation to leave the car—is the conductivity a factor? The air? Perhaps the charge sparks off? Thus, the nature of Ruth and Emma's activity seems to have shifted in response to this question—they've gone into a sensemaking "mode." The pair spent the rest of the episode trying to build an explanation to answer this question.

Initial questions across the two cases. Theoretically, the science education literature on question asking (Chin & Osborne, 2008; Harper et al., 2003; Vanlehn et al., 1992) implies that questions like these are driven by gaps or inconsistencies in knowledge—that is to say, students need to have some activated prior knowledge on the subject to recognize and articulate questions like Jake's and Emma's above. Similarly, in our theoretical framework for sensemaking, before students begin sensemaking they need to have a framework of knowledge readily at hand. This implications is also supported by our analyzed episodes: as seen in Jake and Liam's conversation above, these questions were articulated after the students had been thinking about or discussing their topic for a while.

Returning to the science education literature on question-asking, we can now begin to characterize the types of questions that students use to articulate their gaps or inconsistencies in knowledge. Based on the categories in that literature, the pairs' initial questions seem to be so-called "wonderment questions," or "knowledge questions." That is, they were *how* or *why* questions, rather than questions with a quick, factual answer, and were therefore at a higher cognitive level than factual questions with straightforward answers. More specifically, the two questions we have described so far would fit into the categories (defined by Chin and Brown, 2002) of *prediction questions* (questions of the form "what would happen if…?" like Ruth's question in line 260 about whether charge would disperse off the car), or *anomaly detection questions* (where the student expresses skepticism or detects some discrepant information/cognitive conflict, like Jake's question in line 179 about how charge would leave the car).

Students return to their initial questions

Early in our analysis, we noticed that these initial articulations were often not the only instances of the these questions—students would, in fact, sometimes repeatedly return to their initial questions as they built their explanations. We call these re-articulations *recurrences* of the questions, and in what follows we begin to unpack the role of these recurrences in sensemaking in order to address our research question, what roles do questions play in the sensemaking process?

Jake and Liam's recurrences. Returning to Jake and Liam's case, shortly after Jake articulated his initial question (wondering aloud how the charge would leave the car) the pair returned to the matter of whether it would be safe for a passenger to step out:

183 **L:** I can see how that would [be dangerous]—'cause at that point you're the grounding mechanism. 'Cause charge wants to go down, like it wants to get out of there. So it's like, when you touch that *{L draws a person touching the car, a line going down through the person}* it's all just gonna rush down through you, like all the negative charge.

184 **J:** Yeah. So I don't know how you would—but I don't know how you'd get rid of this charge, then. I don't know if it just, like, as you drive, it just, like... **sigh** (silence, 12s)

Here, in line 184, we see Jake return to his question: how do you get rid of the charge on the car? This question is phrased almost identically to his first articulation of the question in line 179. Furthermore, shortly after this recurrence, Jake gives an audible sigh of frustration, followed by a long (12 second) silence. Jake seemed to be vexed by this question.

Jake articulated his question one more time, a few minutes later in the episode:

188 **J:** But yeah, I understand the... (silence, 8s) **sigh** I guess, I guess my inclination would be to answer the question is you wouldn't get electrocuted just by touching it when you

> get out, like getting out of the car wouldn't be an issue, but, like, I mean like if you were to touch the frame of the car, once you get outside of it, I don't think that you'd get electrocuted because... **sigh** And I don't know how this mechanism happens, but I just feel like that there's a way where like the car gets struck but, like, the charge doesn't stay on there that long. So unless you are like touching the car when it gets struck then obviously you'd get electrocuted but there's a mechanism, I don't know what it is, where the charge on the car gets, whether it's like somehow grounded to the earth, or, um, somehow, like used by the car, like when it hits it and the, um, like your battery on there like gets turned off that why your car turns off and you have to restart it or something, but somehow the charge doesn't stay on the car for that long, and that's why you're able to, like, get out after the storm's done and not be hurt. I just don't know the mechanism by where this charge goes—I don't know where it goes.

Here, when Jake said "I don't know how this mechanism happens, but… the charge doesn't stay on there that long" he was reiterating his conviction that charge should be able to leave the car, along with his uncertainty on the mechanism by which this would happen. This statement of uncertainty was based on the same inconsistency he had noticed before, and was therefore another recurrence of the initial question. Furthermore, in this utterance we also see further evidence of Jake's frustration over the fact that he is unable to articulate a mechanism. Like the recurrence in line 184, this recurrence was accompanied by a frustrated sigh. That, along with his repeated, emphasis of his uncertainty ("I just don't know the mechanism by where this charge goes—I don't know where it goes") shows just how frustrated Jake was by his inability to resolve this vexing inconsistency. However, this frustration seemed to be directed at the unresolved nature of the inconsistency, not the interview context or the prompt itself.

Ruth and Emma's Recurrences. Emma and Ruth also returned to their initial question, and this same type of frustration was also evident throughout their episode. We see one example immediately after the previous transcript excerpt, picking up when Emma exclaimed "Wait, how are they ever gonna get out of the car!?"

267 **E:** Wait, how are they ever gonna get out of the car!?

268 **R:** People get out of the car. That's the thing. So he can't—unless like you need to wait, like, an hour.

269 **E:** But what would waiting do? Like, just dri—like just sitting there? Or like driving? (laughter)

270 **R:** Never been faced with this situation before. No, I think, you can leave. Because I think it's, if the car is on the ground, (E: mm-hmm) if elec—let's say it's, you've gained a net negative charge, then electrons are gonna leave your car and go into the ground.

271 **E:** And go—how? *{E shakes her head}* They can't move in the rubber, right? Isn't that the whole point? Is that charge cannot move in an insulator. And your tires are insulators. And the tires is what's in contact with the ground. So there's no way to like ground the car. *{E turns to Interviewer}* Ugh, you're not gonna tell us the answer either, right? Will you tell us the answer at the end, 'cause this is really gonna bother me. (laughter) We can google it. Okay.

Emma and Ruth’s initial question was based on their uncertainty over how charge could leave the car (line 260/261). In this segment, we see a recurrence of that question, where Emma asks, in line 267, how the hypothetical people in the prompt will ever be able to leave the car. Interestingly this first recurrence was formulated slightly differently from the original articulation. Where the original question focused on *charges* (“where would it [the charge] go?”), the recurrence focused on *people* (“how are they ever gonna get out of the car!?”). Both of these questions, however, point to the same gap/inconsistency in knowledge, which Ruth explicitly states in line 268: people do, in fact, leave cars after they’ve been struck by lightning, but this fact is inconsistent with the explanation the pair initially generated. So, although the two statements are phrased differently, we consider the second to be a recurrence of the first.

Although it’s difficult to communicate in a written transcript, Emma had a strong and overt affective response when she re-articulated the question in line 267. That is, when she asks “how are they ever gonna get out of the car!?” there is a noticeable increase in her volume and intonation—she becomes both agitated and excited by the question. She is, in a word, *vexed* by it, and she explicitly expresses this vexation in line 271 where she says “Ugh, you’re not gonna tell us the answer either, right? ...this is really gonna bother me.”

Over the next few minutes, as they continued to try to resolve this question, Ruth and Emma began a series of brief digressions, culminating in a short discussion of the properties of lightning. At the end of this discussion Ruth returned to their question:

299 **E:** Okay, so it's [lightning] just a build-up of charge, and then it's hitting you, so it's like sending an elec—like, I don't know, sending an electric current, that's kind of how the way I think about lightning, but I don't know if that's accurate. Through the car, but

there's no, nowhere for it to go, is what we're saying, right? I believe my friend, I don't want to get out of the car.

300 **R:** You have to get out eventually.

301 **E:** I know, so how do people do it—yeah.

302 **R:** But how do people get out the car? (E: Does, do…) The safest place is to be in the car, I think you can get out right after.

Here, the pair have returned to the question of how people can leave the car. It is worth noting that this recurrence is phrased very similarly to the last one, focused on people instead of charges, even though in their digression they had focused their discussion on a charge-based model of lightning. However, as previously argued, the question articulated by both Ruth and Emma (lines 301/302) point to the same inconsistency as before.

Recurrences across the cases. In summary, these excerpts provide initial evidence that the initial question not only marks the transition into sensemaking, it also recurs throughout the subsequent explanations. And, based on the students' affective markers (intonation, sighs, and explicit statements like "this is gonna bother me") we are arguing that these recurrences have an affective dimension—these questions are *vexing* or *frustrating* to students—and the students are driven to try to resolve them.

Jaber and Hammer (2016) characterize this type of frustration as one possible dimension of students' *epistemic affect,* the "pleasurable discomfort of a difficult question" (p. 25), which they argue is key to keeping students engaged in sustained scientific inquiry. We make a similar argument here: for both Jake and Emma, the "pleasurable discomfort" they felt seemed to be a key factor that drove them and their partners through the process of sensemaking. However, we go one step further, claiming that this affective quality was specifically tied the questions that Jake and Emma articulated and re-articulated as the pairs built their explanations.

This property of *vexation* also helps explain why these students repeatedly returned to their questions. We propose that these underlying inconsistencies or gaps in knowledge were so frustrating, so vexing (albeit in a somewhat pleasurable way) that the students felt compelled to periodically circled back to them. This act of "circling back," in turn, continued the explanation-building process, "driving" them through the process of sensemaking. In a similar way, researchers studying question-asking in science education have found repeated questioning drives students through the process of inquiry (Cavicchi, 1997; Chin & Brown, 2002; Chin & Chia, 2004; Vanlehn et al., 1992), pushing one to progressively build and refine explanations.

Recurring questions stabilize the sensemaking frame

So far, we have argued that these students repeatedly cycled back to their initial questions due to the questions' vexing nature, and that this behavior helped drive the students through the sensemaking process. However, did these recurrences serve any greater purposes for the sensemaking frame?

The roles of Jake and Liam's recurring questions. To investigate this question, we looked in-depth at the role that the recurring questions played within the conversation itself. For example, returning to the transcript excerpt in which Jake and Liam articulated their first recurrence, we see that the question is, in fact, inextricably linked to the subsequent direction of their explanation:

184 **J:** Yeah. So I don't know how you would—but I don't know how you'd get rid of this charge, then. I don't know if it just, like, as you drive, it just, like... **sigh** (silence, 12s) 'Cause I'm pretty sure lightning has a pretty good negative charge to it, where the fact that it's gonna deposit a large amount of current to like shock you

185 **L:** Yeah. (silence, 9s) I dunno, I guess you don't ever hear about cars being struck where they have to, like, de-charge the car.

Why would Jake return to his question in line 184? Our conjecture is based on Liam's statement in line 185, "I guess you don't ever hear about cars being struck where they have to, like, de-charge the car." Until this point, the pair had been focusing their conversation on the physical situation in the abstract, discussing what hypothetical charges would do on the hypothetical car. Here, however, Liam is taking the explanation in a different direction than before, using what does or doesn't happen in real life as a resource for the explanation. Looking at this statement in relation to Jake's restatement of the initial question, it seems that Jake may have provided an opening for that move by implying that, in theory, one *should* be able to get rid of the charge on the car. By implying that it is possible to get rid of this charge (rather than leaving it as an open question), this recurrence may have opened up new directions for the pair's explanation.

When Jake later re-articulated his question a second time, it seemed to serve another purpose:

187 **L:** I don't know. (silence, 6s)

188 **J:** But yeah, I understand the... (silence, 8s) *sigh* I guess, I guess my inclination would be to answer the question is you wouldn't get electrocuted just by touching it when you get out, like getting out of the car wouldn't be an issue, but, like, I mean like if you were to touch the frame of the car, once you get outside of it, I don't think that you'd get electrocuted because... _*sigh*_ And I don't know how this mechanism happens, but I just feel like that there's a way where like the car gets struck but, like, the charge doesn't stay on there that long. So unless you are like touching the car when it gets struck then obviously you'd get electrocuted but there's a mechanism, I don't know what it is, where the charge on the car gets, whether it's like somehow grounded to the earth, or, um, somehow, like used by the car, like when it hits it and the, um, like your battery on there like gets turned off that why your car turns off and you have to restart it or something, but somehow the charge doesn't stay on the car for that long, and that's why you're able to, like, get out after the storm's done and not be hurt. I just don't know the mechanism by where this charge goes—I don't know where it goes.

Based on Jake's repeated emphasis of his uncertainty (saying "I don't know" no less than four times in the span of a single minute) he seems to be expressing his dissatisfaction with the explanation they've generated. This happened shortly after two long silences (lines 186 and 187), which seemed to indicate that the pair were running dry on ideas for how to resolve this inconsistency. So, without anywhere else to go in his explanation, Jake seemed to be reiterating that there *should* be a mechanism here, he just couldn't see it. Unlike the previous recurrence, this statement did not necessarily open up new avenues for the conversation; rather, by expressing dissatisfaction with the explanation so far, it seems to be a bid to simply keep their sensemaking going, by any means possible.

Taking a step back, though they served different conversational purposes, we would argue that both recurrences were used to keep the process of sensemaking, as a whole, going. More specifically, we propose that both of these recurrences addressed and mitigated ways in which the sensemaking activity could "fizzle" or prematurely end. For instance, one could easily imagine the sensemaking process ending if the students ran out of ideas. The first recurrence combats this tendency by opening up new directions for the explanation, and the second recurrence combats it by essentially signaling "I'm not done yet."

The roles of Ruth and Emma's recurring questions. Looking at Ruth and Emma's recurrences, we see similar conversational functions. For example, their first recurrence went as follows:

266 **R:** But it's a, I mean, if it's on the ground, what takes away charges when it's grounded?
267 **E:** Wait, how are they ever gonna get out of the car!?
268 **R:** People get out of the car. That's the thing. So he can't—unless like you need to wait, like, an hour.

What purpose does this recurrence serve? Prior to this, the pair had been discussing charges in the abstract, but this recurrence shifts the focus to the specific people in the car. So, like the first recurrence in Jake and Liam's episode, this recurrence appears to open up new avenues of inquiry—new possible directions for the explanation. Ruth's next statement supports this assertion: she says “People do get out of the car,” thereby fully shifting their explanation to focus on *people* instead of abstract *charges*.

This function is similar to that seen in Jake and Liam’s segment above, when Liam says “I guess you don't ever hear about cars being struck where they have to, like, de-charge the car” (line 185). However, while the conversational *function* of this recurrence is the same as Jake and Liam’s (line 185), the *way* it accomplishes that function is different. In Jake and Liam’s example above, the recurring question was phrased nearly the same each time. This recurrence opened up new lines of inquiry by *reformulating the question*, focusing on people instead of charges. This reformulation then opens up new directions for the explanation and by extension other paths towards resolution. In other words, it would have been difficult to appeal to reality when discussing charges in the abstract, but by reformulating the question Ruth and Emma shift the conversation to talking more concretely about what people actually do in this type of situation.

The second recurrence in Ruth and Emma’s episode serves a slightly different function:

299 **E:** Okay, so it's just a build-up of charge, and then it's hitting you, so it's like sending an elec—like, I don't know, sending an electric current, that's kind of how the way I think about lightning, but I don't know if that's accurate. Through the car, but there's no, nowhere for it to go, is what we're saying, right? I believe my friend, I don't want to get out of the car.

300 **R:** You have to get out eventually.

301 **E:** I know, so how do people do it, yeah.

302 **R:** But how do people get out the car? (E: Does, do…) The safest place is to be in the car, I think you can get out right after.

This recurrence (line 300) is phrased almost exactly the same as the previous recurrence, so it's not reformulating that question. Instead, we argue that this recurrence served two purposes. First, like Jake's second recurrence, it acted as a bid to keep the conversation (and, by extension, the activity of sensemaking) going. That is, Emma's utterance in line 299 ("I believe my friend") could have easily ended the conversation, had Ruth been willing to concede the point. Since she was not, she restated her question to continue the conversation, signaling her dissatisfaction with the explanation they'd constructed.

Second, and relatedly, the recurrence returned Emma and Ruth to the topic at hand after their digression, effectively resetting their explanation. During this digression, the pair's "task"—and the topic of their conversation—had shifted to resolving the question of "what is lightning?" In line 299, we see the conclusion of this digression, with Emma characterizing lightning as "just a build-up of charge." With this question now resolved, she returned to their original "task," saying "there's no, nowhere for it to go, is what we're saying, right?" This set up the recurrence in line 301/302, which essentially returned them to building their original explanation.

The roles of recurring questions across the cases. To summarize, looking across all four of these individual recurrences, we see that the recurrences served at least three different purposes:

1. They reshaped the question, opening new avenues of discussion
2. They signaled that one of the students didn't feel satisfied with the explanation yet

3. They returned the students to the discussion/topic at hand

Taking a step back from these particular conversational functions, we are arguing that in all of these cases, the recurrences keep sensemaking going by heading off possible ways in which sensemaking might end. For example, students might run out of ideas from which to construct their explanations. They might get side-tracked to a different discussion topic or a different activity entirely, such as arguing over a minor point or detail. They might come to an early conclusion, "short circuiting" their discussion. These various types of recurrences, we argue, each serve to mitigate one of these ways the process might end:

1. ***Returning to the topic at hand*** serves to mitigate the possibility that students might get side tracked from sensemaking. Conversationally, this particular type of recurrence also serves as a "repair" (Sacks, Schegloff, & Jefferson, 1974) bringing them back to the conversation after an interruption and/or returning them back to their original topic

2. ***Reformulating the question*** serves to open up new avenues of inquiry, mitigating the risk of "running dry" on ideas and thus ending the explanation-building process.

3. ***Signaling "not done"*** mitigates the possibility of coming to an early conclusion, before everyone feels satisfied with the explanation

This is, of course, not an exhaustive list of the ways in which sensemaking might end, nor a full taxonomy of the different functions of recurring questions. However, it illustrates our larger point, that recurring questions keep sensemaking going—that is, questions not only mark the students' transition into sensemaking, they also *stabilize* sensemaking as it's happening. This stability is critical because of the "slippery" nature of frames like sensemaking: since frames are inherently dynamic and short-lived (Rosenberg et al., 2006) there are many ways in which the sensemaking frame, and the explanation being built, might prematurely end. By mitigating these possibilities, these types of recurrences stabilize the frame.

DISCUSSION: QUESTIONS AND VEXATION POINTS

Using the cases of Jake, Liam, Ruth, and Emma, we have demonstrated that during sensemaking students may articulate questions that both begin and stabilize the process. In our examples, the initial articulations of these questions mark the students' transition into a sensemaking frame. Once they were in the sensemaking frame, the question both helped drive them through the process and stabilize those frames by heading off potential end-points for their conversations. Throughout all of this, the questions "worked" because they were vexing—the students were frustrated by the underlying gaps or inconsistencies in knowledge and were driven to resolve them.

Since they seem to be critical to the sensemaking process, we propose a specific term to refer to these types of driving gaps or inconsistencies in knowledge: we call them the students' *vexation points.* Because questions, like those described above, are driven by these gaps or inconsistencies in knowledge (Chin & Osborne, 2008; Vanlehn et al., 1992), we would call these recurring questions or statements of uncertainty *articulations* of students' vexation points.

We introduce this term for two reasons: first, we wish to emphasize that these gaps or inconsistencies, and the questions they inspire, are special. That is, we wish to differentiate these types of questions, which are driven by stubborn inconsistencies in understanding, from other types of questions that are more easily resolved. For example, Emma's question "what would waiting do?" (line 269) is a critique of Ruth's suggestion that charge might just disperse over time; it does not demand the same type of resolution as their initial articulation of the vexation point. In other cases students might ask simple fact-based questions like "what is the charge of an electron again?" that could easily be answered by remembering a specific piece of information. These types of questions would not serve the same critical purpose in sensemaking as the recurring questions described above, so we wish to theoretically distinguish them from articulations of students' vexation points.

More specifically, these inconsistencies are frustrating or vexing to students, as shown in the two cases above, and we wish to emphasize this affective dimension. This type of frustration differentiates students' articulated vexation points from the more general category of questions—not all questions or underlying gaps in knowledge are vexing. We see the fact that the students returned to the questions as evidence of the vexing nature of these underlying gaps or inconsistencies in understanding.

Second, we wish to emphasize how, even though recurring questions may be phrased slightly differently (as when Emma reformulated her question) they are focused on the same *point,* or inconsistency, that the students are trying to resolve. Cognitively, we can imagine that the students are trying to approach a particular gap or inconsistency from multiple conceptual "angles," each of which is reflected in the different functions of the corresponding questions and subsequent explanations. Therefore, we are using this term to group together questions that are worded differently but getting at the same underlying point.

Analytically, we propose that vexation points can be identified based on the presence of recurring questions. These recurrences, as we have argued, help to stabilize the sensemaking process; thus, we are arguing that vexation points not only serve key functions in sensemaking, but are also themselves also defined *by* sensemaking. Although this description may seem circular, this circularity is a function of the fact that vexation points and explanation building are both parts of the larger-scale process of sensemaking and so are inextricably entwined.

An analogy might help with this point. In the field of conversation analysis there has been a great deal of study on the ways in which people deliver "news," especially bad news like a poor medical diagnosis (Maynard, 1976). Researchers studying the news deliver process have argued that an utterance is not defined as "news" until someone treats it as such. For example, if Tor says "someone ran over my dog last night," Rosemary might choose to treat this as bad news ("Oh, I'm so sorry to hear that!"), good news ("I never liked that dog anyway") or not news at all ("Yeah, I know, I ran it over"). In this way, the original utterance does not become "news" until one responds to it and evaluates it, and both the utterance and the response are part of the larger-scale process of news delivery.

In the same way, a question or statement isn't identifiable as a vexation point until students return to it as they try to resolve it. If they ignore it, or if it is a fact-based question that is quickly resolved, it remains a simple a question or statement of uncertainty. For this reason, one can't tell a priori whether a student, when asking a question, is articulating a vexation point. This does not mean vexation points are not theoretically useful; since they both mark the transition into the sensemaking process and stabilize it they are arguably a key aspect of sensemaking. However, it does make them more analytically tricky to identify, since one needs to look not only for a student's initial question/statement but also the way they (and/or others) respond to that question/statement.

Although we have presented only two examples of recurring vexation points, there are numerous others in the science education research literature. For example, Jaber and Hammer (2016) describe an example of a 4th-grade science class, led by their teacher Mr. Meyers, who are discussing the water cycle. During this discussion a student, Jordan, articulates a question, "what's in a cloud that makes it hold water?" As the conversation unfolds, it becomes increasingly clear that Jordan is vexed by this question, and she repeatedly returns to it as the class tries to build a satisfactory explanation:

1. **Jordan:** I have a question.
2. **Mr. Myers:** Ok.
3. **Jordan:** What's in a cloud that makes it hold the water?
4. **Alyssa:** *{to Jordan, whispering}* It just does it.
5. **Jordan:** Like, does it float?
6. **Mr. Myers:** Oooo I see a scrunchy face. *{looking at Brian}* What are you thinking about? Did you listen to her question?
7. **Mr. Myers:** Could you say your question one more time Jordan?
8. **Jordan:** Why does—how could water be in a cloud without falling?
   (Silence)

After Mr. Myers has called on several other students to respond, Alyssa speaks up again:

11. **Alyssa:** It gets the water—well it can hold as much as it can *{Jordan taps the floor with her hands}* and then it turns to grey and then and then it just drops it and that's when it rains, but uh—
12. **Jordan:** But—what holds it?
13. **Elea:** Yeah! How does it hold it?
14. **Alyssa:** *{to Jordan}* The clooooud!
15. **Elea:** HOW?
16. **Jordan:** How does a cloud hold it? It doesn't HAVE a magical WALL holding it!
17. **Elea:** Yeah *{laughing}* like—it doesn't have a patch under the cloud so like to keep the water in!
18. **Alyssa:** *{In a lower voice and looking down}* It just holds as much as it can.
19. **Jordan:** HOW—
20. **Elea:** How can it hoooold IT!?

The transcript continues, with the students proposing and rejecting gravity as a mechanism, and eventually breaking into pairs to continue the discussion. However, we feel that this excerpt is enough to illustrate the substantial similarities that this example holds to our two cases presented above, including both the fact that Jordan and Elea are clearly vexed by this gap in knowledge (as can be seen from their excitement in lines 15-20) and the way Jordan's question recurs in line 12 and 16. In fact, during the ensuing discussion, Jordan articulates her question one additional time (line 26, p. 14). Additionally, Elea, in line 13, refines Jordan's question from "what holds it" to "how does it hold it," similar to how both Jake and Emma reformulated their questions. So, we would argue that this recurring question was characteristic of a vexation point and that the students were, in that conversation, engaged in sensemaking.

The science education literature includes numerous other examples of these types of recurring questions during sensemaking discussions: For example, Phillips et al. (2017) describe a case from a 5th-grade class discussing the question of "why does water expand when it freezes, if the water molecules get packed together?" (p. 020107-5); Hayes (2009) describes a case of three upper division physics majors discussing why a two-dimensional oscillator is described by two phase angles (p. 61-73); and Engle and Conant (2002) describe an ongoing discussion in a 5th-grade classroom about whether orcas are best classified as whales or dolphins, which resurfaced on 8 different occasions over an 8-week unit. In each case, the students repeatedly returned to their vexation point, using it as a resource to refine their explanations and advance their sensemaking.

To summarize, based on our two examples as well as the prevalence of this phenomenon in the literature, we propose that vexation points may serve a critical role in the sensemaking process. For this reason, we also see great potential for this construct in future sensemaking research.

CONCLUSIONS AND IMPLICATIONS FOR FUTURE RESEARCH

Based on this analysis, we propose that vexation points can have three key uses for science teachers and educational researchers: first, methodologically, they give us another tool to identify sensemaking which may be more analytically tractable than those currently used. Second, they theoretically help us describe how students persist in sensemaking. Third, they may practically allow us to promote sensemaking in the science classroom.

Methodologically, vexation points give us an additional way to identify sensemaking, which may be easier to use than the many intersecting dimensions that have been described in the science education research literature. Rather than looking for sensemaking by asking whether students are trying to “figure out” something, build an explanation, link together multiple ideas and/or representations, critique aspects of this explanation, etc., we can instead look for a recurring vexation point. In practice, this could greatly speed up and simplify sensemaking-based analyses; for example, Kapon (2016) identified sensemaking using a deep, multi-layered approach of coding along the dimensions of framing, explanatory primitives, and mechanistic reasoning. This approach works well for delving, in-depth, into individual case studies, but quickly becomes cumbersome when analyzing longer or more numerous episodes. Instead, we are proposing that to identify sensemaking, one can analyze student speech to look for moments where they articulate something that doesn’t “make sense” to them, then pursue it. If one observes that the students are repeating their questions this would serve as a key indicator that the activity is sensemaking (though one would also want to make sure that these recurrences were in the service of a developing explanation, rather than, say, a student who is being aggressively argumentative, e.g., Berland & Reiser, 2009).

Theoretically, this approach adds greater detail to the growing theory of sensemaking by providing a mechanism for how students persist in the process. That is, from a framing perspective, sensemaking is expected to be somewhat ephemeral: people will slip in and out of the frame. However, in order to make it a key part of science education, we need to have students consistently sensemaking, and we need to help them continue sensemaking, even when it might be difficult. This analysis suggests that when students have found a sufficiently vexing question, they will stay in the sensemaking frame. That, in turn, suggests future study on these vexation points to try to understand the factors that cause them to emerge and how we might capitalize on them in our teaching practice.

Practically, if vexation points do, in fact, stabilize sensemaking, we may also be able to leverage it to support sensemaking in the classroom. For example, teachers who wish to support sensemaking may want to help their students learn to recognize and/or articulate vexation points either through explicit, metacognitive instruction or by designing learning environments that support students in eliciting and follow up on their vexation points.

However, this is just a general guideline. More research needs to be done to investigate the particular conditions which serve to support sensemaking. For example, one question that remains open is whether students need to learn content before they can make sense of it, or whether they can engage in sensemaking as they learn new material. If the question-asking literature is to be believed, one needs to have background knowledge to elicit vexation points (Chin & Osborne, 2008). However, perhaps this background knowledge need not come from formal settings. These types of questions would represent rich avenues of future study on sensemaking.

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Chapter 4: “Rolling Down the Voltage Hill”; Conceptual Blends, Connections, and Resolution

INTRODUCTION

Physics is all about connections. When we teach physics courses, whether introductory or advanced, we structure them around connections between different units, different principles, and different aspects of principles—circuits theory builds on understanding of voltage, which builds on electric fields, forces, and potential energy. As our students make their way through our courses, we hope they will see these connection, in the process developing deeper, more robust understandings of the subject (Chin & Brown, 2000), a more sophisticated disciplinary epistemology (Adams et al., 2006; Lising & Elby, 2005; E. Redish, Saul, & Steinberg, 1998), and greater confidence in their own understandings (Jaber & Hammer, 2015, 2016).

However, the connection-building process is not necessarily straightforward; it takes time, effort, and often a certain amount of struggle to build these types of connections. To some degree, this is expected; the transition from novice to expert physics student is not easy (Bing & Redish, 2012; M. Chi, Feltovich, & Glaser, 1981). Nevertheless, the fact remains that students coming out of a physics course will often feel that they have emerged with a fragmented understanding; in some cases, this can result in students feeling that physics is nothing more than a jumble of “disconnected facts” (Adams et al., 2006; Elby, 2001; E. Redish et al., 1998). And when students are left with a fragmented understanding, with gaps or inconsistencies in their knowledge, they may be left feeling that physics does not make sense.

Over the years, physics teachers and researchers have developed numerous ways to help their students see connections between the various concepts they learn. For example, bridging analogies (Clement, 1993), embodied activities (Gire & Price, 2014; Scherr, Close, McKagan, & Vokos, 2012), and online simulations (Kohnle & Paetkau, 2017; Mckagan et al., 2008; Wieman, Adams, & Perkins, 2008) all attempt to foster these connections in different ways. However, it can often be difficult to tell when a connection or set of connections has been made, and more importantly *how* and *why* it was made. That is, while certain connection-building techniques have been shown to be effective in large-scale studies (N. Podolefsky & Finkelstein, 2007; N. S. Podolefsky & Finkelstein, 2007), we have less evidence of the specific ways in which they can aid in student sensemaking.

In this paper, we argue that conceptual blends (Fauconnier & Turner, 2002; Gire & Price, 2014; N. S. Podolefsky & Finkelstein, 2007; Wittmann, 2010) can serve a key role in helping students build conceptual connections and make sense of physics concepts. Using the case of a pair of students, Jake and Liam, who are discussing voltage and circuits in a clinical interview setting, we show how a conceptual blend is constructed and argue that conceptual blends can be used in two ways: to help students "defragment" their knowledge frameworks and to help them resolve specific, vexing inconsistencies in knowledge.

LITERATURE REVIEW AND THEORETICAL FRAMEWORK

There has been a great deal of research on the ways in which physics instructors can help students build conceptual connections when learning physics. For example, as a discipline we put a great deal of emphasis on different types of representations for phenomena (equations, graphs, pictures, etc.), and so one way the PER literature has studied connection-building is by looking at the specific connections that students make between different types of representations. Underlying this area of research is the assumption that a particular representation of phenomenon carries some information or meaning, but it may hide other essential information about the system being represented. A graph of velocity as a function of time, for example, tells you nothing about the starting location of an object, nor the context for the physical system. A video recording of the object may provide this, but one still cannot predict how the object will behave after the graph/video ends—that's where equations of motion come in.

The general argument of this body of research is that in order to fully understand unfamiliar or confusing scientific ideas one may have to draw from and unpack several different representational forms. Specific representations that have been studied in PER include mathematical formalism (Gupta & Elby, 2011; Sherin, 2006), pictorial representations (Cao & Brizuela, 2016; Chiu & Linn, 2013; De Cock, 2012; Gire & Price, 2014; Kohnle & Paetkau, 2017), graphs (Christensen & Thompson, 2012; Gire, Nguyen, & Rebello, 2011; Ivanjek, Susac, Planinic, Andrasevic, & Milin-Sipus, 2016; McDermott, 1987), and embodied or gesture-based representations (Manogue, Gire, & Roundy, 2014; Scherr, 2008; Stephens & Clement, 2010; Wittmann, 2010).

Beyond the specific representations of phenomena, research shows there are a variety of ways people could go about the actual process of *connection building*. For example, students may use analogies or metaphors to create and articulate explicit connections between different concepts (Brewe, 2011; Brookes, Ross, & Mestre, 2011; Clement, 1993; Manogue et al., 2014; N. Podolefsky & Finkelstein, 2006; N. S. Podolefsky & Finkelstein, 2007). Students may also use the linguistic affordances of analogies or metaphors to classify certain abstract concepts, implicitly connecting them to other concepts in the same ontological category (Brookes &

Etkina, 2009; Jeppsson, Haglund, Amin, & Strömdahl, 2013), although some researchers have also suggested that these connections can cause trouble for students if they miscategorize concepts (Chi & Slotta, 1993; Slotta, 2011).

Most of this literature focuses on instructional techniques to help students to build conceptual connections. In this study, however, we are interested in the actual mechanisms behind connection-building, i.e. how and why they build certain connections, and the effects these connections have on their reasoning later on. So, to investigate this subject, we are drawing on three intersecting theoretical frameworks: the resources framework, the sensemaking framework, and conceptual blending.

The Resources Framework: building blocks of cognition

In order to understand how students build conceptual connections, we have to look at the ways in which they reason. To do this, we are drawing on an individual, cognitivist theoretical framework focused on connection-building, the *resources* framework (also known as Knowledge in Pieces). This framework describes students' knowledge as a collection of knowledge "bits" or "resources" that are extracted from daily experience and activated depending on context (e.g., DiSessa, 1993; Hammer, 1996; Hammer, Elby, Scherr, & Redish, 2005). Resources are theorized to be tiny, compact bits of knowledge and intuition which are commonly applicable across many contexts. Researchers often visualize these resources as being arranged in a network, within which certain resources, when activated, cue other resources, which cue still other resources, and so on (E. F. Redish, 2014; Sherin, Krakowski, & Lee, 2012). According to this theory, fully-formed ideas are composed of various resources being cued together.

Researchers within PER and science education have proposed a variety of types of resources that may be activated (together or separately) in different contexts. For example, two of the most fundamental types of resources in the PER literature are *p-prims* and *symbolic forms*. *P-prims* or *phenomenological primitives* are bits of physical intuition that students may use in their daily lives to predict how physical phenomena behave, as well as when predicting the qualitative results of physics problems (DiSessa, 1993). Those same students may also use mathematical templates called *symbolic forms* when reasoning mathematically while solving quantitative physics problems (Sherin, 2006).

Researchers have also hypothesized that students may use more complex bits of knowledge when generating explanations, called *explanatory primitives* or *e-prims* (Kapon, 2016; Kapon & DiSessa, 2012). In contrast to p-prims, which are often so fundamental that they are difficult to put into words, e-prims are explanatory building blocks that may be acquired culturally, linguistically, or in formal educational settings. For example, common-sense knowledge like “a car is the safest place to be in a thunderstorm” could be described as an e-prim, since it is more complex (based on numerous other pieces of knowledge) and is encoded linguistically. Researchers have further argued that certain e-prims have greater or lesser priority for different people, depending on how much explanatory power we attribute to them (Kapon & Parnafes, 2014; Parnafes, 2012). For example, one person might consider the above-mentioned lightning safety e-prim to be highly reliable, whereas another might attribute low status to it based on stories they had heard about cars starting on fire after they had been struck by lightning.

The resources framework is a useful theoretical tool for understanding and predicting the ways in which students reason. However, this theory also has more direct instructional implications, suggesting that if we are not careful in designing courses and learning environments, giving students frequent scaffolding and opportunities to connect together the different rules or “bits” they learn, they may emerge with a fragmented understanding of the subject.

This implication has found some support in the research literature (e.g., Adams et al., 2006; Elby, 2001; E. Redish et al., 1998). This literature also suggests that conceptual fragmentation can send a negative epistemological message about the nature of physics learning (Adams et al., 2006; E. Redish et al., 1998). And, at a more basic level, students who leave a course with a fragmented understanding may well feel that the physics they’ve learned is separated or inapplicable to the real world (Hammer, 1989; Lising & Elby, 2005).

Sensemaking: resolving a specific missing connection

Sometimes, students are not suffering from knowledge fragmentation—rather, they feel confident in most of their understanding, but they’ve identified a specific gap or inconsistency in their knowledge, a specific missing connection. Their process for filling in this missing connection is what we call *sensemaking*.

As we have argued elsewhere (Chapters 1 and 2), sensemaking is an observable, multi-step process. This process begins with students assembling a framework of knowledge, connecting together various cognitive resources. In the process, they notice a gap or inconsistency—a missing connection—within that framework, and feel driven to resolve it. We refer to this missing connection as the students’ *vexation point*, since they often feel vexed by it to the point of repeatedly circling back to and restating the question (Chapter 3). Next, students iteratively generate an explanation to try to resolve the gap or inconsistency. In some cases, they are successful in this endeavor; in others, they eventually give up out of weariness or frustration.

We summarize this process as follows:

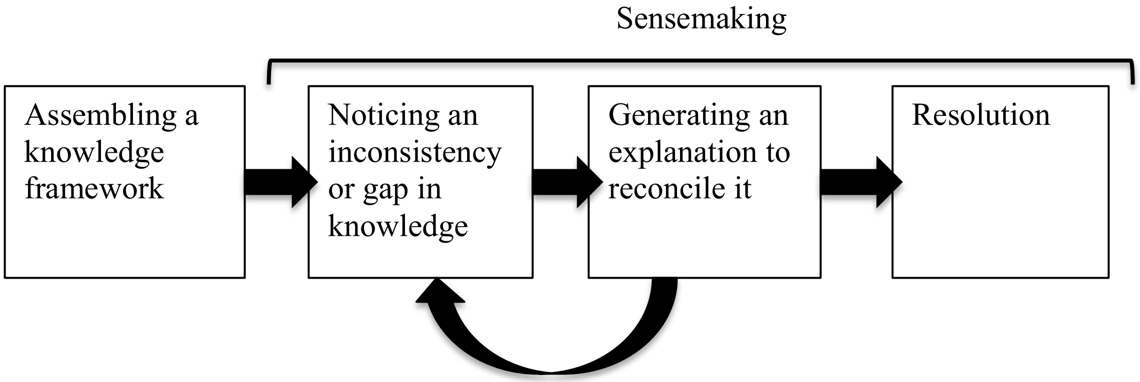

Figure 1: A model of the sensemaking process

Although there has been a great deal of science education and physics education research literature focusing on the third step of this process, iterative explanation building (e.g., Berland & Reiser, 2009; Crowder, 1996; Ford, 2012; Gupta & Elby, 2011; Hutchison & Hammer, 2010; Shen & Linn, 2011), there has been comparably little written about the end product of sensemaking, the specific connections that students use resolve their vexation points. That is, although many researchers talk about sensemaking, few talk about the actual *sense* that students make. Within the small body of research that does focus on this phenomenon, there are two primary themes: first, that the moment when students make this connection is marked by an affective response, and second that we judge whether a particular connection or explanation “makes sense” (that is, resolves a vexation point) based on our internal judgments of coherence.

Several researchers have written about the way in which resolution is marked by an affective, or emotional, response, sometimes characterized as an "ah-ha” moment (Conlin, 2013). Jaber and Hammer have argued that this affective dimension is deeply entangled with the process of scientific inquiry (Jaber & Hammer, 2015, 2016), and Gopnik has argued that it is a feature of explanation more generally (Gopnik, 2000).

How do we judge when an explanation meets our requirements, when the right connection has been made? Kapon (2016) argues that we assess the value of scientific explanations based on their consistency with how the world works, and their ability to explain a range of phenomena based on the fewest possible principles. Sikorski and Hammer (2017) propose that sensemaking is a process of coherence-seeking, and so an explanation that provides resolution is one that achieves coherence between disparate pieces of knowledge. Parnafes goes one step further, arguing that we assign more epistemic priority or "weight" to certain pieces of knowledge—some pieces of knowledge are more important to our worldview than others—and we tend to feel that an explanation achieves resolution only when it is congruent with the knowledge with the highest status (Kapon & Parnafes, 2014; Parnafes, 2012).

Based on both the resources framework and this sensemaking framework, we are assuming that students build new knowledge by connecting it to prior knowledge. However, especially when learning physics, students often have to build connections to and between unfamiliar, abstract, or complex concepts, which may seem unrelated or even conflicting with their everyday understanding. How do they build these more complex connections?

Conceptual blending: conceptual connections that create emergent meaning

Within PER, several studies have successfully used the theory of conceptual blending to investigate student thinking and design interventions that help students build more complex or sophisticated conceptual connections (Bing & Redish, 2007; Hu & Rebello, 2013; Jeppsson et al., 2013; N. Podolefsky & Finkelstein, 2007; N. S. Podolefsky & Finkelstein, 2007; Wittmann, 2010). Conceptual blending is a theory introduced by Fauconnier and Turner (2002) to describe, in overarching terms, how people create new ideas that incorporate concepts and associations from different conceptual domains. A conceptual blend is essentially an idea that is built or assembled from two different conceptual domains, called the *input spaces*. Elements and relationships from these spaces are combined to form a third *blended space* that mixes ideas from both domains.

Conceptual blends are extremely common in our everyday language. For example, Fauconnier and Turner illustrate the idea of a blend using the construct of a “computer virus” which blends meaning both from the domain of “computers” (files, software) and “viruses” (harmful, discrete, replicating) to create a new term that describes a harmful, replicating piece of software (Fauconnier & Turner, 2002, pp. 274–275).

Key to the theory of conceptual blends in the construct of mental “spaces.” These spaces have certain features, as described by Fauconnier and Turner, which facilitate the blending process:

1. **Elements**: These are the bits of knowledge—the discrete entities or “characters”—that populate a mental space. Some (but not necessarily all) elements from each space will typically be carried over to the blended space. For example, the “computer space” includes entities like files, programs, and users, while the “virus space” has elements like viruses, people, and cures.

2. **Structure:** These are the relationships between particular elements or entities *within* a mental space. For example, the “virus space” contains relationships like “viruses infect people.” The computer space includes relationships like “computers run software”

3. **Vital relations:** These are certain isomorphic relationships within the input spaces that facilitate connections between those spaces. For example, a key step in building the “computer virus” conceptual blend is noticing the connection between the way a piece of malicious software replicates and spreads over time and the way a virus replicates and spreads over time.

Conceptual blends are commonly illustrated using *blending diagrams,* like that shown in Figure 2:

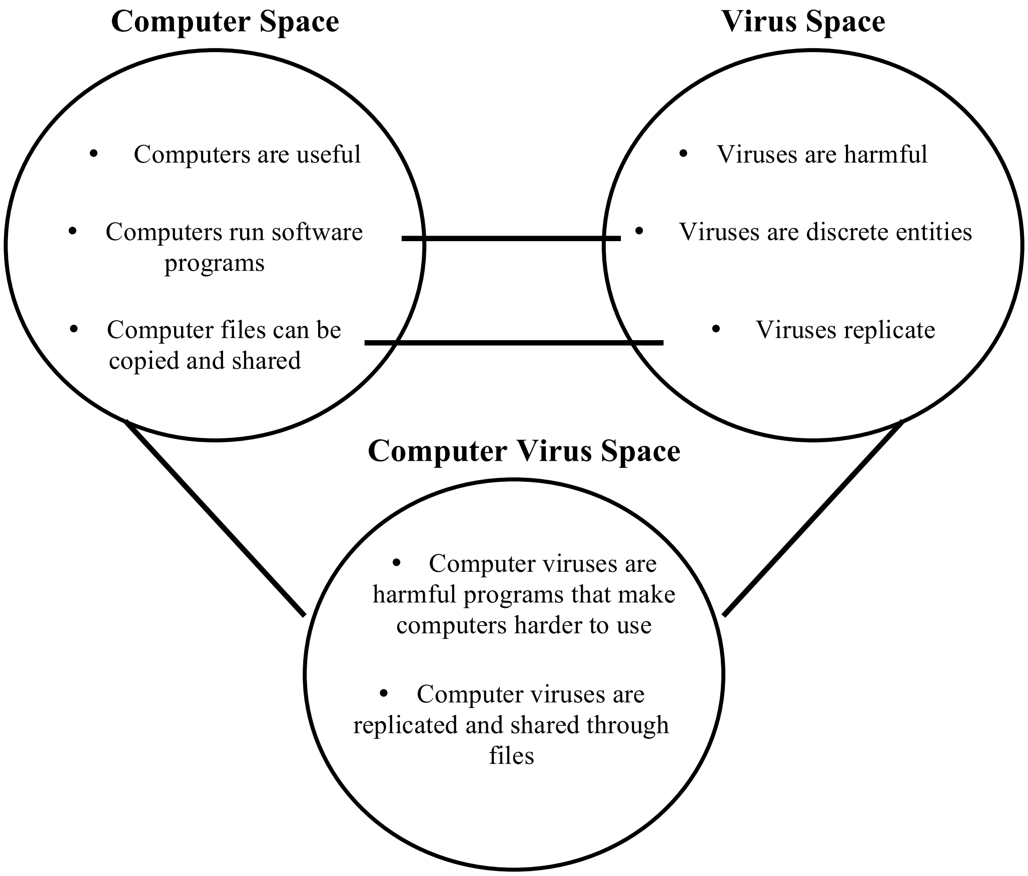

Figure 2: The blending diagram for a *computer virus* conceptual blend

The most important aspect of conceptual blends, according to Fauconnier and Turner, is that the blended idea can create new meaning not present in either of the original spaces. For example, thinking of a malicious program as a computer "virus" naturally brings with it some possible actions to take in response, based on the strategies humans have developed for dealing with infectious diseases, like *antivirus* programs, *sterilization* (i.e., firewalls or rebooting from a backup), *quarantine,* or *rewriting the viral program*. These ideas can then be projected back to the original conceptual spaces, presenting new opportunities and ideas for how to deal with challenges in those respective domains. In the computer space, one might use these insights to design software to deal with malicious programs, while in the virus space one might develop new approaches to virotherapy, for example “reprogramming” a virus to attack cancer cells.

Conceptual blends are similar, in many ways, to the theories of analogy and ontological metaphors (Dreyfus, Gupta, & Redish, 2015; N. S. Podolefsky & Finkelstein, 2007). All three theories describe a process of mapping or creating connections between different conceptual “domains” and rely on the associations from one domain being used to make meaning of or within another domain. However, analogies are direct mappings between a base and a target domain. Although they use one domain to understand the other, in the end there are only really two domains, the base and the target, and those domains remain distinct from one another. For example, an analogical approach to describing computer virus might involve a description like “this program acts like a virus; it’s harmful, it reproduces, and it will slow down your computer.” While this type of analogy is useful for understanding a new phenomenon (i.e., if someone has never encountered a malicious program before), the inferences only go one way, from the “virus space” to the “computer space.” In contrast, a conceptual blend not only connects the two input domains, it also creates a third, blended domain. As previously illustrated, this domain can then be used as a conceptual tool to build new, emergent meaning. Thus, conceptual blends act as a more generalized theory, within which analogies are one particular application.

Using and building the frameworks of resources, sensemaking, and conceptual blends, in this study we delve into two cases of students building conceptual connections around complex electricity and magnetism phenomena. Thus, our research question is as follows:

1. What types of conceptual connections do students build when constructing and using conceptual blends?

2. What effect do these connections have on student sensemaking?

CASE CONTEXT, ANALYSIS, AND DESCRIPTION

Data Selection

The context for this case is a clinical interview-based study which aimed to document and analyze students' sensemaking processes in an introductory physics course. The study population consisted of 9 pairs of students, all of whom were enrolled in the same large-lecture algebra-based physics course at the University of Wisconsin-Madison (physics 104), which had recently been updated to focus on conceptual development and active learning. During the data-collection phase of the study the first author conducted a series of 5 semi-structured interviews with each pair of students over the course of the Fall 2016 semester. The course was a second-semester electricity and magnetism class, so each interview was focused on a specific subtopic from the course, including charge and electric forces, electric fields, electric potential, electric current, and a final retrospective interview.

Out of the entire data corpus (44 interviews, or about 43 hours of video data), the episode we highlight here stood out to us for several reasons.

First, the students in the episode were grappling with a particularly complex, abstract set of topics that most students have great difficulty with—voltage, electric potential, electric potential energy, and circuits. It seems fair to say that very few students come away from an introductory course with a solid understanding of these topics; however, as we will show, by the end of the second interview session, the pair of students had not only made sense of them, but had come to some fairly sophisticated conclusions. Thus, this case serves as a kind of "best-case scenario" or "proof of concept" for student sensemaking in this type of course.

Second, as they were making sense of these topics, both students were quite vocal and metacognitive about their understanding, more so than most others pairs in the study. In particular, they regularly interjected comments about things that did or did not make sense, which provided an unusually candid metacognitive lens on their sensemaking processes.

Third, this case illustrates a particularly interesting circumstance for sensemaking: one in which the students already had a great deal of prior knowledge of the phenomenon, but were still confused about key aspects. That is, they were making sense of a concrete phenomenon (a circuit that they had in front of them) which they had spent a great deal of time investigating. When the sensemaking episode occurred, both students already had what we would characterize as a sophisticated understanding of the system. However, they were not satisfied with this understanding—they needed more.

Data Analysis

Once we had chosen these particular interviews and episodes for in-depth analysis, our analysis proceeded in two stages. First, the first author analyzed the students' sensemaking behavior based on framing cues and discourse features such as construction and critique (Ford, 2012), as well as the presence of vexation points (Chapter 3), and the trajectory of the sensemaking process described elsewhere (Chapter 2).

Since we were interested in the substance of their explanation—how they achieved resolution to their particular vexation point—the first author also coded for possible e-prims based on the students' language, gesture, and his own knowledge of the course content (having taught a previous semester of the course). Specifically, he looked for the explanatory "bits of knowledge" the students used to justify their reasoning, which typically took the form of "ground rules" or first principles the students had learned for understanding circuits, like Ohm's law.[3] To identify possible e-prims, he used the criteria proposed by Kapon and DiSessa (2012), including

1. **Functionality:** The e-prim's function is to help someone make sense of the world, and should be explanatorily useful to an interviewee's goal at that particular moment

2. **Obviousness:** The e-prim has to be "primitive"—self-evident, obvious, or fundamental (it can't necessarily be explained by other primitives)

3. **Source:** The e-prim has to be derived from a "history of successful use" and one should be able to hypothesize a familiar experience from which it could have been abstracted (in this case, explicit instruction)

4. **Frequency/stability:** an e-prim can't be identified from a single utterance, it has to have at least 3-4 instances of use in a variety of contexts during the interview, or (preferably) across multiple interviews

5. **Literature:** if a component of an explanation is similar to an idea/concept that other researchers have discussed in the literature, then that raises the likelihood that it is an e-prim

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[3] One might wonder whether these types of rules can be considered "primitive" in the same way as other types of resources, like p-prims. While it's quite possible to question how and why such principles are true, the students seldom seem to do this because these are the first principles they learn—thus, they are the conceptual building-blocks, for the system, and in this regard are "primitive" (Kapon, 2016; Kapon & DiSessa, 2012; Kapon & Parnafes, 2014; Parnafes, 2012)

In the course of these analyses it soon became apparent that the conceptual blending framework provided a useful description for how the students were building their understanding of abstract concepts like electric potential, equipotential lines, and voltage drops. So, after reviewing the PER literature on conceptual blends, the first author performed a second analysis to identify the elements of the input spaces and blended space, as well as how this blend seemed to be affecting their understanding of E&M concepts. During this analysis, the focus was on their language and gesture, as well as the representations they drew.

In what follows, we present a first-person account of the two linked interviews in which Tor ("I" in the following narrative) helped facilitate the students' construction and application of the conceptual blend.

Case Overview

The two students in the interview, Jake and Liam (pseudonyms) were roommates who were both enrolled the targeted course during the semester of the study. Both were kinesiology majors who were enthusiastic about learning physics. Jake was also a former student of mine (I had been his TA for his introductory mechanics course the previous semester).

The case happened in two parts, over two successive interviews. In the first interview, I aimed to probe Jake and Liam's understanding of the concepts of voltage, electric potential, and electric potential energy. Based on their responses to my probing questions, it seemed clear that their understanding of these concepts was highly fragmented, focused mostly on the functional aspects (i.e., what you can *do* with voltage, rather than what voltage *is*). I then helped the pair create the conceptual blend between E&M concepts related voltage and mechanics-based ideas related to height and kinetic/potential energy. Jake and Liam then used the inferences from the blend to “defragment” this concept space.

In the second episode, a week later, Jake and Liam used the blend in a different way: as a conceptual tool to make sense of a perceived inconsistency in their understanding of circuits.

CONCEPTUAL BLENDS USED TO DEFRAGMENT A CONCEPT SPACE

This first episode focuses on Jake and Liam’s understanding of voltage, equipotential maps, and electric potential energy, and how they used a conceptual blend to build connections between these concepts. The interview took place in three parts: First I probed what the pair knew about these three topics (lines 17-90), which also served to activate their relevant knowledge on the subject. Then, I introduced a conceptual connection between voltage and height (lines 90-170), which helped the pair construct a conceptual blend between those two concept domains. Finally, they used this conceptual blend to build connections within this knowledge space, resolving some of their expressed confusion and applying their newfound understanding to a related system, capacitors.

Jake and Liam express confusion about voltage and equipotential maps

I opened the interview by asking Jake and Liam to describe their understanding of voltage. It quickly became apparent that, although they had some voltage-related knowledge, their understanding of the core concept was fragmented:

23 **T:** How would you explain voltage to somebody who wasn't taking physics, who has heard the term but doesn't really know what it means?

24 **L:** Oh, man. I dunno, I struggle with the concept of voltage. To be honest. (J: I do too)[4] Like, it kind of confuses me.

25 **J:** If I had to explain it to someone, I would say, like you have a battery right here that has 12V in it. And, let's say you have another battery that's like a 3V battery. The 12V battery will have the ability to, like, output more energy than the 3V battery. But, that's about how to explain it. I'd explain it I guess like that. 'Cause I struggle with the voltage, yeah.

From Jake's statement in line 25, it seems that he was comfortable with the idea that voltage can take on different values and that he saw a clear connection between voltage and energy in a circuit. But, when pressed, both students expressed explicit confusion about the actual meaning of the term.

They expressed similar uncertainty when I changed terminology, and asked them about electric potential:

32 **T:** So how do you think about electric potential? (silence, 6s)

33 **L:** I don't know, the only way I can think of it is you have more before you go through a resistor, and then you lose some of that potential to the resistor, and then it just has a drop in potential. I don't know. I can't really... think of a way to describe it.

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[4] Transcription note: Since much of my transcript involved dialogue between the pairs of students, I've chosen to include cases in which one interjects during the other's turn of talk in parenthesis, rather than breaking the turn apart. I feel that this allows one to see a more coherent picture of a student's ideas than if turns of talk were broken into multiple lines.

While the pair struggled to articulate an explicit definition for voltage, I suspected they had a greater understanding than they were able to put into words in response to this prompt. So, shifting gears, I attempted to probe their understanding of voltage in a different way, by asking them to draw and explain a standard representation for voltage, an equipotential map. Specifically, I posed the following challenge: draw an equipotential map for two point charges, one +Q and the other +4Q. The pair had done an activity similar to this in a previous lab, and so had little trouble with the task. Their map is shown in figure 2:

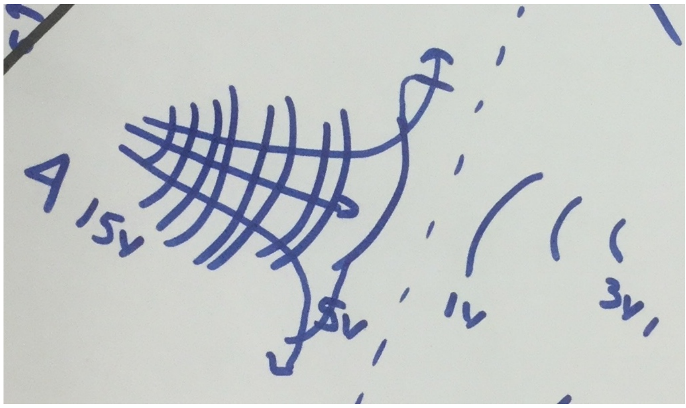

Figure 2: Jake and Liam's drawn equipotential map for a charge +4Q (on the left) and +Q (on the right)

They explained their drawing as follows:

64 **J:** This [the potential around +4Q] would be like a, I don't know, I mean let's say it's 15V, and then out here it might only be like, 5. And that's because this one's stronger, but this one [+Q], which is weaker, would have like a 3V and maybe only like 1V out here.

65 **L:** So the equitential lines [sic] should be getting farther apart (J: yeah) as you go, right? (J: yeah)

Here, the pair revealed several other "ground rules" they had picked up: voltage is a function of position relative to charges, increasing near positive charges and decreasing further away. It also depends on the charges themselves—voltage is greater near a big charge than a small charge. And, equipotential lines are closer together near a charge, and further apart further away.

Based on their response to the map-drawing task, I asked the pair to describe their understanding of electric potential energy. On this subject, they seemed less uncertain:

66 **T:** So, like I've heard people use the term 'electric potential energy' as well. Like, and somehow they seem related. I mean, like, electric potential and then electric potential energy. So, like, what do you guys think the relation is between them?

67 **L:** Just like, the, the closer you would move to this charge, depending on what, so I suppose if you had like a positive charge you'd be getting more elec—electric potential energy?

68 **T:** So like, we got a positive charge here… *{T places a green stress ball on the page}*

69 **L:** Yeah, so like the closer you move this, like, down the, er, I suppose it'd be up the electric potential lines, the more electric potential energy you'd end up having, 'cause it's gonna want to repel each other more.

70 **J:** Yeah. And then it would be the exact opposite for a negative charge.

Here, Liam suggested that electric potential energy was a function of the repulsive force between charges—greater force indicated greater potential energy—and Jake added that it would be the opposite for a negative charge. However, it is not clear whether the pair saw a strong connection between voltage and electric potential energy: while Liam noted in passing the connection between a charge's electric potential energy and its location on an equipotential map, the pair did not seem to explicitly connect the two quantities, even though they had previously labeled the voltage values on certain lines in their drawing.

To summarize, based on their responses to the questions in the first part of the interview, it was clear that Jake and Liam had learned some of the "ground rules" for electric potential and the physics of circuits. From a resources perspective, we would posit that during their time in the physics course, the students had acquired various knowledge "bits" or e-prims related to these topics from their experiences in the class. While not an exhaustive list, these e-prims included

- Greater voltage creates greater energy in a circuit (line 25)
- Electric potential decreases across resistors (line 33)
- Electric potential increases near positive charges, decreases further away (line 64)
- Larger charges produce greater electric potential (line 64)
- Equipotential lines are spaced more closely nearer to a point charge, and their spacing increases further away from a charge (line 65)
- Like charges repel and opposite charges attract (line 69)
- A charge's electric potential energy depends on the size of that charge and the electric potential at its location (line 67, 69)

However, based on their repeated statements of uncertainty, it was also clear that the pair were having some difficulty connecting these concepts together. In other words, Jake and Liam's understanding of these concepts seemed to be fragmented—the pair had pieces of the concepts, but hadn't yet assembled them into a coherent whole. For example, in response to the first prompt they were able to describe voltage functionally—what voltage *does*—as being related to a battery's energy output (line 23), decreasing in a circuit (line 33) or being greater near a positive charge (line 64). However, they had difficulty actually describing in any concrete terms what voltage *was,* and they were aware of this difficulty. Similarly, they had little trouble reproducing the essential features of equipotential maps, but when prompted to talk about electric potential energy, they seemed to see a stronger connection between potential energy and forces between charges than potential energy and voltage.

The students' difficulty is unsurprising, since these are challenging, abstract concepts that introductory physics students usually struggle to understand (Millar & King, 1993). Additionally, the course they were taking, like many introductory courses, mostly emphasized the functional use of these concepts; this may, in fact, have been the first time the pair had ever been called on to explain what voltage meant. That said, once they noticed this fragmentation they both seemed to feel uncomfortable (as evidenced by statements like "I struggle with the concept of voltage," line 24), and so seemed receptive to clarification, which set up the next part of the interview.

Jake and Liam construct a conceptual blend, the Voltage Hill

Having reflected on and discussed what they remembered about voltage, electric potential, and electric potential energy, the pair now had (at least some of) these resources active and readily at hand. This activation "primed" them to draw the connections that would eventually evolve into a conceptual blend. During the next part of the interview, I capitalized on this activation, suggesting a conceptual connection intended to help them better understand these concepts: that one could think of voltage as being similar to “height” for charges.

To introduce this connection, I suggested that “some people,” when looking at equipotential maps like the one they’d draw, saw something akin to a topography map. Liam immediately seized on this connection, remembering a graph from class for the electric potential of a single charge in which the voltage decays as one moves away from the charge. He reproduced the graph (the black decay curve in Figure 3), and Jake explained the drawing as follows:

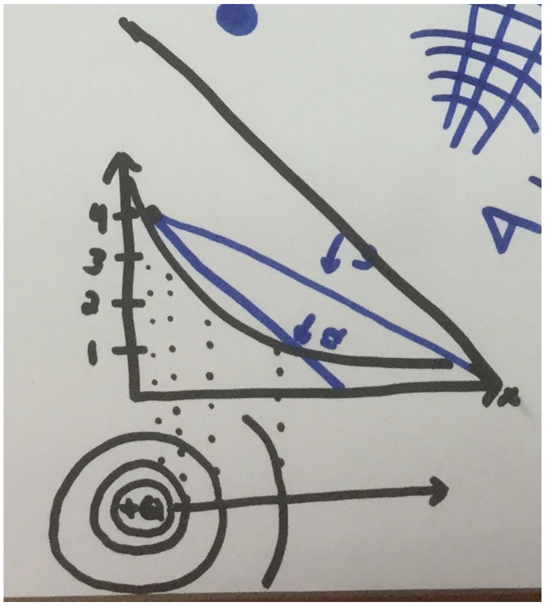

Figure 3: The voltage decay curve for a point charge, drawn by Liam. The decay curve is drawn in black. Specific points on the decay curve are connected with a dotted line to the equipotential map for a point charge, drawn below the graph

109 **J:** So, Liam's drawing, like, this, says that—and you can use like gravity again, I guess. So, topography maps use, like, elevation and so this graph here is showing, like, if this is where the center of your Q charge is, and you want to bring a positive charge closer and closer to it, you have to, like, push it up the hill

110 **L:** You're just like going uphill in voltage.

111 **J:** So, like they imagined it as, like, imagine the Q charge is like a 50-foot hill, you have to like climb up that 50 feet to get to the top. And this is how much, like... *sigh* As you start, like, your energy's smaller and smaller but as you get close to the top of the hill you're steeper and steeper so you have to, like—

112 **L:** And, yeah, and then the electric potential lines get closer and closer to you. *{L traces electric potential lines for a point charge below his graph}* 'Cause you can, like, map it out.

In this exchange, we see Jake and Liam beginning to build a conceptual blend between the "voltage space" (broadly encompassing the concepts of voltage, electric potential, and electric potential energy) and the "hill space" (broadly encompassing the concepts of height and potential energy). Based on Liam's graph, the two have established that the electric potential from a point charge acts as a kind of "hill" in height terms, with greater positive charges creating larger "hills." Additionally, these hills become steeper as one gets closer to the top, corresponding to the increased repulsive force when one brings two positive charges together. Furthermore, Liam has connected this changing force to the variable equipotential line spacing around a point charge, showing how more closely spaced lines correspond to a steeper slope on the "voltage hill."

Elaborating on this connection, I suggested that if you placed a third positive charge in this system, it might behave similarly to a bowling ball dropped on this "mountain." Jake and Liam immediately picked up and ran with this idea, describing how this hypothetical charge would "roll down the voltage hill" and gain kinetic energy:

126 **L:** Yeah, I suppose like if you dropped a positive charge on here it would roll down the voltage hill. *{L traces a path outwards from the circular equipotential map he'd drawn below his decay graph}* Like, it would just roll down the voltage hill, *{L traces his decay graph}* like, slowly,

127 **J:** Yeah, and, so if you dropped it from, like, a, from this mountain *{J points to the smaller charge}* it would, it would gain, so—

128 **L:** Kinetic energy, right?

129 **J:** Yeah, it would gain its kinetic energy, but it doesn't have as much potential energy (L: mm-hmm) to expend. Whereas at the taller mountain, it's like 4 times as high (T: yeah) so it has 4 times as much energy to expend. I mean I think it's 4 times, might be 8 times because of the square, but. So, yeah, whatever, whatever electric potential this one would have at the top you would convert into kinetic energy once it gets all the way down to the end. And, it clearly has much more than this one.

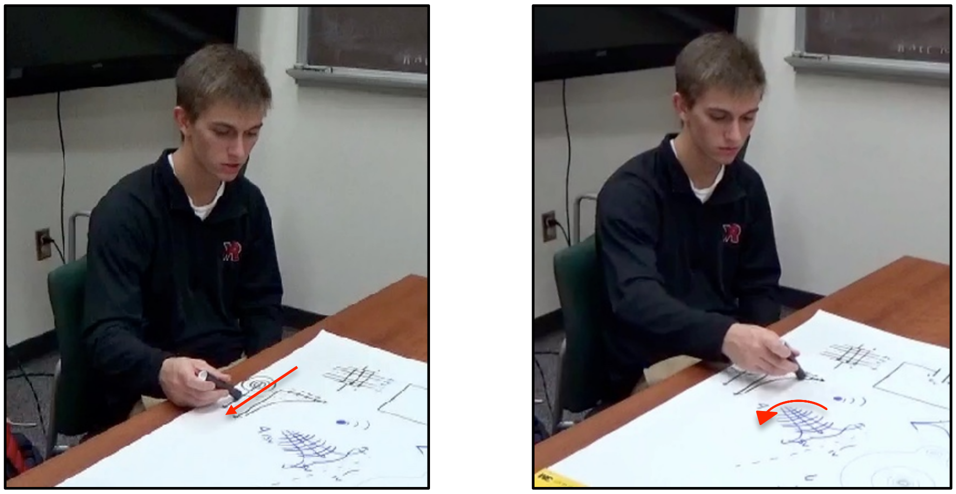

Figure 6: Liam's gestures for "roll down the voltage hill," line 126

At this point, the pair appear to have created a fully functional conceptual blend. This blend seemed to draw from (at least) two different conceptual "spaces" or domains[5], one incorporating the concepts of voltage, potential, and equipotential surfaces, and the other based around the concepts of hills, height, topography, rolling objects, and certain mechanics-based concepts like kinetic and gravitational potential energy. In this blend, they have connected the maps for single charges to mountains, voltage to height, equipotential line spacing to slope, and energy conservation in a mechanics context to energy conservation between charges. As they construct this blend their language has shifted, talking about the "voltage hill" as a single defined entity, rather than an analogy (e.g., "voltage is like height").

What would this blended space look like? While there's no way to know exactly which elements and associations they drew on to construct it, we can hypothesize some connections

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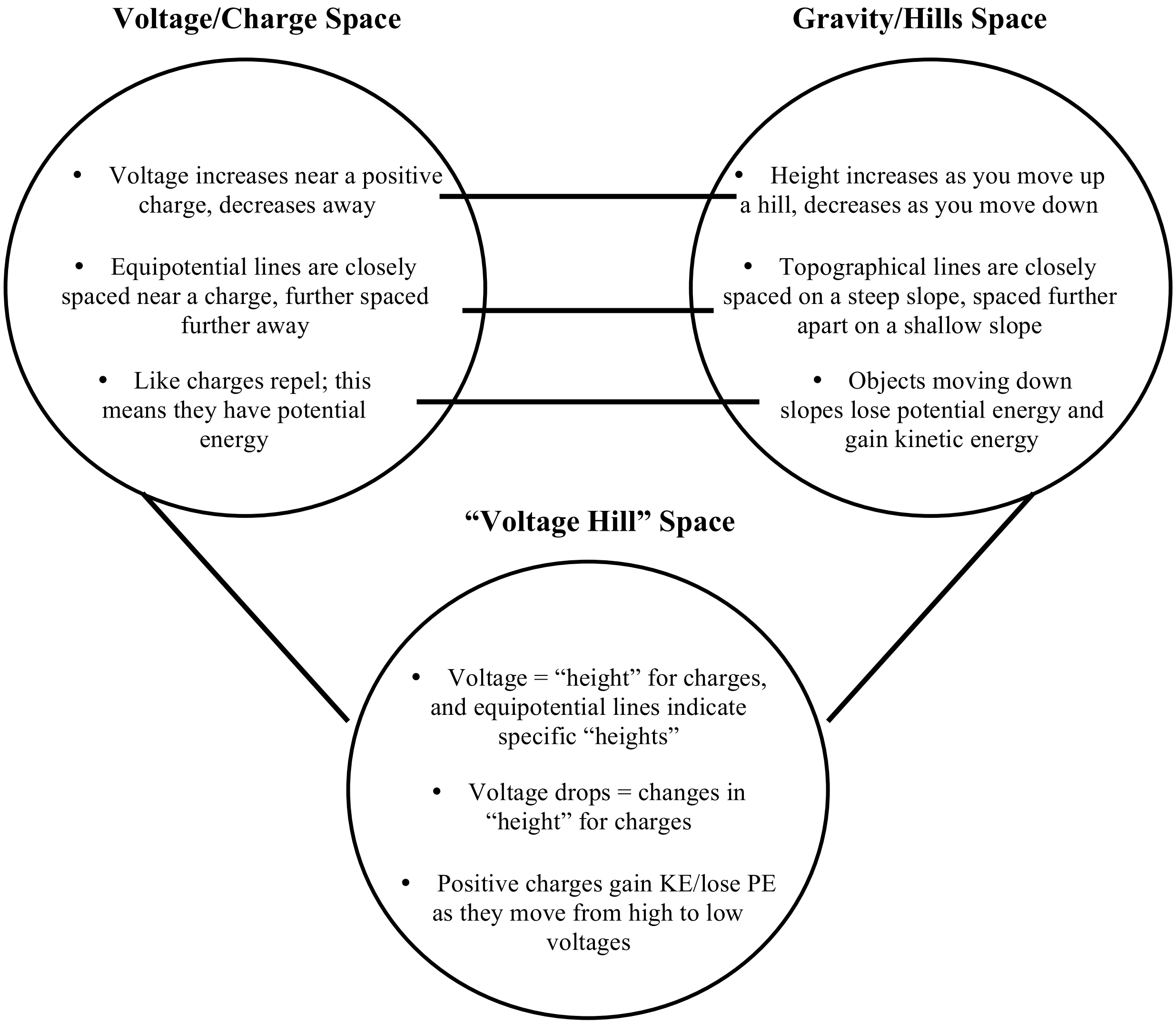
[5] It's possible that there were actually more conceptual domains here—maybe Jake and Liam's knowledge of hills was actually somehow separate from mechanics/energy conservation, or their E&M "voltage space" was different than their "capacitor space." However, I don't have enough evidence to make such fine distinctions, so to simplify my analysis I will model them as two domains.

based on the explicit statements they made in this segment and the e-prims they drew on earlier in the interview. For example, the e-prim “Electric potential increases near positive charges, decreases further away” seemed to be connected to the idea that in this kind of hill with a nonlinear gradient, height increases as one moves to the top and decreases near the bottom. Representationally, the property that “Equipotential lines are spaced closer nearer to a point charge, and their spacing increases further away from a charge” seemed to be connected to the way topographical lines are more closely spaced to indicate a steeper slope, and spaced further apart to indicate a shallow slope. Based on these connections, the repulsive forces two like charges feel when they are pushed together was connected to the increasing difficulty of pushing an object up a slope with an increasing grade.



Voltage/Charge Space

- Voltage increases near a positive charge, decreases away
- Equipotential lines are closely spaced near a charge, further spaced further away
- Like charges repel; this means they have potential energy

Gravity/Hills Space

- Height increases as you move up a hill, decreases as you move down
- Topographical lines are closely spaced on a steep slope, spaced further apart on a shallow slope
- Objects moving down slopes lose potential energy and gain kinetic energy

"Voltage Hill" Space

- Voltage = "height" for charges, and equipotential lines indicate specific "heights"
- Voltage drops = changes in "height" for charges
- Positive charges gain KE/lose PE as they move from high to low voltages

Figure 4: Diagram of the conceptual blend

As predicted by Fauconnier and Turner, the blended space contains new, novel combinations of elements from the input spaces; for example, within the blended space, voltage and height have been combined into a single parameter, "voltage height," which allows one to go "uphill in voltage" (line 110). Charges, within this blended space, take on additional properties not usually discussed in a physics class, such as "rolling" or "sliding" away from one another.

Additionally, when charges change their “voltage height” they gain or lose kinetic/potential energy in the same way that ordinary objects do as they move up or down hills.

Jake and Liam use the conceptual blend to defragment their understanding

According to Fauconnier and Turner’s theory, blends are especially useful because they allow one to make inferences about the two parent domains that might not be apparent without the blend. For Jake and Liam, we would argue that the blend gave them a way to connect the confusing and abstract concepts of voltage, equipotential maps, and electric potential energy to intuitive phenomena like hills and mountains. These connections, in turn, allowed the pair to “defragment” their understanding of those concepts and representations.

More specifically, at the beginning of the interview, the pair seemed to know certain facts about equipotential maps, like the fact that line spacing decreases near point charges and increases further away. However, these e-prims remained free-floating, disconnected—they were rules that the pair knew to be true, but hadn’t yet put together. In contrast, once they’d constructed it, the blend allowed them to describe *why* that was the case: the “hill” was getting steeper! This connection, in turn, helped them connect electric potential to electric force—closely-spaced lines indicate greater slope, which makes it harder to “push” a charge “uphill.” And, a charge on a taller “hill” would therefore have more potential energy.

One way to test the robustness of these connections would be to see them apply their newly constructed conceptual framework to a different system. In this next part of the interview they did just that, using this conceptual blend to understand a different but related phenomenon, capacitors.

Earlier in this interview, as they'd been describing their lab on electric potential, the pair had referenced the equipotential map for a capacitor, using it as a contrast to the map of a point charge and illustrating their point by drawing the following diagram:

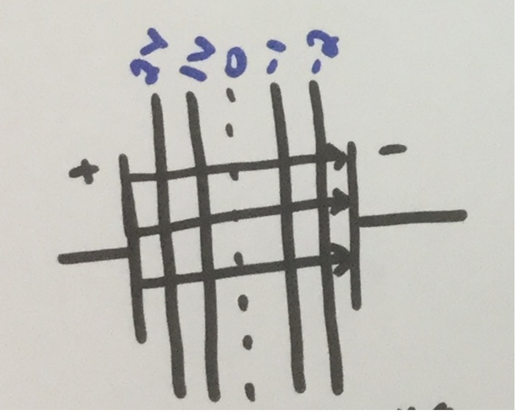


Figure 5: Jake and Liam's drawing of the equipotential lines in a capacitor

Now, interested in seeing where they could take their conceptual blend, I asked Jake and Liam whether these intuitions applied to their capacitor drawing. Looking again at the uniform spacing of the equipotential lines, the pair reasoned that this would mean a capacitor would have a linear voltage drop, rather than the nonlinear decay curve for a point charge:

134 **J:** So, like, *sigh* the voltage, as the voltage drops, like, the change in energy, or the change in electric potential is the same. Which means, like, it's gonna be, like, uniformly rolling down that hill, at the same speed. But in this situation, it's like, I don't know how to explain that.

(silence, 10s)

'Cause, uh, I, I know that, like, each, each, like, going through each thing *{J gestures at the equipotential lines in the capacitor drawing}* is the same amount of, like, energy now. Like, 'cause they're all uniformly spaced, whereas going through here, *{J gestures to point charge e-potential map}* it's like 'oh, there's more here than there is down here.' But I don't know how to, like, put that Coulomb in a picture view. I'd have to imagine it's be something like this, like *{J points to the linear lines on the voltage decay graph}*

135 **L:** Yeah, I think it would be linear, like that.

Here, Jake is grappling with how to apply this new way of looking at equipotential maps to the system they'd described earlier. He articulates this new understanding, saying "I know that…going through each thing [equipotential line] is the same amount of energy, now," and contrasting that equal line spacing with uneven spacing of equipotential lines around point charges. Liam, in turn, characterizes this as a linear slope.

This inference is huge: Jake and Liam have established that the equal spacing between the equipotential lines in a capacitor indicate *linearity.* That linearity opened up a whole new way of talking about capacitors, as Jake indicates with his discussion of changes in energy. In other words, Jake and Liam's conceptual blend has alerted them to the fact that capacitors can be seen through the lens of kinetic and potential energy, and that from that perspective they are dramatically different than point charges.

As this segment of the interview drew to a close, I proposed that, based on their terminology of a "voltage hill," maybe the capacitor could be considered a "voltage slide." Both students agreed with this assertion, and they added several "capacitor lines" to their decay graph (the diagonal lines in Figure 3) to illustrate the point.

To summarize, in the course of this interview Jake and Liam constructed a conceptual blend that combined knowledge of voltage, electric potential, and electric potential energy with knowledge of gravity, hills and falling objects. This blend helped tie together several abstract and complex ideas from the voltage space. This blend was also heavily tied to the graph they drew, which set the stage for its return in the next interview.

CONCEPTUAL BLENDS USED TO MAKE SENSE OF PARALLEL CIRCUITS

In the previous episode, Jake and Liam used a conceptual blend to make large-scale connections between bits of knowledge that they knew to be true, but which they seemingly hadn't yet connected together. In this episode, the connections were different: rather than using the blend to tie together several fragmented concepts, Jake and Liam applied their conceptual blend to create one specific connection and resolve a perceived inconsistency in the behavior of parallel circuits.

This interview took place exactly a week after the previous interview, and was primarily meant to probe the students' understanding of electric current. In addition to several conceptual prompts, I had provided the pair with a circuit board, as well as resistors, wire segments, bulbs, capacitors, and a DMM.

Liam notices an inconsistency in the behavior of parallel circuits

At about 40 minutes into the interview, Liam and Jake had been engaged in an extended episode of free exploration, using the interview as an opportunity to hash out the difference between series and parallel circuits (which they seemed to feel unclear about). Based on their investigations, they had verified that voltage drops are the same across identical light bulbs in a series circuit. However, when they put variable resistors in series, they found that the voltage drops were proportional to resistance.

Building on that observation, I reminded them of our previous discussion of the voltage/height analogy and asked them whether that influenced their intuition about the series circuit system (line 266). In response to my prompt, Jake asked Liam to draw his “slide example” again, and Liam reproduced the decay curve (Figure 4) that he’d previously drawn for the electric potential of a point charge.

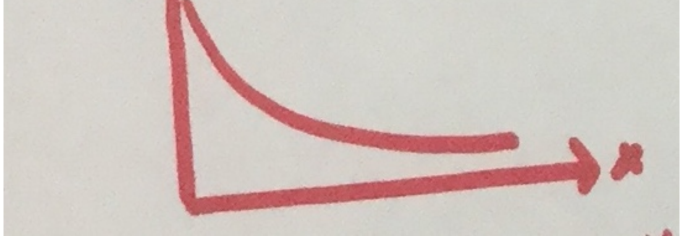


Figure 7: Liam’s reproduction the voltage decay curve for a point charge shown in Figure 4, above

As the pair tried to connect this graph to their measurements of the voltage drops in a series circuit, Liam articulated a question that seemed to have been bothering him for some time:

274 **L:** I get this one. *{L points to the series circuit}* I'm confused on the parallel. Like, why is parallel the same voltage drop as the battery when there's the same amount of—I get it mathematically, like how it ends up working, (J: yeah) y'know, but like why, like it doesn't make sense to me why the same battery can make, um, two bulbs brighter and two bulbs less bright. Like, I get the math, though. But…

275 **J:** Is it—

276 **L:** I do—how do you draw a, can you draw, like, a voltage chart like this for a battery?

Here, Liam seems to be saying that he understands the behavior of a series circuit, but that parallel circuits remain mysterious. More specifically, he understands the mathematics of the situation, but doesn't understand how a single battery can make bulbs shine brighter or dimmer based only on the way they have been connected. This question seems to indicate that Liam has noticed an inconsistency in his understanding of circuits—that is, he has identified a vexation point.

What is this inconsistency? While it is not totally clear at the point, based on the way the episode unfolds it seems that he's uncomfortable with the asymmetry of the current and voltage in parallel circuit branches. That is to say, his question seems to be something along the lines of "If current and voltage are related, how can the voltage drop in both branches be equal to the battery when the current is different?" From a resources perspective, we would posit that Liam had two e-prims, "voltage drops are the same across different circuit branches" and "current splits though different circuit branches" that seemed to conflict.

It is interesting to note that Liam prefaced and framed his question by pointing out that he understands the mathematics of the situation. That is, not only has he verified the current/voltage of a parallel circuit branch empirically, he also stated that he "gets the math." So, Liam is explicitly stating that he already has some knowledge on the subject, but that this knowledge feels unsatisfactory to him. Furthermore, he is ruling out one approach to resolving this inconsistency—more math wouldn't help. But, he is also proposing an alterative direction towards resolution: perhaps it would be useful to draw a "voltage chart" for this circuit? This suggestion guided their subsequent approach to finding the connection that resolved this inconsistency.

Jake and Liam reconstruct their blend

Running with his initial idea, Liam began by trying to draw a "voltage chart" for a circuit with two resistors in series, seemingly as a kind of proof-of-concept:

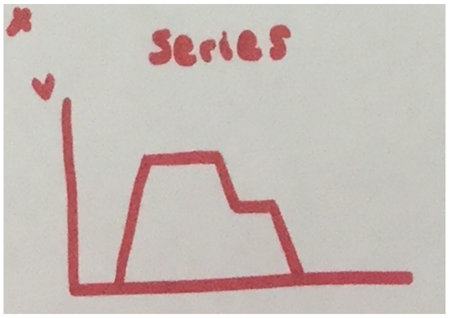


Figure 8: Liam's drawing of a voltage drop throughout a 2-resistor series circuit

Apparently satisfied with this graph, Liam then turned to the question of how one would draw a chart like this for a parallel circuit:

284 **L:** When it's in parallel, how does this chart look? It, it would be like 2 separate charts, I guess.

285 **J:** Or would it be? (L: yeah) Because,

286 **L:** It would have to be.

287 **J:** Well, 'cause it would split, right? It would split and then come back together.

288 **L:** The current would. That's why I'm confused. Because the current splits, right? In a parallel circuit? (J: yeah) But the voltage drop is the same.

Building off of his intuition that a graph (or “voltage chart) might help resolve the point, Liam is suggesting that since the circuit has two branches, the graph for the parallel circuit might have two separate curves. In the process, in line 288, Liam has also refined his question, saying “That’s why I’m confused. Because the current splits…but the voltage drop is the same.” This statement supports our assertion that Liam seems to be looking for a conceptual connection that would tie together these two asymmetric aspects of parallel circuits.

In an effort to resolve this question, Liam tried an experiment: he built a parallel circuit with two different resistors in one branch, and a single resistor in the other. He then used the DMM to measure the voltage drop over each branch, verifying that both had identical drops of 12 volts (the same as the battery):

302 **J:** Still 12. So, if this was like a light bulb that had a 100 ohm resistance it would still have the same voltage going through it.

303 **L:** So, for some reason, all of like these resistors have to, like, drop back down to whatever... (silence, 7s) They have to... (silence, 7s)

While it might appear that the pair, in this segment, are just conducting more investigations of their circuit, we would argue that these investigations are directed towards a specific purpose: to try to reconstruct and extend the conceptual blend they constructed the previous week.

This argument hinges on the fact that the blend appears to have been tightly bound to the “voltage chart” the students drew and re-drew. When they first constructed the blend in the previous interview, they were constantly gesturing to, using, and augmenting their initial graph (Figure 3). In this interview, when I suggested that the blend might be applicable, Liam immediately re-drew that graph (Figure 7). And, during this segment we see them drawing the same kind of graph (Figure 8), but modified to describe an entirely new system, a series circuit. Thus, by working with and re-drawing their graph, the pair seem to be both reconstructing their blend and figuring out how to apply it to the new system of parallel circuits, as Liam explicitly states in line 284.

Thus, it seems that for these two students, this conceptual blend was at least partially "encoded" into their graph. This is unsurprising, since the idea of "encoding" is built into the theory of conceptual blends—complex ideas, built from and accompanied by a huge number of associations, are encoded into relatively simple phrases or representations, like "computer virus." In this case in particular, it seems that the conceptual blend was tied to the term "voltage slide" and their original graph showing the decay function. However, before they were able to apply the blend to the vexation point, they needed several minutes (lines 267-305) to unpack this graph and rebuild the blend; it was only after they'd done this unpacking that they were able to productively use the blend in their sensemaking. The graph thus acted as a conceptual tool, helping them to remember, reconstruct, and use their blend.

Liam applies the blend to resolve the inconsistency

Having reconstructed the blend, Liam now proposed a potential resolution to his vexation point:

305 **L:** It's almost like, as far as the slide example, it's almost like when they split, they, they haven't like dropped in height yet. *{L holds his hands out, parallel to one another}* (J: yeah) And so, like, when they're going across the two resistors, then they, then they both drop. *{L curls his fingers down, then drops both hands down}* And they have to get down to 0 by the time they get across.

Here, Liam seems to have made a conceptual breakthrough: where before he was considering only the voltage drops across the individual resistors or circuit branches, he is now taking into account *the relative voltage throughout the rest of the circuit*.

To elaborate, Liam was initially uneasy because of the asymmetry between the way current splits across parallel circuit branches and the fact that voltage drops are the same. He knew it was true (having verified it experimentally and mathematically) but seemed to be unable to articulate *how* or *why* it was true.

In contrast, in line 305, he says “it's almost like when they split, they, they haven't like dropped in height yet.” Based on this statement, we posit that he’s realized that the reason voltage drops are the same across the parallel resistors is because both branches start out at the same “height” of 12 volts. The circuit is still at that “height” when it splits, but by the time the circuit recombines the “height” has dropped to 0. This idea, that different parts of the circuit can be at different “heights” shows how two entirely different circuit branches can have the same voltage drop, allowing him to connect and align those two e-prims.

The “voltage slide” conceptual blend seems to have been key to helping him make this breakthrough, as evidenced both by his explicit mention of the “slide example” and his gestures during this segment: as shown in Figure 9, when Liam says “when they’re going across the two resistors… then they both drop" he uses his hands to sketch out two parallel "slides" in the air in front of him. Based on these gestures, Liam seems to be visualizing the two branches of the parallel circuit as a pair of "voltage slides," situated side-by-side, which start off at the same "height" and then drop down together.

Figure 9: Liam illustrates parallel voltage drops

The episode continues: building off of this breakthrough, Jake next codified Liam's explanation into a voltage chart, drawing two identical, overlapping graphs in different colors (shown in figure 10):

306 **J:** So, you're saying it would be something like this. *{J draws the axes of a graph}* So it would be like, so they're both up here, right? (L: yeah) And then, resistor 1 and 2, so they both stay there once they split. And then they both equally drop? Like this? *{J draws out the chart of voltage drops in two colors, overlapping, pointing out where the locations on the chart correspond to the locations on the circuit}*

307 **L:** Yeah, but it's, yeah.

308 **J:** So then resistor 1 and resistor 2 comes through. *{Jake draws overlapping diagonal lines sloping downwards to show voltage drop}* But then, once they get back to here again, now they combined, and now its, well, I guess this isn't exactly back down there, but it would be back like that?

309 **L:** No, 'cause they'd both have to drop down to 0. They'd have to drop all the way down to 0.

310 **J:** So, yeah, so just imagine that this is 0, then. *{J adds a mark for 0 on his voltage axis}* So I'd—this is not drawn to scale. 'Cause then it goes back to the battery and comes back up to here. 'Cause then it goes to here, (L: so it would come back up) *{L draws another voltage gain line at the end of the current chart with his finger}* yeah, so this would be the loop, this would be your, your 12 volt side here. *{J traces the graph he's drawn, points to the circuit as he reaches points of change}* Okay, so it comes through the battery, hits this junction right here, splits into your two different currents, and then hits the two resistors, drops down to 0, goes back to the battery, comes back up.

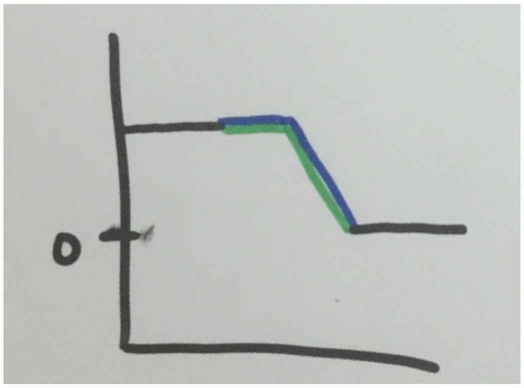


Figure 10: Liam and Jake's graphs of voltage drop around parallel circuits

At this point it seems that Jake and Liam have fully resolved Liam's vexation point. Not only have they accomplished what Liam initially proposed (to create a "voltage chart" for a parallel circuit), Liam has become sufficiently confident in his understanding that he is able to critique Jake's representation, pointing out that both branches have to drop down to 0 by the end of the circuit.

Jake and Liam's subsequent comments confirmed this resolution: as the interview began to wind down, I asked the pair to reflect metacognitively on how they felt about the circuit now, compared to how they felt about it when they walked in.

343 **T:** So what do you guys think of that? Is that, how does that—looking at this circuit now, compared to like when you guys walked into this room, does it seem any different?

344 **J:** I mean, I understand how it works now.

345 **L:** Yeah, it's definitely nice to see, like, what is actually happening, I guess. It's kind of hard to, like, grasp this concept, 'cause like, from your perspective you can see, like, everything that's there, but the battery's perspective, like, doesn't know, like, that there's a second resistor or whatever? You know what I mean? So it's like hard to, it's hard to tell like why things are happening sometimes.

346 **J:** Yeah. And it's kind of like, I don't know … like once you go through and like you fully understand the concept, like you can understand why, like, this voltage drop is different *{J points to circuit branch with two bulbs}* but actually, at the same time, it's the same as that *{J points to branch with one bulb}*.

Based on these responses, it seems that Jake and Liam did indeed feel that their explanation resolved this inconsistency. Jake described how he understood “how it works now,” adding that he was able to see how “this voltage drop is different but actually, at the same time, it’s the same as that,” and Liam agreed, adding that “it’s definitely nice to see, like, what is actually happening.” Although they both felt that the concept was challenging, they seemed to come away from this episode of sensemaking with a greater conceptual understanding than when they went in.

In summary, we are arguing that during this episode the insights that Liam and Jake extracted from this conceptual blend helped them in their sensemaking process. It gave them an intuitive reason *why* the voltage drop should be the same across both branches, beyond just a formal voltage drop rule, by helping them to see the “big picture” view of the voltage at all points in the circuit. This, in turn, allowed Liam to see the connection between current and voltage drops in parallel circuits.

DISCUSSION: CONCEPTUAL BLENDS, CONCEPTUAL CONNECTIONS, AND RESOLUTION

Together, this pair of episodes shows an example of how physics students can create a conceptual blend and then use that blend to build conceptual connections. But on a more general level, what does this case show about conceptual blends and resolution?

First, this case shows a way in which students were able to apply the conceptual connections they’d made in one discussion to a vexation point a week later. Thus, this case demonstrates how sensemaking can evolve over time—students gain an understanding of a tricky concept during one period, then use it to understand further concepts later on. More specifically, this case suggests that conceptual blends might be a useful tool for repeated sensemaking.

How did the blend actually help Liam achieve resolution? Elsewhere (Chapter 3), we have argued that vexation points are gaps or inconsistencies in knowledge, which, from a resources perspective, are "bits" of knowledge that are either missing or feel incompatible with one another. Conceptual blends can address these vexation points in two ways. First, they allow students to create conceptual frameworks that connect up disparate bits of knowledge, essentially "defragmenting" one's knowledge space. We saw this function during the first interview; as we showed in that case, Jake and Liam initially expressed a great deal of confusion about these concepts—though they knew many of the "ground rules" of voltage, electric potential, and circuits, they had difficulty connecting these "rules" together. The blend gave them a framework within which to situate those conceptual pieces, allowing them to see the "big picture."

Second, blends allow students to create new intuitive connections that they may not have seen before. That is, once constructed, the blended space allows one to project inferences back on the parent spaces, creating new connections and giving students new ways to resolve inconsistencies/bridge gaps that they wouldn't see within a single parent space alone. These new connections are what allow one to resolve vexation points. We saw this function in the second episode: Liam was initially uneasy because two things he knew to be true ("voltage drops are the same in parallel circuit branches" and "current splits across different circuit branches") felt asymmetrical and incompatible. He resolved this feeling by constructing a blended space, which showed him a new way to look at the circuit: rather than just looking at the voltage drops across resistors, he began looking at the voltage "height" throughout the circuit as a whole, which allowed him to create new connections between the apparently incompatible e-prims and achieve resolution.

The usefulness of conceptual blends for resolution finds some support in the sensemaking literature. For example, Kapon (2016) argues that we value explanations that explain a range of phenomena with the fewest possible principles. In this case, by creating a blended space that connected the behavior of objects falling down hills to electrostatics phenomena, Jake and Liam were using a single principle ("voltage-height") to explain a range of phenomena, which may have led them to their feeling of resolution.

Additionally, Parnafes (2012) argues that we place more epistemic "weight" on certain pieces of knowledge than others. From a resources perspective, we suspect that the specific e-prims Liam and Jake used to create the blend were also key to the way it helped them achieve resolution. That is, we would posit that Jake and Liam placed high epistemic "weight" on certain bits of knowledge in the blend; physics concepts related to height and energy conservation, for example, are frequently very reliable for students, so it's likely that the pair felt very confident with these ideas. Thus, by connecting the concepts that felt uncomfortable to those they were more comfortable with, they gained increased confidence in the blend.

CONCLUSION: CONTRIBUTIONS TO THE LITERATURE

What is the contribution of this case to the overall literature? First, this case intertwines our theory of sensemaking and the theory of conceptual blends. This seems like a natural extension of the literature on sensemaking based on its emphasis of explanation building and conceptual connections (e.g., Gire & Price, 2014; Kapon, 2016; Scherr, Close, McKagan, &

Vokos, 2012), but this case provides initial evidence that conceptual blends can help students make sense of physics.

While this is just an initial case study—a kind of “proof of concept”—future studies could investigate other ways in which students build and use conceptual blends in sensemaking. For example, one might build a conceptual blend-based intervention, as Podolefsky and Finkelstein did (N. Podolefsky & Finkelstein, 2007; N. S. Podolefsky & Finkelstein, 2007), then observe a group of students using it to see whether they articulate and resolve vexation points, and if so whether the conceptual blend helps them in that process.

This case also suggests that we, as practitioners, could productively use conceptual blends in sensemaking-focused teaching. In other words, physics teachers who are looking for ways to help students make sense of abstract concepts like voltage may be able to use conceptual blends, and blend-based interventions, as a teaching tool. This may be especially effective for students who are enthusiastic about learning physics, like Liam and Jake were, but who are having difficulty “getting” a particular concept.

The case also provides some initial clues for how to foster this type of conceptual blend. As previously argued, the students seemed to use several vital relations to build the voltage slide blend. *Position* (the similarity between drops in height and voltage drops) wasn’t enough by itself; rather, the combination of *position* and *representation* (the way topography maps and equipotential maps look nearly identical) seemed to help Jake and Liam build their blend. This, in turn, suggests that students may need extra scaffolding to build these blends—it’s not enough, for example, to just point out the symmetry between the equations for electric potential energy and gravitational potential energy. Students may need to *see* concrete representations (like the equipotential/topography maps) in order to make these sorts of connections.

From a physics teaching perspective, this case provides an example of what a student might be looking for when he or she says “I get the math, but this still doesn’t make sense to me.” As we have shown, this kind of statement may indicate that the student needs help mapping the abstract concepts or rules that have been stated or formally proven in their courses (e.g., voltage drops across parallel branches are the same) to the student’s intuitions and experiences.

In conclusion, this case suggests that we, as physics educators, must sometimes go beyond proving the truth (mathematical or empirical) of a phenomenon, to helping students make deeper connections between and within conceptual domains. In other words, helping students reach resolution is not necessarily a matter of proving something to them, or even about finding a “key idea”—an e-prim or mechanistic entity—that will clear everything up. It may simply be a matter of helping them to build new connections between ideas and see them in a different light.

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Appendix A: Interview Protocols

CHARGE INTERVIEW PROTOCOL

Materials:
Large sheet of paper
Pens, Colored Markers
Acrylic rod, fur, shredded pieces of paper, soda can?
Calculator?

Conceptual Space – Resources to prime:

1) Charge is a kind of "stuff" that comes in two flavors, + and –
2) Opposites attract, like repels
3) The more charge, the stronger the interaction
4) Charge can move within an object, or be transferred from one to another
5) Electrons, positive ions can move, protons can't
6) Macroscopic affects are caused by lots of little charges all working together
7) Charges come in "chunks" (which we call "q") corresponding to the basic charge
8) "Neutral Charge" is just equal amounts of + and -

Introduction:
My name is… I'm part of a team of researchers from UW-Madison. Today I want to ask you some physics questions. Some of these questions might be about things you've learned about in your physics class, but some of them will probably be about things that you haven't learned yet. So you're probably not going to be very sure about many of the answers. That's okay. We're really just interested in how you think about these things; we're not really interested in whether you get answers right or wrong. So, I'm hoping you'll tell me as much as you can about what you think about the questions that I'm going to ask. Just talk, and I'll listen and ask questions.

Any questions before we start?

1. Core Prompt:
So, actually, before we get started, I was wondering if you could talk a little bit about what you guys have been covering in your class this last week? Like, what big ideas have been coming up in class?

(If they use the word "charge"): *So, could you talk a little more about what you mean by "charge " or "charges?"*

(If they talk about how charges attract, interact, or behave):
Could you say more about that? Like, what kinds of things could you do to increase or decrease the forces between two things that are charged?

What about putting something between the charges? Does the type of material you use make a difference?

(If they talk about objects being “neutral”):
What do you mean by neutral?

2.1 Core Prompt: Charged Acrylic Rod Experiment

(Put a acrylic rod, a piece of fur, and some shredded pieces of paper on the table, demonstrate how you can charge the rod with the fur, then use the charged rod to pick up pieces of paper)

So, here I’ve got a small experiment that you may have seen before: a piece of fur, a plastic rod, and some paper shreddings. As you can see, when I rub the fur on the rod, it suddenly starts picking up these bits of paper. I’d like you to mess around with them a little bit, and as you’re doing so, I was wondering if you could talk about what’s you’re seeing, and why you think it’s happening?

(Follow up): *Specifically, how would you explain what you’re seeing to someone who had never seen this kind of thing done before and had also never taken physics?*

(Follow up): *How would you explain why this is happening to another student in your class?*

(Follow up): *How would you explain what you’re seeing to your TA or physics prof?*

[If they haven’t mentioned charges yet] *I’ve heard some folks talk about this kind of thing in terms of charge. Do you think that plays any role in this setup?*

[If they bring up charge] *So, what do you mean by charges, here? Like, what are you picturing when you’re talking about charges in this setup?*

[Follow up] *I’ve noticed that we seem to lift more pieces of paper by having all of the bits in a pile, touching each other, as opposed to spread out. Why do you think that’s the case?*

(Follow up): *What would happen if you touched this rod to something made out of metal, like the leg of a chair?*

2.2 Challenge: Improve the experiment

Let’s say I’m looking to improve this experiment—I want to get the rod to be able to pick up the most pieces of paper possible. What do you think I could do with or to this setup to make that happen, and why?

[If they bring up adding more charges to the rod] How do you think one would do that?

[If they suggest a larger rod] Why would a bigger rod help?

[If they come up dry] I've heard a few different suggestions in the past:

1. A larger rod,
2. More time rubbing the two together,
3. Using a different material for the rubbing, or
4. Doing this on a particularly dry day in the winter.

How would you rank these four options, from most to least likely to work, and why?

3. Thought Experiment: Charges and the Dryer

In the winter, when I do laundry I notice that when I take my clothes out of the dryer, they tend to cling together, and when I pull them apart I see sparks. However, I recently read that if you put a tightly compacted ball of aluminum foil in the dryer with your clothes, this stops happening. Do you believe this claim? Why or why not?

(Follow up): *So, how would you explain the sparks/cling to another student in your class?*

(Follow up): *How would you explain the sparks to your TA or physics prof?*

(Follow up): *How would you explain the sparks to someone who had never seen this kind of thing done before and had also never taken physics?*

[If they mention "static electricity"] *What do you mean by static electricity?*

[Follow up] *So, after this conversation, will you put a ball of aluminum foil in your dryer next time you do laundry?*

4. Core Prompt: Charges Problems

So, here's a problem you may or may not have seen before. I'd like you to look it over, then talk it over (if partnered interview), *and talk me through how you would solve it.*

4.1 Two friends each contain about 4 x 10^{28} electrons and an equal number of protons. What will happen in terms of their interaction if 1% of one friend's electrons are transferred to the other, who is about 100 m away? What other things about their situation can you determine using this information?

[Follow up] Lets say that somehow this did happen, and that suddenly one friend had a huge number of extra electrons. Physically, what do you think would happen to these two friends next?

[Follow up] During thunderstorms, I've read that the air tends to break down when an electric field becomes stronger than 3 x 10^6 N/C, allowing lightning to strike. Does this information have any bearing on the problem you just solved?

[Follow up] I've also read that during a thunderstorm, about 10^{20} electrons move during a single lightning strike. How does this compare to the extra electrons in the problem, and do you think that would alter your prediction above?

(Or)

4.2 Two charged objects exert a 4.0-N force on each other when separated by 1.0 m. (a) What can you determine using this information? (b) You then perform four experiments: you double the separation, you reduce the separation by one-half; you reduce the magnitude of one charge by one-half; and you double both charges. What quantitative information about the interaction of the objects can you determine for each of the experiments?

(Or)

In a simplified model of a hydrogen atom, the electron moves around the proton nucleus in a circular orbit of radius 0.53 x 10^{-10} m. Use this information to determine at least four physical quantities related to this information.

ELECTRIC FIELDS INTERVIEW PROTOCOL

Materials:

Large sheet of paper
Pens, Colored Markers
Acrylic rod, shredded paper, fur, paper towel
Stress balls (red, blue) to act as charges
4 pre-made drawings of electric field patterns

Conceptual Space – Resources to prime:

9) Positive/Negative charges interact (like repels, opposites attract)
10) Charges don't interact with themselves
11) Charges produce forces
12) Forces become weaker with distance
13) Electric fields show the force on a charge
    a. Test charge
14) Electric fields can overlap, but can't fully cancel each other out
15) Electric fields move charges

Introduction:

My name is… I'm part of a team of researchers from UW-Madison. Today I want to ask you some physics questions. Some of these questions might be about things you've learned about in your physics class, but some of them will probably be about things that you haven't learned yet. So you're probably not going to be very sure about many of the answers. That's okay. We're really just interested in how you think about these things; we're not really interested in whether you get answers right or wrong. So, I'm hoping you'll tell me as much as you can about what you think about the questions that I'm going to ask. Just talk, and I'll listen and ask questions.

Any questions before we start?

1. Core Prompt: What has come up in class?

So, actually, before we get started, I was wondering if you could talk a little bit about what you guys have been covering in your class this last week? Like, what big ideas have been coming up in class?

(If they use the word "charges"): *So, what is charge? I mean, what is this "stuff" we're calling charge?*

(If they talk about how charges attract, interact, or behave):
Could you say more about that? Like, what kinds of things could you do to increase or decrease the forces between two things that are charged?

(If they talk about e-fields):
What do you mean by electric fields? How are they different than electric forces?

(Follow up): *What kind of a "thing" is an electric field? Does it actually exist, or is it just something we imagine to help us explain what we see?*

(Follow up): *So, what effects do electric fields have on things in the field? Like, if there were a really strong electric field in this room, what effect do you think that would have on the stuff around us?*

2. Core Prompt: Charged Acrylic Rod Experiment Redux

(Put a acrylic rod, a piece of fur, and some shredded pieces of paper on the table, demonstrate how you can charge the rod with the fur, then use the charged rod to pick up pieces of paper)

So, I wanted to bring back this experiment that we talked about last time. I was hoping you could mess with it a little more, and as you're doing so, talk through what you think is going on here, and why.

(Follow up): *Specifically, now that you've gotten a bit further in the course, how would you explain what you're seeing to someone who had never seen this kind of thing done before and had also never taken physics?*

(Follow up): *How would you explain why this is happening to another student in your class?*

(Follow up): *How would you explain what you're seeing to your TA or physics prof?*

[If they haven't mentioned e-fields yet]
I've heard some folks talk about this kind of thing in terms of electric fields. Do you think they play any role in this experiment?

[If they do bring up e-fields]
So, what do you mean by electric fields, here? Like, what are you picturing when you're talking about the electric fields in this experiment?

(Follow up): *What would happen if you brought this rod close to something made out of metal, like an aluminum pie pan?*

2.2 Challenge: Improve the experiment

Improve the experiment: *Let's say I'm looking to improve this experiment—I want to pick up all of the pieces of paper, from a further distance away. What do you think I could do with or to this setup to make that happen, and why?*

[If no ideas] Let's say I didn't restrict you to just one rod. Could you do anything more then?

(Or)

Disrupt the experiment: *Let's say that I want to do the opposite of last time—I want to make it so that none of these pieces of paper get picked up at all when I bring the rod near them. What could I do to make that happen?*

[If they come up dry] *So, I've heard some people say that if I wrapped these pieces of paper in some kind of metal, like aluminum foil, that they would be totally unaffected by the rod. Do you believe this, and if so, why?*

[If they still come up dry] *I've also heard people say that we could*

1. *Do the experiment on a humid or rainy day,*
2. *Wrap the paper in aluminum foil,*
3. *Spread out all of the pieces of paper so they don't touch*
4. *Touch the rod to a piece of metal, like a chair leg, before bringing it near the paper*

How would you rank these four options, from most to least effective, and why?

(Or)

2. Core Prompt: How do charges behave when they're near one another?
So I'm going to start out with a pretty general question. How do different types of charges affect one each other? In other words, if you have some charges that are interacting or affecting each other, what kinds of things could you do to them to change the ways they affect each other?

[If they bring up distance, "further apart"]:

(Follow-up, Put two red stress balls on table): *So, let's say each of these balls is positively charged, but the red balls have three times as much charge as the yellow balls. Now, let's say we want to arrange these two charges so they push this third charge straight upwards. How would I do that?*

(Follow-up, Swap one red ball for a blue ball): *What about if there's one positive and one negative?*

(Follow-up, Swap other red ball for blue ball): *What about two negative charges?*

(Follow-up, Put 3rd ball on table, either red or blue): *What if I added a third charge off to the side, either positive or negative?*

Drawing the E-Field: *So, if I had these two charges arranged like this, what would the electric field look like around them? Can you draw it?*

(Follow-up): *Now, lets say I move these charges farther away from one another so that the distance between them is twice as large as it was before. In general terms, how do you think that would change the shape of the electric field?*

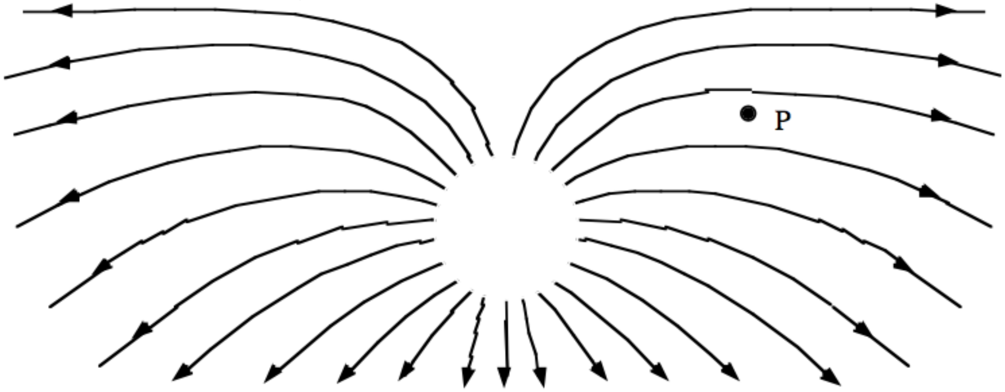
(Follow-up): *So, another interview I've done, I had a student, lets call her Jane, say that she think E-field lines are the paths that test charges would follow if they were placed in the E-field. Do you agree or disagree with her statement?*

(Follow-up, Show students four possible diagrams of differently-shaped e-fields) *So, when I've asked other folks this question, I've seen a few different types of responses. Here are drawings of four of the most common ones. Of these four, which would you agree with the most, and what do you disagree with about the others?*

[If disagree] *Can you give me a counter-example?*

(Possibly) Charges in an electric field
(Provide the students with a diagram of an electric field like the one shown below, with several points marked in the field)

Now lets say that I have an electric field that looks like this



How would a charge act if you dropped it at (X points) in this field?

(Follow-up): *So, can you see electric fields like this?* (If students answer no) *So, if we can't see them, how can we figure out what they look like?*

3. Core Prompt: Thought Experiment

Thunderstorm: *During a thunderstorm, you and a friend wisely decide to take shelter in your car, which you've parked in an open-air parking lot. During the storm, lightning strikes the car. However, besides being a little bit jolted the loud noise and bright flash, you both feel totally fine. After the storm has passed, you feel like getting out to stretch your legs, but your friend yells "Stop!" and warns you not to the surface of the car as you get out, because you might still get electrocuted. Do you believe your friend? Why or why not?*

[If students decided that lightning can't, in fact, strike a car] Let's say, for the sake of argument, that it can. Or, if lightning doesn't strike, let's say that a powerline breaks and falls on top of the car for a second. Is it safe to leave the car then?

[If students haven't mentioned E-Fields in the course of the explanation] I've heard some students say that there's a particularly high electric field around the body of the car afterwards, and that's what makes it unsafe. Do you agree with this statement? Why or why not?

[If they decide it's not safe] So, what could you do to make it safer?

(Or)

Cowboys and Lightning: *I've read that back in the Old West, when cowboys were out in the desert, they would pile up all of their metal objects away from camp in order to lower the risk of being struck by lightning during thunderstorms. Do you believe this claim? Why or why not?*

[If they bring up metal or conductors]
What is it about metal that makes lightning more likely to strike?

(Follow up): *What do you think is actually happening during the lightning strike? Like, on a microscopic level?*

(Follow up): *I've heard some people say that lightning never strikes the same place twice. Based on what you've said, do you believe this claim? Why or why not?*

4. Core Prompt: Problems

4.1 Earth has an electric charge on its surface that produces a 150-N/C E-field, which points straight down toward the center of Earth. How much charge would person would need so that they could float above the earth in this electric field? What assumptions did you have to make to figure this out?

[Follow up] Is this a reasonable idea? Would you let someone put this much charge on you? Explain.

[Probe] Do you think this depends on a person's weight? Would it be different with you vs. a baby?

[Follow up] So, I've read that during thunderstorms, air tends to break down when the electric field gets stronger than 3 x 10^6 N/C, which allows electrons to move through the air in the form of a lightning bolt. Do you think that would happen here? Why or why not?

[If yes] How far away would you have to stand to avoid being struck by lightning from this levitating person?

4.2 The E-field lines for a field created by an arrangement of charged objects are shown in this drawing. (a) Where are these objects located, and what are the signs of their electric charge? (b) What else could you determine using the information? Give two examples.

[Follow up] What do you think would happen if you set up this situation, then let all of these charges move around?

[Follow up] Did you use the E-field at all in making your prediction?

E-Field Diagram:

(Or)

4.3 A 3.0-g aluminum foil ball has a charge of +4.0 x 10^{-9} C. You suspend it on a string in a uniform horizontal E field, and the ball moves until the string makes an angle of 30 degrees with the vertical. What information about the E field can you determine for this situation?

ELECTRIC POTENTIAL INTERVIEW PROTOCOL

Materials:
Large sheet of paper
Pens, Colored Markers
Stress balls (red, blue) to act as charges

Conceptual Space – Resources to prime:

1) It takes energy to move charges around
    a. Therefore, charges can have potential energy
2) E-Potential is a measure of the *potential energy* a *charge* has in a particular place
    a. Can also define it as *electric potential energy per unit charge*
3) E-Potential depends on location
4) E-Potential is created by charges
5) Charges rearrange to minimize their potential energy (they “roll downhill”)
6) Equipotential lines indicate potential “height”

Introduction:
My name is… I’m part of a team of researchers from UW-Madison. Today I want to ask you some physics questions. Some of these questions might be about things you’ve learned about in your physics class, but some of them will probably be about things that you haven’t learned yet. So you’re probably not going to be very sure about many of the answers. That’s okay. We’re really just interested in how you think about these things; we’re not really interested in whether you get answers right or wrong. So, I’m hoping you’ll tell me as much as you can about what you think about the questions that I’m going to ask. Just talk, and I’ll listen and ask questions.

Any questions before we start?

1. 1. Core Prompt: What has come up in class?

So, actually, before we get started, I was wondering if you could talk a little bit about what you guys have been covering in your class this last week? Like, what big ideas have been coming up in class?

(If they use the word “potential”): *So, what do you mean by potential? I mean, how is it different than potential energy?*

(If they talk about how charges attract, interact, or behave):
Could you say more about that? Like, what kinds of things could you do to increase or decrease the potential energy between two things that are charged?

(If they talk about e-fields):
What do you mean by electric fields? How are they different than electric forces?

2. Core Prompt: How do charges behave when they're near one another?
(Pull out the red stress balls, used to model charges)

So, let's say that I have a single positive charge, sitting in the middle of the table, like so. Now, let's say you want to bring in another positive charge, and set it next to the first charge. What's going to happen with the two charges as you bring in the second charge?

(Follow-up): *Would you have to expend any energy to do this? If so, where did the energy go? Has*

(Follow-up, Swap one red ball for a blue ball): *What about if you brought in a negative charge instead of a positive charge?*

(Follow-up, Swap other red ball for blue ball): *What about two negative charges?*

(Follow-up): *what if you were trying to put it at a different point near the first charge? At the same distance away, but on the other side?*

(Follow-up, if electric potential energy or electric potential haven't come up yet): *I've heard some people describe this in terms of electric potential. Could you talk a little bit about how you see electric potential in this example?*

(Follow-up, connect to a gravity analogy): *So, what does the charge see here?*

(Or)

2. Core Prompt: Charged Acrylic Rod Experiment Redux
(Put a acrylic rod, a piece of fur, and some shredded pieces of paper on the table, demonstrate how you can charge the rod with the fur, then use the charged rod to pick up pieces of paper)

So, I wanted to bring back this experiment that we talked about last time. I was hoping you could mess with it a little more, and as you're doing so, talk through what you think is going on here, and why.

(Follow up): *Specifically, now that you've gotten a bit further in the course, how would you explain what you're seeing to someone who had never seen this kind of thing done before and had also never taken physics?*

[If students don't mention energy] I've heard some students describe this in terms of some different kinds of energy. How many forms of energy do you see present here?

(Follow up): *How would you explain why this is happening to another student in your class?*

(Follow up): *How would you explain what you're seeing to your TA or physics prof?*

2.2 Challenge: Improve the experiment

Let's say I'm looking to improve this experiment even more—not only do I want to pick up all of the pieces of paper, but I want to hoist them high into the air. What do you think I could do with or to this setup to make that happen, and why?

[Follow up] I've heard some students say that the critical thing to consider in doing this kind of thing is how to give the scraps of paper enough energy to get them to rise up. What do you think about that?

3. Core Prompt: Thought Experiment

1. (Bring out a red stress ball and yellow stress ball) Let's say I want to make a toy cannon that launches charged rubber balls up into the air. So, I charge up both of these balls to be super negative. I put one in the bottom of a cardboard tube. Then I load the other one in the top, and let go. Can you describe what you think will happen, in terms of the energy of the balls?

[If the students mention the balls gaining kinetic energy] Where did that kinetic energy come from?

[If the students are coming up dry] So, how many kinds of energy are there in this system, at the different points of time? How do they compare with one another?

[Follow up] Does this have any bearing at all on the demo we did last week, picking up pieces of paper with a charged rod?

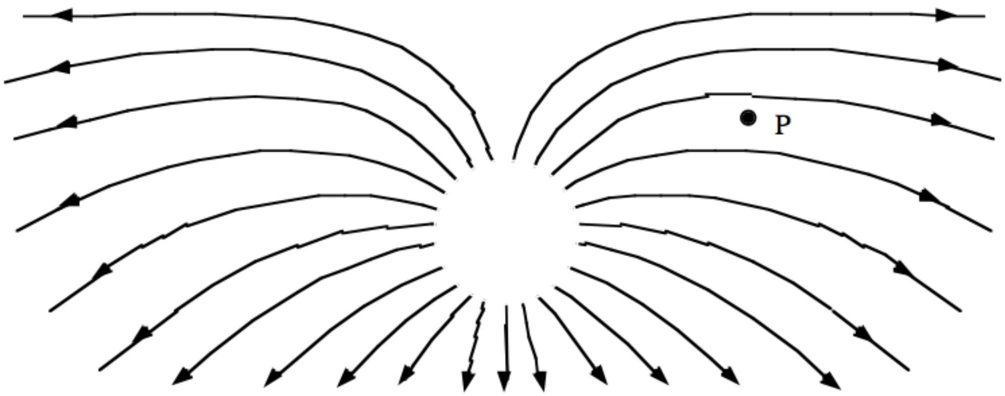
(Or)

3. Core Prompt: Nutcracker *(Bring out two wooden blocks) I've got a friend who's kind of a physics geek, and she recently brought up an idea for making a nut cracker out of two charged blocks. Basically, you would charge one block super negatively, and the other to be super positive, then put a walnut between the two and let go. Can you talk a little bit about how well you think this would work, in terms of the energy of the blocks and the nut?*

4. Core Prompt: Charges and in an electric field and Electric Potential

(Provide the students with a diagram of an electric field like the one shown below, with several points marked in the field)

Now lets say that I have an electric field that looks like this



What would the electric potential be at different points here? Either as a number or as lines of the same potential?

5. Core Prompt: Drawing the electric potential map, discussing and evaluating electric potential drawings
(Provide students with a large piece of paper and put two red stress balls on the paper a certain distance apart. Label one as Q, label the other 4Q,)

So, if I had these two charges arranged like this, what would the electric potential map look like around them? Can you draw it?

(Follow-up): *Now, lets say I move these charges farther away from one another so that the distance between them is twice as large as it was before. In general terms, how do you think that would change the shape of the electric potential map?*

(Follow-up, if/when they draw potential lines): *So, are those potential lines showing high or low potential? I mean, is that positive or negative voltage?*

(Follow-up): *Is there anywhere here where the potential is zero? What would happen if you put a charge there?*

5. Core Prompt: Evaluate Potential maps
Show students four possible diagrams of differently-shaped e-potential maps

So, when I've asked other folks this question, I've seen a few different types of responses. Here are drawings of four of the most common ones. Of these four, which would you agree with the most, and what do you disagree with about the others?

(Follow up): *Lets' say that instead of potential, these maps showed height. So, each line traces an area that's at the same height, and the closer the lines are together, the more the height is changing. In that case, what sort of a map would we be looking at here?*

(Follow up): *If you put a bowling ball down somewhere on this map, where would it roll?*

6. Core Prompt: Electric Potential Problems

6.1 Imagine a 10,000-kg shuttle bus that carries a +15-C charged sphere on its roof. Through what potential difference must the bus travel to acquire a speed of 10 m/s, assuming no friction force exerted on the bus?

[Follow up] How would this be different if the bus were rolling up or down a hill?

[Follow up] So, in this problem, we just assumed that there was some kind of potential difference here that made this setup work. How could we get this kind of potential difference, though? I mean, if we wanted to actually make this into a real form of transportation, what would we have to do?

[Follow up] So, would you ride on a bus that runs like this?

(Or)

6.2 During a lightning flash, -15 C of charge moves through a potential difference of 8 x10^{7} V. Determine the change in electric potential energy of the field-charge system.

(Or)

6.3 The potential difference from the cathode (negative electrode) to the screen of an old TV set is +22,000 V. An electron leaves the cathode with an initial speed of zero. Determine everything you can about the motion of the electron in the TV set using this information.

ELECTRIC CURRENT INTERVIEW PROTOCOL

Materials:
Large sheet of paper
Pens, Colored Markers
Electronics supplies: circuit board, small power supply, resistors, lightbulbs, capacitors

Conceptual Space – Resources to prime:

1) Electric current is a flow or river of electrons
2) Electrons flow "uphill," from low potential to high potential
3) Current depends on voltage ("push," "pressure," or "height") and resistance
    a. Current flows through the path of least resistance?
    b. Current will only flow if there's a place to go
4) Current can split, depending on how resistive two paths are
5) Current changes in response to the circuit; if you change the circuit, the current changes

Introduction:
My name is… I'm part of a team of researchers from UW-Madison. Today I want to ask you some physics questions. Some of these questions might be about things you've learned about in your physics class, but some of them will probably be about things that you haven't learned yet. So you're probably not going to be very sure about many of the answers. That's okay. We're really just interested in how you think about these things; we're not really interested in whether you get answers right or wrong. So, I'm hoping you'll tell me as much as you can about what you think about the questions that I'm going to ask. Just talk, and I'll listen and ask questions.

Any questions before we start?

1. Core Prompt: What have you been learning about?

So, actually, before we get started, I was wondering if you could talk a little bit about what you guys have been covering in your class this last week? Like, what big ideas have been coming up in class?

(If they use the word "charge"): *So, could you talk a little more about what you mean by "charge " or "charges?"*

(If they use the word "induction"):
What do you mean by "induction?" I've heard different people using that word in different ways

(If they talk about "current"):
What do you mean by current? Like, what are you picturing when you're using the word "current?" How would you describe what that means to, say, a 12-year-old kid? Can you draw a picture?

(Follow up): *How is "current" different than when people talk about "electricity?" What do you think people typically mean by "electricity?"*

(If they use the word "resistance"):
What do you mean by "resistance?" What's being resisted? How is it resisting that?

2. Core Prompt: Current Demo

(Put circuit board with scattered resistors, bulbs, wire segments, and a few capacitors on the table)

So, here I've got some supplies that I think you've seen before in lab, although you may not have had a chance to play with lightbulbs in this setup. I'd like you to mess around with them a little bit, and as you're doing so, I was wondering if you could talk about what's going on with this toy in terms of the things that you've been learning about so far in your physics class. In other words, do you see any of the things you've been learning about represented in this setup?

(Follow up): *So, what happens if you put two bulbs in series, vs the bulbs in parallel? Why is it different?*

(Follow up): *What happens if you add more bulbs to one of those branches, or the other?*

(Follow up, if a bulb isn't lit): *Why isn't that bulb lighting up?*

(Follow up): *If you could actually see the electrons running around in this circuit, what would they be doing?*

(Follow up): *So, how would you explain the behavior of this experiment to another student in your class?*

(Follow up): *How would you explain the behavior of the experiment to someone who had never seen one of these before and had never taken physics?*

(Follow up): *So, I've got something here called an "LED," or "Light Emitting Diode." It's similar in some ways to a lightbulb, but different in others. What happens if you add it to part of your circuit?*

Challenge: Improve the experiment
So, let's say I want to get the first bulb here to be as bright as possible. How would I do that?

(Follow up) *Let's say, instead, I want it to be as dim as possible while still being visibly lit. How would I do that?*

3. Thought Experiment: Defibrullators

In a recent CPR course I took, we were trained to use an AED, or Automatic External Defibrillator. It's basically a box that sends a shock through someone's heart when the heart has *stopped beating or has gotten into an irregular rhythm. We were told to put one paddle at the top of a person's chest, the other on the side of the chest, then stand back as the shock is delivered. However, let's say that the patient also need pressure applied to a wound. Would you be safe touching that person to hold pressure on them while the shock is delivered? Why or why not?*

(Follow up): *What if the wound is down on their leg?*

(Follow up): *What if you only use one hand?*

(Follow up): *What if you're wearing rubber gloves (advised in the CPR course)*

(Follow up): *What if it's wet outside?*

(Or)

3. Thought Experiment: Electric Fences
When I was growing up, we had electric fences on our farm to keep our animals corralled. An electric fence sends bursts of current down the wire at regular intervals, a couple of times per second. In the spring, the weeds underneath the fence would start to grow, and once the started touching the fence, they would "ground" it. One or two weeds were fine (they'd actually get burned by the fence) but a large enough number of weeds made it so the fence didn't work properly.

If you were to grab an electric fence after a large patch of weeds, do you think you'd get a shock?

(Follow up): What if you grabbed before the weeds?

(Follow up): What if it were a wet day? What if you were wearing rubber boots?

(Fillow up): What if you took a metal pipe, and used it to connect the fence to the ground instead of weeds? Farmers often call this a "dead ground."

(Follow up): We used a little device to see how the fence was doing. It hooked onto the fence, and had a red, blinking light. If the fence was on, the light blinked; if it was "grounded" or there were too many weeds down the line, the light would not blink. How does this work?

(Or)

3. Thought Experiment: Electrical current and Safety
So, in terms of the physics that you've learned, especially electric current, how would you explain why a bird can perch on a 100,000 V power line with no adverse effects?

(Follow up): *how would that change if the bird were near a telephone pole, or there were a tree near the power line? Does the bird need to touch these things to be in danger?*

(Follow up): *can other animals besides birds safely touch power lines?*

(Follow up): *what kinds of precautions do you think electricians who repair power lines have to take?*

4. Core Prompt: Electrical Current Problems

So, here's a problem you may or may not have seen before. I'd like you to look it over, then talk it over (if partnered interview), *and talk me through how you would solve it.*

Fork in an outlet

A person accidentally sticks a fork into a 120-V electric outlet with one hand while touching a ground wire with the other hand. Determine the current through the body when the hands are dry (100,000 Ohm resistance) and when we (5000 Ohm resistance). If the current exceeds about 10 mA, muscular contractions may prevent the person from releasing the wires—a dangerous situation. Is the person in danger with dry hands? With wet hands? Explain.

(Follow up): What if they've got a pacemaker?

(Follow up): I've also read that you can feel a "slightly annoying" electric tingle with about 1 mA of current. If the person isn't in the danger zone, can they even feel the current?

(Follow up): I've also heard that once the current breaks the skin, the resistance drops to something like 500 Ohms. What happens then?

(Follow up): I've got a voltmeter right here—what's your resistance right now, and how does that compare to what we've been talking about in this problem?

(Or)

Electrons in a Circuit

If a long wire is connected to the terminals of a 12-V battery, 6.4×10^{19} electrons pass a certain point in the wire each second. Make a list of the things about the circuit that you can figure out using this information and determine as many as you can.

(Follow up, if students can't figure out what to determine): I've had some students say they can determine things like current, resistance, and energy dissipated per second (power).

FINAL E&M INTERVIEW PROTOCOL

Materials:
Large sheet of paper
Pens, colored markers
Acrylic rod, fur, shredded pieces of paper, tape
Colored stress balls
Calculator?

Conceptual Space – Charge:

1) Charges produce forces on each other
2) Charges produce e-fields which tell you the directions of forces
3) E-fields exist in space and can add/cancel/overlap
4) Electric potential tells you the potential energy of charges
5) Charges move from high potential to low potential
6) Electric field lines go from high potential to low potential
7) Electric current is the flow of charge
8) Electric current flows from high potential to low
9) Electric current flows along e-field lines

Introduction:
My name is… I'm part of a team of researchers from UW-Madison. Today I want to ask you some physics questions. Some of these questions might be about things you've learned about in your physics class, but some of them will probably be about things that you haven't learned yet. So you're probably not going to be very sure about many of the answers. That's okay. We're really just interested in how you think about these things; we're not really interested in whether you get answers right or wrong. So, I'm hoping you'll tell me as much as you can about what you think about the questions that I'm going to ask. Just talk, and I'll listen and ask questions.

Any questions before we start?

1. Lightning Car Thought Experiment Review

So, I wanted to return to a thought experiment that we talked through during one of the first interviews, the case of the lightning striking the car. As a quick reminder, here was the setup:

During a thunderstorm, you and a friend wisely decide to take shelter in your car, which you've parked in an open-air parking lot. During the storm, lightning strikes the car. However, besides being a little bit jolted the loud noise and bright flash, you both feel totally fine. After the storm has passed, you feel like getting out to stretch your legs, but your friend yells "Stop!" and warns you not to the surface of the car as you get out, because you might still get electrocuted. Do you believe your friend? Why or why not?

I've had a few people mention this in later interviews, and so I was wondering if you'd thought about it or talked about it any more since then, and if so what did you think about? If not, maybe you could talk through it again here?

[After students talk through the situation, if they haven't mentioned charges/e-fields/e-potential/e-current] *Over the semester, you guys have talked about a lot of different ways of describing how charges behave. I was wondering if you could describe this situation in terms of (charge/e-field/e-potential/e-current)*

[Follow up] *Which of these ways of looking at charge do you think is most useful for understanding this situation?*

2. Electric Eel Review

So, I think you guys learned a bit about electric eels earlier in the semester, right?

If you needed to pull an electric eel out of the water, what would be the safest place to grab it, and why?

(Follow up): *What about when you actually have the eel out of the water? Would you expect to receive a greater or smaller shock than when it's in the water?*

(Follow up): (Show video of eel jumping out of water to zap an arm) So, at Vanderbilt they recently observed a new type of behavior by electric eels, where they actually jump partway out of the water to electrocute a perceived predator. Based on what you said above, why do you think an eel would do such a thing?

(Follow up): *Do you think an electric eel would be better modeled as a battery or a capacitor? What do you think a "battery eel" vs. a "capacitor eel" would look like?*

(After students talk through the situation, if they haven't mentioned charges/e-fields/e-potential/e-current) *Over the semester, you guys have talked about a lot of different ways of describing how charges behave. I was wondering if you could describe this situation in terms of (charge/e-field/e-potential/e-current)*

(Follow up) *Which of these ways of looking at charge do you think is most useful for understanding this situation?*

3. Task: Create a mind map of E&M concepts from the course

For the final task, I was hoping you could create a "mind map" of electricity and magnetism concepts from the course. Basically, I'm looking for a visual representation, or picture, of how the two of you see all of these concepts hanging together.

3.1 Analyze the concept map
So, looking back, what are the things in the course that made the most sense to you? What are things that you think were hardest to get a handle on or that you never quite got a handle on?

(If they use the word “charge”): *So, could you talk a little more about what stuck in your head about “charge “ or “charges?”*

(If they use the word “electric fields”): *So, could you talk a little more about what stuck in your head about “electric fields“? Do you think e-fields will play any role in your life going forward?*

(If they use the word “electric potential”): *So, could you talk a little more about what stuck in your head about “electric potential?” Do you think you’ll encounter electric potential again in your life or research?*

(If they use the word “electric current”): *So, could you talk a little more about what stuck in your head about “current?”*

(Follow up): *What do you think was, overall, the most foundational or important idea of the course?*

(Reserve Question) Charges and the Dryer Review
In the winter, when I do laundry I notice that when I take my clothes out of the dryer, they tend to cling together, and when I pull them apart I see sparks. However, I recently read that if you put a tightly compacted ball of aluminum foil in the dryer with your clothes, this stops happening. Do you believe this claim? Why or why not?

(Follow up): *So, how would you explain the sparks/cling to another student in your class?*

(Follow up): *How would you explain the sparks to your TA or physics prof?*

(Follow up): *How would you explain the sparks to someone who had never seen this kind of thing done before and had also never taken physics?*

[If they mention “static electricity”] *What do you mean by static electricity?*

[Follow up] *So, after this conversation, will you put a ball of aluminum foil in your dryer next time you do laundry?*