Dynamics Contributing to the Emergence and Stability of Students' Scientific Engagement Over Multiple Timescales

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Abstract

Many researchers and educators working to engage students in learning science by *doing* science have asked: How can we get students to make sense of the world around them, construct and critique ideas, and recognize and articulate problems needing to be solved? Furthermore, how can we help students develop strong disciplinary identities as well as productive disciplinary feelings, dispositions, and beliefs? These questions were the motivations for this dissertation, which is an in-depth study of three cases of students doing science, ranging from minutes to years. For each of these studies, I explore the dynamics involved in students' scientific engagement and I identify the factors that contributed to starting and sustaining it. In particular, these cases reveal how affective and epistemological dynamics contribute to the emergence and stability of students' engagement and how responsive instruction can support these dynamics.

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Chapter 1: Motivation and Overview

Introduction

In this dissertation, I present a collection of three stand-alone papers, each depicting a case of students' scientific engagement[1]. In general, my purpose in studying these cases was to understand the dynamics that contributed to the engagement—either by stabilizing "doing science" in-the-moment or by supporting the development of more productive patterns of engagement over time. The cases depict students' engagement at multiple timescales and in different participation structures—from a third-grade class's discussion about toy cars to a college student's interest in science that starts in an introductory physics course and persists over 2 years. As a set, these papers raise insights into what stability in doing science looks like at these different timescales (twenty minutes, five weeks, two years) and participation structures (small group + instructor, class + teacher, individual student + university course), and what dynamics contributed to those stabilities.

In this chapter, I discuss the origin stories and summaries of the papers in order of their chronological development (this order is different from how they appear in the dissertation, which is organized from shorter to longer time scale). I then review the field's conceptualizations of "doing science" and how it gets started and sustained in classrooms.

Origin stories and summaries of the papers

I have always been interested in understanding how individuals and groups of students come to engage in *authentic* scientific inquiry. I am interested both in how they come to engage in the pursuit of coherent, mechanistic understandings of physical phenomena in moments of classroom

[1] Throughout this work, I will refer to *scientific engagement* and *doing science* interchangeably.

activity and also in how they come to associate science with particular epistemic practices, norms, aims, and values that may be distinct from other forms of epistemic activity.

A third-grade class studies motion

This interest began with my work on *The Responsive Teaching Project*[2] when I observed Sharon Fargason's third-grade class in their six-week study of motion. I was amazed at how quickly the group took up scientific practices and engaged in scientific discourse and I found myself wondering about the dynamics and mechanisms of this transition. This question inspired the development of the paper, *Attention to student framing in responsive teaching* (co-written with David Hammer, presented in chapter 3).

In this paper, I analyze two episodes from a six week unit on the motion of toy cars. One episode took place during the second week of the unit and the other took place in the sixth week. Both episodes are typical representations of students' classroom activity around those times. In the first episode, there was evidence of an instability in students' epistemological framing, or what they thought was taking place with respect to knowledge. For instance, when sharing their ideas for how to get a toy car to move, students would oscillate between discussing toy cars and real cars. Appealing to real cars that have their own internal sources of power obviates the question of how to get a *toy* car to move, and was evidence that students were not yet stably engaged in the game of "doing science." On the other hand, in the second episode, the kinds of knowledge students drew on and the forms of arguments they made indicated that they were more stably framing the activity as doing science. For instance, even when a student mentioned "free will," as the reason a car moved freely down a ramp, he did not use it to give the toy car

[2] Funded by the NSF grant # DRL 0732233. Website: http://cipstrends.sdsu.edu/responsiveteaching/

human or real-car qualities, but rather he used it as a stand-in for a physical mechanism (gravitational potential energy) that he did not yet have the vocabulary to describe.

While this paper relies on an analysis of the changing stability of students' scientific engagement over time, the main focus is on how the teacher's attending and responding changes in relation to this changing stability. The analyses reveal that as students came to frame their activity more stably as doing science, the scope of Sharon's attention shifted from a wider consideration of the *types* of contributions students offered to a more narrow consideration of the *substance* of students' ideas. In particular, during the first episode, Sharon acted to suppress certain types of contributions and to support others, which helped shape students' developing sense of the discipline. In contrast, during the second episode, Sharon stepped back from this larger-level monitoring to delve deeply into the substance of students' ideas, helping them to further refine their disciplinary framing.

A college student's transformation

My interest in understanding dynamics and stability of students' scientific engagement fit nicely with the goals of the next project I worked on—colloquially referred to as the *Students Doing Science Project*[3]—in which we studied the dynamics of students' scientific engagement in classrooms. For this project, I collected data in several contexts, including David Hammer's introductory physics course, where I was a teaching assistant. In that course, I met Marya[4], a student who initially struggled with intense feelings of anxiety in moments of uncertainty. By the end of the course, however, she spoke excitedly about wanting to pursue a minor in physics. Like in the case of Sharon's class, I was fascinated by her dramatic transformation and wanted to

[3] Funded by The Gordon and Betty Moore Foundation grant #3475, studentsdoingscience.tufts.edu
[4] "Marya" is a pseudonym.

understand how it happened. I asked my colleague Lama Jaber to interview Marya about her experiences in the course and her interview revealed some interesting dynamics of her shift that were worth exploring in more detail. In particular, she described a shift in her meta-affect, or her feelings about feelings of uncertainty, which was entangled with her epistemology, or her ideas about and approach to knowing and learning physics. I conducted a systematic analysis of her written coursework to find evidence of her shifting epistemology and triangulated it with claims she made in her interview about her transformation. I found that over the course of the semester, Marya's engagement in sense-making practices became more stable, which supported a shift in her meta-affect—from feeling anxious to feeling excited in moments of uncertainty. In an interview with her two years later, she spoke about the lasting impact the course had on her subsequent learning experiences. Marya's story is the subject of the paper, *'It's scary but it's also exciting': A case of meta-affective learning in science* (co-written with David Hammer and Lama Jaber, presented in chapter 4), which illustrates her transformation and explores the dynamics involved in shaping it.

A group's persistence with a problem

The purpose of the *Students Doing Science Project* was to collect clear instances of students' scientific engagement in classrooms, conduct in-depth analyses that inform conjectures about what contributed to the dynamics in these cases, and then look across many analyses for themes and patterns. In the paper, *Understanding the stability of students' scientific engagement over twenty minutes of their inquiry* (presented in chapter 2), I present data from one of these cases and explore what contributed to starting and sustaining students' scientific engagement. This case depicts a group of five college students as they discussed a worksheet problem in an optional discussion section for an introductory physics course. This case shared some features with our other project cases, including that students noticed and grappled with some disciplinary uncertainty.

However, there were some key differences between this case and others that sparked my initial interest in it. First, while in most of our cases, students tended to nominate inconsistencies or phenomena that they found inherently interesting or problematic, in this case students did not initially orient to the phenomenon or the problem with any kind of interest or excitement. In addition, in most of our cases there was a single student responsible for stabilizing the group's inquiry. In this case, however, no one student took up this role. Despite the absence of these factors that we found in other cases contributed to initiating and stabilizing the engagement, the group continued to work on this problem for about twenty minutes. In addition, attendance in the discussion section was optional, and the worksheet was not being collected, so why did they persist through their evident struggle?

An analysis of this episode shows that students' feelings of epistemic vexation, or their feeling bothered by an inconsistency both contributed to the stability of students' scientific engagement and provoked expressions of struggle and discomfort. This case provides insight into the complex affective dynamics of these students' encounter with disciplinary uncertainty as well as the distributed nature of their participation in stabilizing the engagement.

Plan for this chapter

As a set, these papers provide some insights into how students' scientific engagement gets started and sustained in moments, and how those moments can, over time, develop into larger-level patterns of stability that have consequences for students' learning, interest development, and the formation of their disciplinary identities. In particular, they speak to the role that students' affect, students' epistemologies, and responsive teaching play in supporting students' short- and long-term scientific engagement.

In what follows, I first give an account of what I mean by "doing science," informed by the science education literature. I then discuss what I mean by the *stability* of students' scientific engagement and how these stabilities form and shift across multiple scales of time (minutes, weeks, years, etc.) and participation structure (individual, small-group, entire class).

Conceptualizations of "doing science" in classrooms

As the science education community shifts towards adopting practice-based models that promote learning science through doing science (Next Generation Science Standards, 2013; National Research Council, 2011), many have attempted to characterize what it means to "do science" in classroom contexts. Some have done this by theorizing about and documenting students' participation in a variety of social knowledge-building practices, such as making and evaluating arguments (Berland, 2011; Berland & Reiser, 2011; Driver, Newton, & Osborne, 2000; Jimenez-Aleixandre, Rodriguez, & Duschl, 2000; Kuhn, 2010; Manz, 2015a), modeling (Manz, 2012), constructing mechanistic explanations (Russ, Scherr, Hammer, & Mikeska, 2008), designing and carrying out controlled experiments (Ford, 2005), and problematizing (Engle, 2012; Engle & Conant, 2002; Manz, 2015b; Phillips, Watkins, & Hammer, under review).

While "doing science" is often characterized as an enactment of these knowledge-building practices, Ford and Forman (2006) argued that seeing evidence of these practices is not sufficient for characterizing disciplinary activity as distinctly scientific. They claimed that these practices must make contact with the physical and material world. In this way, scientific claims are not only held accountable to members of the (classroom) disciplinary community, but are also subject to the "authority" adjudicated by the material world (Manz, 2015b). In other words, students' ideas and arguments must be grounded in their knowledge and observations of the physical world in order to be considered "doing science."

Here, I want to distinguish between students' engagement in doing science and the practices and knowledge that scientists have communally developed and utilized. These practices and bodies of knowledge have certainly proven to be valuable, and we eventually want students to become familiar with these ways of knowing and doing science. However, we also want students to come to see themselves as agents who can construct knowledge rather than merely consume knowledge produced by scientists. This goal requires us to conceptualize doing science in classrooms as making contact with traditional scientific ideas and practices but also as built upon the social and disciplinary norms that are locally co-constructed by the classroom community (Cobb, Stephan, McClain, & Gravemeijer, 2001; Yackel & Cobb, 1996).

Others have also challenged the notion that classroom science should look just like professional science. In particular, Ann Rosebery, Beth Warren, Megan Bang, and colleagues have argued that imposing this model on classroom science further oppresses and marginalizes students from non-dominant cultures whose ways of knowing and speaking are not valued in traditional science. Instead, they argue, science should be conceptualized as "a refinement of everyday thinking" (Einstein, 1936, p. 59) and sense-making in which students' lived experiences and ways of knowing and communicating are legitimized and valued. In this way, "doing science" can and should serve as points of deep connection to students' histories and communities (Bang & Medin, 2010; Bang, Warren, Rosebery, & Medin, 2012; Michaels, O'Connor, & Resnick, 2008; Rosebery, Ogonowski, DiSchino, & Warren, 2010; Warren, Ballenger, Ogonowski, Rosebery, & Hudicourt Barnes, 2001; Warren, Ogonowski, & Pothier, 2005).

Finally, in their seminal study of a fifth-grade class's extended inquiry into whether an orca should be classified as a dolphin or a whale, Engle and Conant (2002) provided some guidelines for identifying instances of students' productive disciplinary engagement, or PDE. Some criteria for assessing students' engagement includes how many students made substantive contributions, whether they coordinated their contributions with others', the degree to which students were "on-task" versus "off-task," the duration of the engagement or the tendency for students to get reengaged after time had passed, and students' emotional displays and expressions of passionate involvement.

This last criterion highlighting students' deep, personal investment in understanding the world around them resembles the emotions that professional scientists describe in accounts of their work (Fox-Keller, 1983; Lorimer, 2008; Thagard, 2008), including curiosity and fascination about a phenomenon, anticipation for finding the solution to a problem, vexation at an inconsistency, and excitement and pride from figuring something out. Many scholars have found evidence that students can similarly experience "doing science" in deeply emotional ways (Conlin, Richards, Gupta, & Elby, under review; Eynde & Turner, 2006; Gupta, Danielak, & Elby, under review; Hufnagel, 2015; Jaber, 2014; Jaber & Hammer, 2016a; 2016b; Pintrich, Marx, & Boyle, 1993), validating Engle and Conant's (2002) use of affective expressions as an indicator of students' authentic engagement in scientific pursuits.

In addition to looking for evidence of students' engagement, Engle and Conant also laid out guidelines for ensuring that students' engagement was *disciplinary* and *productive*. They consider students' engagement to be *disciplinary* simply if "there is some contact between what students are doing and the issues and practices of a discipline's discourse" (Engle & Conant, 2002, p. 402). This definition gives significant latitude to the many different conceptions that educators may be working with for what counts as "disciplinary."

Finally they consider students' disciplinary engagement to be *productive* "to the extent that they make intellectual progress, or, … 'get somewhere'" (Engle & Conant, 2002, p. 403). Building on this broad notion of "productivity," students' scientific progress can be conceptualized along multiple dimensions, including conceptual (e.g., making a connection between ideas, developing a predictive model, constructing a causal narrative, etc.), epistemological (e.g. coming to see doing science as about active sense-making, building rather than consuming knowledge, as a series of conjectures rather than permanent facts, etc.), affective (e.g., coming to orient to epistemic feelings such as uncertainty and confusion in disciplinarily productive ways), and social (e.g., listening to and building on others' ideas, supporting a system of equitable participation, clearly communicating one's ideas to an audience, etc.), amongst others[5].

Making sense of the emergence and stability of students' scientific engagement

The work I reviewed in the previous section provides insight into some of the features of students' scientific engagement. In what follows, I discuss the dynamics involved in starting and sustaining students' scientific engagement.

Part of what complicates study of students' engagement is that it can shift rapidly in moments. These shifts in students' engagement have been well-documented in the literature. For example, Rosenberg, Hammer, and Phelan (2006) describe a group of eighth-grade students working to explain the rock cycle. At first, they approach the task as a matter of compiling a list

[5] To be clear, while I do not consider these dimensions to be theoretically separable—progress in "doing science" necessarily involves movement along many, if not all, of these dimensions—I sometimes analytically disentangle them in order to study how these dynamics contribute to students' PDE.

of facts from their worksheets, but when the teacher intervenes and asks them to "start from what you know, not what the paper says," students begin sense-making about the causal processes involved. In another account, Lising and Elby (2005) show how a college student, Jan, shifted her approach to physics problem-solving in a clinical interview based on where it took place. When she was interviewed in the physics building, she appealed heavily to equations and formalisms. However, when she was interviewed in the education building, she easily made connections to her everyday experience. Finally, Russ, Coffey, Hammer, and Hutchison (2009) provide an account of second-grader Erin, who explains why sucking on straw makes a juice box collapse in terms of everyday mechanisms, i.e., there is a lack of air pushing on the inside to counteract the air pushing from the outside. However, after her teacher continues to push on her explanation, making clear that her answer was not satisfactory, she begins invoking technical vocabulary (e.g., "pressure") and stops making physical, mechanistic sense of the phenomenon.

These and many other accounts (e.g., Conlin, 2011; Hutchison & Hammer, 2009; Manz, 2012; Rosebery et al., 2010) show how students' scientific engagement can start and stop in moments, in response to particular contextual cues or events. Given the dynamic and often chaotic nature of students' classroom activity, any stability or pattern of stability in students' scientific engagement is something to be explained. Before attempting to explain it, I first need to clarify what I mean by *stability in doing science*. I address this issue in the next section, drawing on research on dynamic systems theory and reesarch on students' framing.

Conceptualizing and identifying *stabilities* in "doing science"

Although to this point I have spoken about stability largely in absolute terms (something is stable or it isn't), in reality, any state of apparent stability that emerges in a dynamic system must be thought of as a *relative* stability. This qualifier is necessary because it allows for another important feature of dyanamic systems—their ability to adapt and develop in response to external pressures. According to Thelen and Smith (1994),

> It is important to think of any seemingly stable human thought or action to reside on these cusps of quasi-stability, visiting areas of tight coordination, but also intermittently escaping from them, providing the flexibility to react and assemble new adaptive forms…Fluctuations around stable states are the inevitable accompaniment of complex systems. It is these fluctuations that are the source of new forms in behavior and development and that account for the nonlinearity of much of the natural world. (Thelen & Smith, 1994, p. 68)

So, what do these relative stabilities, or “areas of tight coordination” look like in classrooms?

One can imagine many types of stabilities that may form in a classroom. There can be stabilities in participation structure (e.g., a class of students sitting quietly at their desks while the teacher stands at the front of the classroom), stabilities in how students relate to knowledge (e.g., a majority of students respond to the question, “how do clouds rain?” using causual reasoning), and social stabilities (e.g., students ask the teacher permission before addressing one another), to name only a few. These stabilties can be conceptualized as patterns of behavior that emerge from the dynamic interactions between the students/teacher and their own knowledge, histories, and expectations, the instructional context, material features of the setting, and classroom and institutional norms. Oftentimes (but not always) the dimension of interest in determining whether students are stably doing science is whether they persist for some amount of time.

In addition, what counts as “stable” depends largely on the grain-size at which we are observing the stability. For instance, if we look at a system on a microscopic level, we may see particles moving around seemingly at random. Zoom out a bit and we see that random motion begin to form into organized cells and systems that we can recognize as say, an ant. Looking at the behavior of a single ant, however, we might begin to see chaos again as it moves around seemingly at random. Zooming out further still, we can once again see organization in the collective behavior of the colony, which emerges, not from a central regulatory body but from the interactions between individual ants.

Similarly, relative stabilities in students' scientific engagement can look different at different timescales. Consider Engle and Conant (2002) case, for instance. This case takes place in a fifth-grade class and focuses on a particular debate that emerges in the middle of a four-month "endangered species" unit. The debate centers on whether orcas, commonly known as "killer whales" should be classified as a dolphin or a whale. Engle and Conant (2002) describe this local stability that emerged around the debate as unexpected to the research team:

> At first glance, this question does not seem inherently interesting, relevant, or even especially open: Why does it matter whether they are whales or dolphins? How does this relate to understanding why whales are endangered? Haven't scientists already determined the classification? Couldn't the students just look up the answer somewhere? Moreover, Ms. Wingate's whale group was originally unhappy to be studying whales at all—It was their last choice, their preferred animals having been assigned to other students whose research proposals were judged superior. Given the nature of the question and the students' initial lack of interest in whales, it may seem surprising that they were interested in discussing the orca's classification at all. (Engle & Conant, 2002, p. 412)

They go on to explain that this unlikely debate lasted for twenty-seven minutes in class (which they refer to as the "Big Ol' Argument") and then continued through the end of the unit, as students returned to the debate eight times over the next eight weeks.

Looking at the classroom activity on the day of the Big Ol' Argument, there is evidence of a local stability—students discussed the issue, uniterrupted, for twenty-seven minutes. But what about their enagement over the course of eight weeks? Can we call that a stability despite their leaving and returning to this debate? I would argue that looking over the eight weeks, a stability of a different nature emerges: There is a pattern of students spontaneously reigniting their discussion around this issue. This persistent pattern of shorter episodes of engagement can itself be considered a stability in doing science, albeit on a much larger scale. This larger-level stability can indicate the development of a deeper engagement and it makes contact with developmental constructs such as *interest*, as students continue to return to the topic on their own volition, and *identity*, as students begin to see themselves as authorities to determine the outcome.

If we randomly sampled moments of their activity over the eight weeks, it is likely that at a rough enough resolution, we may never even see evidence of the debate popping back up. However, looking systematically at students' activity, there is clear evidence of this debate resurfacing. In this way, we can think of short-term stabilities as *episodes* of students' engagement that persist over minutes to hours, either with a constant quality or resisting interruptions and disturbances. We can also think of long-term stabilities as a larger-level *pattern of episodes*. In order to see the larger-level stability, it may be necessary to look across many instances of shorter intervals of stable activity.

There is also the question of *stability with respect to what*? In the case I described above, we see stabilities in students' discussing and returning to a particular debate. There is similar evidence of a topical stability in the case from chpater 2. Students persist in their work on a single problem for twenty minutes without external incentives. In other cases, the stability of interest might take a more general form, for instance, in the epistemological stability that Sharon's students develop, over time, in the case from chapter 3. In that case, there is evidence in the second episode of a stability in students' understanding of what it means to do science, for instance, in the kinds of contributions they made and in the form of their reasoning. Contrasted with the first episode, in which there was some evidence of epistemological *in*stability, this later relative stability is interesting and warrants explanation. In the case from chapter 4, there is evidence in Marya's interview of shifting patterns of stability across multiple dynamics of her engagement. Initial patterns of stability suggest that her feelings of anxiety with respect to uncertainty were entangled with a sense of physics as being about absolute rights and wrongs. Later patterns of stability suggest that her excitement about uncertainty was engangled with her sense of physics as being about a process of sense-making. Looking systematically at her written work produced at evenly spaced intervals throughout the semester, we can see that these larger-level patterns of stability were supported by these shorter instances in which she engaged in sense-making practices more and more stably over time.

There is utility in studying these cases through the analytical lens of stability, despite the fact that the stabilities in these cases look different due to their differences in context, time scale, and grain-size. Looking closely at these stabilities can provide insight into the complex dynamics that contribute to producing and maintaining them. In addition, studying how these stabilities form and shift over time can support the field's attempts to construct theories of development that make contact with students' scientific engagement in moments (Sandoval, 2014).

Mechanisms of stability

Now that I have outlined some theoretical and analytical notions of stability, I turn to the issue of how these stabilities emerge and persist over time. To do this, I recruit some ideas from the science education literature on *framing*. Drawing on work from sociolinguistics and anthropology (Goffman, 1974; Tannen, 1993), David Hammer and colleagues (Hammer, Elby, Scherr, & Redish, 2005; Scherr & Hammer, 2009) use the construct of framing to describe the "activation of a locally coherent set of resources" (Hammer et al., 2005, p. 99), reminiscent of Thelen and Smith's (1994) "areas of tight coordination" (p. 68). In other words, framing is an individual or group's sense of what is taking place, and it can have epistemological, affective, positional, and social aspects, amongst others, which are in dynamic interaction with one another. Since human behavior and interaction is the dynamic system that I am interested in understanding, framing, as a construct that models how individuals' and groups' understandings and expectations shape their behavior, is a useful tool to aid my inquiry.

Although Hammer et al. (2005) largely conceive of framing as a cognitive function of individual minds, activating a frame is fundamentally an interactive phenomenon, informed, in part, by features of the local environment and context. As such, individuals can coordinate their framings with others', a process which often happens fluidly in interactions. For example, Tannen and Wallat (1993) analyzed video of a doctor examining a child and found that shifts in the doctor's vocal register and language signaled shifts in the doctor's framing of what she was doing, in particular whether she was speaking to clinicians, to the mother, or to the child. These markers helped the mother and child recognize which audience the doctor was addressing and helped them determine when to respond and when to remain silent. Through these tacit channels of communication, it is possible for participants in an interaction to align their framing with others' (van de Sande & Greeno, 2012).

Alternatively, participants may also make explicit moves to shift or resist another's framing. An example of this phenomenon is described by Hammer et al. (2005), who document the activity of a group of college students as they work collaboratively on a physics problem. One student, Tracy, begins by jumping into a numerical calculation. Another student, Sandy, challenges Tracy's framing by asking, "Do we even need to do all that calculation?" Here, Sandy explicitly rejects Tracy's approach of plugging values into equations and instead makes a bid to approach the problem as an opportunity for intuitive sense-making. Tracy goes along with Sandy's bid, and they continue to reason through the problem conceptually. In this way, shifts and stabilities in framing can be informed by interactional dynamics as individuals attempt to communicate and coordinate their framings with one another.

Framing, as a local activation of a coherent set of resources, is an event that happens in moments. However, those patterns of activations can become stable over time. As individuals or groups activate and re-activate sets of resources, those resources develop some stability as a unit, which can then be compiled more quickly and activated more readily in future moments. Hammer et al. (2005) describe three different mechanisms by which a set of resource activations can become stable:

1. Contextual

Hammer and describe contextual mechanisms of stability as "a passive activation based on the situation, whereby "passive" [they] mean that the pattern forms and persists without metacognitive resources playing any role" (p. 109) In this way, particular aspects of an environment or event can elicit patterns of interaction and activity that may not appear in a different context. For example, when waiting in line, two strangers might spark up a conversation. Disrupt that context slightly—with the introduction of smartphones, for example—and that conversation might never happen.

Accounts of contextual stabilities forming in response to local dynamics and events abound in science education literature. For example, Rosebery, Ogonowski, DiSchino, and Warren (2010) describe how an impromptu fire-drill, that sent students out into the cold without their coats helped spark a productive discussion about how “the coat traps all your body heat”; Rosenberg, Hammer, and Phelan (2009) show how students shift from recording a list of disconnected facts to sense making about the rock cycle after their teacher tells them to “start with what you know”; Conlin and Scherr (in prep) show how a group of college physics students initially dismisses an unexpected irregularity in their data, but after a TA's intervenes asking, “that’s a good question…what do you think happened there?” the group begins to investigate it.

We can see some contextual mechanisms of stability at play in my cases as well. In particular, in chapter 2, the group activates a *sense-making* epistemology only after a fortuitous instructional intervention in which I, as their TA, make a direct connection between their definition of non-conservative force and conceptual notions of heat dissipation. In addition, other contextual aspects supported the emergence and stability of their scientific sense-making, such as aspects of the worksheet problem that elicited students’ inconsistent conclusions and students’ slight discomfort with one another (this was their first time working together) which yielded a willingness to explore each other’s ideas while still holding onto strong commitments of their own. In addition, the classroom norms and culture supported an environment where students were expected to articulate their vexation, argue for and against multiple lines of reasoning, and coordinate across conceptual and mathematical representations of phenomena. While I did not observe these students’ engagement beyond this single episode, it is likely that this stability would not persist in other contexts, for instance, in discussions sessions for other courses.

2. Deliberate

Unlike contextual mechanisms of stability, deliberate mechanisms involve an element of meta-cognition. Stabilities involving deliberate mechanisms can result from an active monitoring of resources. For example, a parent who comes home in a bad mood might easily interpret their child's whining as an act of disobedience and lash out. It requires some conscious effort for that parent to recognize this pattern, suppress it, and activate another pattern, perhaps instead interpreting the whining as useful information as to whether the child is tired or hungry.

There is evidence of deliberate mechanisms of stability at play in the case from chapter 3. If we think of Sharon's class as a cognitive unit composed of Sharon and her students, Sharon acted deliberately to maintain some level of stability by monitoring students' epistemological framings. In the first episode, when students were unable to hold the stability on their own, she made moves to limit the kinds of contributions that were permitted, which sent messages to the students about what counts as doing science in this space. In the second episode, however, as students began to hold the stability on their own, Sharon could reign in her monitoring, and allow students to make decisions more freely as to what counts as a scientific contribution.

Another feature of these deliberate mechanisms is that an awareness of these patterns allows us to actively refine them and recognize nuance within them. For example, in Marya's second interview, we saw evidence of her awareness of scientific sense-making as a "kind of thing" that she could enter into and out of at will. She described having to turn off her sense-making if she was tight on time or if it would otherwise jeopardize her grade. There was also evidence that she had developed a sophisticated set of meta-cognitive tools which allowed her to critically analyze and monitor her own engagement in scientific sense-making. She spoke about the relative epistemological nuances of research compared to the course: At times, constructing ideas from bottom up was not necessary for doing the work, and her sense-making drained time and resources away from her project. In those cases, she might turn to experts for help rather than reinvent the wheel. Sense-making remained centrally important to her, but she recognized that she did not always need to construct something from scratch in order to understand it. In this way, Marya's recognition of "scientific sense-making" as a "kind of thing" allowed her to continuously refine it in response to her ongoing scientific experiences and consciously activate or deactivate it according to context.

3. Structural

Repeated activation of sets of resources can give rise to more robust stabilities in passive activations, that are less dependent on local contextual dynamics. This mechanism is consistent with Thelen and Smith's account of developmental "abilities" such as *object permanence*; the set of resources that presents as *object permanence* gains stability from repeated activations, but the infant does not have to do any work to conjure it up as he interacts with objects in the world.

Similarly, we often encounter students who, upon entering our reformed physics course, passively activate sets of resources that have developed stability from many years of repeated activation. Oftentimes, the activation of these resources is harmful to their learning and may include epistemological resources (i.e., knowledge is transmitted, not constructed; physics is composed of a disconnected body of knowledge; classroom physics is disconnected from the real-world), affective and meta-affective resources (i.e., confusion feels bad; uncertainty feels scary, etc.), social resources (i.e., the professor's job is to explain things well; students should accept, not problematize what the professor says; students don't talk with each other about their ideas, etc.), and others. The work of instruction then, is to disrupt these stabilities and help students cultivate new ones.

In the case from chapter 4, there is evidence that Marya entered the course with similarly harmful patterns of meta-affective and epistemological resources, which likely developed some stability from her past experiences in science courses. This initial pattern got disrupted, however, in local interactions with instructors and other students in the course as well as with the course materials and assignments. In these instances, Marya began to activate more productive (contextual) patterns of meta-affective and epistemological resources. Over time and repeated activation, these contextually stable patterns developed into structurally stable patterns, which retained their stability two years later when we interviewed Marya a second time. The stability of these activations no longer depended on contextual features of the course. Similar to Sharon's class, the grain-size of stability shifted from being held together by the dynamic interaction between Marya and the course's features and participants, to being held by Marya as an individual who carried it with her to other educational contexts.

As a set, the papers I present provide insight into the dynamics contributing to stabilities of students' scientific engagement across multiple timescales and participation structures. Despite the differences across these cases, my findings reveal some overlapping themes, particularly with respect to the role that students' affect, students' epistemologies, and responsive teaching play in supporting students' scientific engagement. These findings will be discussed in further detail in each chapter, as well as in chapter 5.

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Chapter 2: Understanding the stability of students' scientific engagement over twenty minutes of their inquiry

Jennifer Radoff

This chapter was conceived within the context of a larger project focused on studying episodes of students' scientific engagement to understand what contributed to starting and sustaining it[6]. For this project, we collected clear examples of students doing science, analyzed the episodes for what contributed to the dynamics, and then looked across cases for patterns and themes. This chapter presents one of those analyses.

In looking across 10 cases, we discovered common themes that contributed to the dynamics. A few of these themes were related to how participants engaged with disciplinary uncertainty, including positioning themselves as uncertain or confused (Watkins, et al., under review), problematizing, and displaying affective expressions of vexation and puzzlement.

The case I present in this chapter takes place in a discussion section for a reformed introductory college physics course. It follows a group of five students as they engage in a twenty-minute discussion about a worksheet problem. Particular dynamics of this case raise new insights about the role disciplinary uncertainty plays in students' scientific engagement. In particular, my analyses reveal the complex dynamics of students' affective engagement with uncertainty as well as the distributed role of uncertainty in maintaining the group's stability in doing science.

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Uncertainty and confusion in doing and learning science

Everyone is familiar with uncertainty and confusion. These experiences are inherent to the process of making sense of the world around us. In science, where the primary objective is to make sense of the physical world, uncertainty and confusion are seen as core features of that pursuit. For many years, philosophers and scientists have described uncertainty as signaling an opportunity for exploration. For example, Isaac Asimov, biochemist and prolific science fiction writer was widely attributed to have said, “The most exciting phrase to hear in science, the one that heralds new discoveries, is not ‘Eureka!’ (I found it!) but ‘That's funny...’”

Many years of research in psychology and education suggests that some amount of uncertainty and confusion can be beneficial for learning. In the mid-to late-1900s, Piaget proposed cognitive disequilibrium—i.e., an inconsistency between expectation and experience—as a mechanism for cognitive development (Piaget, 1970). Since then, many others have proposed that cognitive conflict may be beneficial, and perhaps even necessary, for conceptual change (D'Mello & Graesser, 2014; D'Mello, Lehman, Pekrun, & Graesser, 2014; Limón, 2001; Posner, Strike, Hewson, & Gertzog, 1982). Dowd, Araujo, and Mazur (2015) explain that confusion may indicate that students are “growing familiar enough with the material that it is conflicting with their prior knowledge and expectations” (p. 1). Conversely, the absence of confusion “may also indicate that the student is not even aware of conflicts between new ideas and prior knowledge. Student recognition of this conflict may assist, rather than inhibit, the learning process” (p. 1). Limón (2001) showed that even when conceptual change was not achieved, students who grappled with contradictory information engaged in a wider range of epistemic practices: They developed more elaborate and sophisticated answers to account for anomalous data, constructed multiple explanations and deliberated between them, integrated additional knowledge into their answers, and checked more deliberately for coherence between their models and the data.

Others have designed for the strategic introduction of uncertainty and confusion into learning environments and activities to promote students' scientific engagement. For example, in their foundational work analyzing an extended episode of 5th graders debating whether an orca should be classified as a dolphin or a whale, Engle and Conant (2002) propose that scientific engagement is more likely to occur if students are encouraged to problematize content and if they are given the authority to pose and solve problems. They claim that students should be encouraged not only to question their own thinking but also to question established assumptions and issues (Hiebert et al., 1996).

Similarly, Manz (2015) recruited Pickering's notion of "the mangle of practice"—or the tendency for the natural world to push back against our attempts to measure, define, and understand it—to design opportunities for children to grapple with uncertainty as they studied "the wild backyard." Manz found that "the forms of uncertainty that students experienced established a need for the practices that they developed" (p. 120). For example, as students identified qualities that indicate successful growth in plants, they quickly realized that it was not obvious which qualities determined success (e.g., the plants that were the tallest did not produce as many seed pods). The complex nature of the data demanded that they make choices about what to measure, decide how to represent and make sense of the collected data, and make connections between their measurements and models of growth. In addition, differences between their experiment and the target phenomenon encouraged students to assess whether their model accurately represented the phenomenon.

Themes of disciplinary uncertainty in our project cases

These accounts suggest that disciplinary uncertainty may support students' scientific engagement. In our project that studies how students enter into and persist in doing science, we have found evidence to corroborate these accounts. In this project, we collected candidate episodes of students doing science in K-16 classrooms, and conducted in-depth analyses of the ones that were deemed by a team of university science faculty to be "clear instances" of students' scientific engagement. At the time I began writing this chapter, 25 episodes had been vetted, 11 were approved, and 10 in-depth written analyses were completed.

Looking across the analyses of these 10 cases, we noticed that students' articulation of and grappling with uncertainty played a central role in supporting the emergence and/or persistence of students' scientific engagement. Uncertainty often emerged from a missing explanation for a puzzling phenomenon or from a lack of coherence amongst ideas, observations, models, intuitions, or outcomes. For instance, in the Clouds case, fourth-grader Jordan grappled with how it was possible for light clouds to hold heavy water. Jordan's articulation of this discrepancy and her attempts to motivate the problem to her peers helped shift the epistemic activity (from telling what they know about clouds to asking questions about mechanism) as well as the positional dynamics (from taking turns talking to the teacher to debating with each other). Similarly, in the Escalator case, although the professor told students that an escalator does *less* work on a person who is walking up versus standing still, Pat struggled to reconcile the "correct" answer with her intuition that walking up an escalator should result in *more* work because there

Episode	Age & activity structure	Summary of students' uncertainty
Clouds	4th grade class discussion about clouds and rain	Students grapple with the question: how can a light cloud hold heavy water?
Water bottle	5th grade class discussion on evaporation	Students grapple with a discrepancy between their model and observations: If molecules spread apart when heated and move together when cooled, then why do water bottles explode when they are put in the freezer?
Escalator	Class discussion in a college physics recitation section	In class, the professor gave the answer to a homework problem: an escalator does less work on you when you walk up vs. stand on one step. However, students are still grappling with an alternative argument: if you walk up, the escalator is putting more force, and thus doing more work on you than when you stand.
Ball on string	Class discussion in a college physics course lecture	In class, a student asks a question: There is a ball on a string spinning in a vertical circle. When the ball is on the side of the circle, what is the net force acting on it? Students contend that in order for the ball to be moving in a circle, there must be a centripetal force inwards towards the center. However, they also notice that there is a gravitational force pointing downward. How can the net force point directly inward if there is a downward component?
Block and cylinder	Class discussion in a college physics course lecture	Students argue over the answer to a homework problem. Most students agree with one outcome, and a small but vocal minority agree with the other. They provide arguments for both sides and grapple with the outcomes.
van de Graaff	Class discussion in a college physics course lecture	When watching the instructor's demonstration using a van de Graaff machine, one student notices a piece of Mylar behaving strangely. Students attempt to account for its behavior.

Isaac's wheels	3rd grade class discussion on motion	One student provides a mechanistic account for how wheels make a toy car move. Students question him about why the car does not continue on forever.
Rubber band	5th grade discussion on water cycle	Students attempt to construct a model for how a cloud rains. They struggle to construct a model that has all the relevant features.
Seconds	Class discussion in a physics course for pre-service teachers	Pre-service teachers try to understand and construct a model for why light shining through a black tube has a fuzzy edge when it hits a surface.
Penny on disk	Small-group discussion of a worksheet problem in an intro physics discussion section	As students work on a worksheet problem, they discover that their calculation is inconsistent with their accounts of energy transfer and conservation.

Table 2.1: Descriptions of the disciplinary uncertainties students grapple with in each case.

is an increased force between the escalator and the person's feet. In her discussion section, Pat and her peers engaged in an extended debate about the issue, as they attempted to bring their intuitions into coherence with the professor's answer. Finally, in the Freezing Water Bottle case, fifth-grader Jared noticed that the class's working model of matter, in which molecules move farther apart when heated and closer together when cooled, was inconsistent with his experience of overfilled water bottles exploding in his freezer. After Jared articulated the problem to his peers, the class spent the rest of the period working to revise their model and devise ways to test it. A list of the uncertainties students grapple with in each case can be found in Table 2.1.

A cluster of 3 themes emerged around notions of disciplinary uncertainty: (1) students' problematizing (Phillips, et al., under review), (2) participants taking up the position of not understanding (Watkins, et al., under review), and (3) students' expressions of epistemic affect (Jaber & Hammer, 2016).

Students' problematizing

Engle (2012) defines problematizing as "any individual or collection action that encourages disciplinary uncertainties to be taken up by students" (p. 168). Whereas Engle frames problematizing as a feature of instruction that is embodied by a learning environment, we conceptualize it as an activity taken up by students that involves "noticing a gap of understanding, identifying and articulating its precise nature, as well as motivating a community of its existence and significance" (Phillips et al., in press). As we see it, problematizing is not merely the act of taking up disciplinary uncertainties planted by an instructor or encountered in a learning environment; it is the process of actively constructing a well-defined problem and motivating its significance to a community.

In 8 of our 10 cases, we found that students' problematizing was central to the dynamics of their engagement. Phillips (in prep) also analyzed the social dynamics of problematizing and found that in many cases, there was an individual student that nominated a problem, a second student that endorsed it, and one or more students who resisted it. For example, in the Clouds case, Jordan nominated the problem *how does a light cloud hold heavy water?* and Elea endorsed it, saying, "Yeah, cause it's as light as a feather." Other students, however, did not initially recognize the *problem* Jordan was pointing to. Alyssa, apparently not orienting to the on mechanism, responded to the question, saying, "it just does it [holds water]." Phillips found that, in general, the group's scientific engagement was more productive when students took up all three roles. In this case, Elea's endorsement of Jordan's problem gave it traction, and Alyssa's resistance provoked a heated debate and established a need for Jordan and Elea to make their focus on mechanism more explicit.

Participants taking up the position of not understanding

Another theme across our cases was that a participant (either student or teacher) publicly exposed themselves as not understanding something, typically by asking a question or by expressing their uncertainty or confusion. Notably, it was not merely the presence of an individual's uncertainty, but their public expression of it that contributed to the group's dynamics. Research on the social and discursive dynamics of uncertainty supports this notion, showing that these public displays can foster productive epistemological, conceptual, and social dynamics of students' inquiry (Kirch & Siry, 2012; Radinsky, 2008; Conlin, 2012).

In a study of 9 of these cases, Watkins et al. (under review) shows how public displays of uncertainty shifted the epistemological, conceptual, and/or positional aspects of the group's framing, which contributed to the initiation or maintenance of their scientific engagement. For instance, when Jordan asked a question about how clouds hold water, she challenged the framing that the teacher established, of students sharing what they know about clouds. By publicly exposing her uncertainty, she made available another mode of participation—asking questions—which became central to the emergence of new epistemic and conceptual substance in the rest of episode. Her question, Elea's endorsement, and Alyssa's resistance shifted the positional framing, from speaking primarily to the teacher to actively debating with each other. Table 2.2 shows how participants positioned themselves as not understanding in each of the cases and how those positionings were consequential to the classroom dynamics.

Students' expressions of epistemic affect

Affect has been shown to be part of the dynamics of students' disciplinary engagement and pursuits (Cobb, Yackel, & Wood, 1989; Pintrich, Marx, & Boyle, 1993), but there have not been many studies that attend explicitly to how moment-to-moment affective dynamics

Episode	Positioning as not understanding	How it was consequential
Clouds	Student forms a question about a phenomenon	Shifts students to question, argue, and make sense of one another's ideas and emphasizes need for mechanism
Water bottle	Student forms a question about a phenomenon	Sustains students' modeling of evaporation, now to account for freezing water expanding
Escalator	Student forms a question about a phenomenon	Sustains and refreshes discussion on work and force when moving on an escalator, applies model to new situation
Ball on string	Student notes an inconsistency in reasoning	Sustains discussion about force and motion, applies model to new situation
Block and cylinder	Student expresses dissatisfaction with reasoning	Shifts from homework review to reconciling differing predictions of two different models
van de Graaff	Student observes unusual phenomenon	Shifts from teacher presentation to discussion about unexpected observations
Isaac's wheels	Teacher asks and expresses confusion about a stu's idea about rolling	Shifts students to make sense of one another's ideas, focus on rolling
Rubber band	Teacher and students ask about stu's idea comparing clouds to rubber bands	Shifts students to finding merits and flaws in ideas, focus on threshold phenomena
Seconds	Student notes an unusual observation	Sustains students' investigations, shifts conceptual substance to include new observations
* Penny on disk	Students raise an inconsistency between their calculation and conceptual/intuitive understanding	Shifts students from the activity of producing a calculation to doing science

Table 2.2: Description of how a student or teacher positioned themselves as not understanding in each case and how that positioning was consequential for the episode dynamics (from Watkins, et al. (under review))

*The *Penny on disk* analysis was completed after Watkins, et al. (under review) was written

contribute to students' scientific engagement, and even fewer around moments of uncertainty and confusion. For example, while Engle and Conant (2002) use affect as an *indicator of* engagement, they do not examine the affective dynamics *as inherent in* disciplinary engagement. Jaber and Hammer (2016b; 2016a) have begun this work, coining the term *epistemic affect* to describe feelings that are closely tied to the epistemic experience of sense-making and knowledge-building, such as the “excitement of having a new idea or irritation at an inconsistency” (p. 189). They found that, like scientists, students experience these feelings and drives as they engage in sense-making pursuits.

These feelings can both signal and be elicited by aspects of our cognition. In this way, I consider affect and cognition to be mutually constitutive; we recognize an inconsistency, in part, because we feel bothered by discrepant information. And we feel bothered, in part, because our expectations of coherence have been violated. Affect not only signals and assigns meaning to aspects of our cognition, but can also move us to action. D’Mello and Graesser (2014) found that,

> Confusion is expected to be beneficial to learning because it signals that there is something wrong with the current state of the world. This jolts the cognitive system out of equilibrium, focuses attention on the anomaly or discrepancy, and motivates learners to effortfully deliberate, problem solve, and restructure their cognitive system in order to resolve the confusion and return to a state of equilibrium. These activities inspire greater depth of processing, more durable memory representations, more successful retrieval, and consequently enhanced learning. (p. 303)

Similarly, Jaber and Hammer (2016a) described feelings within the epistemic pursuit that *drive* inquiry, such as “the desire to understand a puzzling phenomenon” (p. 161). They contrast what they call *epistemic motivation* with other forms of interest and motivation that are related to but distinct from the epistemic practice of science itself, such as studying science because it confers elite status or employment opportunities. They showed that while epistemic motivation can shape students' long-term interest and identities, it is fundamentally rooted in the moment-to-moment dynamics of an epistemic pursuit.

We found that in almost all of our cases, students grappling with disciplinary uncertainty displayed a particular form of epistemic affect, what I call *epistemic vexation*, or feeling bothered by an inconsistency. Although epistemic vexation can signal discomfort, which is, in part, what drives attempts for resolution, these expressions were often paired and layered with other forms of animated affect as students experienced and collaboratively grappled with disciplinary uncertainties. For instance, Jordan and Elea displayed vexation toward the inconsistency of how light clouds hold heavy water as well as frustration as they tried to convince their classmates of their inconsistency. At the same time, however, layered onto their vexation and frustration were signs of enjoyment as they smiled and laughed. Although their feelings of epistemic vexation produced discomfort, they were also eager and excited to figure out a solution to the problem. This was a common pattern in many of our cases—that students' inquiry appeared to be driven, in part, by feelings of vexation layered with their interest and excitement.

The case

In this chapter, I present an analysis from one of these cases. The case I discuss is similar to our others, in that it depicts an extended episode of students' scientific engagement in which disciplinary uncertainty appears to be a central feature of what started and sustained it. Like in other cases, there is evidence of students' problematizing and of their positioning themselves as not knowing. In this episode, however, there are different patterns of students' affect than we see in other episodes. Whereas in most cases, we see expressions of excitement and interest paired with students' expressions of vexation and puzzlement, in this case, students' affective expressions of excitement and interest were muted. In fact, in a majority of the episode, students appear primarily to be experiencing discomfort. Part of our understanding of what contributed to students' engagement in other cases involved students' deep emotional investment in doing science that was evident in their animated expressions of affect, so this case was puzzling to us. What motivated students to persist? Their attendance in the discussion section was not mandatory and the worksheet was not graded or even collected, so they could easily have given up or moved onto the next problem if they were not enjoying themselves. This pattern required an explanation.

Furthermore, this episode shows different patterns of participation in students' problematizing. Whereas in most of our cases, individual students take up the roles of nominator, endorser, and resistor, in this case, no single student fell into each of these roles. In the Clouds case, Jordan's commitment to the problem of how clouds hold water was a central feature of what contributed to the class's engagement. However, in this case, no student took the lead (and perhaps this is not disconnected from their lack of emotional expression). Without a "Jordan" to do the work of articulating, motivating, and encouraging others to consider the problem, how does this group maintain stability in their inquiry around it? In addition, Phillips (in preparation) found that cases where a student initially resisted the initiator's problem had more productive patterns of engagement than those that lacked a source of resistance. In this case, however, the resistance was responsible for destabilizing the engagement. Why did the resistance, in this case, shut down the engagement rather than help sustain it, like in other cases?

In the remainder of this chapter, I attempt to answer these questions in service of understanding what contributed to the emergence and persistence of students' scientific engagement in this case.

Study context and methods

In this section, I first give an overview of my methods for data collection, episode selection, and data analysis. Then, I provide a brief description of the physics course and discussion section where the data was collected. Finally, I provide some background for the episode, including a description of the physics concepts that student reference in the episode.

Data collection

The data for this paper come from a reformed introductory calculus-based physics course taught by David Hammer. This was the off-sequence version of the course taught in the spring of 2014, with around 65 students enrolled. I was a TA for this course, and the episode in this chapter took place in my discussion section at the end of February 2014. I set up one camera in the corner of the classroom to capture all groups simultaneously. External audio-recording devices were randomly placed near groups throughout the classroom.

The group that I focus on in this chapter was seated far from the camera, which reduced the video quality. After linking the audio to the video footage, I enhanced the video to magnify the focal group in order to capture any possible gestures and facial expressions. Only 3 members of the group appear squarely in the camera's frame (see Figure 2.2) and only two of the members are facing the camera, though their faces and bodies are frequently obscured by the backs of students who are sitting closer to the camera.

Episode selection and bounding

This episode was originally selected as a candidate case for the *students doing science* project. The only selection criterion for these cases was that they depict a clear instance of students doing science. These cases often involved one or more students engaged in an extended pursuit (~10-25 minutes, on average) to understand a physical phenomenon.

Episodes for the project were bounded on a case-by-case basis. When there was evidence of an onset of scientific engagement we included as much data as was necessary (and available) to study the shift. Other times, students were already in the middle of doing science when filming began, in which case we bounded the episode at the beginning of the available data. Sometimes we only included enough data to show sufficient evidence of students doing science. Other times, we included an activity up to its natural conclusion, which was typically marked by a change in subject (i.e., when students changed problem or topic) or by a shift in epistemic activity from doing science to doing something else (i.e., students stop doing science and start following an algorithmic procedure). The episode presented in this chapter shows a group working for 19 minutes on a single question. The episode has clear bounds—it starts when they begin work on the question and it ends when they move to the next one.

Methods of Analysis

I first conducted a moment-to-moment analysis of the episode for the project, in which I developed thick descriptions and evidence-based conjectures about what was taking place using methods of knowledge, conversation, and discourse analysis (Derry et al., 2010; diSessa, Levin, & Brown, 2016; Jordan & Henderson, 1995; McDermott, Gospodinoff, & Aron, 1978; Stivers & Sidnell, 2005).

In the analyses developed for the project, we were careful to distinguish between 4 levels of inference when making interpretations:

(1) At the most basic level, we documented participants' talk and actions, using text from the transcript and often including descriptions of their tone of voice, prosody, and volume. We also documented relevant gestures and facial expressions to the extent that the information was available. Because it was not possible to describe every aspect of the

activity, we focused on details that seemed relevant to the activity. For example, in one of our cases, many students wore the same brand of shoe in varying colors. Though this detail may be relevant for a sociological study of fourth grade clothing fads, there was no evidence that it played a role in the dynamics of students' activity, thus, we did not note it in our analysis.

(2) At another level, we described the structure of participants' activities, noting both the epistemic nature of the activity (such as whether students were developing a model, questioning a conclusion, seeking a mechanism, or computing an algorithmic solution) and the participation structure of the activity (such as whether students were addressing answers to the teacher or to each other, or whether students were building or seeking knowledge).

(3) At times, it was necessary to make interpretations about the meaning that students were making. For instance, when a third-grade student, Isaac, said that a car without wheels will "rag and stop," we made interpretations about what he meant by *rag*. We used Isaac's speech and accompanying gestures, such as dragging a car against his hand, as evidence to support our interpretation that for Isaac, *rag* means something similar to *drag*. We also looked at other instances where Isaac used the word *rag* to determine whether he was using it consistently. From this analysis, we discovered that the word *rag* held quite technical and specific meaning for Isaac.

(4) Finally, we made some interpretations about participants' intentionality. We did this quite carefully and sparingly, reserving this level of analysis for when we thought it was necessary to understand what was taking place.

I used this moment-to-moment analysis to develop conjectures about what contributed to the emergence and stability of students' engagement in this case.

Course background

This physics course focused on supporting students' engagement in scientific sense-making. Because this was an off-sequence course, many of the students were freshman or sophomore chemical or environmental engineers who were taking physics as an elective course. The course was "flipped," with students watching pre-lectures prior to each lecture, where students worked in pairs to respond to a series of "clicker questions" and were encouraged to reason through multiple arguments for any given problem. Students completed weekly problem sets and were awarded points for clear and sensible reasoning regardless of whether they answered it correctly.

In teaching assistant (TA)-led discussion sections, for which attendance was optional, students had space to pursue their own inquiries. If no student-generated questions arose, I and other TAs generally provided worksheets with challenging questions for students to solve. We closely monitored students' progress and prepared material that was responsive to each section's needs. Sometimes we wrote questions that highlighted an issue students were grappling with; other times we would share a student's question that stumped us.

The discussion section I describe below had about 15 regular attendees. In discussion sessions, I normally gave students tasks to work on in groups, which they completed at their own pace. Sometimes students would opt to work alone on their own problems, but most often they worked with others who were sitting near them, typically in groups of 2-5 students. The focal group in this episode did not, to my knowledge, work together regularly.

Episode background

The week before this discussion session, which took place about a month into the semester, students had taken their first exam on forces and motion, and since then, they had two lectures on the topic of work and energy, including about kinetic and potential energy, and conservative forces. At the start of this discussion session, I returned graded exams from the previous week and gave students a worksheet with three questions on the topic of work and energy.

The episode follows a group of students as they work on the second question on the worksheet (shown in Figure 2.1), which I wrote based on a question from their practice exam.

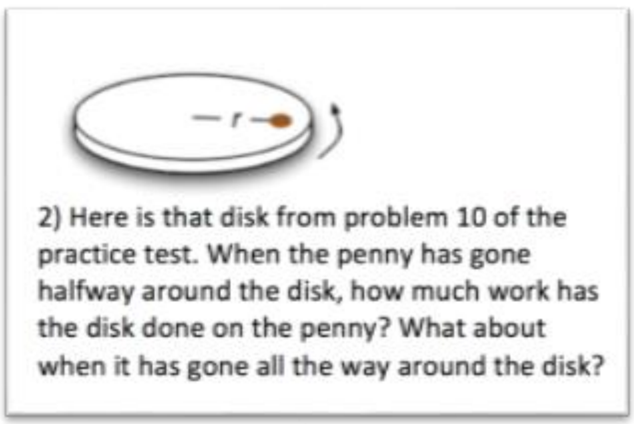

Figure 2.1: Question 2 from the worksheet. This question references a previous one that describes the following situation: "a penny of mass m sits on a disk at a radius *R* from the center of the disk. The coefficient of friction between the penny and the disk is μS. The disk rotates at a constant rate. In other words, the penny is moving in a circle of radius *R* at a constant speed."

By this point in the semester, students have studied that the centripetal force is $\frac{mv^2}{R}$ (where *m* is the mass, *v* is the speed, and *R* is the radius) for constant circular motion. They have also learned multiple definitions of work:

(1) Work is equal to $\int_d \vec{F} \cdot d\vec{r}$ where the dot product is taken between the force, $\vec{F}$, and an infinitesimally small change in position[7], $d\vec{r}$, over a distance, d. In the case of a constant force, they have learned to approximate this equation as $W = \vec{F} \cdot \vec{d}$, or, $W = |\vec{F}||\vec{d}| \cos\theta$, where $|\vec{F}|$ and $|\vec{d}|$ are the magnitudes of the force and distance vectors, and θ is the angle between them. In essence, this equation picks out the component of the force that is in the direction of motion and multiplies it by the distance traveled. In the case that $\theta = 0$, the equation simplifies to $W = F * d$. In the case that $\theta = 90°$, as is the case for the penny in problem above, none of the force is in the direction of motion, and therefore no work is done.

(2) The total work done on an object (by all forces acting on it) is equal to ΔKE, or the change in kinetic energy of the object (where $KE = \frac{1}{2}mv^2$ or $KE = \frac{1}{2}m\vec{v} \cdot \vec{v}$). That means, for an object with an unchanging mass, doing positive work on an object (applying a force in the direction of motion) increases its speed and doing negative work on an object (applying a force opposite to the object's motion) decreases its speed. Since work is calculated from the dot product of two vectors in either case, it is a scalar quantity, meaning, it has no direction.

These definitions highlight two different aspects of work. Definition (1) is a process-oriented account, which considers how the force is transferring energy to the object at every point along the object's path. Definition (2) is an outcome-oriented account of work, which looks at the beginning- and end-states to determine whether the speed/kinetic energy has increased or decreased. Students have also learned about conservative and non-conservative forces, which have implications for the conservation of mechanical energy (for example, gravity conserves mechanical energy, but kinetic friction does not) and how to calculate work (for conservative

[7] The position, *r*, is not to be confused with the radius of the disk, which I will designate with a capital *R*.

forces, only the total displacement is taken into account and for non-conservative forces, work is calculated along the entire path traveled). I designed this problem to help students disentangle as well as make connections between these two definitions of work. I hoped that it would elicit their physical intuitions about energy and motion to serve as resources for sense-making about the formal physics. The focal episode follows the discussion of a group of five students—George, McKenzie, Brian, Elijah, and Jackson—as they work on this question (see Figure 2.1).

Episode analysis

In what follows, I divide the episode analysis into 5 segments. There is a link at the top of each segment to the corresponding video, and I encourage the reader to watch the video before reading the analysis. When necessary, line numbers are referenced in-text, and a transcript with corresponding line numbers can be found in Appendix 2.1.

1. Initially approaching the problem as a simple calculation (Lines 1-51)

Students immediately approach this problem by plugging numbers into an equation and methodically chugging through the calculation. They first calculate work by multiplying the centripetal force on the penny with the distance it travels around the disk. This equation assumes that the force is in the same direction as the displacement, which is not true in this case, but it is typical for students to use this equation when calculating work more generally[8]. In fact, when designing the problem, I expected that many students would employ this method early in their problem solving and that it would inevitably contradict with their ideas about energy conservation. However, the group does not stop to think about the physical implications of this calculation, so they do not notice the contradiction.

[8] This is similar to how students apply the equation $x = \frac{1}{2}at^2$ to cases of non-constant acceleration.

In their activity, there is little evidence of scientific engagement. The dialogue progresses in a steady and unexcited manner as students chug through the calculation. This pattern gets interrupted briefly when Elijah draws their attention to a potential flaw in their reasoning—that perhaps they should be calculating work using the penny's displacement rather than distance it traveled. However, they quickly settle the issue and return to their rote calculation.

2. Instructor intervenes and a problem emerges (Lines 52-121)

When I first approach the group, George asks me to verify that friction, a non-conservative force, is path-dependent. Here, George frames Elijah's question, not as a substantive issue, but as a definitional discrepancy that can be settled by asking an authority—more evidence that they are not yet orienting to their activity as sense-making. I respond to George's question by drawing a conceptual connection between work and energy in the case of kinetic friction, in particular, pointing to heat dissipation as a path-dependent mechanism of energy transfer. Prior to this point, the group had not discussed conceptual notions of work or energy nor did they use evidence from the physical world to make sense of their calculations. After this point, however, students begin to problematize their solution.

In particular, George points to something puzzling when he asks, "Um, so I guess because it's non-conservative, then we would have a force which would just be the - or work-which would just be the force times the distance it travels. But I was wondering-…what- what is-like, the- how is energy being transferred? /2s/ In this case" (lines 88-9, 91, 93, Appendix 2.1). Although George does not fully explain the issue, here is my interpretation of it: If static friction does work on the penny (which they calculated using the equation $W = F * d$, and if work implies energy transfer, then the static friction force must somehow be transferring energy to the penny. If so, what is the mechanism of energy transfer? As he articulates his problem, George explicitly marks his uncertainty by positioning himself as *wondering* (line 91, Appendix 2.1). George appears genuinely unsure about whether static friction can dissipate heat like kinetic friction; he displays some skepticism about it (lines 63-4, Appendix 2.1) but at the same time he is unable to identify an alternative mechanism. Here we see George starting to make sense of the physical implications of their solution. Namely, how is the static friction between the disk and the penny transferring energy from the disk to the penny?

Like George, McKenzie begins to consider the physical implications of their solution, but whereas George wonders *how* the disk transfers energy to the penny, McKenzie wonders *whether* it transfers energy at all (lines 96-7, 101-2, Appendix 2.1). Although she does not fully articulate it, McKenzie points to an inconsistency between their calculation and the work-kinetic energy theorem[9]. Namely, if net work is done on the penny, then its kinetic energy, and thus its speed, must increase. However, the problem explicitly states that the penny is moving around the disk at a “constant rate,” and so in McKenzie’s words, “it doesn't have more energy” (101). As she says this, she puts an emphasis on the word *have*, revealing a slight sense of urgency in her articulation of the problem.

In this segment, both McKenzie and George begin making physical sense of their calculation, an orientation which was markedly absent at the beginning of the episode. Whereas they first approached the problem by plugging numbers into an equation without attending to the physical implications, we now see them starting to check their solution for coherence with other parts of their understanding and experience. These productive resources appear to have been cued up, at least in part, by my answer to George (lines 59-62, Appendix 2.1), in which I

[9] Although McKenzie does not explicitly reference the work-kinetic energy theorem, she is certainly appealing to an outcome-oriented definition of work when she says that the penny “doesn't have more energy” (line 101, Appendix 2.1) at the end of its rotation.

conceptually link work and energy transfer; as George and McKenzie consider the physical implications of their solution, they become increasingly aware of inconsistencies and gaps in their understanding. However, this awareness does not automatically tip them into stably sense-making. In fact, when I say, "So it seems like you guys think that there isn't a transfer of energy" (line 108, Appendix 2.1), McKenzie and George defer to my authority and quickly agree, despite the fact that this conclusion contradicts their calculation. Neither attempts to reconcile these contradicting arguments (lines 109-111, Appendix 2.1), more evidence that, while they have begun articulating their uncertainty, they are not yet stably sense-making.

3. Initial attempts to reconcile the inconsistency (Lines 122-170)

After I leave the group, charging them with the task of reconciling this discrepancy, they immediately start deliberating. George offers a potential solution, saying, "Well now I think that it- doesn't do work…and I think our flaw was we were just multiplying it and not taking the dot product of the vectors…so the force is like constantly changing, so then, I want to say because it's changing around the circle, it always cancels out" (lines 123, 125-6, 128-130, Appendix 2.1). Here, George suggests that the effects of the force vectors *cancel out*, resulting in zero work done. However, he does not offer a tangible reason for why the dot product would produce this cancelation effect. In addition, his use of the word *just* positions the problem as trivial—evidence that he is still orienting to this problem as easily reconcilable.

Immediately, Brian points to a flaw in George's reasoning, arguing that George's explanation relies on symmetry, which the half-rotation case does not satisfy. Brian's challenge destabilizes George's orientation to the problem as easily reconcilable. George responds by positioning himself as uncertain (line 133, Appendix 2.1) (Watkins et al., under review) and reiterating the discrepancy. He says, "But then if you think about what- it's not speeding up, it's not being raised up. So like, how is it /. / gaining energy? Like if there is work done" (lines 137-8, 140, Appendix 2.1). As he says this, he opens and upturns his palm slightly, a gesture which typically indicates or communicates uncertainty. He then moves his hand to his head in what appears to be a head-scratching gesture (see Figure 2.2), indicating puzzlement. Here, we see George and Brian taking up the respective roles of constructor and critiquer of claims (Ford, 2008). Brian's critique of George's claim reveals his attempt to sense-make, which George takes up and further stabilizes as he expresses his uncertainty about how the penny might have gained energy.

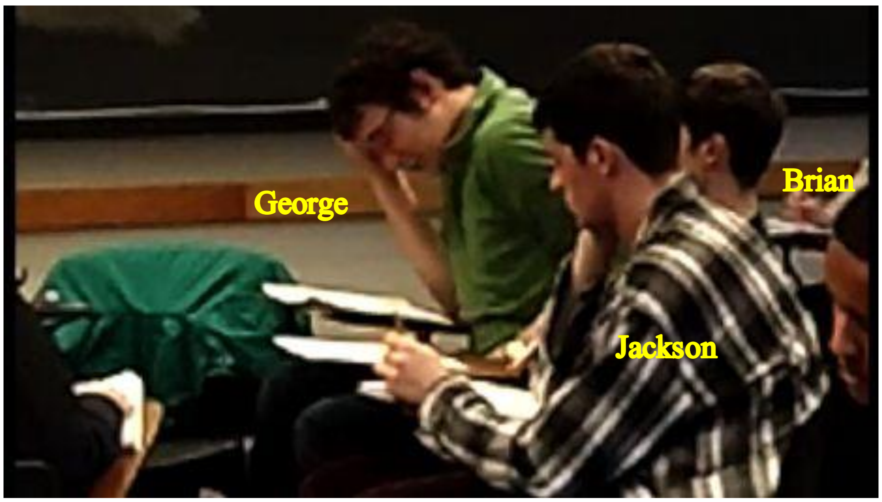

Figure 2.2: George's head-scratching gesture

In another attempt to reconcile the discrepancy, McKenzie revisits and questions her earlier assumption that the penny "doesn't have any extra like potential energy or kinetic energy" (line 102, Appendix 2.1) because it is "not moving any more like once it gets to the end" (lines 96-7, Appendix 2.1). She claims that perhaps their flaw was misinterpreting the v in the kinetic energy equation to mean speed rather than velocity. Brian and Elijah help her develop this claim, saying that “there is an acceleration” (line 144, Appendix 2.1), so the penny’s “velocity is changing” (line 147, Appendix 2.1) even though its “speed's not changing” (line 147, Appendix 2.1). If the v in the kinetic energy calculation ($KE = \frac{1}{2}mv^2$) refers to the penny’s velocity, rather than its speed, then this new account implies that the penny’s energy changes as it rotates, which is consistent with the results of their original calculation. Almost immediately, however, McKenzie and Elijah identify a flaw in their reasoning (lines 156, 158, Appendix 2.1) — “the velocity will be the same once it gets all the way back to where it started cause it'll be in the same direction, and it's not speeding up” (lines 159-60, Appendix 2.1). If they are calculating the penny’s change in energy based on the changing direction of its velocity, then once it gets back to its starting point and returns to its original velocity the net change in energy should be zero. This solution is problematic because if the penny gains energy after a half-rotation, but not after a full-rotation, there is still a conflict with their earlier calculation. In addition, more explanation would be needed to account for how energy is gained and then subsequently lost as the penny travels around the disk.

As McKenzie and Elijah critique their own claim, Brian continues to argue for it, saying, “But, since like, friction is the one that's, like, kind of acting on it, it's not conservative so it- /. / it does depend on the path it takes” (lines 161-2, Appendix 2.1), alluding to their earlier discussion about the effects of a non-conservative force being path-dependent. Here he argues that they must consider the work friction does along the entire path the penny travels and not merely take the difference between its initial and final velocity. Elijah responds, “So then where does the energy go?” (line 164, Appendix 2.1) with increased pitch and volume, emphasizing the word *energy*[10]. Elijah's tone communicates some urgency as he challenges Brian to account for *how* the disk does work on the penny. Although Elijah does not participate as actively as other students, this moment shows that Elijah is aware of the discrepancy and is feeling some vexation about it.

Brian continues to argue, "Cause like, if you don't do anything, your just- thing sits there, versus if it goes all the way down- around once, friction did play a big role. And, it did do something as it was going around, and it's not gonna like- I don't know like cancel out with itself if it just goes back around once" (lines 165-8, Appendix 2.1). As he says this, he puts his pen down and uses his hands to model an imaginary penny *just sitting there* (see Figure 2.3) and then moves his finger around to indicate *going all the way around once*, physically embodying the motion of the penny. He also raises the volume of his voice and emphasizes the word *something* while he drops his hand to his side in an upturned palm. Brian appears to be experiencing a tension in this moment, perhaps between his strong intuition that friction does work on the penny[11] and his lack of a plausible mechanistic argument to support it.

In this segment, we see the group's growing awareness and appreciation of the non-trivial nature of the discrepancy stimulate their vexation and elicit more stable patterns of sense-making. Students are engaged in constructing, critiquing, and communicating claims, they are thinking deeply about the physical context of the problem and are making sense of each other's claims using evidence and intuition. This pattern appears, at least in this segment, to be elicited and maintained by the entire group, rather than by any one student. For example, Brian's initial

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[10]Since Elijah's normal prosody is extremely monotone, even slight excitement in his voice is evidence of heightened affect.

[11] And this intuition is reasonable: Circular motion is one of the few cases of perpendicular acceleration, in which a force acts to accelerate an object but does not do work on it. Brian is correct that force *is* doing something to the penny—it is changing the direction of its velocity.

Figure 2.3: Brian's embodied gesture

challenge to George activates a more productive pattern of engagement that is then taken up and sustained by George, McKenzie, and Elijah.

Also contributing to this stability are feelings of vexation which are evident in students' expressions of uncertainty, in the urgency and puzzlement in their speech, and in their physical gestures and non-verbal expressions. These feelings appear to be entangled with individual students' identification of or renewed attention to the discrepancy as well as with their attempts to seek out a solution.

4. George's new case (Lines 171-248)

Up to this point, the group has made several attempts to reconcile the results of their calculation with their ideas about energy transfer. So far, they have proposed and found flaws in arguments for both sides, but have not made much progress toward finding a solution. At the start of this segment students continue to construct and critique solutions but their new lines of reasoning rely on mathematical technicalities that are disconnected from the physical phenomena they represent.

About a minute into this segment, George shifts the conversation by drawing the group's attention to another vexing phenomenon. He says, "What I don't get is like how something that's really heavy and you push it and it doesn't move, like where does the energy go?" (lines 194-5, Appendix 2.1). At first George appears to be entirely departing from their problem, but he goes on to mark the connection more explicitly saying, "It's similar to like static friction. /2s/ So like how /. / does /. / static friction transfer energy between the penny and the spinning? /3s/ Cause like it's not- I mean I guess maybe it is heating up and that's just like- but I can't conceive of something like heating up like that" (lines 195-9, Appendix 2.1). Even with George explicitly linking these cases, the conceptual connection between them is not immediately clear aside from the presence of static friction in both cases. In the penny case, friction is the only force acting on the object, which results in acceleration; in the heavy object case, friction acts to keep the object stationary by opposing a pushing force.

However, both cases speak to the question George asked at the beginning of the episode: "how is energy being transferred?" (lines 93, Appendix 2.1). Namely, in both of these cases, the mechanism of energy transfer is obscured. Where does all the energy from the pushing go when an object remains stationary? Similarly, where does the energy from the friction force go if the penny does not speed up? Notably, this new case assumes that energy has been transferred, and shifts the problem to identifying a mechanism of energy transfer that might account for a loss of energy (like in the form of heat), rather than an increase of the penny's kinetic energy.

It is unclear whether George is leveraging this familiar situation to make sense of the penny problem or whether the penny problem has sparked his curiosity about this new case. There is evidence that elements of both are happening for George: When he makes a bid to transition back to their previous activity, he says, "I don't know if this is important to this problem or if it's just a tangent" (lines 241-2, Appendix 2.1), marking his ambivalence about the value of this new case for their original problem.

Either way, George appears to be vexed enough by this new problem to disrupt an ongoing discussion and persist in seeking a solution to it. He introduces it by explicitly marking his uncertainty ("What I don't get…") and rubbing his forehead, a gesture indicating puzzlement. He also raises the volume of his voice when he says the word *how* (line 195, Appendix 2.1), communicating his interest in and sense of urgency for identifying a mechanism of energy transfer. Finally, when he says, "Cause it's not- I mean I guess maybe it is heating up and that's just like- but I can't conceive of something like heating up like that" (lines 197-99, Appendix 2.1), he opens uplifted palms in a display of uncertainty (see Figure 2.4), reminiscent of the glimmer of vexation he displays about this issue in Segment 2 (lines 63-4, Appendix 2.1). George's skepticism about heat as a possible mechanism is only exacerbated by McKenzie's arguments challenging the notion that friction might be dissipating heat. She appeals to George's physical experience, saying, "But, if you think about it, like, it's not [dissipating heat], you'd feel it, if like- unless your feet start to move, then you like might feel like the heat" (lines 232-3, Appendix 2.1). This tension helps us better understand George's vexation in this moment—he cannot fully convince himself that heat is dissipated in this case but he also cannot identify a plausible alternative.

McKenzie, on the other hand, does not appear bothered at all about lacking an energy transfer mechanism, possibly because she is not convinced that energy transfer is even happening in these cases. Brian, however, who has consistently argued that the disk *does* do work on the penny, appears to display some vexation about it. George's new problem seems to appeal to Brian's physical intuition in a way that parallels his intuitions in the penny case. The tension for

Brian is evident here as well, when he says, “But it feels like- like you do push against it and it doesn't move, so you are like transferring it but it’s just like not enough or something, I don't know” (lines 203-4, 206, Appendix 2.1). As he says this, Brian pushes his arms out in front of him, again connecting to his physical intuition by imagining he is pushing on something. Just like in the penny problem, vexation seems to emerge for Brian in the tension between his physical intuition that the force is *doing something* and his lack of a mechanistic account of what that *something* is or how it relates to work.

As the students discuss this problem, George continues to display vexation over whether and how energy is transferred. For instance, when he says, “But does that energy dissipate as heat then?” (line 207, Appendix 2.1) he inflects his voice, and uplifts his palms (like in Figure 2.4), indicating uncertainty. He also reiterates the problem multiple times, saying, “But still, how is that friction like transferring energy if you’re just standing there, but pushing?” (lines 225-6, Appendix 2.1), speaking in a higher pitch with upturned palms, indicating urgency and puzzlement. Finally, after George says, “But if I press really hard to the ground for a long time, I don't, feel heat” (line 238, Appendix 2.1), he rapidly clicks the back of his pen, indicating some agitation.

Figure 2.4: George upturning his palms

Although George's question does not end up illuminating much for the penny case, it elicits a productive discussion in which students are constructing and critiquing claims, making nuanced arguments, and drawing on analogical reasoning. McKenzie continues to argue against the idea that heat is dissipated in this case, recruiting the limiting case of a wall to show that for extremely heavy objects, it is the object's mass, not heat-dissipating friction, that is responsible for keeping it in place (lines 209-210, Appendix 2.1). George suggests that they can think of the wall as a really stiff spring that compresses when you push it, but insists that in the case of pushing a heavy object, like a refrigerator, it is the friction and not the springiness that keeps it from moving (lines 211-213, 215, 217, Appendix 2.1). Elijah points out that if you are pushing on a wall, there is friction between your feet and the ground (line 221, Appendix 2.1), which George considers for a moment (line 222, Appendix 2.1), but then McKenzie challenges him, saying that the friction under your feet keeps the person, not the wall, from moving (lines 223-4, Appendix 2.1).

This segment marks another shift for students in the episode, not into sense-making but towards the articulation and pursuit of a new problem. One might expect this shift to disrupt the science—since students had not yet answered the question they were pursuing—but it does not. In fact, George's question helps shift the group toward thinking about physical mechanisms, arguably closer to doing science than was the detached mathematical reasoning they had been doing moments earlier.

George's vexation may be contributing to his scientific inquiry by establishing a need to seek out innovative solutions, which he does in this case by drawing on an adjacent phenomenon to make sense of the penny problem. This move contributes to the stability of George's engagement, and it is also evidence that George is seeking coherence more generally. The shift, from mechanically calculating solutions at the start of this episode to seeking out new phenomena to wonder about and leverage is quite drastic.

Although others do not display the same level of interest in solving this new problem, they seem to empathize with his pursuit. Even when McKenzie challenges George on the issue of heat dissipation, she does not challenge the underlying premise of his pursuit or the framing of it more generally. Rather, she engages it. Furthermore, when George suggests that perhaps this case was a “tangent” from the penny problem (lines 241-2, Appendix 2.1), McKenzie reassures him of its value, saying, “It's kind of a tangent. But if we could figure it out it would probably help us with this. Maybe” (lines 243-4, Appendix 2.1). Perhaps it is this empathetic stance that has the group’s scientific inquiry continue undisrupted, despite George having abruptly shifted the group from its previous discussion. George’s question provides the opportunity for students to build coherence between the penny problem and other physical phenomena, and establishes the need for their engagement in a wide range of epistemic practices; it also serves to further stabilize the group’s sense-making.

5. McKenzie finds a solution but others are still unsatisfied (Lines 249-350)

George shifts the discussion back to the penny case by problematizing the notion that energy was transferred. He says, “My issue with the like- work being positive, is that, like the force is constantly changing direction” (lines 249-50, Appendix 2.1). It is not completely clear what George’s “issue” is, but one possibility is that he thinks that as the direction of the friction force changes, the “sets” of opposing forces will eventually *cancel out*, resulting in zero net work. He made some version of this argument earlier, saying, “So the force is like constantly changing, so then, I want to say because it's changing around the circle, it always cancels out” (lines 128-130, Appendix 2.1).

Moments afterward, the students discover that the force and displacement are perpendicular to each other, which means work would be zero. This discovery is technically correct, but the group still does not appear to have a deep conceptual understanding of why this fact is true. Brian provides mathematical support, saying, “Because cosine of ninety is zero” (line 274, Appendix 2.1)[12], but no one offers a conceptual explanation. When McKenzie hears this revelation, she exclaims, “If they're perpendicular, it's zero?... Oh, so it's zero!...That's the answer!...There we have it! It's zero!” (lines 263, 266, 268, 270, Appendix 2.1). McKenzie’s response conveys excitement and relief, the most affect we have seen from her to this point. Looking back at her contributions, she has been actively engaged in reconciling their calculation with their conceptual notions of energy. For McKenzie, this discovery resolves the conflict and supports her initial observation that the penny’s energy does not appear to change. This moment reveals some emotional relief—evidence that she may have been experiencing some pent-up vexation.

In stark contrast to McKenzie’s displays of relief are George and Brian’s expressions of lingering dissatisfaction. The source of Brian’s dissatisfaction is clear—this conclusion conflicts with the physical intuitions he appealed to earlier, that friction *somehow* does work on the penny (lines 165-168, Appendix 2.1). He voices this sentiment again, saying, “But it still- it seems like friction, a non-conservative force, it's what's like causing it like to go around, you'd think that like-” (lines 277-8, 280, Appendix 2.1). However, when McKenzie challenges him, saying, “But where does it go, then? Cause with- with kinetic friction you can say it's heat but like, where does- where does it go? Energy is conserved. But it doesn't have more eh- but like the penny

[12]Although they had been using an equation that assumes the force and displacement are in the same direction, $W = F * d$, the more precise equation is $W = |\vec{F}||\vec{d}|\cos\theta$, which takes the angle between the force and displacement into account. Since, in this case, the angle between the force and “displacement” is 90 degrees, work is equal to zero, since $\cos\theta = 0$.

doesn't have more energy!" (lines 284-6, Appendix 2.1), he still cannot provide her with a plausible mechanistic account for how the penny gains energy.

The source of George's dissatisfaction is less clear. After all, he just finished expressing doubts about "work being positive" (lines 249-50, Appendix 2.1) and he seems to agree with McKenzie's conclusion (lines 284-6, Appendix 2.1), saying, "Yeah. Like when it's on the other side, it's not going any faster and it's not, any high- it doesn't have any more kinetic energy or potential energy" (lines 287-8, Appendix 2.1). From these accounts, George should be satisfied with the answer that work is not done on the penny. Yet, he hardly reacts to McKenzie's exclamations and he immediately voices lingering concern (line 269, Appendix 2.1). Something is clearly still bothering George; however, the precise nature of his vexation is unclear, possibly even to him.

The group eventually decides that the disk does positive work on the penny after a half-rotation, more evidence that McKenzie's conclusion was not stably rooted in a conceptual understanding of the phenomenon. This discussion triggers more of George's confusion. He starts to say, "So then, does it do positive work through the first half? And then-" (line 308, Appendix 2.1), but then he trails off. He then gives a more complete description of his confusion, saying, "But what I'm confused is that- so I get why it would be zero when it goes all the way around. Because like, the way I see it is like the forces all cancel out at every point. Cause if you like consider like the vector force at every point there's also an opposite one, so it cancels out, but if you go halfway? does that mean that, it's like, the work done's positive on the first way around? and negative on the other way around? so they cancel out?" (lines 322-3, 326-8, Appendix 2.1). Here George is raising an issue of symmetry: No point along the penny's path is distinguishable from the next, so why would the disk do positive work over the first half of the path and negative work over the second half? This explanation might work in the case of a full rotation, but it falls apart for explaining the work done on the penny at any other point along its path. George appears to be struggling with mapping his mathematical intuitions about vectors ‘canceling out’ onto the physical world. He says, “Why would one be positive and one be negative? I guess it just depends on which direction it's going. And which direction on the plane is positive” (lines 333-4, Appendix 2.1), and then, “But what gives it that negative sign? I guess it's the direction of-” (line 342, Appendix 2.1), before trailing off again. On the one hand, he tries to explain the tension away with an arbitrarily defined coordinate system, but on the other hand, this “magical fix” seems to deeply trouble him. This problem induces more vexation for George, who repeats the problem another few times (lines 339-40, 342, 344-5, 347, Appendix 2.1).

McKenzie, Brian, and Elijah seem to empathize with George’s struggle at first, but they eventually appear to lose interest. They move from engaging and challenging George’s vexation (lines 309-321, Appendix 2.1), to merely affirming it (lines 324, 325, 329, 331, 335, Appendix 2.1), to finally dismissing it (lines 337, 341, 343, Appendix 2.1). Eventually, McKenzie makes an explicit bid to move onto the next problem (line 349, Appendix 2.1), and George, although still visibly struggling, agrees (line 350, Appendix 2.1).

The start of this segment marks another shift in conceptual substance but the group remains stable in their sense-making. However, that stability is quickly disrupted when McKenzie discovers a potential solution to their problem. Although George is still grappling with the ‘canceling out’ argument and Brian is still struggling to reconcile this conclusion with his intuition, McKenzie’s vexation appears to be resolved, and there is a corresponding shift in her participation. Before this moment, she played a fundamental role in shaping the conceptual and epistemic substance of the discussion—she offered ideas for how to reconcile their inconsistency and took up others' ideas to explore their physical and logical consequences. After, however, she makes multiple bids to reach a conclusion (lines 270, 272, 276, 281, 284-6, Appendix 2.1), including her final bid to move on to the next problem, which the other students take up.

There is also evidence that McKenzie made the bid to move on despite not being fully satisfied with the answer. Here is some transcript from a few minutes later (not included in the video data), when I return to check on the group:

Jen: You guys figure it out?

McKenzie: No.

George: No.

Jen: Which one's wrong?

(everyone laughs)

McKenzie: Sort- No.

George: Sort of.

McKenzie: We like came up with more arguments /./ for both of them (laughs).

George: I think we've reached a middle ground- it's zero when it goes all the way around and positive when it goes halfway around.

When I ask if they figured it out, McKenzie says, "no" and then laughs and says that they came up with more arguments for both of the outcomes, perhaps aware that this conclusion violates my directive that they should have agreed on a single outcome.

Discussion

My goal for this study was to understand what contributed to the emergence and stability of this group's scientific engagement in an extended episode of their inquiry. In other cases, we have identified some common contributing factors to the scientific engagement, including students' problematizing, their positioning themselves as not understanding, and their affective expressions of vexation layered with interest and excitement.

My analyses in this chapter reveal that these themes indeed contributed to the dynamics of students' engagement, but this study also reveals new insights into the affective and social dynamics of these students' disciplinary uncertainty. In particular, they call attention to (1) the complex dynamics of students' epistemic vexation in supporting as well as disrupting students' engagement, and (2) the distributed nature of the group's stability amongst its members and the instructor.

(1) The complex dynamics of students' epistemic vexation

In other cases, we found that students' epistemic vexation was paired with expressions of interest and excitement. In these cases, although the vexation served as a kind of irritant, students experienced it as an agitated excitement to figure out a solution, which contributed to their productive scientific engagement. In this case, although students do not express their vexation as similarly energizing, it nevertheless appeared to be a primary factor contributing to the emergence and persistence of their engagement. Students initially oriented to the problem as a simple calculation but shifted to doing science when they recognized an inconsistency. It was the puzzle of the inconsistency, rather than an interest in the phenomenon, that initiated their inquiry, and their initial attempts to resolve the inconsistency resulted in some productive scientific work: Students offered and found flaws in arguments, they developed thought experiments to "test" their ideas, they critically examined their assumptions, and coordinated across mathematical, conceptual, and intuitive representations of phenomena.

Although their engagement did not appear to be driven by an independent interest or investment in the phenomena, some students developed these feelings as their inquiry progressed. For example, George seeking out a new case to explore mechanisms of energy transfer was evidence of his developing curiosity about the phenomenon more broadly. Finally, there is evidence that the group's persistence in the face of challenges and many failed attempts at reconciling the problem was driven, in part, by their feelings of vexation. For instance, at the end of the episode, George expressed intense puzzlement and uncertainty as he attempted to reconcile why work would be negative for one half of the penny's rotation and positive for the other half, and he pursued this problem despite other students' apparent loss of interest in it.

While epistemic vexation played a central role in initiating and sustaining students' inquiry, there is also evidence that these same feelings of vexation were responsible for eventually disrupting it. In most of our other cases, students' engagement would come to a natural conclusion when the inconsistency or problem was resolved. In this case, however, the group's engagement was disrupted before they came to a satisfying conclusion, when McKenzie made a bid to move on to the next problem. Unlike in other cases, where students' feelings of vexation acted to energize their engagement, in the last few minutes of this episode vexation appeared to inhibit the group's engagement. In particular, there is evidence that after McKenzie's vexation was alleviated, she resisted returning to that state of discomfort. Despite her initial excitement at finding "the answer," there is evidence that she was not fully satisfied by their conclusion that positive work is done halfway but no work is done all the way around the disk. Nevertheless, she resisted engaging with George's and Brian's lingering uncertainty about it.

This is certainly not meant to be an indictment of McKenzie, nor do I wish to attribute to her a stable stance or orientation toward uncertainty or vexation. In fact, McKenzie actively participated to advance the group's inquiry throughout the first half of the episode, and at times she appeared to enjoy the challenge. In addition, McKenzie was not solely responsible for the cessation of the group's engagement. When McKenzie made the bid to move on, neither George nor Brian protested. Even if George and Brian were feeling intense social pressure to move on, we see students in our other cases push back against similar moves to shut down their inquiry. Jordan, for instance pushed back against her best friend Alyssa, when she challenged the legitimacy of her problem. In the moment George gave consent to move on, it is possible that he, too, welcomed the prospect of abandoning the discomfort of his vexation despite his simultaneous desire to resolve his inconsistency.

To understand the functional variability of students' epistemic vexation within and across moments of their inquiry, I draw on the construct of meta-affect (deBellis & Goldin, 2006), or students' feelings about their feelings. In their work studying students' emotions about mathematics, DeBellis and Goldin (2006) refer to the complex structures of layered emotions that people construct and derive meaning from as "towers of meta-affect" (p. 136). In an example of one of these "towers," they describe how "one may feel *guilt* about one's *anger* about the *pain* of perceived rejection for academic failure by a parent whom one *loves*. At the core, perhaps, is the love; but the negative meta-affect transforms it into something painful, and the anger and guilt contribute to an enduring, albeit dysfunctional, structure" (p. 136).

Conceptualizing affect as *layered* helps us to escape the simplistic narrative of classifying emotions according to positive or negative valence (Pekrun & Stephens, 2012). Instead, we can think of epistemic vexation as a core emotion that, in local moments of activation, can be layered with other emotions such as curiosity or annoyance which can determine whether students engage in the hard work of articulating the precise nature of their vexation and seeking out a resolution or whether they abandon it.

For scientists, who engage with moments of uncertainty every day, the feeling of vexation, though still agitating, signals the promise of discovery rather than the fear of failure. They have learned, over time, that actively engaging with their vexation can eventually lead to satisfaction. This feeling is what makes the discomfort of vexation worthwhile, and it is, in part, what motivates scientists to spend their lives seeking out and solving challenging problems. Over time, we hope for students to learn to approach their vexation like scientists do, and we see evidence, even in this episode, of students starting to do the work of engaging and interrogating their vexation.

(2) The distributed nature of the group's stability

In our other cases, we found that, in general, a single student or a small group of students were responsible for articulating, motivating, and encouraging others to address a potential problem. In this case, the stability of the group's scientific engagement was a collective accomplishment, not attributable to any one student. Although at first glance, George appears to have driven much of the group's inquiry, the other students (McKenzie and Brian, in particular) were fundamental to starting and sustaining the group's sense-making. For instance, when George initially dismissed the discrepancy as trivial, it was Brian who challenged the lack of coherence in his argument. In addition, when George shifted the focus to the immutable-object case, other students empathized with his vexation, thus maintaining the stability of the group's engagement. Finally, McKenzie proved to be an essential player in maintaining the dynamics: As soon as her own vexation was alleviated, it was not long before the stability of group's scientific engagement dissipated.

Although epistemic feelings and motivations are experienced by individuals, this case shows how they can inform and be informed by others around us. Expressions of epistemic vexation can call others' attention to the existence of a problem, and motivate collaborative sense-making. In addition, we can empathize with others' epistemic vexation like we do with other forms of affect such as excitement or grief. Even if we do not feel vexed ourselves, we can recognize and feel moved by the passion of another's pursuit. My analysis of this case shows that students' epistemic vexation was quite powerful for activating their scientific sense-making in moments, but also highlights the importance of group dynamics for providing the energy and support to help that spark catch fire. On the other hand, we also saw that this energy can be quickly dissipated if any members of the group work to actively resist it.

Finally, although my instructional intervention was simple and brief, it played a fundamental role in eliciting their vexation and guiding their subsequent activity. As soon as I noticed their expressions of vexation, I encouraged them to articulate it, saying, "What do you guys think? /3s/ What's your confusion about that? Why does it seem /3s/ weird?" (lines 94-5, Appendix 2.1). This move provided the opportunity for students to contemplate their confusion as an object of reflection and for me to better identify what they were struggling with. In addition, when McKenzie and George quickly agreed with me that there did not appear to be a transfer of energy, I pushed them on it (lines 114-19, Appendix 2.1). Before walking away, I clearly articulated the two discrepant arguments that needed reconciling and I charged them with the task of reflecting on and sorting out their confusion. Had I merely walked away at that moment without intervening, they may have simply decided that "no work is done on the penny" and moved on to the next problem without examining their assumptions or figuring out why their calculation violated the principles of energy conservation. Rather than allowing them to stick with the unexamined “correct” answer, I encouraged them to problematize it. This finding points to the importance of instruction, not only for designing opportunities for students to grapple with uncertainty and confusion, but for the ongoing support that is necessary in these moments.

Implications and conclusion

In this paper, I presented an episode of students’ scientific engagement and analyzed it to understand what contributed to starting and sustaining the engagement. The analysis revealed that students’ feelings of being bothered by an inconsistency—i.e., their epistemic vexation—were consequential for the starting and sustaining students’ inquiry as well as for eventually disrupting it. The analyses also showed the stability of students’ engagement was a collective achievement, with each student (and the instructor) playing a role in sustaining the group’s inquiry.

Together, these findings have implications for research and instruction. First, this study contributes to research on students’ scientific engagement by highlighting the central role of affect, not only as an indicator of engagement (Engle & Conant, 2002), but as central to the dynamics of stability of students’ engagement. In particular, I have provided empirical support for Jaber and Hammer’s (2016) argument that epistemic motivations play a fundamental role in driving students’ scientific pursuits (Jaber & Hammer, 2016).

In addition, I have shown that some epistemic motivations, such as epistemic vexation, can function in complex and variable ways to both support and hinder students’ inquiry. This finding suggests that students’ vexation can be leveraged to support scientific engagement, but it also reveals challenges in doing so: Students’ meta-affect as well as contextual dynamics such as social pressure can also impact how readily they engage their vexation. Just recognizing that there is more to sort out is not always enough to initiate engagement, especially if the student has had a long history of peers and instructors perceiving these “tangential” avenues of inquiry as unnecessary detours. With so much value placed on getting the right answer, the value of identifying the flaw in the wrong answer is not always apparent to students. Furthermore, studies show that instructional incentives designed to reward answer-getting over sense-making can prevent even highly engaged students from taking the time to examine their own confusion (Danielak, Gupta, & Elby, 2014).

This is compounded by the fact that many teachers have difficulty letting their students struggle. Teachers’ concern with creating safe, caring environments for students (Burgess & Carter, 1992; Nias, 1989; 1999; Noddings, 1984) often translates to sheltering students from disagreements and challenges that trigger averse emotions such as confusion, anxiety, and frustration (Gellert, 2000; Hargreaves, 2000; Varelas, Becker, Luster, & Wenzel, 2002; Zembylas, 2005). Although this sentiment comes from a place of deep care for students, it can keep them from fully participating in the practices and pursuits of the discipline (Jaber, 2015). In addition, students and teachers often perceive uncertainty and confusion as “a sign that the student has failed in his learning: He hasn't been working hard enough, or he's just not smart enough” (Lipson, 1992, p. 91). Paired with these perceptions, feelings of vexation can trigger anxiety and frustration, which have been shown to hinder students’ engagement (Leander & Brown, 1999). These feelings can have long-reaching negative consequences for students’ developing disciplinary identities. For some, it can turn them off to science altogether.

This was almost the case for Marya, a freshman engineering major who took this course the previous year, began the semester with extreme anxiety in moments of uncertainty and confusion (Radoff, Jaber, & Hammer, 2016). Marya’s feelings of struggle led her to believe that she was not good at physics. However, after taking a reformed introductory physics course focused on helping students develop more productive approaches to learning, Marya experienced a dramatic shift. Rather than avoiding these feelings, Marya immersed herself in them. Eventually, she began actively seeking out opportunities to grapple with uncertainty and confusion; the feelings that initially alienated her were the very ones that drew her to the scientific enterprise.

Marya's case as well as the one presented here show how uncertainty and confusion may trigger negative meta-affect such as frustration or anxiety (DeBellis & Goldin, 2006; Radoff et al., 2016) which can feed back into students' self-image and self-worth. Fear of engaging these feelings may have students running from even the slightest hint of discomfort. However, since feelings of vexation often precede an understanding of its precise nature, fleeing at the first sign of confusion prevents the necessary work of examining and interrogating it. Thus, in order to support students' engagement in productive scientific inquiry, educators may need to do more than just design activities that elicit students' confusion. They may need to provide explicit affective and epistemological support for students as they experience and grapple with feelings associated with uncertainty and confusion.

In addition, this study informs our understanding of how to design for students' uncertainty by showing the value of instructors attending and responding to expressions of students' uncertainty in moments of their inquiry. In this case, I designed the penny question to elicit students' uncertainty and to support their active grappling with the ideas. However, I still needed to actively monitor for evidence of their confusion and uncertainty and make moves to support them both tacitly and explicitly. I not only provided an opportunity for students to grapple with their uncertainty by making the nature of it visible, but by positioning it as an object of reflection, I may have helped students tap into productive resources for framing uncertainty and confusion as potentially useful for uncovering deeper questions and understandings in science. This finding provides further support for conjectures about the importance of moment-to-moment responsive teaching for fostering the development of students' productive epistemological and meta-affective dispositions in science (Radoff et al., 2016; Robertson, Scherr, & Hammer, 2015).

While this study offers insight into some of the ways epistemic vexation plays out within students' scientific sense-making, it examines only a single occurrence of this phenomenon; more study is needed to understand how epistemic vexation and other forms of epistemic motivation play out in the individual and group dynamics of scientific sense-making. This work informs a broader endeavor to look across many more cases for how epistemic vexation gets expressed, taken up, and the role it plays within students' disciplinary pursuits. We have already begun this work by looking at the role epistemic vexation and other affective expressions play in individual and group-level scientific sense-making among in-service teachers enrolled in a blended-online PD course (Jaber, Hufnagel, & Radoff, in preparation). I hope to continue studying this construct across many contexts and timescales to better understand how it emerges and how to support it.

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Appendix 2.1: Episode Transcript

Segment 1

[1]**George:** This is going constant speed? Right?
Brian: Mhmm. So there's um, the only force would be um, that matters–
George: The one inwards
Brian: Yeah, so, (writing on his paper) mv squared over r /3s/ and then times the distance, which would be=
George: If it's halfway around it's–
Brian: =one half, two R, Pi, so [Pi R]?
George: [Pi R]
Brian: So it'd be like Pi mv squared
/3.5s/
George: Yeah. And then all the way around would just be pi? er– two pi R squared– two pi R
Brian: Two pi mv squared
George: Which, I suppose you'd expect that– for it to be double
/5s/
Elijah: Wait, but once it gets all the way around?
Brian: Oh:::
Elijah: It's at zero displacement.
George: Oh, yeah.
/3s/
Brian: Yeah, I think– I think I'm [[…]] (erases something on his paper)
McKenzie: Wait, so then also, the displacement when it only gets halfway around, it wouldn't be like–
Brian: Oh it would be [just straight across?]
McKenzie: [it would just be the–] two times the radius. ||**George:** Yeah.||
Brian: So t– ah::
George: (Orients to paper, writes) Just 2 R mv squared? Or– 2 mv squared? (Lifts his head. Looks at McKenzie?)
/2s/
McKenzie: Yeah.
/3s/

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[1] [ ] = overlapping speech
|| ||= overlapping speech, in-line
( ) = gesture or action
(( )) = non-discursive vocal expression
[[…]] = inaudible
[[?]] = uncertain transcription
/./ = short pause
/s/ = duration of longer pause
underline = emphasis
x::: = elongation
x- = false start, broken off speech

George: But, it's, not a conservative force though. So doesn't it dependent on the path? Cause it's, like- friction's doing it? /2s/ Like, if it were gravity, the displacement would be zero (drags pen in a vertical line downward on his paper) but-
McKenzie: Oh yeah.
George: Because /2s/ yeah because it's non-conservative? I think?
Brian: Is it non-conservative?
George: Yeah. I don't know. I'm not positive about it. ((laughs))
McKenzie: ((laughs))
/11s/
Brian: Oh yeah, cause aren't the only conservative forces gravity and like a spring?
George: Yeah.
Elijah: Wait so only conservative forces are path-
George: Yeah. Path independent.
Brian: Yeah.
/7s/
Elijah: So the::n:, it wouldn't–
George: So then- then I don't think that all the way around would be zero either, because
McKenzie: No.
George: because you'd still be traveling around the whole path. So then that would be two– two pi mv squared.
/6s/

Segment 2

Jen: How're you guys doin?
Elijah: Uh::::
George: So for two- since the force is friction, and that's a non-conservative force, it's not independent of the path. Right?
Jen: R::ight.
George: So even if it goes all the way around, it's still gonna
[have positive work?   ]
Jen: [And that makes sense, right?] Because if friction, we're thinking about is like, it's dissipating heat, right? If I go from here to here. Or from here around here all the way to here (drags water bottle across the table), I definitely dissipated more heat the second time than the first time, right? So clearly that's not path independent.
George: If the force that's being applied is ||**Jen:** Does that make sense?|| static friction, how is that, dissipating heat.
Jen: Ah. ((laughs)) So that's a gr:eat question. (George sits back in his seat and smiles) Um, ((laughs)) and I was just talking about it with a different- with one of the physics professors in the department.
/6s/
Jen: ((sighs)) So, when we're thinking about sta- so this is obviously not static friction ||**George:** Yeah.|| (drags water bottle) right? Um, and if I'm pushing on something and it's not moving, then it's not speeding up, right? I'm not moving it- it's not doing any- putting any force on it

through any distance, so there's no work- it's not doing any work on it, right? I think what you're asking is in the case of like the block, [on the cart-]

George: [Or like the penny turning] around.

Jen: Or the penny turning around.

George: Yeah.

Jen: So, the block in the truck is a little bit different than the penny turning around the turntable. Um, for reasons that I will let <u>you</u> figure out. Why are those two things different? ((laughs))

/7s/

George: I guess::- I don't know if this is it, but what if it's primarily[[?]] because the block is just accelerating in one direction whereas, so there's constant acceleration whereas the penny is changing direction at all times. ||**Jen:** Ok.|| I'm not sure why that affects, the way that the work is applied.

Jen: So, (points to the worksheet) come back to this situation now. It's non-conservative, and then before I went off on a tangent, what was the rest of what you were gonna say?

/3s/

George: Um, so I guess because it's non-conservative, then we would have a force which would just be the- or work, which would just be the force times the distance it travels.

Jen: Yeah.

George: But I was wondering-

Jen: Force dotted with the distance it travels. Yeah.

George: But then, what- what is- like, the- <u>how</u> is energy being transferred? /2s/ In this case.

Jen: What do you guys think? /3s/ What's your confusion about that? Why does it seem /3s/ weird?

McKenzie: Well because it- like, at the end, its- hasn't- it hasn't gone anywhere, and like, it's not moving any more like once it gets to the end.

/3s/

Jen: Ok. /2s/ You mean when it makes a full circle, it hasn't gone anywhere by the end of it. What about when it makes a half circle?

McKenzie: I mean, it's gotten somewhere but it's also like- it doesn't <u>have</u> more energy. It's not like it's been like- it doesn't have any extra like potential energy or kinetic energy.

Jen: Ok, so it's not- it hasn't been raised against gravity.

McKenzie: Yeah.

Jen: And it's going the same speed that it was going before.

McKenzie: Yeah.

/5s/

Jen: So it seems like you guys think that there <u>isn't</u> a transfer of energy.

George: I guess so. ((laughs))

McKenzie: Yeah. I mean we like, said that there was, but it doesn't make sense that there would be.

Jen: So what did you say that there was, when you said that there was transfer of energy? This?

McKenzie: Ye::ah.

Jen: Ok, so now you have these two different arguments, right? Just from your group you developed these two different arguments and one of them's wrong. I'm not gonna tell you yet

which one's wrong. ((laughs)). But, try to find- and I'm gonna pull a David- try to find the thing that's wrong about the other argument than the one you believe most about. If you think one is really right, try to find what's wrong about the other argument, because one has to be wrong. It can't be that it did work and it also didn't do work. Right?
McKenzie: Yeah.
Jen: K. C'mon guys, look alive! ((laughs)) (walks away)

Segment 3

Elijah: What- what do you think the energy-
George: Well now I think that it, doesn't do work.
Elijah: Yeah.
George: Just because we were- and I think our flaw was we were just multiplying it and not taking the dot product of the vectors.
Brian: What?
George: We were just multiplying it and not taking the dot product of the vectors. So the force is like constantly changing (drops his pen and McKenzie returns it), so then, I want to say because it's changing around the circle, it always cancels out (rotates his pen through an angle).
Brian: Does it?
George: I'm not sure. ((laughs))
Brian: Or like- but when you do a half circle,
George: Yeah, then it seems to me like it wouldn't.
Brian: Yeah::.
George: But then if you think about what- it's not speeding up, it's not being raised up. So like, how is it /. / gaining energy?
McKenzie: [It's not.]
George: [Like if]there is work done. Yeah.
Brian: Well like, the velocity is changing though so there- there is a force being applied.
McKenzie: Is it?
Brian: Or the direction of the velocity is changing.
Elijah: The velocity is changing. Cause there is an acceleration.
Brian: Like, cause even with like just regular centripetal force, um, there is still an acceleration even though the velocity isn't changing, since the direction is changing of the velocity.
Elijah: The velocity is changing, the speed's not changing.
Brian: Yeah.
George: Kinetic energy is dependent on speed. Or-
McKenzie: One half mv squared is acceleration[2].
George: Yeah.
McKenzie: So that's velocity.
George: Right.

[2] It is likely that McKenzie misspoke here and meant to say *kinetic energy* instead of *acceleration*.

/3s/

George: So velocity is changing, so then- but what if we just, what is the change of velocity?

McKenzie: But once it goes all the way around the disk, then it'll be-

George: Then it'll still change [[?]]

Elijah: So it ends and it starts in the same direction?

McKenzie: Yeah, the velocity will be the same once it gets all the way back to where it started cause it'll be in the same direction, and it's not speeding up.

Brian: But, since like, friction is the one that's, like, kind of acting on it, it's not conservative so it- /. / it does depend on the path it takes.

George: Yeah.

Elijah: So then where does the energy go?

Brian: Cause like, if you don't do anything, your just- thing sits there, (puts down pen, mimes an imaginary penny moving around a disk) versus if it goes all the way down- around once, friction did play a big role. And, it did do something (upturns palm) as it was going around, and it's not gonna like- I don't know like cancel out with itself if it just goes back around once. /3s/

George: Yeah.

/3s/

Segment 4

McKenzie: But like, do we think of it as like negative work done, then they might. Like, cause the dire- does the direction of- the direction of the work is taken into account.

Brian: Um, work doesn't have a direction.

McKenzie: Oh it doesn't have a direction?

Brian: I actually emailed him on my way from our lecture, that question, does work have a direction, he said no, it's scalar.

McKenzie: Wait.

Brian: Or like- well it has like- it has like

George: Like negative or positive

Brian: positive or negative, but there's no like direction.

McKenzie: Oh, ok. Because like-

George: But force has a direction. But the dot product gives you a scalar. Right.

McKenzie: Ok. But wait, so when is work negative? When it's- when the force is- when the force is in the opposite direction?

Brian: I think so, yeah.

McKenzie: Ok, so even if you think of it that way, then. When the force- cause if it goes all the way around the circle, the net work should be zero cause half the time it'll be negative

George: Yeah.

McKenzie: Cause the force will be in the opposite direction of the disp- no. It won't.

George: Well but it's perpendicular to the velocity. But I guess the displacement it's- mm I don't know what you could say about displacement in a circle.

McKenzie: No, the force will- wait, the force has to be in the opp- well it's in the same-

/3s/

George: What I don't get is like how something that's really heavy and you push it and it doesn't move, like where does the energy go? It's similar to like static friction. /2s/ So like how (points to his paper) /. / does /. / static friction (moves his pointing finger around in a circle) transfer energy between the penny and the spinning (spins his finger around)? /3s/ Cause like it's not- (moves his forearms out with palms facing upward) I mean I guess maybe it is heating up and that's just like- but I can't conc[eive of something like heating up like that.]
McKenzie: [Is it? She never said that.]
George: Yeah. ((laughs))
McKenzie: ((laughs))
Brian: But it feels like- like you do push against it and it doesn't move, so you are like [transferring (pushes his arms out in front of him) it but]
George: [You are clearly like transferring energy [[…]]]
Brian: it’s just like not enough or something, I don't know, like-
George: But does that energy dissipate as heat then?
Brian: I don't know, like-
McKenzie: I don't think it does cause if you push- like- you push against just like the wall, it's not like there's like [some] friction force [that's like- I mean there is-]
George: [Yeah] [Well I was thinking, the wall it could be] cause like, you know he's mentioned how like when you're standing there's like a tiny bit of a compression, so maybe the wall can kind of be seen as [like a really stiff] spring.
Brian: [Well if you- mm.]
George: But if you're pushing on like a refrigerator or something
McKenzie: Yeah.
George: and it's not moving, it's not because of like the springiness, it's because of the friction.
McKenzie: Yeah.
/2s/
George: I don't know.
Elijah: If you push on a wall though it'd be like the friction of your, feet. Right?
George: Right. [Yeah. Then there's that.]
McKenzie: [But that's not the] friction that's keeping the wall from moving, that's the friction that's keeping you from moving backwards.
George: But still, how is that friction like transferring energy if you’re just standing there, but pushing?
McKenzie: Yeah.
George: I don't know. /1.5s/ I mean I guess it could just be transferring heat, I just don't know that it is dissipating heat, it'd just [be such a tiny amount that I don't know.]
McKenzie: [But, if you think about it,] like, it's not.
George: Yeah.
McKenzie: You'd feel it, if like, unless your feet start to move, then you like might feel like [the heat.]
Brian: [Yeah cause you do] feel heat if you like sli::de [your] like feet on the ground
George: [Yeah.]
Brian: you can [kind] of feel the heat.
McKenzie: [Yeah.] Yeah.

George: But if I press really hard to the ground for a long time I don't, feel heat.
McKenzie: Yeah.
/3s/
George: (rapidly clicks his pen) I don't know if this is important to this problem of it's just a tangent ((laughs)) but-
McKenzie: It's kind of a tangent. But if we could figure it out it would probably help us with this. Maybe.
George: At least help our understanding of it.
((laughs))
George: All right.
/3s/

Segment 5

George: My issue with the like- it being positive, is that, like the force is constantly changing direction.
Brian: Yeah.
/3s/
McKenzie: Well so is the displacement.
George: Yeah.
Jackson: But is the displacement in the same direction as the force?
McKenzie: Nnn-
George: No. The displacement's like perpendicular to the-? I think-? Yeah.
McKenzie: Cause the force-
George: Cause the velocity's perpendicular.
Jackson: So then could we ever calculate-?
George: But then if they're perpendicular, work would be, zero.
Jackson: Right.
McKenzie: If they're perpendicular, it's zero?
George: Yeah.
Jackson: Cause there's no-
McKenzie: Oh, so it's zero!
George: Yeah.
McKenzie: That's the answer!
George: But then that still seems weird, like-
McKenzie: There we have it! ((George laughs)) ((laughs)) It's zero! ((laughs))
Brian: But wait, is it zero?
McKenzie: I think it's zero.
Jackson: I might agree, I don’t know.
Brian: Because cosine of ninety is zero.
George: Yeah.
McKenzie: It's definitely zero, guys.
Brian: That does make sense. But it still- it seems like friction, a non-conservative force, it's what's like causing it

George: Yeah.
Brian: like to go around, you'd think that like-
McKenzie: But is static friction a non-conservative force? ((George laughs))
Brian: Well the only conservative forces are like gravity and springs. ||**George:** Springs.|| Any kind of friction is non-conservative. ||**George:** Yeah.|| I mean like tension's non-conservative-
McKenzie: But where does it go, then? Cause with- with kinetic friction you can say it's heat but like, where does- where does it go ((small laugh in her voice))? Energy is conserved. But it doesn't have more eh- but like the penny doesn't have more energy!
George: Yeah. Like when it's on the other side, it's not going any faster and it's not, any high- it doesn't have any more kinetic energy or potential energy.
Elijah/Brian/Jackson?: Right.
George: But I guess if you like push something across the table, and it stops, it doesn't- there's no work done, right?
McKenzie: Friction.
George: But there's no- but if you like- go like that, there's no work done between here and here because there's no change in energy. Because it like speeds up- like first there is work done and then there's negative work done. But- this isn't slowing down, this is staying- staying constant speed. So that doesn't- That analogy doesn't matter ((laughs)) /2s/
Brian: Wait, but also, your change in- like support for why it's zero, maybe is if your change in velocity- like your change in kinetic energy is zero.
George: Yeah.
Brian: If you go over to the other side, I think. Cause you have the same velocity here-
George: Yeah.
Brian: there if you go around.
McKenzie: But then it might not be zero- it's probably not zero at half way because its velocity is different.
George: Opposite.
Elijah: Yeah, it's definitely not zero.
McKenzie: It's definitely zero all the way around though. I'm convinced.
George: So then, does it do positive work through the first half, (draws on his paper) and then-
Elijah: What direction is the displacement vector when it's halfway around? Doesn't it point like out of the circle?
Brian: Isn't it like the same as velocity?
Elijah: I don't think so. Wait, isn't it like the distance?
McKenzie: Wait, the displacement? Or the distance-
George: Yeah, the displacement is like, like circling.
McKenzie: No, the displacement is like the direct, like, line between where it starts and where it is. Where it started and where it is.
George: So, the displacement's across.
McKenzie: Yeah, but I think that- don't you- because it's a non-conservative force so you do distance.
Brian: So you have to take the path taken.
McKenzie: Yeah.

George: But what I'm confused is that- so I get why it would be zero when it goes all the way around. Because like, the way I see it is like the forces all cancel out at every point.
Brian: Mhm
McKenzie: Yeah.
George: Cause if you like consider like the vector force at every point there's also an opposite one, so it cancels out, but if you go halfway? does that mean that, it’s like, the work done's positive on the first way around? and negative on the other way around? so they cancel out?
Brian: Well, they wouldn't all cancel out because-
George: Yeah, because you'd have- only the two opposite ones would cancel out.
Brian: Yeah::.
/7s/
George: Why would one be positive and one be negative? I guess it just depends on which direction it's going. And which direction on the plane is positive.
McKenzie: Yeah. You'd have to decide that.
/7s/
Brian: So, for halfway would it be pi mv squared?
Elijah: Interesting:::
George: I think so? But does that mean that it would be negative pi mv squared for the second half? It would have to be to be zero.
McKenzie: Well, yeah.
George: But what gives it that negative sign? I guess it's the direction of-
McKenzie: Cause it's in total going like the opposite direction-
George: But I'm just trying to figure out what would- what would give it the negative? I guess the force would be negative-
Elijah: I don't think it-
George: Like something has to make it negative. ((laughs))
/8s/
McKenzie: Maybe we should try the tennis ball problem.
George: Yeah.

Chapter 3: Attention to student framing in responsive teaching

Jennifer Radoff & David Hammer[13]

Among the challenges of responsive teaching is deciding where and how to focus one's attention. Teaching involves many choices, mostly tacit, that influence what the teacher notices and what aspects of students' thinking he or she pursues.

In this chapter, we present a case study from a third-grade class studying motion. We present two episodes from their work over the course of a fourteen-day unit[14] on the motion of toy cars—one from the second day and one from the fourteenth. We claim the evidence shows a change from the first episode to the second in the scope of the teacher's attention. She shifts from a wider consideration of the class's sense of what they are doing—their epistemological framing—to a narrower consideration of the conceptual substance of particular ideas. We suggest this shift is itself responsive to the students' thinking: The class is more stably doing science on day 14, which lets the teacher relax her attention at that level to focus more attention on students' particular ideas within their inquiry.

Attending to students' thinking

Human attention is limited (Simons & Chabris, 1999). It is not possible for anyone to notice, let alone focus on, all aspects of a classroom's dynamics. Teachers must constantly decide, explicitly or tacitly, how to distribute their attention. Prior analyses have focused on when and how teachers direct their attention to the substance of student thinking, arguing that it is context-sensitive and influenced by many factors, including the teacher's long- and short-term instructional goals, (pedagogical) content knowledge, epistemologies, local classroom dynamics,

[13] A version of this paper is printed in A. D. Robertson, A. D., Scherr, R. E. & Hammer, D. (Eds.) (2015), *Responsive Teaching in Science and Mathematics*. New York: Routledge.
[14] This unit was fourteen class-periods, which spanned over five weeks of real-time.

and by institutional expectations and time constraints (Lau, 2010; Levin, 2008; Maskiewicz & Winters, 2012; Richards, 2013).

Much of the discussion has addressed attention to the scientific substance of student thinking as opposed to, for example, student behavior, logistics, or canonically correct vocabulary (Coffey, Hammer, Levin, & Grant, 2011). But “attention to scientific substance” is quite broad itself. Robertson, Richards, Elby, and Walkoe (2015), for example, show a teacher shifting among several foci of attention, all aspects of the substance of students' thinking.

In this chapter, we study the choices that one teacher, Sharon Fargason, makes while attending and responding to student thinking. In particular, we identify her tacit choice between focusing more “widely” on students’ epistemological framing and more “narrowly” on specific conceptual substance.

Attending to students’ epistemological framing

Sharon’s “wider” attention is to what activity students think they are engaged in, or what “game” they think they are playing (Ford, 2005; Lemke, 1990). Students are beginning scientific inquiry, for example, when they are in pursuit of coherent, mechanistic accounts of natural phenomena. For teachers, much of the challenge is in recognizing and supporting students beginning that pursuit (Hammer, Goldberg, & Fargason, 2012; Radoff, Goldberg, Hammer, & Fargason, 2010). It is difficult, in part, because students’ sense of what is taking place can vary, from student to student as well as from moment to moment. In this analysis, we are interested in students’ sense of what is taking place with respect to knowledge, which we will discuss in terms of their epistemological framing (Redish, 2004; Scherr & Hammer, 2009).

Redish (2004) proposed the construct of epistemological framing to connect research on epistemological resources (Hammer & Elby, 2002) with research on framing (Goffman, 1974;

Tannen, 1993). The former describes people as having rich collections of resources for understanding knowledge and epistemic activities, which they draw on in various ways in different contexts. The latter concerns how people form their sense of what is taking place, in different contexts and dynamically moment-to-moment.

Refining these epistemological resources and drawing on them in contextually appropriate ways is an aspect of learning, which starts as young children become familiar with various kinds of epistemic activities—storytelling, guessing games, pretending, and so on—each with various rules or heuristics for engagement, values and assumptions, goals and criteria. Learning science, in this respect, means becoming familiar with science as a kind of epistemic activity, including its aims, values, and disciplined ways of constructing and assessing knowledge (Chinn, Buckland, & Samarapungavan, 2011; Ford, 2006; Ford & Forman, 2006; NGSS, 2013).

Thus, responsive teaching should include attention to framing—to how students are approaching and understanding the activity—which is a wider scope of attention than to their particular ideas and questions within the activity. The dynamics of framing makes attending at this wider scope more complex than simply assessing whether or not students are doing science. For young children in particular—who are learning many kinds of epistemic activity—how they frame what they are doing in one moment may not be the same as in another moment, and part of their becoming familiar with science is their developing stability in their framing.

The reflexive relationship between conceptual substance and epistemological framing

Sharon's "narrower" attention is to details within the conceptual substance of student thinking. Here, for instance, students consider whether a car will catch on fire. Hearing them raise the idea, Sharon could focus on it, eliciting further and more detailed thinking about fire and cars and motion, or she could keep her attention wider in scope, a broader survey of the kinds of ideas students are offering.

The two levels interact: There is a "reflexive relationship" (Yackel & Cobb, 1996) between interpreting the conceptual substance of what students are trying to say and interpreting their epistemological framing. Teachers can infer the kind of epistemic activity in which students are engaged from the kinds of conceptual substance they offer, and they understand that substance based on their sense of what students are doing.

Imagine, for example, a student telling a story about her family's trip to the theme park. She says it was raining, and so the bumper cars were closed. She asked a park attendant why she couldn't ride the bumper cars in the rain, and he told her that the tires might slip around on the wet road and the driver could lose control of the car. The student might be trying to explain what she knows about tires and traction, or she might be trying to convey her disappointment at missing the ride. The teacher and other students listening would be influenced in their sense of her meaning by the epistemic context, whether it has been a discussion about friction or a discussion about what she did over the weekend.

At the same time, the teacher's and other students' responses would help to shape that context. The conversation could go one way if the teacher presses the student to unpack the connection between the slippery surface and the possibility of losing control of the car, and it could go another way if a student responds with a comment about his trip to that same park.

If there are multiple ways for students to interpret what is happening, a teacher might zoom out to a wide view in order to help students come to some stability around what they're doing. Instead of deeply pursuing the conceptual substance of an idea, she might serve as the gatekeeper to allow or deny entry for certain kinds of ideas, hoping to affect students' expectations around what kind of conceptual substance is appropriate. Once the students are more stably engaged in a particular kind of epistemic activity (in this case, doing science), the teacher can zoom in to a narrower view where she delves deeply into particular aspects of students' thinking.

In this chapter, we focus on Sharon Fargason, who was part of the Responsive Teaching in Science project (Goldberg, Hammer, Bendall, Coffey, & Maskiewicz). Sharon's teaching is featured on the project website (cipstrends.sdsu.edu/responsiveteaching/) as well as in several published accounts (Bresser & Fargason, 2013; Hammer et al., 2012; Radoff et al., 2010).

In what follows, we examine two focal episodes to argue that, when students showed more stability in doing science, Sharon focused her attention more narrowly on the ideas within their inquiry than she did when students showed less stability in doing science.

Methodological considerations

Episode Selection

The episodes we present took place on the second and fourteenth day (which took place on the first and fifth week, respectively) of the Toy Car unit (cipstrends.sdsu.edu/responsiveteaching/carmodule/), which began with a launching question about how to make a toy car move.

In the first episode, the students and teacher were in the throes of co-constructing expectations of what they were doing, both socially and scientifically. In the second episode, the students were evidently framing what they were doing as a pursuit of coherent, mechanistic accounts of (a toy car's) motion.

We selected these episodes for evidence of a contrast in how Sharon chose to pursue ideas. In the first, she was selective, actively discouraging lines of reasoning and frequently refocusing the discussion. In the second, she took up a student's idea that, on its own, would not seem scientific, and her choice led to a productive discussion.

Evidence of student framing

To build this argument, we begin with evidence of student framing. In essence, we are making conjectures about Sharon's thinking on the presumption that, in the moment, she noticed at least some of this evidence too. There are some indications of Sharon's attention in what she says and does, and we have checked our interpretations with her own memory and sense, but our argument depends on plausible inferences.

There is evidence of students' framing in their discourse, as Tannen (1993) described in several studies. In one, she examined interview data of women talking about a short movie they had seen, to show how "surface evidence" can give insight into framing. For example, many subjects noted things that did not occur in the movie, evidence suggesting they expected those things were possible. There was evidence as well in linguistic markers that indicated attitudes such as surprise and judgment. Still other evidence included linguistic registers, shifting in ways that indicated, for participants in the conversation, how to interpret the meaning of an utterance.

In another study, Tannen and Wallat (1993) analyzed video data of a doctor examining a child. Similar sorts of evidence—of vocal register and language—signaled shifts in the doctor's framing of what she was doing, in particular whether she was speaking to clinicians, to the mother, or to the child. These markers helped the mother and child to recognize which audience the doctor was addressing. In effect, Tannen and Wallat made explicit the tacit channels of communication among participants in the conversation.

In what follows, we similarly study students' discourse for evidence of their framing—evidence that was available to them and their teacher. We invite readers to watch the video and assess our interpretations themselves. Transcripts of both episodes are available in Appendix 3, and videos of both episodes are available online at http://www.studentsthinking.org/rtsm. In the analysis that follows, we reference line numbers from the transcripts in Appendix 3.

Data and Analysis

We begin with our analysis of an early episode, which reflected instability of student framing. That is, the class had yet to settle on the kind of conversation they were having, and this influenced how Sharon attended and responded to the framing. We then turn to a later episode, which took place approximately 5 weeks after the first.

Early Episode overview

On the first day of a unit on motion and energy, Sharon held up a toy car in front of her third-grade class and asked the launching question, "How would you get this toy car to move?" The students spent some time in small-group discussion and then shared with the class how they might get the toy car to move. On the second day of the unit, the students worked in small groups, recording and illustrating their ideas on butcher paper to share with the entire class. Isaac and Jimmy were the first to share their idea: A large and complex roller coaster, equipped with fiery loop-the-loops and terrifying jumps over shark-infested waters (see Figure 3.1).

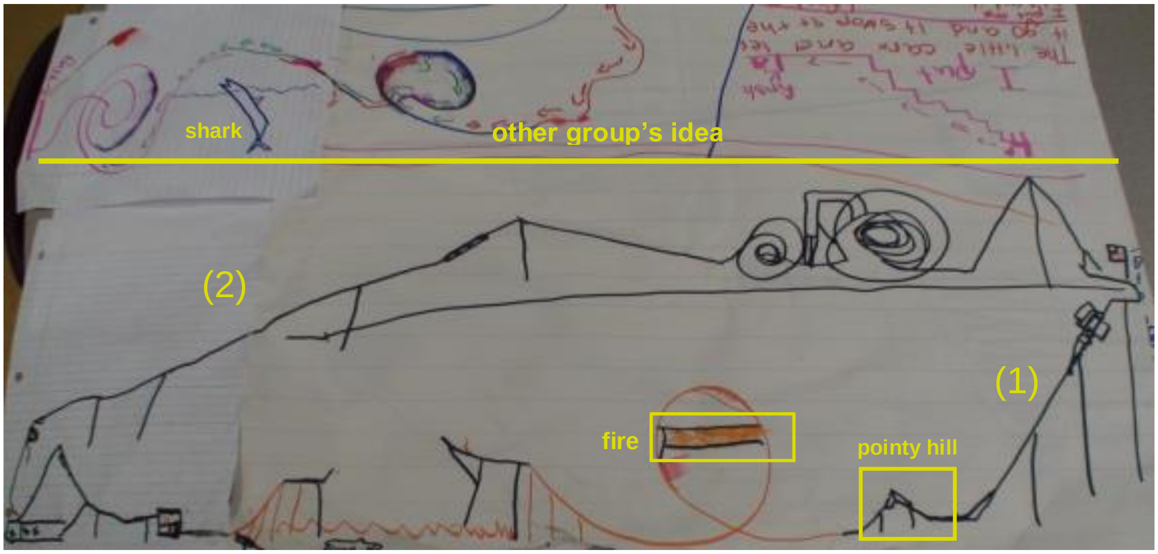

Figure 3.1: Isaac and Jimmy's roller coaster

As Isaac and Jimmy presented their idea, the students attended to many different aspects of it. Some picked up on the sensational features of the roller coaster, while others held Isaac and Jimmy accountable to whether the idea would actually work to make a toy car move. Several students switched between talking about a toy car that lacks a power-source, and thus relies only on the roller coaster's design to move, and a real car that has an internal energy source, which allows it to move independently.

Throughout the episode, there was evidence of variation in how students framed their participation. While there were glimmers of proto-scientific engagement in students' attention to plausible mechanisms for the motion of a toy car, the students were not stable in it. Sharon, we show, attended and responded largely at the level of the students' framings, apparently picking up on and trying to draw out the glimmers of plausible mechanisms for the toy car's motion. For example, she asked students to clarify or repeat contributions that suggested attention to mechanism, and she disregarded or deferred those that focused on other things, such as fantastical design features. At times, she was explicitly directive, such as telling students that they should think of a toy car, not a real car with an engine.

We turn now to the analysis, to show (1) students' unsettled framings, and (2) Sharon's attention and responsiveness.

Early Episode analysis: Student contributions and teacher response

In analyzing this episode, we looked for stability in students' tangible reasoning about the motion of a toy car. Our purpose is to articulate evidence of students' framing that were available for Sharon during class. We consider how Sharon responded to students' contributions as evidence of her interpretations and local intentions. For example, her persistence in driving the conversation away from real cars indicates that she noticed that students kept returning to the topic. Her multiple attempts to shift the conversation indicate her effort to disrupt what she saw as a local stability around discussing real cars.

Throughout the Early Episode, Sharon promoted students' tangible reasoning about the motion of a toy car. For example, at the start of the episode, Priscilla asked, "Is there something that pushes [the car] up here (referring to the stretch of incline labeled (2) in Figure 3.1), because I cannot believe them that it goes by itself" (line 2, Appendix 3.1). Her question is about causal mechanism, and evidence of her expectation that there must be one. Her critique is about the physical viability of Isaac and Jimmy's idea. Sharon tried several times to make Priscilla's question a focus of student attention, by asking Priscilla to repeat it (line 4, Appendix 3.1), by asking other students if they heard her question (lines 4, 6 Appendix 3.1), and by re-voicing it (line 8, Appendix 3.1).

Another example is Gustavo's concern that the car might fall at the top of the loop-the-loop (lines 11, 15, Appendix 3.1), and Jimmy's response that because of the initial drop (labeled

(1) in Figure 3.1), the car will be going fast enough to make it around (lines 42, 47, Appendix 3.1). Sharon repeated Gustavo's idea twice (lines 16, 38, Appendix 3.1) and then pursued Jimmy's response, "It'd have to go really fast" (line 42, Appendix 3.1) even though she already called on another student (lines 41, 46, Appendix 3.1).

A third example is Jamir's concern about how the car would move when it gets to the "pointy hill" (lines 82, 84, Appendix 3.1): "Won't the car jump and crash into the [loop-the-loop]…?" Again, Sharon supported the question, asking Jamir to repeat it and commenting that she "was kind of wondering that too" (line 83, Appendix 3.1).

In other moments, however, students' contributions suggest that they were not thinking about the physical plausibility of the phenomena but about the drama of the roller coaster ride and fantastical design features.

For example, Isaac's response to Jamir's question about the pointy hill was to describe an implausible device—"a thing right there that knows if it's gonna crash… and opens up a spot" to let the car through without crashing (line 89, Appendix 3.1). Sharon pointedly discouraged this response, laughing and articulating a tacit rule that she had in mind: "You're making stuff up as you go along! You can't do that!" (line 90, Appendix 3.1).

In some moments, students focused on flashy aspects of the design that were not relevant to how the roller coaster made the toy car move. For example, early in the episode, Jourdan asked, "What is that part with the big fish right there on the other paper?" (line 60, Appendix 3.1). Sharon deferred his question (lines 62, 64, 66, Appendix 3.1), asking for further conversation about an idea she had heard about the car's motion.

When Scarlett kicked off a conversation about whether the car will get burned by the fire on the loop-the-loop, Sharon initially supported this conversation, especially highlighting Ray's contribution that incorporated speed into the explanation, but shut it down when it moved too far away from issues concerning the car's movement and quickly dismissed Kyleigh's suggestion to reposition the fire to the top of the roller coaster (lines 67-81, Appendix 3.1).

In addition to discussing the dramatic design elements of the roller coaster, students frequently shifted to thinking of "real" cars—cars that have engines and drivers. That framing of the topic would obviate questions such as Priscilla's, of what pushes the car up the hill. Sharon tried repeatedly to keep students thinking about a toy car.

One example is when Jamir and Isaac considered how the point of the pointy hill could get caught on "the bottom engines" and "materials" on the underside of a "real car" (lines 103-125, Appendix 3.1). Sharon asked, "Can we talk about toy cars just to make this easier?" (line 126, Appendix 3.1).

Another example is when Jose and Jimmy discussed how many times the car would go around the loop-the-loop (lines 127-130, Appendix 3.1). Presumably because they did not seem to be discussing plausible toy car behavior, Sharon asked if they were talking about a toy car (line 131, Appendix 3.1) and then followed up by insisting, "Make sure you're talking about a toy car. There's no driver in this car" (line 133, Appendix 3.1). When Jourdan suggested that perhaps the car is automatic (line 134, Appendix 3.1) and Gustavo suggested that a remote control car is still a toy car (line 136, Appendix 3.1), Sharon responded, "Just to be clear, we all need to be talking about toy cars today, not cars that people drive. All right?" (line 138, Appendix 3.1).

Early Episode discussion

In the Early Episode, when students showed instability in their framing, the game was about getting students to recognize what kind of conversation she wanted them to have—one about tangible mechanisms for a toy car's motion. Sharon did this by selecting and promoting certain kinds of contributions and discouraging others. Each time Sharon discovered that students weren't discussing the motion of a toy car, she changed the direction of the discussion, often quite abruptly.

It is important to note that even in moments where students were discussing the toy car's motion, Sharon did not focus much on the particular substance within those ideas. Most of her interaction with students' ideas involved revoicing or clarifying, rather than delving deeper into students' meaning or asking follow-up questions about the ideas.

The only instance in which she delved into a student's idea was in line 85, when she asked Jamir what would make the car jump. Certainly there were other opportunities. There were several places, for example, when students focused on the car's motion in the loop-the-loop. Jourdan remarked that the car would not fall at the top of the loop "because it goes down really fast" (line 60, Appendix 3.1); later, Jimmy focused on the car's motion in the loop (lines 128, 130, Appendix 3.1). Sharon could have asked Jourdan why going fast would keep the car from falling at the top of the loop-the-loop, or asked Jimmy what would make the car loop around multiple times. However, her response to Jourdan was to deflect his closing question about "the big fish" (line 62, Appendix 3.1); her response to Jimmy was to check that he was "talking about a toy car" (line 131, Appendix 3.1).

Our conjecture is that Sharon was aware of the variation in students' framing of what they were doing, and for this reason she continued to attend and respond at a wider view for the entire episode.

Late Episode overview

By day 14 of the toy car unit, the students had discussed various factors that could affect a toy car's speed as it moves down a ramp, including the weight and shape of the car, and the slickness of the ramp's surface.

At the beginning of class on day 14, Jamir shared something he had discovered the day before: when he put a rubber doorstop on a steep ramp, the doorstop didn't move at all. Jamir suggested that the doorstop's shape kept it from rolling down the hill. When he tried to demonstrate the phenomenon for the class, however, the doorstop slowly slipped down the ramp. Attempting to make sense of the discrepant results, some students argued that the ramp wasn't steep enough, and others argued that the doorstop wasn't slippery enough. After about fifteen minutes of discussing why the doorstop sometimes moved and sometimes did not, Ray said, "It's free will."

We chose this episode because of Sharon's response to the idea of "free will": She delved into it for an extended discussion. Free will hardly seems, in itself, a likely topic in the pursuit of mechanistic understanding. By this point in the lesson, however, the students seemed to have established a shared framing of what they are doing together—making sense of different things that impact a toy car's motion—and Sharon had seldom needed to intervene to promote mechanistic sense-making. Here, we propose, her sense of the students' stability in what they've been doing impacted her interpretation of an idea that, on the face of it, wouldn't belong in a conversation about the motion of toy cars.

Late Episode analysis: Student contributions and teacher response

The episode began with the puzzling observation that the doorstop would sometimes slide and sometimes just sit still at the top of the ramp. Sharon asked Jamir if he pushed it down the ramp, and Jose said, “He let it go.” Then she asked whether “pushing it” and “letting it go” were the same.

Sharon’s question prompted Ray to say, “It’s free will.” In response to Ray’s comment, Sharon first asked the class whether the car or the doorstop had free will, and then she asked Ray what he meant (line 149, Appendix 3.1). Ray responded that free will is when “you just let it go, because you're not pushing it, that's all” (line 150, Appendix 3.1).

Sharon tried three more times to elicit a definition (lines 151, 153, 155, Appendix 3.1) before she offered one herself, appropriating Jourdan’s example of “letting a dog go for a walk by itself” (line 157, Appendix 3.1): “Free will means you get to choose what you want to do” (line 151, Appendix 3.1). She then asked, “Does the car or the doorstop have free will?” (line 158, Appendix 3.1), to which several students responded, “No.” Sharon seemed to expect this response, because she quickly followed up with what seems to be the central question, “What makes the car and the doorstop go down that ramp then?” (line 160, Appendix 3.1).

It would be reasonable to expect the students to start working on other explanations, but Jourdan responded, “The car had free will” (line 161, Appendix 3.1). Sharon’s exclamation, “Wait, a car has free will?” (line 163, Appendix 3.1), is evidence she was not expecting that response. Again, she chose to pursue the topic.

Throughout the rest of the episode, Sharon attempted to understand what students meant by “free will.” Jourdan suggested that the car has free will because its wheels allow it to slip freely down slippery things, but the doorstop does not have free will because it gets stuck going down the ramp (lines 165, 172, Appendix 3.1). Alexis responded to Jourdan’s comment, noting that free will is about moving without a push, not about being able to slip freely on a slippery surface (line 174, Appendix 3.1). Gustavo added that a remote control car doesn’t have free will because “you’re controlling it” (line 176, Appendix 3.1).

At this point, it seemed clear to Sharon that students considered a car not to have free will if a person controls its movement (line 175, Appendix 3.1). But then what do they think it means for a car to have free will? To narrow down the students’ meaning, Sharon asked a clarifying question, “Ok so is that free will if a car goes down a slide by itself?” (line 179, Appendix 3.1), to which some students replied, “Yes.” Rather than thinking about anthropomorphized cars, some students were using free will as a way to distinguish the car’s motion on a ramp (where you can just let it go) and the car’s motion on a flat surface (where it requires a push), and Jourdan was using it to describe the state of non-impeded motion.

In response, Sharon clarified her definition of free will to involve only matters of choice: “Ok so free will means that you get to make a choice. So Jourdan, did that car make a choice to go down that hill?” (line 181, Appendix 3.1). Jourdan responded, “I don’t think, because cars can’t go alive” (line 183, Appendix 3.1) and Gustavo added, “Yeah, they can’t go alive only persons can” (line 184, Appendix 3.1). Kyleigh added that a real car does not have free will either, “Because the person’s driving the car” (line 189, Appendix 3.1). Following Sharon’s clarified definition, Alexis concluded, “It didn’t have free will because it didn’t have another choice of staying or going, it had to go down…Because like if you're on top of a hill and the car goes down a slippery thing, like it has to go down because like there's nothing that could hold it. Unless if it was a real car, then the brakes” (line 204, Appendix 3.1).

For much of the rest of the day, the students’ framing was more clearly stable around coherent, mechanistic reasoning. Later, for example, the class sustained a 20-minute conversation about how wheels work to make a toy car move. The conversation focused deeply on mechanism, the students listened and responded to each other, and they held each other accountable to the larger framing so that Sharon didn't need to do much to maintain those boundaries. As a result, Sharon was able to focus her attention on eliciting the substance of a student's particularly complex idea that involved comparing rolling wheels to gears [More about that episode, "Isaac's Wheels," is available online. See http://www.studentsthinking.org/rtsm].

Late Episode discussion

Our core contention about the Late Episode is that it shows a different pattern in Sharon's attention and responsiveness to student thinking from her attention and responsiveness in the Early Episode.

At the outset of the episode, the students' participation was at least consistent with, if not indicative of mechanistic sense-making: They were focused on making sense of an inconsistency in the doorstop's behavior, citing evidence to support their arguments for what might account for that inconsistency. Ray's suggestion of free will as an explanation could easily be seen as a move to a different kind of conversation. But Sharon chose to take it up, asking him to clarify and guiding the class to think about the idea.

There was another decision point for her a moment later, when Jourdan said, "The car has free will," after many students had already agreed that it did not. Sharon could have shut down further consideration of free will, but again she chose to pursue it.

Jourdan's response indicated a need for Sharon to stop and reassess what she had previously taken for granted as shared understanding. On the face of it, the notion of free will has no place in a discussion about causal mechanisms, and it would be natural to see it as disruptive to that framing. Accordingly, had it come up in the Early Episode, Sharon would have been more likely to interpret it as a matter of epistemology—a shift, perhaps, to ideas about anthropomorphized cars—and so been more assertive in closing the topic. Recall how she quickly closed discussions about whether the car would get burned in the loop and discussions about "real cars."

On the few occasions when Sharon put considerable effort into understanding students' ideas in the Early Episode, the ideas ended up falling outside the epistemological boundaries of the conversation. For example, when Jamir claimed that the car might get stuck if it doesn't jump off the pointy-hill, it took about 40 turns for Sharon to realize that he was considering some sort of toy-car/real-car hybrid. Jamir's idea, although it ended up being epistemologically out-of-bounds, seemed relevant on the surface. Free will, on the other hand, did not seem epistemologically appropriate on the surface, yet Sharon still pursued it.

In the latter case, Sharon saw the students as more stably framing their activity, in ways that would exclude ideas about living cars from the landscape of acceptable knowledge. With reason to be more confident about the students' epistemological framing, Sharon could feel freer to draw out the conceptual substance of students' thinking and consider the possibility that what she meant by free will might not be the same as what the students meant by it.

Discussion and Implications

We have argued that the scope of Sharon's attention and responsiveness changed in response to the stability of students' epistemological framing. In the Early Episode, there was evidence of the students' varying, unstable sense of what they were doing together, and there was evidence that Sharon's attention was mainly at that level: Rather than delve into students' ideas, she focused more on the kinds of ideas students were offering. In the Late Episode, by contrast, students were relatively stable in their sense-making, and Sharon responded to student thinking by probing into specific ideas. She did so even with an idea, free will, that on its own seems like the wrong kind of idea for a discussion about physical mechanism.

This claim, of variation in Sharon's attention to students' thinking, dovetails with Robertson et al.'s (2015) case that a teacher's attention can shift "among multiple foci within the substance of student thinking" (p. 232) Similarly, Maskiewicz and Winters (2012) compared across two successive years in "Mrs. Charles's" class, showing connected differences in the students' inquiry and the teacher's attention. They showed that the epistemic norms were different between the two classes, for the same teacher, and they argued that it would be a mistake to attribute the difference simply to Mrs. Charles having made progress in responsive teaching.

Like these authors, we are arguing that there are interesting, important dynamics of attention within a focus on the substance of student thinking. Where Maskiewicz and Winters compared across successive years, with different groups of students, we have compared across episodes within a single 14-day unit. Where Robertson et al. identified multiple foci of conceptual substance, we have characterized a shift between a wider view of the kind of activity the class is engaged in, and a narrower view of the particularities within conceptual substance. Sharon, we claim, dynamically shifted between these views in response to the stability of students' epistemological framing.

On a larger scale, we are interested in understanding how a class makes progress toward establishing shared expectations around epistemic activities, in particular, progress toward disciplinary practices. We suspect that Sharon's skillful attending and responding played a large role in this progress. Even in the limited context of these two episodes, we can see the beneficial consequences of Sharon's attending to students' epistemological framing:

(1) For making sense of the substance of student thinking

Student thinking takes on different meaning according to the epistemological context. As we have discussed, whether a contribution is epistemologically appropriate depends largely on why the student is offering it. An awareness of epistemological framing can help teachers engage more meaningfully with students' ideas. As we have shown, Sharon's treatment of "free will" in the Late Episode differed from her treatment of "real cars" in the Early Episode. Although on the surface, the topic of "real cars" seems more tightly linked to about a toy car's motion than the topic of "free will" does, Sharon's attention to the epistemological context helped her decide which ideas to pursue further and which ones to hold off.

(2) For helping students refine their disciplinary expectations

If learning science means becoming familiar with it as a kind of epistemic activity, then teaching science means, in part, helping students develop a sense of the epistemic norms and values of the discipline. Research shows that how teachers engage with the substance of student thinking impacts what students come to see as valued and valuable forms of knowledge in the classroom (Cobb, Wood, Yackel, & McNeal, 1992; Coffey et al., 2011; McClain & Cobb, 2001; Yackel & Cobb, 1996). In light of this research, how a teacher responds to student thinking impacts how students come to understand what it means to do science.

In Sharon's case, she responded to students' varied epistemological framings by acting as a gatekeeper, winnowing kinds of ideas, supporting some and suppressing others. She discovered, recognized, and supported productive aspects of students' contributions, which in turn signaled to the students what kind of contributions are valued, leading to further contributions to discover. In this way, she supported the emergence, development, and stability of students' sense of the discipline. When the class was more stable in their epistemological framing, she focused less attention on forming shared expectations and more on delving into the substance of particular ideas, which in turn may have helped students to refine their framing. Moving forward, we plan to analyze more of the data, from the fourteen days of the Toy Car investigations, in order to better understand the reflexive dynamics of how Sharon's attending and responding to students' framing contributes to their progress in scientific engagement.

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Appendix 3.1: Transcripts of Early and Late Episodes

Transcript of the Early Episode

Line	Transcript
1	Sharon: Priscilla.
2	Priscilla: Is there- is there something that pushes it up here because I cannot believe them that it goes by itself.
3	Jimmy: Actually, Jimmy did this part.
4	Sharon: Ok, but- Ok, that's fine, but did you hear her question? Can you say your question again?
5	Priscilla: Um, does something push it up here for it can go fast.
6	Sharon: Do you guys hear what she's asking?
7	Students: Ye:::ah.
8	Sharon: Is there something that pushes it up here. And then she said that she doesn't believe that it could do that. By itself? Is that what you said?
9	Priscilla: Yeah. (3.5 seconds)
10	Sharon: Gustavo?
11	Gustavo: Can't the car fall when it's going on the- when it's gonna turn on the thing that- that it goes fast?

12 Sharon: Which one, on the orange ramp?

13 Gustavo: Yeah.

14 Isaac: It's not gonna like [crash on this side and fall because like] the track goes like that.

15 Gustavo: [Because right there- because it could like when it's going up, it could fall down.]

16 Sharon: Hold on, two people were talking at once. Gustavo is saying that, won't it fall down right here? At the top?

17 Gustavo: No like, at the top.

18 Sharon: Right here?

19 Gustavo: Yeah, right there.

20 Sharon: It will fall down?

21 Jamir: No because it will go because that's why they drew that thing-that has a bridge.

22 Sharon: What thing?

23 Student: The fire.

24 Alexis: No that's fire.

25 Jamir: Oh I thought that was a bridge there.

26 Sharon: Oh, like, right here? This thing?

27 Jamir: Yeah.

28 Alexis: I thought it was a bridge too.

29 Sharon: That's a bridge? Is it a bridge?

30 Jimmy: This?

31 Sharon: No. That.

32 Jimmy: Fire?

33 Sharon: No.

34 Isaac: This?

35 Jimmy: This?

36 Sharon: Yeah.

37 Jimmy: No.

38 Sharon: So there's no bridge. So, Gustavo are you saying that it will fall down?

39 Gustavo: Yeah.

40 Alexis: No, it won't because it will go fast and it will go around.

41 Sharon: Jourdan.

42 Jimmy: It'd have to go really fast.

43 Jourdan: It won't go down.

44 Sharon: Wait, what?

45 Jourdan: It wouldn't go down.

46 Sharon: Wait, so hold on, sorry, you're next I promise. Hold on. Hold on. Yes, Jimmy?

47 Jimmy: See how when it goes, and it go up the big hill and that's why it go fast, and like it jump over and then his speed like go a little bit more faster.

48 Isaac: And this makes it go even faster because it falls down.

49 Sharon: What makes it go faster? Sorry.

50 Isaac: The thing that- because it makes it go down and when cars go down at the same time they're driving it, it makes it go even faster.

51 Isaac: So that's why it can jump here.

52 Sharon: Ok.

53 Isaac: And it could jump over because the side's not that flat. This is the side of the car,

it's a little bit like that, so we made it more wider like that so it wouldn't like fall over the side.

54 Sharon: You made the track wider than the car so that the car would stay on?

55 Isaac: Like if the track was like this and the car was going through, then we made the track like that so it could go through. Like if it landed on this side like it would still make it. Because then it would [inaudible] to the track and then fall.

56 Sharon: Do you guys get that?

57 Students: Yeah.

58 Jourdan: I do.

59 Sharon: What did you want to say?

60 Jourdan: It wouldn't fall because it goes down really fast, and then when it makes the jump, it jumps back down, and then- cause, it jumps back down and then it goes down that hill, and then it makes it more faster to zoom up there, and then when it jumps it could do like tricks and stuff. And what is that part with the big fish right there on the other paper?

61 Student: That's in the water.

62 Sharon: Oh, we'll get to that in a second.

63 Isaac: That's from their side.

64 Sharon: Ok.

65 Jourdan: Is that the shark?

66 Sharon: Let's talk about Isaac and Jimmy's idea for just a minute more. Scarlett.

67 Scarlett: What if the car gets burned when it goes through the fire? It will get burned.

68 Alexis: No it won't.

69 Sharon: Will it get burned?

70 Isaac: No.

71 Jourdan: Nope.

72 Jimmy: No.

73 Ray: But if it does, it will just- cause like if it's going really fast the fire will just go off.

74 Isaac: Wait, Jimmy, did you mean like little- on the side, there's like fences and on the fences side there's like little candles with fire? You meant that? (Jimmy nods his head no.)

75 Sharon: Ok, so, but what you're saying is the car's gonna go so fast that the fire won't get to it?

76 Jimmy: Yeah.

77 Ray: But if like a little fire does, it still is going really fast, so when it's coming down and it goes up a big hill, so when it jumps up the fire will go off [inaudible] and little sparks.

78 Scarlett: Why don't they just don't make a flame cause it will get burned?

79 Sharon: Kyleigh.

80 Kyleigh: Why couldn't they just put the fire over the um- put like a big fire on top of it?

81 Sharon: Well they could've but this is how they did it. Sorry, I can't see. Jamir.

82 Jamir: In that little hill, won't that car jump and crash into the bridge? (students laugh.)

83 Sharon: Could you say that again? I was kind of wondering that too...

84 Jamir: In that thingy little hill, won't the car jump and crash into the ramp or whatever.

85 Sharon: What would make the car jump right there?

86 Alexis: No, it will crash to the back of the [inaudible, many voices at once].

87 Jamir: This hill because it will go like that.

88 Sharon: Wait, wait, wait, wait.

89 Isaac: Because there's like a thing right here that knows if it's gonna crash right here, so if it does crash right there, it opens a spot so people can go through fire and come back.

90 Sharon: You're making stuff up as you go along! (laughter) You can't do that! So is it gonna go up- sorry. Is it gonna go up here into here? Or is it gonna go down like that?

91 Jimmy: It's gonna go down like that.

92 Sharon: You think so Jamir?

93 Gustavo: No, but it's a jump!

94 Jamir: Once I tried that before, but if it does that, it's gonna get stuck right there.

95 Sharon: What do you mean?

96 Jamir: Like if it doesn't jump, it might get stuck right there.

97 Ray: Yeah, that happened to me once.

98 Brittney: I don't understand him.

99 Sharon: Brittney say that again.

100 Brittney: I don't understand him.

101 Sharon: Can you try to explain it again? Thank you for saying that.

102 Jamir: Because the car is flat and this is like a pointy spot, it might just get like stuck right there.

103 Isaac: Jamir's right, it might get stuck to the bottom engine.

104 Jamir: It might get stuck right there because you know right there under the car there's like a bunch of materials, there's like a bunch of holes on top there. So it might get stuck right there.

105 Priscilla: Oh, I think I get what he's trying to say. Can I explain it? (Sharon nods yes.)

106 Priscilla: It's cause, I do not know if- is this a pack that he is carrying? When he goes

here, the bottom's gonna get stuck here.

107 Jamir: No, no, no, not like that. Not like that. No, this part, it's gonna get stuck because, like, where's the little car?

108 Sharon: I don't know. Use your words.

109 Jamir: No, it's cause I need the little car to show you.

110 Jimmy: Oh, back over here.

111 Jamir: Oh, no. It's cause there's some other cars that have like the stuff right here, but it doesn't have no cap right here so it might get stuck right there. And this little part might get stuck.

112 Jourdan: But that's probably a rocket booster.

113 Jamir: No. Can you give me another car? That has some materials- it has materials so the car can move down here.

114 Scarlett: Like a real car?

115 Gustavo: Oh, like the real cars.

116 Jamir: Yeah, like the real cars-

117 Sharon: Oh, like the engine?

118 Jamir: No, like-

119 Alexis: Oh, like the bottom stuff? Like tubes and stuff?

120 Jamir: No, like- the real car- a real car-

121 Ray: Are you talking about the wires that will get stuck?

122 Alexis: Yeah, but that thing is on top and the bumper's like right here-

123 Jamir: A real car has like a bunch of material right here but it doesn't have no cap or nothing. So it might get stuck right there.

124 Sharon: Ok.

125 Students: Oh::: yeah, it might get stuck there.

126 Sharon: Can we talk about toy cars just to make this easier? Ok wait, one more question or idea about this drawing and then we're gonna go on. Jose.

127 Jose: I don't get it cause it's going to go like this in the circle. It's going to go like this and it's going to go through fire.

128 Jimmy: No, it'll go like this, and it could go on that, and it could go a third.

129 Jose: Yeah, but its gonna repeat it. It's gonna keep on repeating it and he can't go down here.

130 Jimmy: But, it'll just repeat two times. It's gonna go like that-

131 Sharon: Jimmy, are you talking about a toy car? (Jimmy smiles.)

132 Jamir: But it might get on fire because like there's a fire down there, so it might get on fire.

133 Sharon: Make sure you're talking about a toy car. There's no driver in this car. Yes?

134 Jourdan: There it's probably automatic.

135 Sharon: No, it's not automatic. It's a toy car.

136 Gustavo: There's a bunch of toy cars that are remote control cars.

137 Jourdan: Yeah, like that.

138 Sharon: Ok, Jose, I want you to scoot back to where you were. Jamir, scoot back to where you were. We're looking up here. And Lex, turn around please. Thank you. Now we can all see. Ok, just to be clear, we all need to be talking about toy cars today, not cars that people drive. All right?

Transcript of the Late Episode

Line	Transcript
139	Sharon: Is that the same? Pushing it and letting it go?
140	Students: No!
141	Gustavo: Because, like, if you let it go, it just like, stays there.
142	Jamir: But pushing it-
143	Ray: It's free will.
144	Jamir: But putting it, it's like letting it go. If you just put it on there, it's like letting it go.
145	Sharon: Does a car have free will?
146	Students: No!
147	Sharon: Or does that doorstop have free will?
148	Ray: The doorstop has-
149	Sharon: What do you mean by free will?
150	Ray: I mean like free will- has free will if you just like, you just let it go, because you're not pushing it, that's all.
151	Sharon: But what is free will?
152	Ray: Free will means like, it's- how am I going to explain this?
153	Sharon: Who can explain free will?
154	Jourdan: I don't know what free will is.
155	Sharon: That's why we need to explain that. What you mean. Kyleigh, what do you mean?
156	Kyleigh: I think free will means, I probably think free will means like letting it go, just go.
157	Jourdan: (lots of students talking) Oh, like letting a dog go for a walk by itself, huh?

158 Sharon: Yeah, like a dog can walk by itself. Free will means that you get to choose what you want to do. You guys have free will when it comes to choosing a place to sit. You get to choose where you want to sit. You lose your free will if you make bad choices. Then I choose for you. Does the car or the doorstop have free will?

159 Students: No!

160 Sharon: What makes the car and the doorstop go down that ramp then?

161 Jourdan: The car had free will.

162 Gustavo: Pushin' it.

163 Sharon: Wait, a car has free will?

164 Josmary: On the wheels!

165 Jourdan: Yeah, the wheels because um, can I demonstrate? Because, um, when Jamir put the board and he put the doorstop and the car, the car had free will because he just let them go and the car went by itself, it didn't, like, do like the doorstop. Because the free will is because of the wheels, because the wheels are really slippery, so it goes on slippery things.

166 Scarlett: But like, when you're like putting the thing, you're telling it where to go. Because when you're putting it straight, you're putting it straight so it goes straight.

167 Sharon: Brittney, you wanted to talk and I interrupted you, I'm sorry.

168 Brittney: I think it's cause the gravity- I think the gravity with the air, it makes it kind of go slower. I mean like, the gravity and the air could make it kind of faster, but if it's only the gravity, it could make it more slower.

169 Sharon: Ok. So, ok, I have a question. Was it free will that made that car go down? Kyleigh. (Jourdan starts talking and Kyleigh makes a frustrated face.) I know.

170 Kyleigh: He could go.

171 Sharon: That was so nice. But really I think the reason she did that is because she didn't want to be frustrated, so she wants to let you go first. But that was really nice.

172 Jourdan: Um, the reason- something just popped in my mind because of- about the free will because of the free will when Gustavo yesterday- when Gustavo and the car went down the slide, the reason why the car won so many times is because of the free will of the car. Because the um, the wheels are slippery so it goes on slippery things and the slide is really slippery so it goes down it really really fast.

173 Sharon: Alexis.

174 Alexis: The car doesn't only goes on slippery stuff. It could go on flat stuff like this. Um, like right here if you push it, it's not free will because you need to push it right here.

175 Sharon: So that's not free will because you push it.

176 Gustavo: Not either a remote control is not either free will because, like, you're controlling it with the remote control.

177 Jourdan: No, because when you put it down the hill and you don't control it, it's going free will.

178 Alexis: Yeah, and if you get a car and put it right here, it's not free will because it's not going down. You need to push it.

179 Sharon: Ok so is that free will if a car goes down a slide by itself?

180 Students: Ye:::s.

181 Sharon: Ok so free will means that you get to make a choice. So Jourdan, did that car make a choice to go down that hill?

182 Gustavo: No it didn't. It just went down the hill because-

183 Jourdan: I don't think, because cars can't go alive.

184 Gustavo: Yeah they can't go alive, only persons can.

185 Sharon: Kyleigh, it's your turn now.

186 Kyleigh: It's kind of like a person driving a real car, cause it doesn't have free will. But-

187 SF: Who doesn't have free will?

188 Jourdan and Alexis: The car.

189 Kyleigh: The...car...doesn't have free will because the person's driving the car. But- (students call out)

190 Sharon: Wait, let her finish! Let her finish.

191 Kyleigh: But the person- a toy car is not in- like a person's not inside a toy car so you have to push it. So, like, if it doesn't start and you have a flat surface and it's kind of like this, and if you put the car on a flat surface, it's then has power cause you push it, so that it could have power to go down.

192 Sharon: So pushing gives power?

193 Gustavo: Yeah, pushing it gets power and like energy because it uh-

194 Sharon: You said pushing gives power and energy? (Sharon writes on the board for 7.0 seconds) What about when you don't push? Cause just now when Jamir put those down the ramp, he did not push.

195 Gustavo: Yeah, but he could try pushing them.

196 Sharon: So did the car have free will then when it went down?

197 Alexis: No!

198 Jourdan: Yes!

199 Sharon: Because he didn't push.

200 Alexis: No, it didn't have free will because like it didn't have another choice of staying or going, it had to go down because--

201 Sharon: It had to go?

202 Alexis: Yeah.

203 Sharon: Why did it have to go?

204 Alexis: Because like if you're on top of a hill and the car goes on a slippery thing, like it has to go down because like there's nothing that could hold it. Unless if it was a real car, the brakes.

205 Kyleigh: Oh, I see what he's talking about.

206 Sharon: Wait, so he said it has to go down because there's nothing to hold it.

Chapter 4: "It's scary but it's also exciting": A case of meta-affective learning in science

Jennifer Radoff, Lama Jaber, & David Hammer

We present the case of "Marya," a college freshman who made significant progress during her first semester of introductory physics. She began the course anxiously trying for right answers in ways disconnected from her experience and understanding of the physical world. By the end, as she put it in an interview, she was working genuinely to understand:

> *I could throw in symbols all over the place and get the right answer but do I honestly have a good grasp of what was going on conceptually? Does this make sense?*

She also changed with respect to her feelings of anxiety:

> *And it was like, this whole anxiety about not knowing, it disappeared, and I was like, "Oh, I don't know, but ok. I don't know but we can work it out," you know? And if we don't, then we have a question that we're just going to have to wonder about.*

In fact, Marya described the course as transformative for her beyond physics, altering her experience in other classes and her anxiety more generally. Two years later, she still speaks of it as having stimulated her interest in research, and she is applying for doctoral programs in environmental engineering.

In this paper, we offer our account of Marya's dramatic and lasting transformation. We argue, based on data from her work in the course and an interview the afternoon after she took the final exam, that her progress involved *meta-affect* (DeBellis & Goldin, 2006), her feelings about feelings, and *epistemology*, her sense of what it means to know and learn. In particular, it involved her coming to enjoy feelings of uncertainty, which supported and was supported by her coming to see not-knowing as inherent in doing physics.

Prior work, as we review in the following section, has identified roles of affect and meta-affect in moments of disciplinary engagement; Marya's case shows a long-term stability that we call meta-affective learning. After describing the course and our methodology, we present data and analyses to show that meta-affective learning was central to Marya's progress. In the final section of the paper, we discuss implications for research and instruction. Our ultimate purpose is to suggest that meta-affective learning may be of general significance for science education.

Feelings about feelings

Epistemic affect and meta-affect

For several decades, research has highlighted the role of affect in learning (Alsop & Watts, 2003; Arango-Munoz & Michaelian, 2014; Damasio, 1994; Pintrich, Marx, & Boyle, 1993; Thagard, 2008; Wolpert & Richards, 1997). In education, Pintrich and colleagues (Pintrich et al., 1993) argued that "affectively charged motivational beliefs…may influence the process of conceptual change" (p. 172). In neuroscience, Damasio (1994) found that patients with brain lesions that damaged parts of the brain that regulate emotion became incapable of rational decision-making, arguing that emotions are integral to cognition.

Building from these ideas, Jaber and Hammer (2016b) suggested that affect is entangled with intuitive epistemology: People understand and recognize an epistemic state in part by the affective aspects of the experience, for example the excitement of having a new idea, or the discomfort of discovering an inconsistency.

Descriptions of such feelings pervade accounts of professional science: the "joy of going at it" (Fox-Keller, 1983, p. 125 quoting McClintock); "the pleasure of finding things out" (Robbins, 1999 quoting Feynman in the book's title); the "torment of the unknown" (Bernard, 1865, pp. 222-3); the "angst required to motivate the search" (Root-Bernstein, 2002, p. 77).

Some sound unpleasant, in particular, feelings of not-knowing and confusion. But scientists come to seek them out, "finding pleasure in mystery" (Firestein, 2012, p. 17), perhaps for having learned these feelings can build toward the satisfaction of explanation (Gopnik, 1998; Thagard, 2002).

DeBellis and Goldin (2006) described the phenomenon of enjoying otherwise undesirable emotions, or finding desirable emotions unpleasant, as *meta-affect*—"feelings about [or with respect to] feelings" (p. 137). Thus people seek out fear in amusement park rides or horror movies; people appreciate and are energized by nervousness before public speaking or rock-climbing or deadlines. DeBellis and Goldin discussed the relevance of meta-affect for mathematics education:

> Just as the knowledge that a roller coaster ride is 'really safe' can render fear pleasurable, mathematical exploration in an environment where the student knows making mistakes is 'safe' can transform negative emotions into positive ones. […] For example, frustration could and should indicate that a mathematical problem is non-routine and interesting. It should carry with it anticipation of possible elation at understanding something new, or achieving a difficult goal. Then frustration itself is experienced as interesting, curious, even euphoric. (DeBellis & Goldin, 2006, p. 137)

Jaber and Hammer (2016b) applied DeBellis's and Goldin's reasoning to students doing science. Fifth-graders Jordan and Elea, for example, showed frustration as they tried to convince their classmates' of an inconsistency: How can a cloud, when "everyone thinks it's light," hold water, which is heavy? At the same time, layered onto this frustration, they showed signs of enjoyment, smiling and laughing. Similarly, Phillips, Watkins, and Hammer (under review) describe college student Michael's motivation to think more about a problem when he "wasn't really happy" about his solution.

These instances are both part of a larger study to collect and analyze what is happening in moments when students are doing science[15]. As of this writing, we have analyzed nine cases, and in nearly every one there is evidence of students' feeling "epistemic vexation" (Radoff, chapter 2 of this dissertation) that helps drive their engagement. There is similar evidence across many cases in the literature, such as, famously, Engle's and Conant's (2002) account of fifth-graders' "Big Ol' Argument" about orcas; Manz's (2012) account of third-graders investigating plants with "explosions" of their activity and interest; and Salter's and Atkins's (2013) account of undergraduate elementary education majors' studies of light, and learning "that beyond the frustration is a moment where ideas come together and make sense" (p. 168).

Of course, students' productive meta-affect is not a common outcome or expectation, as every teacher knows and researchers have documented. Feelings of frustration or uncertainty often result in students' disengagement (Leander & Brown, 1999). In light of this, we ask, when and how might learners be driven to do science rather than discouraged by "negative" feelings?

The forms of evidence we have cited so far afford two general answers to that question. One is contextual—aspects of the situation that favor productive meta-affect, such as the known safety of a roller coaster or a math class where risk-taking is celebrated. Researchers have worked to identify aspects of learning environments that support disciplinary engagement (Azevedo, 2006; Engle & Conant, 2002), drawing on evidence from case studies of students doing science.

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The other answer attributes productive meta-affect to individuals, as stable aspects of their “disciplinary dispositions” (Lehrer, 2009). The evidence comes mostly from accounts of scientists, but there are also studies of young students who have formed longer-term interest in science (Barron, 2006; Bricker & Bell, 2014; Jaber & Hammer, 2016a). Eighth-grader Estevan (Conlin, Richards, Gupta, & Elby, under review), for example, described his interest in science as related to his love of challenges.

Meta-affective learning

Marya’s case provides an unusual opportunity to study learning. She began the introductory physics course focused on learning facts and formulas provided by the text, instructor, and other authoritative sources. As we show below, she was stable in that pattern of epistemology, persisting in it for several weeks at the start of the course despite the instructors’ ongoing advice, repeated in lectures, the syllabus, and in problem set assignments, to take a different approach. At the same time, she was struggling with anxiety over learning and applying the information correctly.

Then, as we show, she began to work in different ways, in particular moments at first, which did not last. Marya’s experience on exams, in particular, shifted her back into her original pattern of feelings and approach to doing science. By the end, however, she was showing stability in a pattern of working to make sense of phenomena and ideas, and taking pleasure in feelings of uncertainty. That pattern has apparently lasted beyond the course; Marya seems to have developed new dispositions for learning.

We describe her as having learned productive meta-affect, in particular with respect to uncertainty and confusion. We argue that this happened in concert with her coming to a more productive understanding of the discipline, in particular learning that uncertainty is inherent to doing physics.

In the next section, we describe the context of the course, how we discovered Marya as a research participant, the data we collected and our methods for studying her meta-affect and epistemology. There were other dynamics involved as well, including her identity and goals. We focus on meta-affect and epistemology, however, because they are prominent in the evidence.

Methodology

Context of the course

Marya was one of 70 students in a calculus-based introductory physics course. I was a teaching assistant (TA) and David Hammer was the professor. A main goal was for students to experience physics as "a refinement of everyday thinking" (Einstein, 1936, p. 59), and the instructors framed the course to encourage genuine sense-making, much as described in Redish and Hammer (2009). For example, the syllabus advised students they would get credit on problem sets for "good, sensible effort....Being right on a problem is of no value at all if you haven't understood what you were doing. Being wrong in a thoughtful way is almost always of value." In labs, rather than follow a set of guidelines, students completed a challenge by designing and conducting their own experiments.

The "text" for the course was smartPhysics[16] in the form of online video pre-lectures. These lectures came with conceptual "checkpoint questions," which played a central role in the course and in our analyses of Marya's progress. The professor read students' checkpoint answers just before each lecture, replying to many by e-mail and quoting some in lecture. Lectures involved extensive student discussion, including around clicker questions. In these ways, the

[16] Now called "FlipIt Physics," https://www.flipitphysics.com/

course as a whole reflected a form of "responsive teaching" (Robertson, Atkins, Levin, & Richards, 2015 describes an example from lecture). Students also attended weekly discussion sections run by TAs, and many attended optional "help hours" sessions.

Activities across the course had students considering multiple lines of reasoning. Problem sets and exams, for example, included 3-part questions asking students to come up with and deliberate between two sensible opposing arguments and to articulate the problem with the reasoning they considered incorrect. The instructors and course materials discouraged students using equations or terminology they could not explain in simple terms, as if "to a 10 year old." They also encouraged students to critically analyze their thinking, to find the balance between when to trust their intuitions and when to be skeptical of them.

Finally, from time to time the instructors explicitly addressed affect. They spoke of confusion as part of doing science, something to pursue and engage rather than avoid, and of scientists as having "stamina and enjoyment for the game of not knowing the answer" (Hammer from the first lecture). They also encouraged students' working to articulate confusions, describing the formulation of questions as important progress in science and learning (Phillips et al., under review).

Discovering Marya

I was Marya's discussion section TA in the spring semester of 2014. At our first meeting, Marya expressed anxiety[17] about taking the course; she spoke to Professor Hammer as well, early in the course and around the first exam. Marya sought counseling, and she eventually received a diagnosis of generalized anxiety disorder. As the semester progressed, however, Professor Hammer and I noticed evidence in her coursework that she was shifting in her

[17] Source: Video data of the first discussion section, on 1/21/14

approach and also noticed a shift in her anxiety. She relapsed at the second exam, and Professor Hammer granted her extra time after seeing her anxious and distressed. For the rest of the semester, she resumed making progress, and she showed no anxiety at the final exam—in fact, she told Professor Hammer she had enjoyed it even though she could not answer every question. Towards the end of the semester, she expressed an interest in pursuing a minor in physics and excitedly told me about physics books she purchased to read over the summer.

Seeing what was happening for Marya, I proposed conducting a case study. Because we did not plan this study from the start — there was no way to anticipate what happened — the challenge was to find sufficient data to make insights. As a first step, I asked Lama Jaber, who was not affiliated with the course, to interview Marya about her experiences.

Data collection and analysis

Lama interviewed Marya a few hours after the final exam, with a semi-structured approach described in Appendix 4.1. I conducted a follow-up interview two years later, after our analyses were complete. Both interviews were video- and audio-taped. The second interview provided evidence of Marya's long-term stability in meta-affect and epistemology, and it allowed me to check what Marya thought of our interpretations.

We also collected copies of Marya's written work, including checkpoint questions, problem sets, and exams. Each smartPhysics unit provided three to four checkpoint questions, and there were 20 units over the semester. These questions were mostly multiple-choice with explanation, with one routine question titled "Lecture thoughts," where students could post their confusions or musings about the pre-lecture or the course in general. The problem sets consisted of 4 or 5 challenging problems, 11 sets over the semester. Students typically took several hours to complete these, and they handed in their solutions on paper and TAs commented on them extensively. There were also three exams, made up of 8 multiple choice questions and 3 essay questions.

Finally, we videotaped the lectures, discussion sections, and office hours throughout the semester as part of a larger project. There is, however, relatively little of Marya in this video, so it played little role in our analysis.

Analyzing Marya's interview data

To analyze the interview data, we first transcribed it and identified excerpts where Marya reflected on her learning experiences in the course. To track her use of affect-laden language, we highlighted words including *excited, scary, anxious, frustrated, tempting*, etc. We also highlighted places she spoke of something in transition, that is starting or stopping, changing or shifting. We then analyzed the transcript for evidence of what contributed to Marya's affective transition, with the highlighted terms helping us identify relevant text. For example, Marya statement, *"Definitely **not knowing**, **at first**, was such a huge factor in causing **anxiety**,"* links *anxiety* to *not knowing*, and it marks a transition with *at first*.

Looking across the transcript in this way, we developed two main claims: (1) Marya's transition from feeling anxious to feeling excited in physics was linked to how she experienced feelings of uncertainty, and (2) this change in meta-affect was linked to her changing sense of the value of uncertainty both in the field of physics and in her personal experience of problem-solving. In particular, Marya spoke of her "anxiety about not knowing" as connected to her viewing physics as "about absolute right or wrong," and she spoke of "excitement about not knowing" as connected to her realizing that physics is "about the journey and the question."

From the interview data, we generated narrative themes (Braun & Clarke, 2006) to describe the patterns we identified in Marya's account of her epistemological and meta-affective shifts. We present these themes in a subsection under *Results and Analysis* entitled "Marya's account of knowing and feeling in physics."

Analyzing Marya's written work

As a complement to Marya's self-reflections, we analyzed Marya's written work, focusing on her responses to 20 sets of checkpoint questions over the semester. While these provided some indications of affect, such as in expressions of excitement, most of the evidence concerned Marya's epistemology, which became the focus of this analysis. More precisely, we looked at her checkpoint questions for evidence of how her epistemological framing (Hammer, Elby, Scherr, & Redish, 2005), that is, how she understood what she was doing with respect to knowledge, shifted over time.

Lama and I developed a coding scheme using grounded-theoretical methods (Charmaz, 2006), characterizing how Marya approached reasoning about the problems. We coded a fourth of the data together, developing a rough initial scheme, which included 10 different coding categories, and then we applied it individually to the rest of the smartPhysics dataset. The results informed a refinement and simplification of the scheme. The final coding scheme is comprised of five categories:

(1) extending past a problem's boundaries,

(2) constructing counter-arguments and revising her thinking,

(3) connecting to prior experiences and "messing about" (Hawkins, 1965),

(4) using multiple approaches to solve a problem, and

(5) identifying and articulating her own confusion.

The codes are neither hierarchical nor mutually exclusive.

Since we wanted to capture Marya's sense-making of her own initiative, we did not consider as coding instances the cases where a question explicitly asked students to engage in any of the activities represented by the five codes, such as considering an alternative argument. It is also important to note that we coded for evidence of sense-making regardless of canonical correctness. We discuss each of these codes with illustrative examples, and present the results of our coding analysis, in the section entitled "Tracking Marya's epistemological framing." The inter-rater reliability was 94%, using the simplified scheme, including no-code decisions.[18] Lama and I then discussed the remaining disagreements and reached 100% consensus.

Finally, while we did not subject Marya's problem set solutions to systematic analysis, we used them to help us understand and validate data in the interview. In particular, we provide an excerpt of her work on the seventh problem set, which she described in her interview as a particularly exciting instance of sense-making (in the section entitled, "An example from Marya's later work").

Results and analyses

We first present data from Marya's interview immediately after her final exam, in which she reflected on her own transformation, as evidence that her changing epistemology shaped her meta-affective learning. We then provide examples from her written work and our coding of the checkpoint question data as evidence of her epistemological shift over the semester.

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[18] That is, the two raters agreed in 94% of their coding decisions broken out by category, with the possibilities of no-codes and codes in each of five categories. As we explain below, however, our argument in this article depends only on the sum of codes across the five categories.

Marya’s account of knowing and feeling in physics

In an interview conducted immediately after the final exam, Marya recalled how her feelings about uncertainty shifted.

> *Definitely not knowing, at first, was such a huge factor in causing anxiety because it was just always like, you don't know! And the chances are for most part nobody's gonna give you the answer....but physics, even though it caused anxiety, it started not causing anxiety…it was more fueling a weapon against anxiety than fueling the anxiety itself. […] It started being like, if I don't know the answer then ‘Ooh goody we have another problem to solve!*

While Marya felt anxious about uncertainty at first, by the end of the semester she felt excited about it, viewing it as an opportunity to problem-solve. She continued,

> *And all that because I think it was more about the process, it was just really about learning […] it's about the journey and the question. It wasn’t about absolute right or wrong.*

Marya attributed the shift in her feelings to a shift in her sense of what it means to learn physics, from being about “absolute right or wrong” to being about “the journey and the question.”

In what follows, we examine this shift more closely, to describe three patterns of relationship between epistemology and meta-affect evident in the interview (see Table 4.1). We present these patterns as a linear progression to preserve the flow of Marya’s own narrative, but we do not contend that Marya’s shift was, in fact, linear.

Epistemology	**Meta-affect**
Science is about absolute rights and wrongs	Anxiety about feeling uncertain
Science is about the journey and the question	Comfort with feeling uncertain
Science is a sense-making pursuit	Excitement about feeling uncertain

Table 4.1: Patterns of relationship between epistemology and meta-affect

Marya's sense of science as "absolute right and wrong" contributed to her initial anxiety about "not knowing"

Marya described feeling disempowered in her early experiences of physics. She said,

> *I've always been intimidated by physics. […] A lot of the time growing up I would walk around and see something happening in the physical word, and be like, 'Hmm I wonder how that works,' but I was like, 'It's probably way above me' you know, way beyond me to know.*

There is evidence that Marya's sense of herself and her abilities were connected to her understandings about the nature of knowledge in science and her role as a science learner. She said,

> *It's like, it's really interesting, but do I really have the brains for that? I'm not sure. […] Science was always portrayed as a very inflexible thing, you know it's like, science is science, laws are right. […] As an outsider it just looks really complex. It was really interesting but I didn't think I could do it.*

She remembered approaching physics as a body of knowledge she must learn:

> *You know, like Newton discovered all things and here are the laws he came up with. Just study those well and you're gonna be fine, and you're gonna know how to handle the world.*

Seeing physics, as a complex body of fixed, incontestable knowledge produced by others, Marya understood her role as a knowledge-receiver rather than a knowledge-builder. This view could not afford a productive role for not-knowing; uncertainty is problematic, and lingering in uncertainty antithetical to being a successful learner.

> *I think I'm a bit of a perfectionist with myself. I always want[ed] to get things really fast and do them quickly.*

This expectation, paired with the fact that "a lot of the time [she] didn't know a lot of things," fit with "anxiety about not knowing" that for Marya, even "led to the development of a little bit of depression." In this way, Marya's early epistemological view of physics as "being about absolutes" contributed to her anxiety with respect to uncertainty.

Marya's sense of not-knowing as part of science helped her develop comfort with uncertainty

Marya recalled experiencing "a really interesting shift" from thinking of physics as "absolute right or wrong" to thinking of it as "about the journey and the question."

> *Honestly in the sciences- if you're an engineer, if you're a scientist, if you're a doctor, the things you don't know literally can fill books. There is a ton you don't know! Rather than being intimidated by what you don't know, it's just like, work on what you do know and add to it.*

This shift allowed her to see the value in the pursuit of sense-making instead of worrying about finding the quickest path to the correct answer. She said, "I don't need to get it instantly, because it's not about getting it, it's about how you got it." Within this view, uncertainty is a precursor for discovery rather than an indicator of failure. As Marya came to realize that uncertainty is at the very core of the scientific enterprise, her anxiety about not knowing began to dissipate.

This whole anxiety about not knowing, it disappeared and it was like, 'Oh, I don't know, but ok, we can work it out,' you know? And if we don't, then we have a question that we're just gonna have to wonder about.

Additionally, she started to enjoy lingering in questions and curiosities.

There's this appreciation of just wondering sometimes, just like 'I wonder' and then you work at it, and then you wonder more, and then you figure it out, or maybe it's a question that stays with you for a while.

She even carried these new feelings about uncertainty into her final exam:

So like for example, this test I just took- we had the final today, and there was this just one question where I just I did not know. I did everything, I tried everything, I just don't know. And I was ok with not knowing because I know I can still work on it, I can get it. Because not knowing now does not mean that you're not gonna know all the way…I was like 'ok, I'm still gonna work on it. I'm still gonna figure things out.'

Even though there was a problem she did not know how to answer, she felt empowered to "still work on it." In this way, coming to see not-knowing as inherent to physics eased Marya's anxiety about uncertainty. The reverse seems true as well: That she felt "ok with not knowing" helped support her seeing it as part of science.

Approaching physics as a pursuit of understanding contributed to Marya's enjoyment of not knowing

Finally, there is evidence Marya went beyond acceptance of not-knowing as part of science to seeing it as the motivation and opportunity for discovery:

Rather than depending on a teacher to give you the right answer or a professor to tell you that's right, […] we were approaching physics as if we were just discovering physics.

And that, she said, was a pleasurable experience. She burst into a smile as she explained how she felt when facing a new problem:

> *When you're an engineer you have no shortage of problems to deal with. And just like, this idea of like, 'Oh, we have this big problem,' you know, and it's like so complex. And it's scary but it's also exciting because, 'Let's see if we could figure this out' you know? And when you do, it's so rewarding in the end because like it's just, I don't know, it's such a high when you figure something out, you're just so excited and just like I dunno- you see the smile on my face!*

Marya expressed what is evident in accounts of scientists, enjoying a new problem — scary but exciting — in part for the anticipation of the "high when you figure something out." Even when the physics got difficult, she described it as "too tempting" to give it up. She said,

> *I would get frustrated at times, and be like, 'you know what? I just give up.' And I would drop physics for like a day or two and be like, you know what, the deadline is not even tomorrow, it's like three days away and I don't have to deal with this right now, so I'm not. And I would just like get up and do something else. But then I'd come back, you know, because it was just like too tempting not to.*

For Marya, physics was not only too tempting to pass up, but it became "a weapon against anxiety." The excitement she felt when solving a new problem overshadowed her feelings of anxiety:

> *Yes, there is the anxiety about physics and like can I do it and it's difficult and…can I handle that difficulty? But then, you go and figure something out, about inelastic collisions, for example, and you're so excited, it's like a kid walked into a candy store,*

and you're like, 'You know what? Who cares? The anxiety can just like take a back seat because physics is just too awesome to pass up.'

This shift, from feeling anxious to feeling excited about not knowing, enabled Marya to approach her physics learning in healthier and more productive ways. It even impacted her experience in other courses, where she found herself looking for sense-making opportunities even when sense-making was not required or even supported:

So I'm taking calculus and I found myself doing the same things, like 'why does this work?' and some things I couldn't answer because it required like a higher-level math understanding but lots of things I could, you know, trace back to like basic things and you know, 'yeah that makes sense,' and I would- it was not required for the course but I would do it because I truly know it.

In Marya's second interview, two years after taking the introductory physics course, she retained this sense of excitement for "not knowing." Since taking physics, Marya got involved in a research lab in environmental engineering, where she was given the latitude to define her own problems, design and run her own experiments, and collect and analyze her own data. She is currently applying to doctoral programs to continue along this path. When asked what excites her the most about research, she said:

I think it's figuring out the answers despite the confusion. I think that's really fun. You know, to go from looking at something and be like, 'I have no clue what's going on,' to being like, 'Oh, I know what's going on.' I think that's great. Like, that literally makes me giggle and jump. I love that. I love the idea of just sitting with something, you know, struggling with it, and figuring it out. And, like, you know, struggling is not always fun. Like there's the frustration, like, 'Oh my god, like really this makes no sense.' And then *you sit with it for a while, or you leave it, and like you storm out of the room and you come back in and you sit with it and you think and you figure it out and you come up with different solutions, and some work some don't, but then at the end of the day, you come up with a tangible thing to say about your confusion. It's either like, 'Oh, I figured out what this means,' or 'I figured out what I don't understand.' Which, I think that kind of clarity through confusion is so interesting to me. Um, I mean, it makes me feel great when I achieve that kind of clarity through confusion, it makes me feel wonderful.*

Marya has come to experience the struggles and frustrations of research as part of what drives her, like scientists feeling "torment of the unknown" (Bernard, 1865, pp. 222-3) and "angst required to motivate the search" (Root-Bernstein, 2002, p. 77). She has also developed a stable sense of "clarity through confusion," including that figuring out what she does not understand is itself a pleasurable intellectual achievement. Though this feeling toward uncertainty and confusion was evident only in moments when she first began the course, she revealed it as a stable and integral part of her disciplinary identity two years later.

Evidence of a shift in Marya's written work

Here, we shift our analysis to focus on Marya's responses to the online checkpoint questions in smartPhysics. We first present an example of Marya's response to an early checkpoint question, as evidence of her initial epistemological framing. We then present findings from coding her responses over the semester, which show evidence of a different framing.

An example from Marya's early work

This example comes from the second smartPhysics unit, in the first week of the course (see Figure 4.1). Responding to the question, "Which ship gets hit first?", Marya wrote:

I think enemy ship 1 has the greater speed because it[s] parabolic trajectory shows a steeper positive slope than does enemy ship 2. If we were to go back to the two time values at which the projectiles are at zero, the second value (where the projectile hits the ship) is dependent on the initial speed and the gravitational pull [$2\,v_0/g$]. The greater the speed in the [numerator], the greater the result of the fraction meaning the greater the time. Enemy ship 2 will be hit first because it has the lower speed.

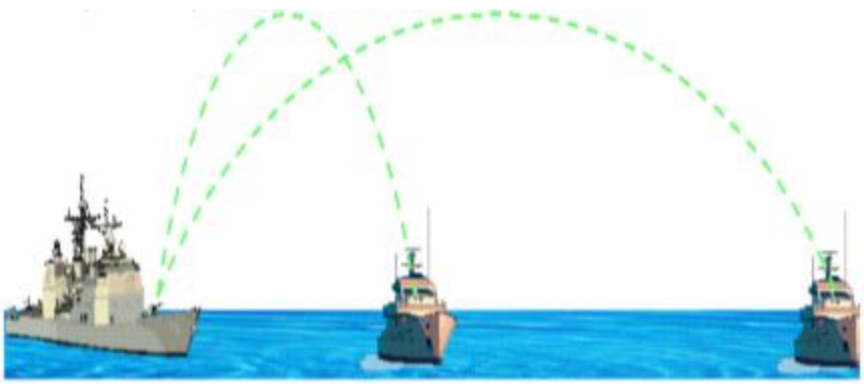

Figure 4.1: A destroyer simultaneously fires two shells with different initial speeds at two different enemy ships. The shells follow the parabolic trajectories shown. Which ship gets hit first? (Unit 2)

The most common response to this problem is that enemy ship 1 gets hit first, by the physically sensible reasoning that traveling less distance should take less time.[19]

Marya's claim that a steeper positive slope means greater speed is true about a position vs. time graph, but the problem depicts the trajectory in terms of 2-dimensional position (y vs. x), and time is not directly represented in the image of the trajectory. She uses that idea in the

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[19] That reasoning would be correct, for objects moving at the same speed along that distance, but in this case the shell launched at ship 2 would be moving faster. The correct answer is that the two ships are hit at the same time: They have the same vertical component of velocity, because they reach the same height. Shell #2 has a greater horizontal component of velocity, so it travels a greater horizontal distance.

equation $t = 2\, v_0/g$, which the instructor and smartPhysics pre-lecture derived for vertical motion. Thinking the shell for the first ship has a larger speed, she concluded it takes a shell less time to reach the ship that is farther away, "because it has the lower speed."

Her reasoning here has a logic to it, a "means-ends analysis" often seen in novices (Larkin, McDermott, Simon, & Simon, 1980), but it is not physically sensible. This example illustrates the early, pre-sense making epistemological stance that Marya described in her interview.

Tracking Marya's epistemological framing

As outlined in the methodology section, we looked for evidence of Marya's sense-making, classified into five codes: (1) Extending past a problem's boundaries, (2) Constructing counter-arguments and revising her thinking, (3) Connecting to prior experiences and "messing about" (Hawkins, 1965), (4) Using multiple approaches to solve a problem, and (5) Identifying and articulating her own confusion. We first provide examples of each category, and then we show the trend over the semester.

1. *Extending past a problem's boundaries*

For example, a checkpoint question asked about a block on a frictionless surface hit by a ball. Would the block move faster if the ball bounces or if the ball sticks (see Figure 4.2)? Marya's response provides examples for the first three categories of coding.

First, she extended past the checkpoint question: "[This] makes me wonder, is there loss in kinetic energy in the [bouncing] scenario?"

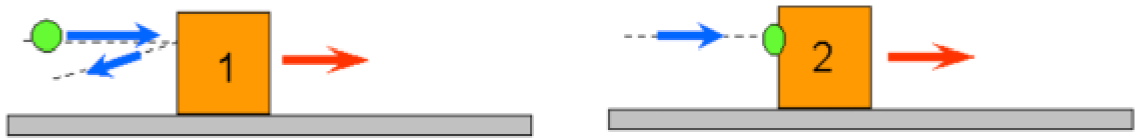

Figure 4.2: Two balls of equal mass are thrown horizontally with the same initial velocity. They hit identical stationary boxes resting on a frictionless horizontal surface. The ball hitting box 1 bounces back, while the ball hitting box 2 gets stuck. Which box ends up moving faster? (Unit 11)

During her interview[20], Marya described the importance of asking her own questions beyond assigned problems, and she recalled doing this often: "It was not required for the course but I would do it because then I'd truly know it."

2. *Constructing counter-arguments and revising her thinking*

Answering her question, Marya wrote:

I think there would [be a loss] because the box does end up moving after the collision and I can imagine the ball slowing down after the hit but I also feel that it would speed up. Actually, I take that back. I just watched a video of billiard balls being hit and the ball that does the hitting changes directions and slows down… I just hit a ball against the wall and I varied the speeds. It seemed to me that the ball bounced back with the same speed that I hit it with. I tried but I couldn't make it go faster than its original speed no matter how hard I hit. At least, it looked that way to me. In scenarios like this, would it be correct to say that the ball can either go slower or the same speed but never faster? I think the ball would speed up only if the box was pinned to the floor or would it bounce right back with the same speed?

[20] All interview excerpts from this section come from Marya's first interview.

We coded this as evidence of her considering counter-arguments and revising her thinking. She considered that the answer might be context-dependent—that the ball would speed up only if the box were pinned to the floor—which might account for why she could so easily move back and forth between two opposite lines of reasoning. Perhaps both answers could be right depending on context, and the job is sorting out under which conditions (if any) her intuitions hold true.

Note that it was Marya's initiative to think through multiple possibilities. Throughout lectures, problem sets, and exams, the course explicitly required that students consider counter-arguments, but the checkpoint questions did not. That she did so by her own initiative was evidence of her epistemological framing. During her interview, Marya reflected on the importance of coming up with multiple arguments to support opposing answers, a practice she came to value as central to her learning in physics:

> *If you reach a conclusion...what are the counter-arguments and how would you break down those counter-arguments? And if you can't break down the counter-arguments then examine your own because there is a big chance that the counter-argument is right.*

3. *Connecting to prior experiences and messing about*

Much of the course emphasized students making tangible connections to everyday experiences and encouraged them to play around with familiar objects. We coded in this category when there was evidence of Marya's doing so. For example, "hit a ball against the wall" as part of working on her question. Again, this was by her initiative; checkpoint questions did not explicitly ask students to conduct informal (or formal) experiments.

Marya described the importance of connecting to the familiar world:

> *I just truly wish I had more classes like this. Um they're just so fun (smiles), and they're really interesting because they just bridge the gap between what we say is the really*

enclosed academic bubble and, you know, the outer world. Because it didn't feel like it was a closed academic bubble, that class. One question that was always asked, you know, 'go try it,' you know, if we're talking about, I dunno, rotation and a stick and a penny. [The problem] was like 'go grab a stick and a penny and throw the penny on the stick and see what happens,' you know. It was always like 'go do it.'

4. Using multiple approaches to solve a problem

Here we shift to another question, which asked which axis of rotation would the moment of inertia of a dumbbell be smallest (see Figure 4.3). Marya first reasoned through the problem without doing any explicit calculations.

3M is three times as big as M so the center of mass will be three times farther from M than from 3M…at L/4. So at B the only rotation would be around the center of mass [which is] stationary. In both A & C, the center of mass would contribute to the moment of inertia of the two balls. So B has to have the lowest moment of inertia. If the two masses were equal then we can easily say that C would have a lower moment of inertia than A because the mass is distributed over longer distances than in C. However, the masses are different and I need the math to help figure that out.

Marya then went on to calculate algebraic expressions for the moments of inertia around each axis.

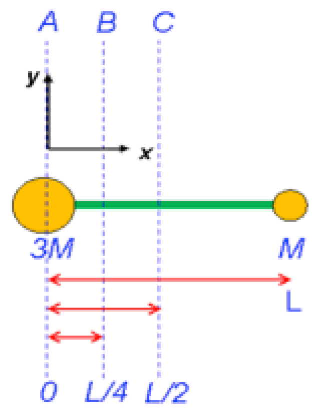

Figure 4.3: A ball of mass 3M at x=0 is connected to a ball of mass M at x=L by a massless rod. Consider the three rotation axes A, B and C as shown, all parallel to the y-axis. For which rotation axis is the moment of inertia of the object smallest? (It may help you to figure out where the center of mass of the object is.) (Unit 15)

Marya's answer was also evidence of extending the problem boundaries, as she was curious about comparing the moments of inertia of A and C, which was not a required element of the problem. In reasoning through the comparison of A and C, she created a thought experiment to help her make sense of the situation. She imagined the masses to be equal, which would logically follow for A to have a higher moment of inertia than C[21]. But since the mass at A is 3 times as large, it wasn't straightforward how to compare them without using mathematics. After working through the mathematics, she excitedly concluded, "So in fact the moments of inertia about A & C are the same!" Marya first reasoned through the problem intuitively and turned to mathematical calculation when it was necessary.

In her interview, Marya talked about checking her intuitive reasoning with mathematics, and her mathematical reasoning with her intuitions. After she found the answer with one method,

[21] The moment of inertia for this object is $I = \frac{1}{2}M_1R_1^2 + \frac{1}{2}M_2R_2^2$, where M_1 and M_2 are the first and second mass, and R_1 and R_2 are the distances of those masses from the axis of rotation. Since R is squared, and M is not, changing the distance from the axis of rotation has more impact on the moment of inertia than changing the mass does.

she would approach the problem from a different angle, “making sure the different pockets in [her] brain were combined”:

> *A lot of times in the course...we'd had these intuitions, and I'd get the right answer you know, but I wouldn't be able to tell you or explain to you why that is the right answer and that means that I have a lot of work to do.*

She also recalled needing to use mathematics purposefully in this course. She said,

> *Usually, doing problems, it was always um, math. Just doing math. And the challenge with this course is that it wasn't just about math. In fact, it was more about why are you doing the math. So like it's not enough to state this equation it's like, tell me why you're gonna use it.*

She described how she began to use mathematics in the service of, rather than in lieu of, sense-making. She asked herself,

> *I could throw in symbols all over the place and get the right answer but do I honestly have a good grasp of what was going on conceptually? Does this make sense?*

5. *Identifying and articulating her own confusion*

In her lecture thoughts for Unit 9, Marya wrote,

> *When we say that work is equal to the change in kinetic energy of an object, what does that really mean in terms of what the work and energy are to each other? I tried digging up an answer and I found the following. I was a little hazy on what exactly do we mean by energy and I found the definition that energy is the ability of a physical system to perform work. So now it seems to me that work and energy are basically the same thing. Energy is the base here and work is a way to label energy that's being spent. Is that a good description of the relationship between work and energy?*

Here, Marya identified that she did not understand the relationship between work and energy. Having articulated the confusion, she searched for an answer and then described her subsequent understanding. Making her confusion explicit allowed Marya to expand her understanding of a conceptually complex phenomenon.

In her interview, Marya explained that part of doing physics is about "examining your own thought process and examining your own learning process...checking after yourself and not just relying on tests and homeworks to check if you know things, just having this constant conversation with yourself about your knowledge." In this way, she began to assess and interrogate her knowledge in an effort to recognize and articulate her own confusion, a process that took a great deal of patience and endurance:

> *It's not enough to tell me you're confused. Tell me why you're confused, what's confusing you, and can you work at that confusion? Do you have the endurance to sit down with it and figure out why you're confused and can you break it down?*

Coding results

A visual representation of our coding for Marya's entire semester of smartPhysics data (see Figure 4.4) shows that her engagement in sense-making generally increased from the beginning to the end of the semester. For our purposes here, we combine all five categories to give a single, overall measure. Each square's intensity corresponds to the total number of instances evidence of any code appeared, with darker squares corresponding to a higher number of instances, with a range from 0 to a maximum of 7 codes in unit 12. There is no evidence of Marya's active sense-making until unit 4 (the end of week 2 in the course).

Thus, the evidence from checkpoint questions over the semester supports an interpretation of increasing incidents of Marya's framing her work as sense-making, progressing over the semester toward a stable, lasting stance. This is consistent with Marya's own account of her changing epistemology.

Total Code Frequency																				
Unit	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**

Figure 4.4: Coding for Marya's enactment of knowledge-building strategies and practices

An example from Marya's later work

We have focused our analyses of Marya's written work on checkpoint questions. Her work on problem sets was generally similar, although because they often explicitly requested counter-arguments, informal experimentation, and articulating confusion, they are not as valuable for *systematic* tracking of Marya's epistemology. They do, however, provide evidence of the entanglement of epistemology and affect.

Here we present data from Marya's work on the problem about inelastic collisions that she excitedly mentioned in her interview, from week 7 of the course (see Figure 4.5), which supports her recollection.

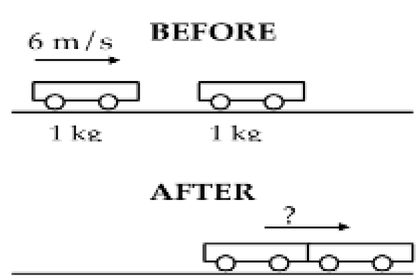

Figure 4.5: An inelastic collision

The first question of the multi-part problem read: "A 1 kg cart, rolling at 6 m/s, collides with and sticks to an identical cart that's initially at rest. So, after colliding, the carts roll together as a single, 2 kg unit. How fast does the pair of carts roll?" The problem went on to ask about the kinetic energy of the carts before and after the collision, and then asked students to redo the problem with a 2 kg cart initially at rest.

Marya used this problem as an opportunity for innovative sense making, going significantly beyond what it asked her to do. She attempted to generalize behavior from this specific collision, developing and testing a rule to apply to all similar collisions. For the original case of two 1 kg carts, she wrote,

Before collisions *Total KE = 1/2m1v^2 = 1/2 1kg (6m/s)^2 = 18J*

After collisions *Total KE = 1/2(m1+m2)vf^2 = 1/2 2kg (3m/s)^2 = 9J*

And for the second case with a stationary 2 kg cart, she wrote,

*KE before collision = 1/2 1kg * (6m/s)^2 = 18J*

*KE after collision = 1/2 3kg * (2m/s)^2 = 6J*

Then, Marya made a general observation about these two cases. She wrote,

Interesting! So it seems that when the cart collides with an object with the same mass, half the initial kinetic energy is lost. When it collides with an object twice its mass, two thirds of the KE energy will be lost. So there's a relationship between the KE lost and the fraction of the mass of the stationary object and the total mass of the system. Specifically,

$KE_{lost} = KE_i \times (m_{stationaryObject}/m_{totalSystem})$

Marya recognized that she could derive a general relationship from these two specific cases that would apply to any similar case. She went on to write, "I want to further check my expression. Now I'll consider the same system but cart 2 now has a mass of 4kg." She then calculated the relationship in this new case and wrote, *So the relationship holds true!! From this expression we can also infer that the system will always have a quantity of KE after collision. However as the stationary object gets larger and larger, the kinetic energy will start becoming negligible. In other words, the stationary object will always have a velocity but if its large enough, the velocity becomes so small that we can safely say that the stationary object remains stationary for the most part to our naked eyes.*

Marya not only constructed a generalized expression for the amount of kinetic energy that gets lost in an inelastic collision, but she went on to check and physically interpret those results. She concluded that the larger the stationary object is, the more kinetic energy is lost. She considered the limiting case, of a very large stationary object that essentially slows the moving object to a point where the human eye can no longer perceive movement, which is consistent with our experience of a car crashing into a brick wall, for example.

Marya's solution itself provides evidence both of epistemology and affect. First, instead of merely solving the assigned problem, she took the liberty to build on the problem in ways that led to a new and exciting scientific discovery. On her own initiative, she took an extra step to explore the generality of the tacit rules behind the specific case presented in the problem. Not only did she discover a generalized mathematical relationship, but that relationship also helped her understand something physically meaningful about collisions. In these ways, the substance of her solution is evidence, like her checkpoint solutions, of her framing her work in the course as a pursuit of her own understanding.

Second, excitement was evident in the affect she expressed, with "Interesting!" on first noticing a pattern, and "So the relationship holds true!!" after confirming her ideas. What she put on paper supports her recollections of this problem in her interview two months later:

I remember there was this problem set where I figured something out about inelastic collisions and kinetic energy. And it was just like this natural conclusion from something, like the question, but I took it just a tiny little bit further and I reached this conclusion and I was completely sure that it was a valid conclusion to make. And I got so excited and like I wrote, like, tons of exclamation points because I was just so excited. So yeah it was really rewarding.

This example illustrates the entanglement of Marya's meta-affect and her epistemology in situ. In addition to her recollections, we see evidence in her written work that she came to deeply enjoy the experience of making sense of the world.

Discussion and Implications

The case of Marya contributes to and connects two lines of research on learning, first concerning affect and the second, epistemologies.

A great deal of prior research has argued for and shown evidence of the role of affect in learning science (Jaber & Hammer, 2016a; 2016b; Pintrich et al., 1993; Thagard, 2008). Marya has allowed us to observe and analyze a dramatic affective transformation that took place during a college physics course and lasted well beyond it. We have argued that her transformation involved a change in how she understood and experienced feelings of uncertainty. We have called this transformation meta-affective learning.

In this way, this study supports and extends DeBellis and Goldin's (2006) account of meta-affect. They suggested that meta-affective learning is possible; Marya's case provides evidence. As well, it shows an entanglement of meta-affect and epistemology: Marya's experience of being uncertain shifted with how she framed her work in physics.

The case contributes as well to research on epistemologies, building on recent work that explores the relationship between epistemology and affect (Geller, Gouvea, & Sawtelle, 2014; Gupta, Danielak, & Elby, 2010; Jaber, 2014). This work, and other research on epistemologies, has made significant progress in identifying local contextual dynamics (Hammer et al., 2005; Sandoval, 2005), but, as Sandoval (Sandoval, 2014) argued,

> [t]o account for the consequences of students' participation in school science experiences on their epistemic cognition in and out of school, including both how they make sense of science for themselves and how they understand the work of professional science, science education needs a developmental theory of epistemic cognition that situates such cognition in the settings in which it occurs and explores the consequences of participation in these settings at multiple timescales. (p. 386)

Marya's case is a step in that direction. In our account, Marya came to enjoy doing physics, as she formed a different sense of what doing physics involves: Once she began to approach physics in a different way, her feelings towards uncertainty changed. Her excitement to sense-make enabled her to recognize it as "a kind of thing to do in physics" and allowed her to further refine her approach to learning. Eventually, she not only sought out opportunities to sense-make, but she brought them about. In this way, Marya developed productive meta-affective dispositions in concert with productive epistemologies.

Our account may also speak to current perspectives on "grit" and "mindset." The former concerns learners' "perseverance and passion for long term goals" (Duckworth, Peterson, Matthews, & Kelly, 2007, p. 1087). Grittier individuals apply sustained effort in the face of failure and adversity. Within this framework, uncertainty and confusion may be seen as barriers, and educators should help students build up the stamina to push past them. More broadly, research on social and emotional learning (Durlak, Weissberg, Dymnicki, Taylor, & Schellinger, 2011; Elias, 1997) has focused on students' learning skills and strategies for managing negative emotions, such as counting to 10, breathing techniques, and other forms of meditation. Finally, Dweck and colleagues' (Dweck, 2006; Yeager & Dweck, 2012) account of mindsets concerns how learners understand the nature of intellectual abilities. Those who see intelligence as fixed tend to avoid challenges and give up easily; those with "growth mindsets" tend to seek out challenges and persist in the face of difficulties. This work has suggested instructional attention to students adopting a growth mindset.

We do not contest the value of students building stamina for struggle, learning how to manage their emotions, and seeing themselves as having the capacity for growth. However, something different seems to have happened for Marya. She came to understand the nature of the activity in a different way, and with this different understanding uncertainty and confusion had new meaning. Those feelings no longer represented or signaled struggle, but held the promise for sense-making and discovery. This process fundamentally involved a restructuring—of the way Marya understood the role of uncertainty in physics and of the way she experienced that uncertainty. While we have evidence that Marya did come to see herself as a more capable learner, it was not because her "mindset" changed. It was because her sense of the game changed, from one she did not think she could play to one she did.

This was, of course, a single case study. We suspect that further study will show a similar entanglement of meta-affect and epistemology in other students. Going forward, we propose studies designed to identify cases of progress, and as early as possible, collect data to study their trajectories over time. Identifying cases is a core challenge; in this instance we got lucky.

Somewhat like astronomers studying events that are not in their control, we plan to look in likely places with a wide-view, focusing more tightly when we see evidence of something happening.

Unlike astronomers, to the extent we can influence instruction, we can try to make events of interest more likely. There is evidence to support instructional attention to epistemologies (Redish & Hammer, 2009), which informed the design of Marya's course. While this study does not directly examine what role instruction played in Marya's shift, she did cite its impact. For example, in her first interview, she remembered always having the option to select "I don't know" as an answer to clicker questions. She said,

> *One of Professor Hammer's like favorite things to say it was like '[I don't know] is a very honorable answer. Because I'd rather you say you know that you don't know than be- say you're sure about something you're not sure about.' […] A lot of times it wasn't a bad thing not knowing. And it was actually very humbling experience.*

Marya's experience suggests that we can help cultivate students' meta-affective learning by attending to how we frame instruction and assessment, by giving them opportunities to engage in genuine sense-making, and by explicitly addressing the affective challenges inherent in doing so. This means reaffirming for students that struggle is not only normal, but it is necessary for progress. It means validating students' positioning themselves as uncertain and confused (Watkins, Hammer, Radoff, Jaber, & Phillips, under review). It means helping students experience the pleasures and discomforts of sense-making and supporting them through moments of frustration and vexation, rather than alleviating those feelings or providing ways for students to avoid them. As students come to interpret these moments of discomfort as safe and potentially fruitful, they may—as Marya did—begin to experience them as exhilarating rather than terrifying.

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Appendix 4.I: Questions from the interview protocol

1. What is your major/what do you think you will pick as your major? Why did you choose this?
2. Tell me about your experiences in this course so far
3. How is this course like other science courses you've taken? How is it different?
4. What have you enjoyed learning in this course? Why?
5. What have you found challenging [or surprising]?

Chapter 5: Discussion and Implications

The collection of papers in this dissertation showed cases of students' scientific engagement that spanned multiple timescales and participation structures. The first paper, *Understanding the stability of students' scientific engagement over twenty minutes of their inquiry*, showed how a group of college students persisted in scientific sense-making around a worksheet problem for around twenty minutes. The second paper, *Attention to student framing in responsive teaching*, showed snapshots of a third grade class's progress over the course of 5 weeks. Finally, the third paper, *'It's scary but it's also exciting': A case of meta-affective learning in science*, showed a college student's drastic transformation from feeling anxious to excited about doing physics that lasted for years. In this chapter, I first discuss some implications and future directions of each paper. I then look across the papers and describe their contributions as a set.

Implications and future directions of each paper

In this section, I discuss the implications of each chapter for research and instruction and some future directions that the papers inspire.

Paper 1: Understanding the stability of students' scientific engagement over twenty minutes of their inquiry

In chapter 2, I analyzed video data of a group of college students working collaboratively to solve a physics problem in order to understand what contributed to the emergence and stability of their scientific engagement. I found that the students' epistemic vexation—i.e., feeling bothered by an inconsistency—at once contributed to the stability of students' scientific engagement and provoked expressions of struggle and discomfort that eventually disrupted their engagement. In addition, I found that the stability of the group's scientific sense-making was constituted and sustained by the dynamic interaction of its members and the instructor.

First, this work connects research on designing for disciplinary uncertainty (Ford, 2005; Kapur & Bielaczyc, 2012; Lehrer, 2009; Manz, 2015; Metz, 2004) with research on responsive teaching (Lau, 2010; Levin & Richards, 2011; Levin, Grant, & Hammer, 2012; Pierson, 2008; Richards, 2013; Robertson, Scherr, & Hammer, 2015). On the one hand, it provides more evidence of the disciplinary value of providing opportunities for students to grapple with uncertainties. For these students, the desire to solve a puzzle appeared to support the local stability of their scientific engagement when a general interest in the phenomenon did not.

This finding suggests that epistemic vexation can be leveraged as an entry point for students who may not otherwise be curious about or interested in the target phenomenon. This connects to Hidi and Renniger's (2006) work on interest which theorizes that a situational interest can develop into a more stable, individual interest. Tapping into the natural urge to reconcile inconsistencies may encourage local moments of sense-making that, though brief, may spark students' more robust interest in understanding the target phenomenon. This happened for George, who began to wonder about energy transfer in the case of pushing on an immutable object; it is possible that the puzzle piqued his interest in understanding the phenomenon more broadly. This finding supports Jaber and Hammer's (2016a) claim that students can develop an interest, not only *about* or *towards* science, but locally, *within* the doing of science.

However, this case also speaks to the complex nature of how these feelings function within students' inquiry. Students' vexation did not unilaterally support the stability of their engagement; it also disrupted it. The feelings of discomfort that necessarily accompany vexation may have contributed to McKenzie's resistance to re-entering a state of vexation.

In addition, while this study suggests that creating opportunities for disciplinary uncertainty can be effective for supporting students' scientific engagement, it also shows that providing these opportunities does not necessarily mean that students will automatically take them up. In this case, although I had designed the original question to elicit students' conflicting ideas, it took work in the moment to help students articulate the nature of the inconsistency they were grappling with. Even so, it took time for students to recognize that the inconsistency was worth reconciling; in fact, when I gave the first indication that energy might not be transferred, George and McKenzie quickly yielded, despite the fact that this conclusion blatantly conflicted with their original solution. I made one more attempt to encourage their problematizing by explicitly charging them with the work of further articulating and resolving their two discrepant solutions. Even after this last attempt, George still oriented to the problem as having a simple solution. Had the other students accepted his explanation with its ambiguous mechanisms, they might have quickly moved on without much discussion. Only once Brian skeptically probed at George's explanation did they orient to the problem as something to be seriously considered.

From this we see that getting students to problematize may require more than strategically dropping breadcrumbs of uncertainty for students to find. For instance, it can take time to cultivate traces of epistemic vexation into well-articulated problems. Oftentimes, students are not even aware of what these feelings are communicating to them, as they often try to push away the discomfort of uncertainty and confusion. Thus, students may need help noticing and engaging these feelings to productive ends. In addition, the expectation that things should fit together is necessary for feeling bothered when they don't, and students may need help developing and activating expectations of coherence.

To be sure, there is hard work involved in getting students to problematize. It requires advance planning as well as attending and responding in the moment. However, students' affect (Jaber, 2015) can help clue teachers in to problems that may be lurking beneath the surface.

Students' expressions of vexation, even subtle ones, may serve as opportunities for teachers to elicit students' ideas and confusions and draw awareness to these feelings as objects of reflection. In this case, I was able to detect their vexation and help them notice and articulate it. In this way, attending and responding to students' affective expressions not only supports students engagement in problematizing but can also serve as opportunities for meta-affective learning.

In addition, this work contributes to research on the role of epistemic affect in students' disciplinary engagement (Jaber, 2014; Jaber & Hammer, 2016a). Although it has primarily been conceptualized as constitutive of (or providing evidence of) students' disciplinary engagement (Engle & Conant, 2002), we see from this study that it can also play a role in driving and sustaining the engagement. Like Jaber (2015), this work suggests that attending explicitly to students' epistemic affect and motivations can help, not only to inform a sense of what students are doing, but to promote their productive disciplinary engagement. In addition, this study found that students' epistemic vexation not only supported individuals' sense-making, but served to cultivate the group's stability in collaborative scientific sense-making (Engle, 2006). More research is needed to learn how epistemic vexation plays out in group-level dynamics as well as to explore how other forms of epistemic affect and motivation impact students' disciplinary engagement.

While this study offers insight into some of the ways epistemic vexation plays out within students' scientific sense-making, it examines only a single occurrence of this phenomenon; more study is needed to understand how epistemic vexation and other forms of epistemic motivation play out in the individual and group dynamics of scientific sense-making. This work informs a broader endeavor to look across many more cases for how epistemic vexation gets expressed, taken up, and the role it plays within students' disciplinary pursuits. Colleagues and I have already begun this work by looking at the role epistemic vexation and other affective expressions play in individual and group-level scientific sense-making among in-service teachers enrolled in a blended-online PD course (Jaber, Hufnagel, & Radoff, in preparation). I hope to continue studying this construct across many contexts and timescales to better understand how it emerges and how to support it.

Paper 2: Attention to student framing in responsive teaching

In chapter 3, I presented an analysis of data from Sharon Fargason's third grade class at two points during a unit on the motion of toy cars. I showed that the focus of Sharon's attending and responding changed as students made progress in doing science. At first she attended at the level of students' framings, imposing a significant amount of structure on their discussion. As students engaged more stably in doing science, however, Sharon relaxed her attention at the wider level, and instead focused more narrowly, delving deeply into the substance of students' ideas.

This paper contributes to the field's understanding of how students make epistemological progress in science (Elby & Hammer, 2010; Sandoval, 2005). In particular, it provides more evidence of the dynamic interaction of students' conceptual and epistemological resources as they refine and stabilize their sense of what it means to do science (Scherr & Hammer, 2009). We see how the substance of students' reasoning and aspects of their epistemology are not separable—each informs the other as students make progress in doing science. Furthermore, this progress happened *within* moments of their inquiry, which supports Ford's (2008) findings that students can develop a "grasp of practice" from engaging in extended scientific inquiry.

This paper also speaks to an eternal tension that teachers face: How is it possible to value the substance of students' ideas while also holding them accountable to disciplinary norms and values (Engle, 2012; Engle & Conant, 2002)? Attending and responding to students' framing may be a useful tool for navigating this complex space. In this case, I showed how Sharon evaluated contributions according to students' own sense of what they were doing (Hutchison, 2008).

For example, in the Early Episode, a student challenged Isaac and Jimmy's design, saying that the car would crash into the side of their rollercoasters loop-the-loop. In response, Isaac invented a trap door that magically opened as the toy car approached it. Sharon contested Isaac's idea, which was typical behavior for cars in video games or movies but not for toy cars on toy rollercoaster tracks. I claimed that this move was informed not by Sharon's sense of what was disciplinarily appropriate, but by her *sense of Isaac's framing*, namely, that Isaac was not thinking about toy cars on toy tracks. Similarly, when Sharon delved into Ray's question about free will, she did not merely assess whether his contribution aligned with the disciplinary canon but she assessed it according to her sense of Ray's framing, namely whether he was orienting to the activity as make a plausible, causal arguments for how toy cars move. Here we see that while Sharon played the role of gatekeeper to legitimize some ideas and discourage others, these assessments were highly dependent on her sense of students' own goals and meanings.

I also showed how Sharon expanded her notions of what counts as science in response to her students' ideas. For example, Ray's idea likely pushed Sharon to think about downhill motion in new ways that were unfamiliar to her. Jaber, Southerland, and Dake (under review) refer to this as epistemic empathy—or, "the act of understanding and appreciating someone's *cognitive* and *emotional* experience within an…activity aimed at the construction, communication, and critique of knowledge." Sharon's willingness to learn from her students' scientific expertise conveys her deep respect for their intellectual agency. In these ways, attending and responding to students' framing can help guide teachers in taking up the substance of students' ideas in ways that are accountable to disciplinary norms and values.

Furthermore, while I did not explore the connection in the chapter itself, this work raises questions about power and equity (Bianchini, Akerson, Barton, Lee, & Rodriguez, 2012; Boaler, 2008; Gutiérrez, 2011; Herbel-Eisenmann, Choppin, Wagner, & Pimm, 2011; Rosebery, Ogonowski, DiSchino, & Warren, 2010). In particular, the implication that students' progress may be reflexively related to the ways teachers assess and evaluate their students' ideas (Coffey, Hammer, Levin, & Grant, 2011; Yackel & Cobb, 1996) raises ethical issues, since interpreting students' ideas is subject to biases that are often racialized and gendered. In addition, teachers have the power to privilege and legitimize particular ways of knowing over others, which may perpetuate inequities. This concern is particularly relevant for teachers like Sharon, who teach immigrants and English language learners (Enyedy et al., 2008; Herbel-Eisenmann, Drake, & Cirillo, 2009). Despite Sharon's attempts to encourage student-to-student discussion, students often had difficulty understanding one another. In order to help students understand and appreciate one another's ideas, Sharon often had to interpret and re-voice them. This position granted her a great deal of power to assess and evaluate students' ideas, which she used to support some ideas and reject others.

This case raises complex questions about how teachers can employ their "interpretive power" (Rosebery, Warren, & Tucker-Raymond, 2015) to value students ideas and diverse ways of knowing while still holding them accountable to disciplinary norms and values. Certainly, no one would argue that teaching involves pursuing and legitimizing every contribution from every child. However, teachers must also confront their power and privilege when making decisions about which ideas to validate and which to deny. In the future, I hope to study how responsive teaching can make contact with issues of equity, in particular with respect to these moments of tension.

Paper 3: 'It's scary but it's also exciting': A case of meta-affective learning in science

In chapter 4, I presented the case of "Marya," a freshman engineering major who showed and spoke of a drastic shift in her feelings and approach to learning physics, during an introductory course. In this paper, I illustrated her shift using data from her written coursework as well as from interviews with Marya at the end of the course and two years later. I analyzed her interviews and coursework for trends in her feelings and approach towards learning physics and argued that Marya's transformation involved the co-development of *meta-affective* and *epistemological* aspects of her learning.

This work contributes to research on students' affect and meta-affect (DeBellis & Goldin, 2006; Jaber, 2014; Pintrich, Marx, & Boyle, 1993) and research on students' epistemologies (Elby & Hammer, 2010; Sandoval, 2005) by providing additional evidence of how these constructs are entangled in moments (Geller, Gouvea, & Sawtelle, 2014; Gupta, Danielak, & Elby, 2010; Jaber & Hammer, 2016b; 2016a) and an account of how they develop over time (Sandoval, 2014). In particular, Marya's shift from feeling anxious to excited about doing physics was influenced by her shifting sense of what doing physics involves, from absolute right and wrong to a journey of sense-making. At the same time, her excitement to sense-make enabled her to recognize it as "a kind of thing to do in physics" which allowed her to further refine her approach to learning. In this way, her short- and long-term engagement and interest in science was supported by the co-construction of productive meta-affective and epistemological dispositions.

For those interested in students' epistemological development, Marya's case suggests that attending to affect and meta-affect might be useful for promoting productive epistemologies. Conversely, for those studying students' affect and meta-affect, Marya's case suggests that the development of productive epistemologies might stimulate and sustain students' long-term interest and engagement in science.

Marya's case also connects to work on uncertainty and confusion in STEM education (D'Mello & Graesser, 2014; D'Mello, Lehman, Pekrun, & Graesser, 2014; Lipson, 1992; Watkins, Hammer, Radoff, Jaber, & Phillips, under review; Zaslavsky, 2005). It suggests that while it may be tempting to relieve students' anxiety by sheltering them from what can be uncomfortable feelings, it may not ultimately benefit their learning or their development more generally—after all, the case in chapter 2 showed how fundamental uncertainty and confusion were to the stability of students' scientific engagement. By developing the construct of meta-affective learning and exploring how it played out in Marya's transformation, we showed that it is possible to preserve these foundational affective experiences while working to shift the negative feelings that students assign to them.

Finally, this case has implications for how instruction can foster productive feelings and beliefs. Marya's course focused explicitly on promoting these dimensions of students' progress, and in her interviews, she cited particular aspects of the course as being influential to her transformation, including the instructors' epistemological and affective messaging, the opportunities provided for students to engage with interesting and challenging problems, and the support available to students as they struggled through this process. The instructors were responsive to students' learning and monitored their progress throughout the course. In addition, instructors spoke explicitly about the challenges and benefits of confusion and uncertainty and framed these feelings as needing to be sought out and utilized. The methods of assessment were consistent with these messages: Students were given credit for sensible reasoning even if it did not lead them to the "correct" answer.

This effort was not only successful in supporting Marya's scientific sense-making, but it helped her feel at ease with her uncertainty and confusion. Most important, it enabled Marya to feel a sense of belonging which helped her identify as a capable scientific sense-maker. To be sure, supporting these multiple dimensions of students' learning takes time and effort, but it also holds the possibility of persistent long-term change which may—as it did for Marya—enrich other parts of her life and strengthen her disciplinary identity.

Although there is much to learn from Marya's case, more research is needed not only to identify students who might be receptive to this type of change, but also to follow those students longitudinally to see how these types of instructional interventions play out in their other courses and in their experiences more broadly.

What we learn from looking at cases of engagement across multiple timescales

This set of papers documents stabilities of students' scientific engagement across multiple timescales, from minutes to years. Taken as a set, these papers have implications for both research and instruction.

Studying stability over different timescales affords different types of understanding

It is important to study both short-term stabilities in episodes of students' scientific engagement as well as long-term accounts of their progress. However, short- and long-term accounts of engagement provide insight into different kinds of dynamics.

Looking at engagement over short time scales helps us understand the dynamics and mechanisms involved in starting and sustaining students' scientific engagement. Understanding what contributes to students' engagement can help us design environments with these factors in mind as well as make moves to support their emergence in moments. Sometimes, these factors are easy to predict. For example, in our project studying the dynamics of students' scientific engagement in classrooms [22], there is one student in a number of our cases who is persistently engaged and often helps to elicit generative energy from those around him. However, we cannot always rely on having students like that in our classes. Thus, we have to study more cases of students' spontaneous engagement to help us understand the variety of other dynamics at play.

These dynamics can be complex. For example, in the case from chapter 2, it was not enough to merely give students a problem that highlighted the gaps in their thinking. In-the-moment interventions were required to spark students' sense-making resources which enabled them to notice the existence of an inconsistency. Once they had momentum, however, the stability was self-sustaining by all the members of the group, until, of course, that balance was disrupted. By looking in-depth at the moment-to-moment dynamics of this case, we can glean understandings that would be impossible to examine at a larger scale.

Conversely, studying episodes of students' engagement in-depth, while useful for understanding how students shift into and out of moments of doing science, cannot answer questions about students' long-term progress. Many people study long-term progress by looking at students' performance on tests and assessments over time, by interviewing students at strategic moments, or by randomly sampling moments of classroom activity over time. These methods can be helpful for identifying the large-scale dynamics involved in students' progress. For

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[22] Funded by The Gordon and Betty Moore Foundation grant #3475, studentsdoingscience.tufts.edu

example, in Sharon's case, I had identified the class's long-term progress by looking at moments early and late in the toy car unit.

In addition, looking at a large-scale can sometimes reveal patterns and dynamics that may not be as clear in moments. For instance, there was compelling evidence of the entanglement of Marya's meta-affective and epistemological learning in her interview and looking across her entire data set; however, that pattern would have been impossible to locate in any one moment of her inquiry. Zooming out to look at the patterns of stability over large timescales help us see larger-level shifts and patterns of development, that we might not see in moments.

Finally, finding evidence of students' long-term progress might necessitate a deeper look into moments of their inquiry. For instance, after analyzing Marya's interview, we determined that examining her engagement in moments (from her written work) was central for understanding her transformation. Looking at these moments over time helped us understand the pattern of Marya's progress in more robust ways. However, *identifying* this pattern from moments of her inquiry alone would have been extremely difficult. The resolution matters here—a random sampling of Marya's work would not have shown the larger-level progress that was evident in her interview because her progress was not linear; in fact, she relapsed back into her old patterns a few times during the semester. Thus, from these cases we see that it is sometimes necessary to look at both large-scale progress and moment-to-moment dynamics to develop holistic understandings of students' scientific engagement.

What happens in moments informs longer-term stabilities

These papers suggest that instructional attention to both short- and long-term stabilities is necessary for students' successful science learning. Short-term stabilities of engagement that do not connect to students' disciplinary ideas, beliefs, and feelings will not have lasting impact.

Alternatively, it is unlikely for students to develop long-term interests in science without making contact with authentic disciplinary experiences in moments of their engagement.

There is some evidence that moments of students' engagement help contribute to longer-term stabilities (Conlin, Richards, Gupta, & Elby, under review; Ford, 2006; Jaber & Hammer, 2016a). For example, Jaber and Hammer's (2016a) account of Sandra, a student they followed from grades 4-7, show how moments of Sandra's scientific sense-making were central in the formation of her long-term disciplinary interests and identity. Similarly, Conlin et al. (under review) show how 8^{th} grader Estevan's dogged persistence in science was rooted in his love of figuring out challenges, which was aligned with his experience of doing science.

We see a similar dynamic in Marya's progress—moments of her sense making were formative for the development of her interest and identity; and for Sharon's students as well—it was within moments of doing science that Sharon was able to discover the scientific substance in their thinking as well as signal to students what kind of activity they should be engaging in.

In chapter 2, we see opportunities for long-term meta-affective and epistemological learning playing out in moments of students' scientific sense-making. For instance, when I tasked students with articulating and sorting out their confusion, it subtly signaled that feelings of confusion and vexation should be seen as informative rather than punitive. However, this type of instructional intervention needs to happen with consistency. In this case, I said, "I'm gonna pull a David," making reference to the normative status of this practice. It was integrated into the messaging and tasks they received day-to-day. While this work helps us understand some of the dynamics connecting students' short- and long-term progress, more research is needed to examine the impact of moments of students' inquiry on their long-term engagement.

Participation structure informs stabilities

In trying to understand how stability of students' scientific engagement emerge and persist in these cases, it was important to think about participation structure. The unit of stability was different in each case, and in chapters 3 and 4 the unit of stability changed. In chapter 2, the unit was five students and the instructor; in chapter 3, the unit was initially Sharon and her third grade class, however, as time passed, students developed some stability independent from Sharon; in chapter 4, Marya started out pretty stable in her patterns, and then developed a different stability in interaction with the course. Finally, she maintained those patterns by herself, persistently over time.

Although in all of the cases, instructors contributed to the initial stability of students' engagement, their involvement eventually phased out, and students held the stability on their own. In chapter 2, I may have "triggered" students' initial engagement, but when I left the group, they picked up and continued the engagement without me. In chapter 3, Sharon, who once had to monitor the class's epistemology, was able to relax her attention once students developed a more structurally stable sense of what it means to do science. Finally, in chapter 4, the course helped to disrupt Marya's unhealthy patterns of engagement and set up the conditions and context for her develop healthier patterns. However, as Marya's stability in doing science became more structural and deliberate, she was able to draw on these productive patterns beyond the context of the course. Eventually, she could even reflect on these patterns and elicit or suppress them deliberately.

My study of these varying participation structures and their impact on the stability of students' scientific engagement reveal the importance of setting up an interactional context that supports students' repeated, contextual activations of sense-making resources. If these contextual supports are persistent, then, over time, students will hopefully take them up in ways that are not sensitive to context.

Conclusion

In this dissertation, I analyzed three cases of students' scientific engagement for evidence of what contributed to starting and sustaining the engagement—either by stabilizing "doing science" in-the-moment or by supporting the development of productive feelings and beliefs over time. These cases highlight the centrality of affective and epistemological dynamics within and contributing to the emergence and stability of students' scientific engagement as well as the role that responsive instruction plays in supporting these dynamics across multiple timescales. More research is needed to explore these dynamics in a broader range of contexts and disciplines, as well as how they relate to other constructs.

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