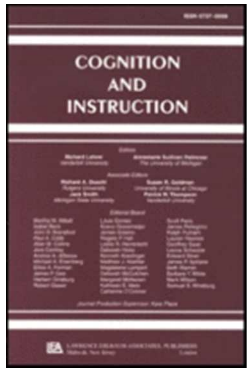

"It's scary but it's also exciting": Evidence of meta-affective learning in science

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"It's scary but it's also exciting": Evidence of meta-affective learning in science

We present "Marya[1]," 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:

> *Marya*: 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:

> *Marya*: 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 spoke of it as having stimulated her interest in research, and influenced her decision to apply for doctoral programs in environmental engineering.

In this article, 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), i.e., her feelings about feelings, and *epistemology*, i.e., 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 to doing physics.

[1] "Marya" is a pseudonym.

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 methods, 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 twofold: On the one hand, we aim to nominate the theoretical construct of meta-affective learning as central to learning science. On the other hand, we use Marya's transformation to provide empirical evidence for how this construct manifests and functions within Marya's science learning. Although this single account is limited in its generalizability, we presume that the construct of meta-affective learning may be of general significance for science education.

1. Affective dynamics in doing and learning science

1.1. Epistemic Affect

For several decades, research has highlighted the role of affect in learning (Alsop & Watts, 2003; Arango-Muñoz, 2014; Damasio, 1994; Pintrich, Marx, & Boyle; 1993; Thagard, 2008; Wolpert & Richards, 1997). In education, Pintrich and colleagues (Pintrich, Marx, & Boyle, 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 & Hammer (2016ab) 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. They coined the term *epistemic affect* to describe the feelings that people experience in the doing of science.

Descriptions of such feelings pervade accounts of professional science: The "joy of going at it" (McClintock, quoted in Fox-Keller, 1983, p. 125); "the pleasure of finding things out" (Feynman, quoted in Robbins, 1999); the "torment of the unknown" (Bernard, 1865, p. 222-223); the "angst required to motivate the search" (Root-Bernstein, 2002, p. 77). Some sound unpleasant, in particular, feelings of uncertainty and confusion. Nevertheless, 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). These accounts motivate the study of how negative emotions can be experienced as pleasurable for science learners.

1.2. Meta-affect

DeBellis and Goldin (2006) coined the term *meta-affect*, or "feelings about feelings" (p. 137), to describe the many levels of meaning and emotion that are layered onto affective experiences. Meta-affect is what enables the enjoyment of otherwise undesirable emotions. Thus people seek out fear in amusement park rides or horror movies; they appreciate and are energized by nervousness before public speaking or deadlines. DeBellis and Goldin discussed the relevance 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. (p. 137)

Jaber & Hammer (2016a) 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 hold water, which is heavy, when "everyone thinks [clouds are] light"? At the same time, layered onto this frustration, Jordan and Elea showed signs of enjoyment, smiling and laughing. Similarly, Phillips, Watkins, and Hammer (2017) described college student Michael's motivation to think more about a problem when he "wasn't really happy" about his solution. Rather than discouraging him, his dissatisfaction drove him to persist in finding another solution. Both of these instances are part of a larger study to collect and analyze what is happening in moments when students are doing science[2]. As of this writing, we have analyzed ten cases, and in nearly every one there is evidence of students' feeling "epistemic vexation" (Radoff, 2017). In these cases, the discomfort produced by vexation also helped drive students' engagement.

There is similar evidence across other cases in the literature, such as, famously, Engle's and Conant's (2002) account of fifth-graders' "Big 'Ol Argument" about orcas; and Salter's and Atkins's (2011) account of undergraduate elementary education majors' studies of light, where students learned "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 (e.g. Leander & Brown, 1999). In light of this, there is a

[2] Funded by the Gordon and Betty Moore Foundation, Grant #3475: The Dynamics of Learners' Persistence and Engagement in Science.

need to understand when and how might learners be motivated rather than discouraged by "negative" feelings that emerge while doing science.

DeBellis and Goldin (2006) begin to grapple with this question, theorizing that the development of productive meta-affect fundamentally involves reframing rather than avoiding moments of struggle:

> Careful consideration of meta-affect suggests to us that the most important affective goals in mathematics are *not* to eliminate frustration, remove fear and anxiety, or make mathematical activity consistently easy and fun. Rather they are to develop meta-affect where the emotional feelings *about* the emotions associated with impasse or difficulty are *productive* of learning and accomplishment. (p. 136-7)

However, they do not articulate *how* students might develop productive meta-affect, nor do they provide empirical evidence of such a transformation.

1.3. Meta-affective Learning

Marya's case provides an unusual opportunity to study how productive meta-affect stabilizes over time—what we call *meta-affective learning*. Marya began the 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 moments at first, which did not last. Before exams, in particular, Marya reverted to 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 of 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 meta-affective learning, or having developed stable and 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, learning that uncertainty is inherent to doing physics. Marya's case informs our understanding of meta-affective learning at two levels: It allows us, first, to examine the interplay of meta-affect and epistemology in moments and, second, to study how those moments support the development of productive meta-affective dispositions over time.

In the next section, we describe the context of the course, how we met Marya and selected her as a focal participant, the data we collected, and our methods for studying her meta-affective and epistemological shifts[3].

2. Methods

2.1. Course Context

Marya was one of 70 students in a calculus-based introductory physics course. The first author, Jen Radoff, was a teaching assistant (TA); the third author, 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

[3] 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.

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[4] (Freeman Worth), 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. Students also attended weekly discussion sections run by TAs, and many attended optional "help hours" sessions, in which students would collaboratively solve problems brought by students or provided by the TAs. In these ways, the course as a whole reflected a form of "responsive teaching" (as described in Robertson, Atkins, Levin, & Richardson, 2016).

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 flaws in the reasoning they considered incorrect. The instructors and course materials discouraged students from 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 and spoke about the

[4] Now called "Flip It Physics"

practice of formulating questions as important to progress in science and learning (Phillips et al., 2017).

2.2. Encountering Marya

Radoff was Marya's discussion section TA in the spring semester of 2014. At their first meeting, Marya expressed anxiety[5] about taking the course; she spoke to 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, Radoff and Hammer noticed evidence in her coursework that she was shifting in her approach and also noticed a shift in her anxiety. She seemed to shift back, at the second exam, and Hammer granted her extra time after seeing her express anxiety and distress. For the rest of the semester, she resumed making progress, and she showed no anxiety at the final exam—in fact, she told 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 Radoff about physics books she purchased to read over the summer.

Seeing what was happening for Marya, Radoff proposed a deeper study into Marya's experience. 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 derive insights. As a first step, Radoff asked Lama Jaber, who was not affiliated with the course, to interview Marya about her experiences in the course. Marya's articulate descriptions of her transformation provided a unique opportunity to study the dynamics of her change. While Marya's experience is hardly typical, we expect that the theoretical insights derived from studying it may have broad significance.

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

2.3. Data Collection

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

As part of a larger project, we also had collected copies of students' written work throughout the semester, including checkpoint questions, problem sets, and exams. Each smartPhysics unit provided 3-4 checkpoint questions, and there were 20 units over the semester. These questions were mostly multiple-choice with space to provide an 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 contained 4 or 5 challenging problems, 11 sets over the semester. Students typically took several hours to complete these, and they turned in their solutions on paper. The TAs commented on them extensively and returned them to students within the week, so that students could read and respond to the feedback. There were also three exams, made up of 8 multiple-choice questions (which counted towards 40% of their exam grade) and 3 essay questions (60%).

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

2.4. Data Analysis

2.4.1. 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. Within these excerpts, we tracked her use of affective expressions by highlighting words such as *excited, scary, anxious, frustrated*, etc. We also highlighted places she spoke of something in transition, that is starting or stopping, changing or shifting. Using the highlighted terms, we identified excerpts within interview which we analyzed for evidence of what contributed to Marya's affective transition. In doing so, we noted causal language that linked affective expressions to factors that may have contributed to an affective transition. For example, in Marya's statement, "Definitely *not knowing*, **at first**, was such a *huge factor in causing* **anxiety**," we first highlighted the affective expression, "**anxiety**," and the transitional marker, "**at first**", which together marked an affective transition. We then noted that the word "anxiety" was discursively linked to "*not knowing*" with the use of causal language in the utterance, "*was such a huge factor in causing*."

Looking across the transcript in this way, we developed two main claims about the nature of and contributing factors to Marya's affective transition: (1) Marya's transition from feeling anxious to feeling excited in physics was linked to how she experienced feelings of uncertainty (i.e., was meta-affective in nature), and (2) Marya's meta-affective transition 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 (i.e., her epistemology). 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 *Findings* entitled “Marya’s account of *knowing* and *feeling* in physics.” (sections 3.1.1-3.1.3).

2.4.2. 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. We looked at her checkpoint questions for evidence of shifts in her epistemological framing (Hammer, Elby, Scherr, & Redish, 2005), that is, relative stabilities in how she understood what she was doing with respect to knowledge. More specifically, we looked for instances of Marya’s agentive sense-making.

We developed a coding scheme using a semi-grounded approach (Charmaz, 2006), characterizing how Marya reasoned about the problems. That is, the initial coding categories were informed by the literature and our knowledge of what constitutes agentive sense-making, but they developed in response to the data, in iterative applications and refinements. Radoff and Jaber coded a fourth of the data together, developing a rough initial scheme, which included 10 different coding categories (these initial categories can be found in Appendix II), and then they worked individually to apply it to the rest of the smartPhysics dataset. The results informed a refinement and simplification of the scheme with the merging of coding categories that represented functionally similar types of sense-making activities and the removal of categories that were not represented in the data. The final coding contained five coding categories, which are neither hierarchical nor mutually exclusive:

(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.

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 her arriving at a canonically correct answer. We discuss each of these codes with illustrative examples, and present the results of our coding analysis, in section 3.2.2 entitled "Tracking Marya's sense-making approach". The inter-rater reliability was 94%, using the simplified scheme, including no-code decisions.[6] Radoff and Jaber then discussed the remaining disagreements and reached 100% consensus.

In addition to the interview and smartPhysics data, we draw on Marya's problem set solutions to help us understand the entanglement of epistemology and meta-affect that she described in her interview (in section 3.2.3). In particular, we provide an excerpt of her work on the seventh problem set, which she referenced in her interview as a particularly exciting sense-making accomplishment.

3. Findings

We first present data from Marya's interviews, in which she reflected on her own transformation, as evidence of her meta-affective learning and of the reflexive relationship between meta-affect and epistemology. We then provide examples from her written work and

[6] 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, not on the breakdown of codes in any one category.

our coding of the checkpoint question data as evidence of her epistemological shift over the semester.

3.1. Marya's Account of *Knowing* and *Feeling* in Physics

In an interview conducted a few hours after the final exam, Marya recalled how her feelings about uncertainty had shifted over the course of the semester:

> *Marya*: 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:

> *Marya*: 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 (Table 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.

Table 1

Patterns of relationship between epistemology and meta-affect

Section	Epistemology	Meta-affect
3.1.1	*Physics* is about absolute rights and wrongs	Anxiety about feeling uncertain
3.1.2	*Physics* is about the journey and the question	Comfort with feeling uncertain
3.1.3	*Doing physics* is a process of making sense of the world	Excitement about feeling uncertain

3.1.1. 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:

> *Marya*: 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 of Marya's sense of herself and her abilities, connected to her understandings about the nature of knowledge in science and her role as a science learner:

> *Marya*: [Physics is] really interesting, but do I really have the brains for that? I'm not sure. […] 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 rather than invent or discover on her own:

> *Marya*: Science was always portrayed as a very inflexible thing, you know it's like, science is science, laws are right. […] 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; if uncertainty is problematic, then lingering in uncertainty is antithetical to being a successful learner:

> *Marya*: 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," produced an "anxiety about not knowing" that Marya said "led to the development of a little bit of depression." In this way, Marya's early epistemological framing of physics as "being about absolutes" contributed to her anxiety with respect to uncertainty.

3.1.2. Marya's developing sense that not knowing is part of doing 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." At the same time, Marya began to see uncertainty as inherent to the work of becoming a scientist or an engineer:

> *Marya*: 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 core of the scientific enterprise, her anxiety about not knowing began to dissipate:

> *Marya*: 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:

> *Marya*: 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:

> *Marya*: So like, for example, this test I just took- we had the final today, and there was this 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: Her comfort with not knowing helped support her seeing it as part of doing science.

3.1.3. Approaching physics as a sense-making pursuit contributed to Marya's enjoyment of not knowing. There is evidence that Marya went beyond merely accepting uncertainty as part of doing science to seeing it as the motivation and opportunity for discovery:

> *Marya*: 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.

She burst into a smile as she explained how she felt when facing a new problem:

> *Marya*: 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:

> *Marya*: 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, 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:

> *Marya*: 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 supported:

Marya: 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 then I'd truly know it.

In Marya's second interview, two years later, she retained this sense of excitement for "not knowing." Since taking physics, Marya got involved in an environmental engineering research lab where she was given the latitude to define her own problems, design and run her own experiments, and collect and analyze her own data. In her second interview, Radoff asked what excited her the most about research:

Marya: 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 the "torment of the unknown" (Bernard, 1865, p. 222-223) 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. Although 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.

3.2. Evidence of an Epistemological Shift in Marya's Written Work

Here, we shift our analysis to focus on Marya's shifting approach to doing physics, using her written work as evidence. 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 her developing stability in a different epistemological framing. Finally, we present an example of Marya's sense-making later in the semester to show evidence of entanglement between her epistemology and meta-affect.

3.2.1. An example from Marya's early work. This example comes from the second smartPhysics unit, in the first week of the course. Responding to the smartPhysics question depicted in Fig. 1, 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.

The most common response to this problem is that Ship 1 gets hit first, by the physically sensible reasoning that traveling less distance should take less time.[7]

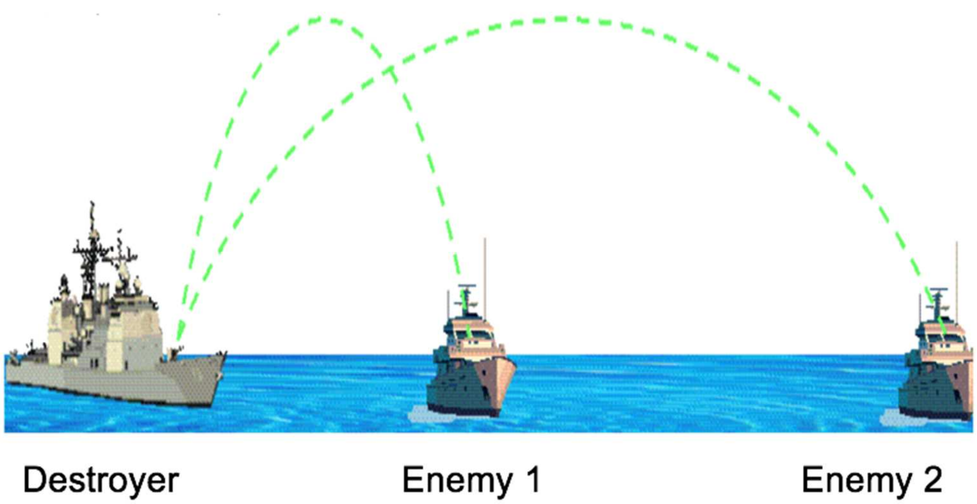

Figure 1. smartPhysics question from unit 2: "Which ship gets hit first?"

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 equation $t = 2\,v_0/g$, which the instructor and smartPhysics pre-lecture derived for vertical

[7] 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: The shells 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.

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 epistemological stance that Marya described in her interview[8], of manipulating equations and recruiting reasoning that is disconnected from the physical world.

3.2.2. Tracking Marya's sense-making approach. As outlined in the methods, we looked for evidence of Marya's agentive sense-making, classified into five coding 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. We first provide examples of each category, and then we show the trend over the semester.

(1) Extending past a problem's boundaries. We coded a response "extending past a problem's boundaries" if Marya constructed a thought experiment to test her logic in new contexts or with different initial conditions, or if she began to wonder about things that were not asked for in the problem. 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 off it or if the ball sticks to it? (Fig. 2). Marya's response provides examples for the first three categories of coding.

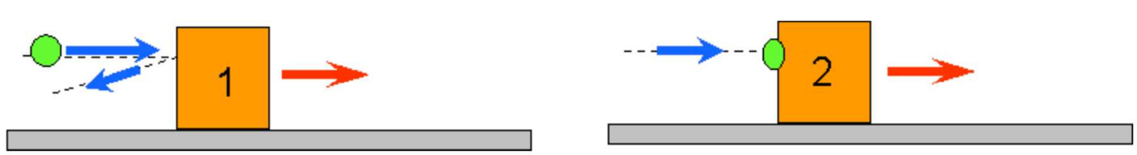

Figure 2. (smartPhysics question from unit 11). Two balls of equal mass are thrown horizontally with the same initial velocity. They hit identical stationary boxes resting on a frictionless

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

horizontal surface. The ball hitting box 1 bounces back, while the ball hitting box 2 gets stuck. Which box ends up moving faster?

First, she explained her answer to the checkpoint question: "I think that box one will end up moving faster because the interaction in situation 1 would not take away as much of the kinetic energy as the situation in 2." She then extended past the checkpoint question to ask her own: "[This] makes me wonder, is there loss in kinetic energy in the [bouncing] scenario?" As we show below, she spent some time deliberating the answer, despite having already sufficiently explained her answer to the checkpoint question.

During her interview, Marya described the importance of asking her own questions that extend beyond assigned problems, and she recalled doing this often, even in her other courses: "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. We coded a response "constructing counter-arguments and revising her thinking" if Marya explicitly considered an argument that opposed her own or if she revised her thinking in response to a counter-argument. For example, answering her own question from the checkpoint above (Fig. 2), Marya wrote:

> I think there would [be a loss of kinetic energy] 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… 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?

We coded this, in part, 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 by 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:

Marya: 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, as she considered whether the bouncing ball would gain or lose kinetic energy in the checkpoint, she reported doing her own experiment to test it out:

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 it's original speed no matter how hard I hit. At least, it looked that way to me.

Again, this was by her initiative; checkpoint questions did not explicitly ask students to conduct informal (or formal) experiments. In her interview, Marya described the importance of connecting to the familiar world:

> *Marya*: 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 [in homework problems], 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. We coded a response "using multiple approaches to solve a problem" if Marya recruited multiple methods in her solution, despite one method being sufficient to solve the problem. Oftentimes, Marya would try to align her conceptual reasoning with her mathematical reasoning. Other times, Marya would try to coordinate across physics concepts, to make sure she got the same answer by reasoning with momentum or with energy, for example.

Here we shift to another checkpoint question, which asked around which axis of rotation would the moment of inertia of a dumbbell be smallest? (Fig. 3). Marya first reasoned through the problem without doing any explicit calculations. She wrote:

> 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.

After determining that B has the lowest moment of inertia, Marya went on to compare A and C. by formulating 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, since distance from the axis is weighted exponentially while mass is only weighted linearly[9]. But since the mass at A is 3 times as large, it wasn't straightforward how to compare them without using mathematics. Marya then went on to calculate algebraic expressions for the moments of inertia around each axis. After working through the mathematics, she excitedly concluded, "So in fact the moments of inertia about A & C are the same!"

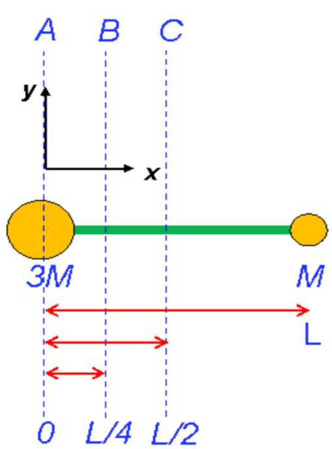

Figure 3. (smartPhysics question from unit 15). A ball of mass 3M at x=0 is connected to a ball of mass M at x=L by a massless rod. Consider the three rotation axes A, B and C as shown, all

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[9] The moment of inertia for this object is $= \frac{1}{2}M_1R_1^2 + \frac{1}{2}M_2R_2^2$, 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.

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.)

Marya first reasoned through the problem intuitively and turned to mathematical calculation when it was necessary; she used mathematics as a tool to further her conceptual understanding. Furthermore, Marya's answer was also evidence of *extending past the problem boundaries*, as she was curious about comparing the moments of inertia of A and C after she already found an answer to the problem.

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, she would approach the problem from a different angle, "making sure the different pockets in [her] brain were combined." She described the insufficiency of relying on intuitions without the support of a plausible explanation:

> *Marya*: 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:

> *Marya*: 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:

Marya: 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. We coded a response "identifying and articulating her own confusion" if Marya explicitly marked that she was uncertain or confused and if she articulated the nature of her confusion. For example, 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 fully understand the relationship between work and energy. Having articulated the confusion, she searched for an answer and described her subsequent understanding. Making her confusion explicit allowed Marya to broaden her understanding of this conceptually complex relationship.

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:

Marya: 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 (Table 2) shows that her agentive 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 number of instances that any code appeared in a given unit, 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 agentive sense-making until unit 4 (the end of week 2).

Total no. of coding instances	0	0	0	1	4	0	1	2	1	1	4	7	3	1	5	2	1	3	4	1
Unit[10]	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20

Table 2. Coding for evidence of Marya's epistemological framing

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

3.2.3. An example from Marya's later work. We have focused our analyses thus far on Marya's work on checkpoint questions. Here, we present data from Marya's work on a problem about inelastic collisions (Fig. 4) from her homework in week 7 of the course. This is the

[10] The units roughly correspond to the lecture number. There were two lectures per week, and roughly one unit per lecture.

problem that she excitedly referenced in her interview (reported in sec. 3.1.3), and we bring her written response as evidence of the entanglement between her epistemology and affect.

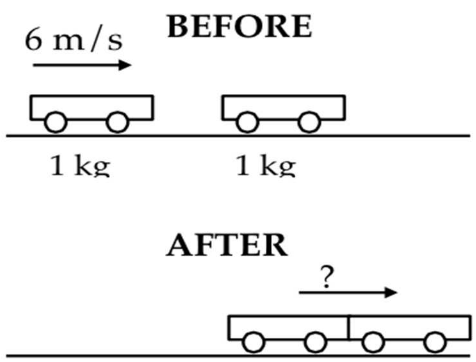

Figure 4. An inelastic collision from homework 7

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 repeat 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 $\quad \text{Total KE} = \frac{1}{2}m_1v^2 = \frac{1}{2}\cdot 1\text{kg}\cdot\left(\frac{6\text{m}}{\text{s}}\right)^2 = \underline{18\text{ J}}$

After collisions $\quad \text{Total KE} = \frac{1}{2}(m_1 + m_2)\cdot {v_f}^2 = \frac{1}{2}\cdot 2\text{kg}\cdot\left(\frac{3\text{m}}{\text{s}}\right)^2 = \underline{9\text{ J}}$

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

$$\text{KE before collision} = \frac{1}{2}\cdot 1\text{kg}\cdot\left(\frac{6\text{m}}{\text{s}}\right)^2 = 18\text{ J}$$

$$\text{KE after collision} = \frac{1}{2} \cdot 3\text{kg} \cdot \left(\frac{2\text{m}}{\text{s}}\right)^2 = 6 \text{ J}$$

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, $\text{KE}_{\text{lost}} = \text{KE}_{\text{i}} \times \left(\text{m}_{\text{stationaryObject}}/\text{m}_{\text{totalSystem}}\right)$

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 more mass the stationary object has, the more kinetic energy is lost. She considered the limiting case, of a very massive 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 of both 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 coming to frame her work in the course as a sense-making pursuit.

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 theory. Her written solution supported her recollections of this problem in her interview two months later:

> *Marya*: 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, along with the evidence from her written work, illustrates the entanglement of Marya's meta-affect and her epistemology in situ: She came to deeply enjoy the experience of making sense of the world. The unknown transformed into a sandbox where she could play and invent.

3.3. Summary of Findings

As our findings show, Marya began the semester feeling anxious about uncertainty, as connected to her sense of physics as about absolute right and wrong and knowing the correct answer. However, as she began to see physics as a journey into the unknown, she felt less anxious about uncertainty, and her approach to problem solving shifted. She experimented with a sense-making approach, which she came to deeply enjoy. These feelings of enjoyment fed into her feelings about uncertainty, and she found herself excited to approach challenging new problems for which she did not know the answer. In this way, Marya's meta-affect and epistemology supported one another to produce stable and lasting effects.

4. Discussion and Implications

Our findings contribute and connect two lines of research on learning, the first concerning affect and the second concerning epistemologies.

A great deal of prior research has argued for and shown evidence of the role of affect in learning science (e.g., Jaber & Hammer, 2016ab; Pintrich, Marx & Boyle, 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 feeling uncertain shifted with how she framed her work in physics.

This study contributes as well to research on epistemologies, building on recent work that explores the relationship between epistemology and affect in science (Geller, Gouvea, Sawtelle, & Turpen, 2014; Gupta, Danielak, & Elby, in press; Jaber & Hammer, 2016ab). This body of work, and other research on epistemologies, has made significant progress in understanding how affect and epistemology play out in local contextual dynamics (Hammer et al., 2005; Sandoval, 2005). However, there is also a need to understand how local dynamics support the development of more stable "disciplinary dispositions" (Lehrer, 2009). As 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)

This study is a step in that direction. Marya's story sheds light on how local moments play out in the development of longer-term stabilities which were supported, in this case, by the dynamic interaction of meta-affect and epistemology. 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 in educational psychology on “grit” and “mindset.” The former concerns learners’ “perseverance and passion for long term goals” (Duckworth, Peterson, Matthews, & Kelly, 2007). 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, Zins, Weissberg, Frey, Greenberg, Haynes, Kessler, Schwab-Stone, & Shriver, 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. Dweck and colleagues’ 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 intellectual 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. Rather than requiring learned strategies or expressions of grit, 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 within the doing of physics. 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 study of a single student’s experience in one physics course. The particular dynamics of this phenomenon would likely play out differently with different students in different contexts. Going forward, we propose studies designed to identify cases of progress, and as early as possible, collect data to examine 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 noted the impact of having the option to select “I don’t know” as an answer to clicker questions:

> *Marya*: 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.

Acknowledgements

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Appendix 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]?

Appendix II. Initial coding categories

1) Formulating questions about the problem or underlying physics concepts
    a. Formulating a question (e.g., "what does momentum mean in real life?")

    b. Attempting to answer the question

2) Constructing new problems to solve that extend past the original problem's boundaries
3) Playing with a problem's input conditions to explore the boundaries of the underlying concept
4) Connecting to and contrasting with other problems and situations (e.g., "it's just like the high speed camera video with the mallet hitting the bowling ball and basketball")
5) Using two different approaches to solve or explain the solution to a problem
    a. Coordinating across physics concepts (e.g., coordinating linear with rotational physics, or energy with momentum, etc.)
    b. Coordinating mathematical reasoning with conceptual reasoning
6) Messing about in real life (e.g., bouncing a ball against a wall to whether energy is conserved)
7) Elaborating beyond stating and explaining the correct answer (e.g., explaining why the wrong answers are wrong, exploring relationships between problem elements, etc.)
8) Abstracting a generalizable rule from a particular problem context
9) Connecting to everyday experiences and intuitions
10) Reflecting on and revising reasoning

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