“It’s scary but it’s also exciting”: A case of meta-affective learning in science

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Research suggests that students lose interest in science over the course of their schooling, attributing this loss to their perceptions of science as intimidating or as closed-off to them (e.g., Boe, Henriksen, Lyons, & Shreiner, 2011; Jenkins & Nelson, 2005; Osborne & Collins, 2001; Sjøbeg & Schreiner, 2005). Many students feel like they do not have access to the discourse and practices of science, and doubt their abilities to participate in the scientific enterprise.

In light of this research, we present the case of “Marya”—a freshman college student who transitioned from feeling extreme anxiety at the start of her physics course to feeling empowered and excited to do physics by the end of the course. She described her transition in a post-course interview, saying,

> *I’ve always been intimidated by physics. And physics this semester was a big trigger for me with anxiety […] As an outsider it just looks really complex. It was really interesting but I didn’t think I could do it […] But I reached a point in this class where I was more fascinated than intimidated. I was so fascinated that the anxiety didn’t matter anymore.*

Not only did Marya consider minoring in physics after taking this course, but she also described the course as a transformative experience that drastically altered her experience in other classes and of her anxiety more generally.

In this paper, we study Marya’s transformation, which, we claim, was largely characterized by a shift in how she emotionally experienced feelings of uncertainty in physics. We show how Marya, who at first felt anxious about facing the unknown, came to view uncertain terrain as an exciting opportunity to sense make. We call this shift *meta-affective learning*, and in this paper, we illustrate this new construct and study the dynamics involved in shaping it.

1. Feelings about feelings: an introduction to meta-affective learning

Until relatively recently, most people considered science to be a purely rational enterprise, unaffected by human emotion (Crotty, 1998; Phillips & Burbules, 2000; Phillips, 2004). Increasingly, however, philosophers and science education researchers have recognized the central role emotions play within the scientific enterprise. Emotions are at the very center of the human drive to know and they regulate the ways in which we explore and seek understanding of the world (Gopnik, 1998; Polanyi, 1958; 1966).

Jaber & Hammer (in press a & b) have referred to feelings and emotions endemic to the pursuit of knowledge as ***epistemic affect***, which is instantiated in “the excitement about new ideas, the irritation at inconsistencies, and the drive to formulate coherent explanations” (Jaber & Hammer, in press b, p. 1). Thus, feelings and emotions are not only inseparable from sense making, but they are necessary for making progress in science (Damasio, 1994). Sometimes, these feelings even precede cognitive awareness of a problem or question: One can feel vexed about an inconsistency long before coming to awareness of the nature or particularities of it. In fact, that feeling of vexation might be what drives someone to define the problem—an integral part of doing science. Similarly, frustration can signal that the problem is interesting and worth solving; struggle can push someone to invent more creative solutions.

The very notion that epistemic feelings with traditionally negative associations such as frustration and struggle can be experienced as pleasurable and productive hints at the inherent complexity of our emotional landscape. DeBellis and Goldin (2006) coined the term ***meta-affect*** to refer to the "feelings about [or with respect to] feelings" (p. 137) that characterize the way we experience various epistemic emotions. These feelings about feelings can be experienced as positive or negative. For example, feelings of nervousness associated with public speaking might elicit feelings of anxiety or feelings of exhilaration.

Part of what we want students to learn in science is how to manage and navigate their meta-affective feelings productively. Jaber and Hammer (in press b) have shown that part of what scientists learn as professionals in the discipline is how to embrace uncertainty, and perceive inconsistencies and challenges as stimulating rather than intimidating and menacing. As Firestein (2012) argues, "[s]uccess in science, either doing it or understanding it, depends on developing comfort with ignorance" (p. 87), where "[m]ucking about in the unknown" (p. 15) is considered an adventure and a privilege.

These examples highlight what we call ***meta-affective learning***, whereby students come to experience "emotions associated with impasse" (p. 137) as signs of productive struggle, which can be leveraged to stimulate and inspire thinking rather than trigger feelings of defeat. DeBellis and Goldin (2006) describe how, for instance, one might re-attribute negative feelings associated with the feeling of frustration: "[Frustration] 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). They propose that "frustration coupled with productive meta-affect suggests the problem is worth pursuing, and motivates further exploration rather than disengagement" (p. 137).

We classify a meta-affective shift as *learning* when it brings someone closer to more productive scientific meta-affective dispositions. We specifically care to highlight the *meta*-affective dimension because, for the purposes of understanding and supporting students' learning in science, it is necessary to specify what aspect of affect is changing. Epistemic feelings of uncertainty and confusion are endemic to scientific inquiry, and we would not expect nor want a student to shift from feeling uncertain to feeling certain in the doing of science. It is the development of scientifically productive (meta-affective) feelings *about* (epistemic) feelings such as confusion and uncertainty that we care to highlight as an important aspect of science learning. Little is understood, however, about how meta-affect is produced and regulated. If we want to help students achieve meta-affective learning, we must first seek understanding of the factors that impact meta-affective development.

1.1. Meta-affect and epistemology

As one might expect, we do not develop meta-affective dispositions in a vacuum; rather, how we attribute particular meta-affective dispositions to epistemic feelings involves a complex and dynamic interplay amongst our feelings (affect), our sense of what we're doing (epistemology), who we imagine ourselves to be (identity), and the social and institutional dynamics at play. DeBellis and Goldin (2006) describe meta-affect as functioning within a complex ecology of cognition, identity, beliefs and values. For example, cognitive awareness "that a roller coaster ride is 'really safe' can render fear pleasurable" (p. 137). Similarly, "mathematical exploration in an environment where the student knows making mistakes is 'safe' can transform negative emotions into positive ones" (p. 137). In the same way that cognitive awareness of 'safety' can shift someone's meta-affective experience of fear from negative to positive, students' epistemological beliefs about what it means to know and learn in science can have consequences for students' meta-affective development.

For example, students who hold the epistemological belief that learning science is about arriving quickly at a clear solution may view confusion as an impediment to progress, which may lead them to experience feelings of confusion as stressful and anxiety-provoking. Scientists, on the other hand, understand that the goal of science is not to find the easiest or quickest solution, but to find the most robust solution—one that prevails in the face of falsifying evidence (Popper, 1963). Thus, scientists seek ways to introduce confusion into their models to see how they hold up under different conditions and across contexts. They experience confusion as productive and fascinating rather than counter-productive and menacing. For scientists, moments of struggle, confusion, frustration, and vexation are understood to be essential for progress in science and are often experienced as pleasurable.

In this way, we see that part of becoming a scientist is not only developing productive epistemological beliefs but also developing productive meta-affective dispositions. However, we still know very little about how the dynamic relationship between epistemology and meta-affect plays out for students in science classrooms. Marya's case provides empirical support for that the connection between meta-affective learning in science and the development of a "productive stance toward knowledge" (Elby & Hammer, 2010, p. 409) whereby knowledge-building is difficult but rewarding, failure is likely to precede success, and confusion can be leveraged to advance one's conceptual understanding. In what follows, we tell the story of Marya's meta-affective learning and show how it was supported, in part, by her changing epistemology.

2. Methodology

2.1. Marya's physics course

Marya's physics course was designed according to a view that "the whole of science is nothing more than a refinement of everyday thinking" (Einstein, 1936, p. 59) in which scientific ideas and conceptions are rooted in everyday experiences, reasoning, and intuitions. A main goal, which was reflected in the course's overall structure, was for students to experience physics as a sense-making pursuit. For example, students got credit on their homework 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" (course syllabus). In grading homework, the TAs paid particular attention to students' argument construction irrespective of correctness: A correct answer without a valid argument received no points, but a well-constructed argument for an incorrect answer could receive full credit. In labs, students completed a challenge by designing and refining their own experiments, and the TAs supported them in carrying out their own ideas and solutions.

Students would watch pre-recorded smartPhysics[1] lectures twice a week before coming to each class so that the professor, David Hammer, could instead facilitate collaborative sense making and problem solving. During class, students would answer clicker questions and then participate in a large-group discussion. David typically asked students to make an argument both for the answer they thought was right, and against the answers they thought were wrong. He would also ask them to construct an argument that "someone else might give," so that students would get in the habit of considering multiple possibilities. Frequently, David would veer from his plan in order to follow up on students' questions or ideas (See Robertson, Atkins, Levin, & Richards, 2016, pp. 24-27 for an example of David's lecture from the previous year).

David and the TAs promoted practices like articulating confusion, making arguments for divergent solutions, and messing about in the real world to find answers to their questions. Students were encouraged to explain things simply ("to explain it to a 10-year old") so as not to rely on complicated jargon as a proxy for doing science. They were also encouraged to critically analyze their own thinking in order to find the balance between listening to their intuitions and learning when to be skeptical of them.

In addition to engaging students in the pursuit of understanding conceptual substance, David and the TAs strove to promote students' productive epistemological attitudes and feelings within that pursuit. For example, David once told students that their job was to seek out confusion like firefighters seek out fires. This kind of messaging framed confusion—a feeling that students typically try to avoid—as an integral part of science that students should seek out. He positioned struggle and uncertainty as necessary for making progress in science. The first day of lecture, David said, "In order to become someone who advances the knowledge of humanity, you need to have some stamina and enjoyment for the game of not knowing the answer. You need to take up the pursuit of it [...] I am going to try to build up your stamina for not knowing the answer, for making sense of things."[2]

2.2. Discovering Marya

I was Marya's teaching assistant (TA) in the spring semester of 2013. During the first discussion section of the semester, she expressed anxiety[3] about taking the course. About a month later, David granted her extended time on her exams after noticing that she was visibly anxious during the first exam. A few weeks into the semester, Marya received a diagnosis of generalized anxiety disorder. Although she continued to struggle with anxiety around testing, as the semester progressed, David and the TAs noticed that she began to thrive in her coursework. Towards the end of the semester, she expressed an interest in pursuing a minor in physics and told me about physics books she excitedly purchased to read over the summer. Knowing how challenging physics

[1] SmartPhysics (www.smartphysics.com, Freeman Worth Publishers) is an online repository of short lectures and conceptual questions that the students were required to watch and answer before every course lecture.
[2] Source: Transcribed from video data of the first lecture, on 1/16/14.
[3] Source: Video data of the first discussion section, on 1/21/14

had been in the beginning of the semester, I was interested to hear about her experience, so I asked her to participate in an interview.

2.3. Data collection and analysis

Immediately after the course ended, Lama Jaber (who was not affiliated with the course) interviewed Marya about her experiences in physics. The semi-structured interview was video- and audiotaped (a list of questions from the interview protocol is available in Appendix I).

In addition to the interview data, I collected video data from Marya's physics lectures, discussion sections, and office hours throughout the semester for a larger project studying the dynamics of students' engagement and persistence in science[4]. I also collected copies of Marya's written work, including her responses to the smartPhysics checkpoint questions that were issued twice a week throughout the semester, and her written problem sets, which were collected once per week. Each smartPhysics unit (there were 20 units in total) consisted of a pre-recorded lecture that lasted approximately 10 minutes and 2 or 3 multiple-choice questions that students were required to solve, explaining their reasoning. There was also an optional "lecture thoughts" section where students could post their confusions or general musings about the pre-lecture or course in general. The problem sets consisted of about 4 or 5 challenging problems, and typically took students multiple hours to complete.

2.3.1. Analyzing Marya's interview data

In Marya's interview, we were struck by her description of how the course transformed her feelings and attitudes regarding physics. To make sense of the interview data, we first transcribed it and identified excerpts where Marya specifically reflected on her learning experiences and on her feelings about uncertainty and intellectual challenges in physics. We did a rough analysis of these excerpts to understand how Marya was making sense of her experience. We first highlighted words that marked positive and negative meta-affect, such as "tempting" and "excited" or "scary" and "anxiety." Whenever possible, we noted factors that Marya indicated to be involved in eliciting a meta-affective response, paying close attention to temporal language that marked a transition or shift. For example, in the following excerpt from Marya's interview, we noted "anxiety about not knowing" as an instance of negative meta-affect (double-underline), which appeared to be coupled with epistemological value placed on having the right answer, even if that answer is given to her by someone else (single-underline).

> *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.*

We also noted the temporal language that Marya associated with her meta-affective descriptions. The temporal marker "at first" (bolded above) sets up a contrast between Marya's feelings at two different points in the semester. Other examples of temporal language were phrases such as "started (or stopped) causing" and "has changed."

Looking across these rough analyses, we noticed that Marya often described her meta-affect in relation to aspects of her epistemology. In particular, she stably associated her "anxiety about not knowing" with viewing physics as "about absolute

[4] Funded by the Gordon and Betty Moore Foundation

right or wrong" and associated her "excitement about not knowing" with viewing physics as "about the journey and the question." We also noticed that Marya used temporal language to mark a shift in both her meta-affect and her epistemology. Using a thematic analysis (Braun & Clarke, 2006), we generated narrative themes to describe Marya's account around her reported epistemological and meta-affective shifts. We present these themes under *Results and Analysis* entitled "Marya's account of *knowing* and *feeling* in physics." (sections 3.1.2-3.1.4).

2.3.2. Analyzing Marya's smartPhysics data

In order to systematically track how Marya's enacted epistemology shifted, we coded Marya's textual smartPhysics data over the course of the semester. Since we had a comprehensive record of all her responses, collected twice per week throughout the semester, this dataset provided a unique opportunity to observe how Marya's sense-making and problem-solving changed over time.

To analyze the smartPhsyics data, we adopted a constructivist grounded approach (Charmaz, 2006). We were primarily interested in documenting how Marya entered into and persisted within a productive sense-making approach, so we first broadly identified sense-making based on practices and strategies that were promoted in the course, including building from everyday experiences, messing about in real life, considering multiple perspectives, and so on. These practices and strategies also aligned with Marya's description of the course from her interview.

There was no hierarchical value for our coding system, meaning that each coding category carried equal weight in our interpretation of the data. We recorded a code every time Marya employed one of the practices or strategies, and since the codes were not necessarily mutually exclusive, we could assign multiple codes to a single response. In addition, we wanted to capture the sense-making practices and strategies that Marya employed on her own initiative. Meaning, if a problem explicitly asked students to create or consider an alternative argument, we did not mark the response with a code. We also coded for evidence of sense-making regardless of canonical correctness.

Lama and I coded half of Marya's smartPhysics data together, creating more coding categories as needed to represent the scope of Marya's sense-making activity. After multiple rounds of negotiations and revisions, our final coding scheme included five codes which we separately applied to the second half of the smartPhysics dataset.

The five codes we developed are: (1) extending past a problem's boundaries, (2) constructing counter-arguments and revising her thinking, (3) connecting to prior experiences and messing about, (4) using multiple approaches to solve a problem, and (5) identifying and articulating her own confusion. After coding the data, we looked back at her interview to see whether and how Marya reflected on these practices and strategies. We first provide excerpts from Marya's interview that illustrate her thoughts about these practices and strategies in section 3.1.4. We then discuss each of these codes with illustrative examples, and present the results of our coding analysis, in section 3.2.3 entitled "Tracking Marya's enacted epistemology."

3. Results and analyses

In this section, we first present data from Marya's interview, in which she reflected on her own transformation, and we show how her changing epistemology supported her meta-affective learning. We then provide two in-depth examples from her written work to show some fine-grained dynamics of her epistemological shift. Finally, we present our analysis of the entire set of her smartPhysics data as evidence of her changing epistemology over the course of the semester.

3.1. Marya's account of *knowing* and *feeling* in physics

3.1.1. An overview

In an interview conducted immediately after the final exam, Marya recalled how her feelings about facing uncertainties in physics shifted over the course of the semester. She said,

> *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!*

Marya described a shift in the *feelings* she attributed to the *feeling* of uncertainty—at first, she felt anxious about feeling uncertain, and by the end of the semester, she felt excited about feeling uncertain. Because this shift brought her closer to scientifically productive meta-affect, we call it an instance of meta-affective learning. She continued,

> *And all that because I think it was more about the process, it was just really about learning.*

Marya attributed her meta-affective learning to a shift in her epistemology about what it means to learn science. Marya spoke more about this shift, from viewing science as about "absolute right or wrong" to viewing it as about "the journey and the question." As part of this shift, she began to view herself as a builder rather than a receiver of knowledge. She learned that doing science involved sense making about the world, a process she began to love. In what follows, we provide evidence from Marya's interview to illustrate how Marya's shifting epistemology contributed to her meta-affective learning[5].

3.1.2. Theme 1: Marya's sense of science as "absolute right and wrong" contributed to her anxiety about "not knowing"

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

> *I've always been intimidated by physics. […] As an outsider it just looks really complex. It was really interesting but I didn't think I could do it. […] A lot of the time growing up I would walk around and see something happening in the physical word,*

[5] To be clear, we do not claim that epistemology is the *only* factor contributing to her meta-affective learning. In fact, in our first round of analyses we noted many connections between Marya's meta-affect and her identity. We focus on epistemology because it is centrally and explicitly foregrounded in Marya's own account of her transformation. Identity dynamics, though present, were not as obvious, which made them more difficult to disentangle analytically. We speak more about the role of identity in the "Discussion and implications" section.

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.

She carried these feelings of self-doubt with her into the physics classroom, along with beliefs about the nature of knowledge in science and her role as a science learner. She said,

I've always been intimidated by physics. […] 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.

Despite thinking physics was interesting, Marya viewed herself as an "outsider" with respect to a "complex" and "inflexible" body of knowledge. She described viewing her role as a knowledge-receiver rather than a knowledge-builder. In the interview, Marya mocked some of her earlier attitudes,

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.

This epistemological view of physics, as a body of incontestable knowledge produced by others, treated learning as a binary process: Either you understand the laws or you don't. And if you don't understand them, then you probably don't "have the brains for" it.

According to this "absolute right or wrong" epistemological view, uncertainty became synonymous with failure. In fact, Marya expressed that her sense of herself as a successful learner was determined, in part, by how *little* she lingered in uncertainty. She said,

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 epistemological expectation, paired with the fact that "a lot of the time [she] didn't know a lot of things," appeared to provoke an "anxiety about not knowing" that Marya said "led to the development of a little bit of depression." In this way, we see how Marya's early epistemological view of science as "being about absolutes" partly shaped her early meta-affective anxiety about "not knowing."

3.1.3. Theme 2: Marya's sense of science as about "the journey and the question" and of herself as a knowledge-builder contributed to a reduction in her anxiety about "not knowing"

Marya recalled experiencing "a really interesting shift" in how she thought about physics. She described abandoning the notion that science learning is about "absolute right or wrong" for an alternative view that "it's about the journey and the question." She described feeling that "I don't need to get it instantly, because it's not about getting it, it's about how you got it," which placed value in the process of sense-making rather than taking the quickest path to finding the correct answer.

Marya described how she began to view herself as a knowledge-builder rather than a knowledge-receiver. She said,

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.

Thus, uncertainty became a necessary precursor for discovery rather than an indicator of failure. She spoke about this new attitude, saying,

> *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 attitude was supported by the course instruction. She recalled that David positioned “not knowing” as “honorable.” She said,

> *One of Professor Hammer's like favorite things to say it was like um, you know, he put like options because we used clickers in class, so an option almost always was like ‘I don't know’ and he'd be like, ‘That 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. We learned to be like really humble about our opinions and are we really sure?*

With help from David’s explicit and tacit messaging, Marya came to realize that uncertainty is at the very core of the scientific enterprise, and her job is to seek out uncertainty and build new knowledge about the world. With that realization came relief from her severe anxiety. She said,

> *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.*

Not only did her anxiety about “not knowing” dissipate, but she developed a deep appreciation for lingering in uncertainty. She said,

> *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*.

Even in her final exam, where stakes were presumably high, uncertainty did not provoke anxiety. She said,

> *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 she didn’t know how to answer a problem in her final exam, she described herself as an empowered agent that “can still work on it.” In this way, Marya’s developing epistemological views of herself as a knowledge-builder and of uncertainty as necessary and productive eased her anxiety about “not knowing.”

3.1.4. Theme 3: Marya’s approach of physics as a sense-making activity contributed to her enjoyment of it

Marya’s newfound role as a knowledge-builder required a new set of tools for making sense of the world. She began to develop a set of practices and strategies for sense making, which were supported, in part, by the course instruction. We later track her use of five particular sense-making practices and strategies in her written work to determine whether and how her epistemology (as it is enacted in her sense making) changes over the course of the semester. In her interview, Marya referenced these practices and strategies, and told us about how she got excited by the experience of sense making. In what follows, we first provide excerpts from Marya’s interview in which she describes her engagement in these five sense making practices and strategies. We then provide excerpts in which Marya describes her excitement to sense make. Marya describes her sense making practices and strategies

Extending past a problem's boundaries

Marya expressed that assigned problems were just a starting point for real disciplinary work. She described the importance of asking herself more questions about the problem context to further explore the phenomenon. Sometimes, a problem would trigger her to ponder another phenomenon entirely. She recalled pursuing many questions that were not part of the course requirements. She said, “It was not required for the course but I would do it because then I'd truly know it.” She framed this practice as an important for her learning.

Constructing counter-arguments and revising her thinking

Students were encouraged to come up with multiple arguments to support opposing answers, but very few students actually did this without explicit instruction. By contrast, Marya reflected on utilizing this practice in her physics class. She said,

> *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.*

Connecting to prior experiences and messing about

Marya reported an appreciation for how the course instruction connected theoretical ideas with the real world. She said,

> *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.’*

Not only did Marya describe the course as connecting to what happens in the real world, but she also described the world as having utility for figuring something out.

Using multiple approaches to solve a problem

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 reflected on the need to explain her intuitions, saying,

> *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?

Identifying and articulating her own confusion

Students were encouraged to articulate their own confusion, but many students did not actually take up this practice in a way that was visible to us. Marya, on the other hand, described the importance of making her confusion explicit. For Marya, part of doing physics became 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 her own learning. She interrogated her own knowledge rather than merely rely on external measures to monitor her understanding.

And merely recognizing her own confusion wasn't enough. She discussed the importance of articulating her confusion and using it to make progress, a process that took a great deal of patience and endurance. She said,

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?

Conclusion: Marya describes her excitement with respect to sense-making

Marya described becoming enthralled with this process of sense making. Instead of merely solving the assigned problems, she took particular liberties to build on problems in ways that led to new and exciting scientific discoveries. In this way, the assigned problems were just launching points for her own inquiry. Marya mentioned a particular homework problem in which her open exploration led to a new discovery. She said,

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.

In this problem, she "took it just a tiny little bit further" than what the problem asked for and she constructed a bit of knowledge that she could take ownership of. The excitement that she felt seemed to stem, in part, from the pure act of creation—one that was unprompted and that yielded scientifically valid results. In this way, uncertainty became an opportunity for scientific innovation.

When talking about her changing relationship with uncertainty, Marya occasionally burst into a brimming smile. Her enthusiasm was electric as she spoke about the excitement she felt when facing a new and unknown challenge. She said, *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!*

The complexity that once intimidated and alienated Marya soon became "scary but...also exciting." More than just enjoying sense making, Marya became intoxicated by it. 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, 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.

In this way, Marya described the drastic shift from extreme anxiety to addictively seeking out the unknown. And a big factor supporting that shift, at least according to Marya, was her development of a new epistemological stance—one in which learning science became about the process of sense making.

3.2. Evidence of an epistemological shift enacted in Marya's sense-making

As we just illustrated, Marya described a drastic shift in her understanding of what it means to learn physics. In order to further explore this shift, we analyzed her written work for evidence of her enacted epistemologies and looked at how those enacted epistemologies changed over time. In what follows, we first contrast an example from Marya's early work with an example from her later work. We then present an analysis of her smartPhysics data for a view of her enacted epistemologies throughout the semester.

3.2.1. An example from Marya's early work

This example comes from Marya's response to a smartPhysics question (Figure 1) in the first week of the course.

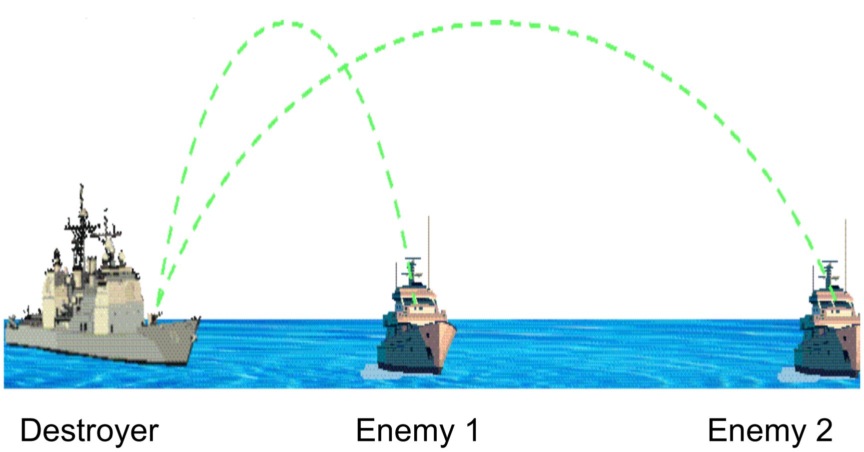

Figure 1. (Unit 2) Which ship gets hit first?

To the question, “Which ship gets hit first?”, Marya responded:

> *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 enemy ship 1 gets hit first. Intuitively, this makes sense; traveling less distance should take less time—if they are moving at the same speed. But upon further examination, the two projectiles aren’t moving at the same speed, which also makes sense: if you imagine throwing a ball to each ship, you would have to throw the ball to ship 2 faster, since it reaches the same vertical height as it does for ship 1, but travels a larger horizontal distance. The correct answer is that the vertical height is what determines the projectile’s airtime because only the vertical component of motion is impacted by gravity’s downward pull. Both projectiles travel the same vertical distance, so they must hit at the same time.

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. This reasoning lead her to conclude that “enemy ship 2 will be hit first because it has the lower speed” since in the equation she uses, $t = 2\,v_0/g$, a lower initial speed, v_0, results in less time. This equation is only valid for vertical motion since it was derived assuming the presence of gravitational acceleration (*g*). In this case, a lower initial vertical speed would indeed result in shorter airtime. Because the two projectiles reach the same height, and height is a function of vertical acceleration, they must have the same vertical initial speed.

However, Marya inappropriately drew on her mathematical intuitions about position vs. time graphs and then plugged her reasoning into an equation, stripping the problem of physical meaning. She didn’t connect her solution back to the physical context to make sure it is sensible, and in fact, Marya’s strategies lead her to argue for the least sensible answer, that the slower projectile traveling the larger total distance would hit first. This example highlights the early, pre-sense making epistemological stance that Marya described in her interview. She did not employ any of the sense making strategies or practices that, in the interview, she described coming to value as part of sense making in physics.

3.2.2. An example from Marya’s later work

By contrast, in a homework problem from week 7 of the course (figure 2)—the one about inelastic collisions that Marya excitedly mentioned in her interview—Marya enacted practices and strategies that indicated a sense making epistemological stance.

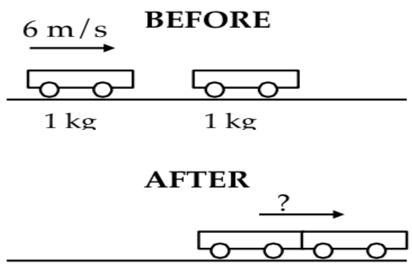

Figure 2. An inelastic collision

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 that’s initially at rest.

Most students approached this problem without much interest. They chugged through the problem mechanically, and if they had any compelling insights, they certainly did not share them. Marya, however, used this problem as an opportunity for innovative sense making. 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.

This problem, which seems unremarkable compared to the more interesting problems that students answered in this class, was memorable for Marya. 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. Her excitement was evident both in the affect she expressed in her writing (use of exclamation points, language such as *interesting*) and in how she reminisced about this problem months later in her interview.

3.2.3. Tracking Marya's enacted epistemology

In order to track Marya's enacted epistemology over the course of the semester, we developed a coding scheme to reflect Marya's engagement in productive sense making practices and strategies. As shown previously, Marya also described these practices and strategies as central to her later understanding of what it means to sense make in physics.

As we outlined previously, the codes we developed were: (1) Extending past a problem's boundaries (2) Constructing counter-arguments and revising her thinking (3) Connecting to prior experiences and messing about (4) Using multiple approaches to solve a problem, and (5) Identifying and articulating her own confusion. We provide some brief coding criteria and examples from the data of each coding category and then we show the trend over the semester.

Examples of coded data

Extending past a problem's boundaries

We coded Marya's work as "extending past a problem's boundaries" when she explored beyond what was required. For example, she was asked whether a block on a frictionless surface would go faster if hit with a ball that bounces off of it than it would if hit by a ball (with equal mass and the same speed) that sticks to it (Figure 3). After answering the question, Marya pondered, "[This problem] makes me wonder, is there loss in kinetic energy in the [bouncing] scenario?" This self-generated question led her down an adjacent path of inquiry, which not only opened up opportunities to explore a different phenomenon, but also enriched her understanding of the question posed to her.

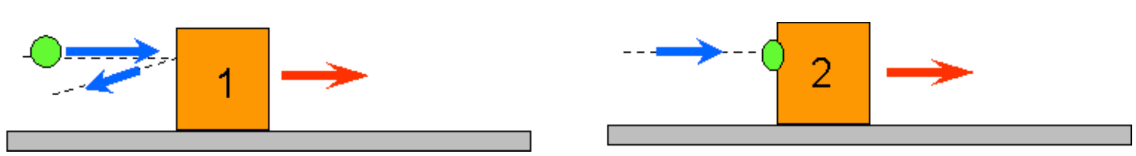

Figure 3. (Unit 11) Two balls of equal mass are thrown horizontally with the same initial velocity. They hit identical stationary boxes resting on a frictionless horizontal surface. The ball hitting box 1 bounces back, while the ball hitting box 2 gets stuck. Which box ends up moving faster?

Constructing counter-arguments and revising her thinking

We coded Marya's work as "constructing counter-arguments and revising her thinking" when she explicitly volunteered (meaning, it wasn't asked from her in the problem) a counter-argument. Sometimes exploring counter-arguments would lead her to change her mind and revise her thinking. For example, in the same box-and-ball problem (Figure 3), she began to answer her own question about whether kinetic energy would be lost in the bouncing scenario: "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…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?" Here, she considered multiple possibilities, and as she considered them, the conceptual space she was exploring broadened. 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.

Connecting to prior experiences and messing about

We coded Marya's work as "connecting to prior experiences and messing about" when she drew on everyday experience as a resource for doing physics. This included drawing on prior experiences as well as her explicit reports of trying things out in order to solve a problem. For example, when deliberating multiple lines of reasoning in the previous problem (Figure 3), she turned to the real world for arbitration. She wrote, "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. In scenarios like this, would it be correct to say that the ball can either go slower or the same speed but never faster?" Marya threw a ball at a "pinned down box" (a wall) and the real world told her that it would never bounce back faster, no matter how hard she threw it. Marya sought out and found an answer to her question by messing about in the physical world.

Using multiple approaches to solve a problem

We coded Marya's work as "using multiple approaches to solve a problem" when she used both formal and informal reasoning to make sense of a problem. For example, when asked to determine which axis of rotation would the moment of inertia of a dumbbell be smallest? (Figure 4), Marya first reasoned through the problem without relying on the mathematics. 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…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…over a longer distance than in C. However, the masses are different and I need the math to help figure that out." Marya then went on to calculate mathematically the moments of inertia for each axis.

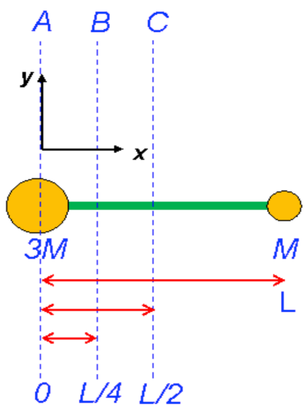

Figure 4. (Unit 15) A ball of mass 3M at x=0 is connected to a ball of mass M at x=L by a massless rod. Consider the three rotation axes A, B and C as shown, all parallel to the y-axis. For which rotation axis is the moment of inertia of the object smallest? (It may help you to figure out where the center of mass of the object is.)

Interestingly, Marya already concluded that B had a lower moment of inertia, but she was now 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, Marya 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[6]. 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 conceptually and only turned to mathematical reasoning when it was necessary. This is a clear departure from Marya's early work, when she turned immediately to mathematics, often to the detriment of conceptual understanding.

Identifying and articulating her own confusion

We coded Marya's work as "identifying and articulating her own confusion" when she critically reflected on her thought process. In her lecture thoughts in Unit 9, she 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 didn't understand the relationship between work and energy. Having articulated the confusion, she searched for an answer and then described her

[6] The moment of inertia for this object is I=1/2M1R1^2+1/2M2R2^2, where M1 and M2 are the first and second mass, and R1 and R2 are the distances of those masses from the axis of rotation. Since moment of inertia depends on R^2, the distance plays a larger role than the mass.

subsequent understanding. Making her confusion explicit allowed Marya to expand her understanding of a conceptually complex phenomenon.

Coding results

A visual representation of our coding for Marya's entire semester of smartPhysics data (Figure 5) shows that her engagement in knowledge-building practices and strategies generally increased from the beginning to the end of the semester. Each square's intensity corresponds to the total number of instances a code appeared, with darker squares corresponding to a higher number of instances. There is no evidence of Marya's agentive sense making until unit 4 (the end of week 2).

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 5. Coding for Marya's enactment of knowledge-building strategies and practices

We interpret Marya's increased enactment of these practices and strategies to reflect her gradual development of a sense-making epistemological stance. This finding is consistent with Marya's own account of her changing epistemology.

4. Discussion and implications

In this paper, we have illustrated Marya's meta-affective learning and argued that it was impacted by her changing epistemology about what it means to learn physics. She shifted from thinking that physics is about "absolute right or wrong" to thinking it is about a "journey" and a "process" of sense making. At the same time, she re-conceptualized the role uncertainty plays in physics as well as her role as a learner. As she began to see herself as a knowledge-builder and learn that uncertainty is endemic to science, she stopped feeling anxious about "not knowing" and she began to sense make. As she began to sense make, she discovered a deep appreciation for the process of figuring things out, and became excited at the possibility of a new and unknown challenge.

Marya's case invites us to recognize meta-affective learning as an aspect of disciplinary learning. Her case also suggests that meta-affective learning involves the development of a "productive stance toward knowledge" (Elby & Hammer, 2010, p. 409). To take up science as a pursuit, students need to develop epistemological and meta-affective dispositions that support their engagement, such as acceptance of uncertainty, proclivity to seek criticism, appreciation of the tentative nature of knowledge, and motivation to work through challenges. Meta-affective learning should thus become an important goal for science teachers to target and address. By encouraging students to linger in inquiry, by legitimizing their struggle, and by helping them recognize, reflect on, and manage their feelings, as we saw in Marya's case, educators can help learners develop productive meta-affective stances as part of learning science.

Marya's case also has implications for research. It has helped expand our understanding about the dynamics involved in meta-affective learning, specifically informing our understanding of the ontological relationship between epistemic affect, meta-affect, and epistemology. Gupta et al. (in review a) has begun this work, showing how affect can mediate epistemological experience, either by stabilizing or disrupting a student's local epistemological stance. Marya's case suggests that epistemology could also mediate meta-affect. Returning back to the rollercoaster example, whether someone meta-affectively interprets their fear as exhilarating or debilitating depends, in part, on how safe they believe the ride to be. The knowledge of safety, then, is mediating the relationship between their affect (fear) and their meta-affect (exhilaration or terror). In Marya's case, we have shown that how she came to experience uncertainty was shaped, in part, by her changing epistemology. Ontologically, we might think of her epistemology as mediating between her epistemic affect (i.e., her uncertainty) and her meta-affect (i.e., her anxiety or excitement with respect to uncertainty).

However, there is much more to learn. For simplicity, our analysis focused on the ways Marya's epistemology shaped her meta-affect. In reality, however, we believe this relationship to be complex and reflexive. Meaning, just as Marya's epistemology shaped her meta-affect, her meta-affect also shaped her epistemology. It is likely that Marya's initial anxiety (her Meta-Affect) prevented her from taking the risks required to sense make (her Enacted Epistemology). Once her anxiety (MA) dissipated, however, she began to sense make (EE) and she enjoyed it (MA), trapping her in a positive feedback loop in which sense making (EE) excited her (MA) and her excitement (MA) and made her seek out opportunities to sense make (EE).

While we did not directly examine it in this paper, researchers in psychology have conducted powerful studies that reveal the impact meta-affect has on students' developing epistemologies and cognition. For example, Carol Dweck's work on mindsets has shown that students' beliefs about the nature of intelligence—i.e., whether it is fixed or fluid—have drastic impact on their affect and engagement (Dweck, 1975, 2000, 2006; Dweck & Leggett, 1988). Dweck found that students who believe that intelligence is fixed typically focus on appearing outwardly capable, which often causes anxiety when the student is faced with a challenge. Conversely, students who believe that intelligence is fluid and cultivated through hard work are often focused on learning rather than appearance. When faced with a challenge, these students consider it an opportunity for growth rather than a test that might implicate their intelligence. Students' beliefs about the nature of intelligence impact how they perceive and thus experience challenges (meta-affect), which, in turn, impacts how they approach their learning (epistemology and cognition).

Steele and Aronson's (1995) work on stereotype threat has shown that students who are made aware of their minority status before taking a test perform considerably worse than minority students who take the tests unprompted. They concluded that students who were cued to think about their minority status (for example, by checking a box indicating race or gender) felt additional pressure not to confirm the negative stereotypes attributed to their particular group. This additional pressure, they conjecture, triggers feelings of stress and anxiety (meta-affect), which keeps students from taking necessary risks in how they approach learning and problem solving (epistemology and cognition). Drawing on Steele & Aronson's work, others have found that cuing different aspects of identity can trigger either a negative or positive affective state, which directly impacts performance. For example, Ambady and colleagues (Ambady, Shih, Kim, &

Pittinsky, 2001) found that female Asian students perform better when asked to cue their Asian identity than when they are asked to cue their female identity. In these cases, negative affect triggered by an explicit attention to one's identity may prevent students from adopting productive yet seemingly risky epistemologies for fear of failing.

Krashen's work in second language learning has revealed that students who are in a heightened state of anxiety (which emerges as a meta-affective response to the fear of failure) do not learn at the level of those without anxiety. Krashen calls this the "affective barrier" and it has been widely applied to make sense of students' learning challenges. These affective barriers can keep students from making progress, both conceptually and epistemologically by keeping students from engaging in sense-making, preferring instead to take the quickest (but less epistemologically productive) route to the correct answer. Similarly, work on state-dependent learning (Weingartner, Miller, & Murphy, 1977) has shown that bipolar individuals experiencing a heightened emotional state have difficulty encoding and processing events. In fact, many participants reported losing all memory of events that occurred while they were in a manic state. This connection, between a person's experience of an emotional state and various aspects of their cognitive functioning, appears to be quite robust. Thus, if we want to support students' learning in science, it is necessary to focus more effort to understand how they experience and make sense of feelings and emotions within a disciplinary pursuit.

Finally, though we did not foreground it in our analysis, we believe that Marya's identity as someone who loves to sense make played a large role in her meta-affective learning. Research on the dynamic interplay between identity, epistemology, and affect in science speaks to the role students' identities play in how they come to feel about science. For example, Danielak et al. (2014) studied the case of Michael, an engineering student whose program did not support "his personal search for deep conceptual understanding" (p. 9). They showed how Michael's identity—one that clashed with the department's values and practices—was so closely coupled with his personal epistemology as a sense-maker that he almost dropped his engineering major. Similarly, Geller et al. (2014) looked at how identity and epistemology impact students' affective responses toward science. They demonstrated that Gavin's locally enacted identity as a "'why' kind of person" (p. 3) either aligned or clashed with his epistemological beliefs about physics and biology. The alignment of his identity with physics' focus on mechanism produced positive affect, while the tension between his identity and biology's non-mechanistic, largely phenomenological focus produced negative affect.

In addition to Marya's identity playing a role in her meta-affective learning, we have evidence that Marya's meta-affective learning impacted her identity formation: She described it as partly responsible for the personal progress she made in how she managed and understood her anxiety. She said,

> *The way you look at physics just works for about everything in life. Because it's about the journey and the question. It wasn't about absolute right or wrong. And that started translating into my other courses. It started translating in how I dealt with my personal problems with anxiety. So I think it was a very defining course for me in literally all aspects of my life, not just physics itself.*

For Marya, the implications of her meta-affective learning transcended disciplinary pursuits. It was a truly transformative experience for "all aspects of [her] life."

Marya's case illustrates the drastic impact that attending to students' feelings and emotions in science can make. But our understanding of the role meta-affect plays in students' disciplinary learning has only scratched the surface. The more cases we find of students' meta-affective learning, the more we can understand about how this phenomenon occurs for all students, so we can do our best as researchers and educators, to promote it.

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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]?