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Beyond “asking questions”: Problematizing as a disciplinary activity

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Abstract

The Next Generation Science Standards states that “science begins with a question.” (NGSS Lead States, 2013). Yet scientific inquiry among students and scientists alike often begins without a clear question. In this article, we describe *problematizing* as the intellectual work to identify, articulate, and motivate a gap or inconsistency in one’s own or a community’s current understanding. We describe problematizing in professional science to show how it is central to disciplinary practices of science. We then present an episode of fifth-grade students’ problematizing, as a detailed illustration of the construct and as an example of evidence that students can engage in this work. Through these two approaches, we show problematizing is central to the disciplinary practice of science and that it is a part of students’ engagement. We further show that it is missing from the description of practices in the Next Generation Science Standards. Lastly, we make recommendations for research on student problematizing, for revisions to the Standards, and for instruction.

Keywords: Standards, Science Education, Policy, Nature of Science (NOS), History and Philosophy of Science

Introduction

The Next Generation Science Standards, like the Framework for K-12 Science Education, state, “Science begins with a question.” (NGSS Lead States, 2013; NRC, 2012). But science very often begins before there is a question, with a sense that something amiss, puzzling, or surprising. Turning an uneasy feeling into a question is often a significant achievement, the result of extended effort we call *problematizing*: the work of identifying, articulating, and motivating a problem or clear question. In a previous article (Phillips, Watkins & Hammer, 2017), we have shown that problematizing is central and essential to students’ and physicists’ inquiry.

In this paper, we build on that work in several respects: We first discuss how the construct relates to prior research in science education on students’ questions and uncertainty; we present it as relevant across the sciences, not just physics; and we provide a new example, showing problematizing in a fifth-grade class discussing clouds. We then turn to our main new purpose here, which is to analyze the NGSS account of disciplinary practices, focusing particular attention on "Asking Questions," to show that it does not sufficiently capture the often-extended activity by scientists and students to produce those questions. We conclude with suggestions for supporting problematizing in classrooms, including examples from our own teaching.

Research on students’ questions and uncertainty

For some time, researchers have studied how the questions students ask within science classrooms may impact and relate to their engagement in other practices. Student questions have been studied for their role in constructing explanations and knowledge (Chin, Brown, & Bruce, 2002; Chin & Chia, 2004; Chin & Osborne, 2008), encouraging engagement and argumentation (Chin & Osborne, 2010a; Chin & Osborne, 2010b), and designing experiments and investigations (Chin & Kayalvizhi, 2002). Student questions have also been studied as evidence of students’ existing knowledge (Chin & Chia, 2004; Chin & Osborne, 2008; van Zee Iwasyk, Kurose, Simpson & Wild, 2001) and of their interest in science (Baram-Tsabari Sethi, Bry & Yarden, 2006). Work in these veins value questions for their broader roles in students' learning, including as part of developing skills within other disciplinary practices.

While most attention in the literature has been on what follows from questions, some work has focused on helping students pose questions that can contribute to scientific inquiry. Researchers have explored scaffolding the kinds of questions students ask when listening to classmates’ presentations (Herrenkohl & Guerra, 1998; Herrenkohl, Palincsar, deWater, and Kawasaki, 1999), providing model questions within a problem-based-learning intervention (Hung et al, 2014), and using research papers within classroom instruction (Brill & Yarden, 2002). Lee & Choo (2007) specifically targeted students’ “problem finding” as an area of study, examining factors that influence students’ success. They found, for example, that for ill-structured problems, “scientific knowledge and personality traits positively affected problem finding, and divergent thinking negatively affected problem finding” (p. 113).

Much attention in the literature (e.g., Chin & Kayalvishi, 2002; Cuccio-Schirripa &Steiner, 2000; Dkeidek, Mamlok-Naam & Hofstein, 2010; Hung et al, 2014) has been on scientific questions as investigable, especially through empirical study. That is often taken as the definition, including in the NGSS: students should learn to “identify scientific (testable) and non-scientific (non-testable) questions.” (NGSS Lead States, 2013, Appendix F, p. 4).

Some researchers, however, have considered the importance of questions that are not yet investigable, as part of scientific inquiry. Scardamalia and Bereiter (1992) examined students' "wonderment questions" that "reflect curiosity, puzzlement, skepticism, or a knowledge-based speculation, in contrast to a groping for basic orienting information" (p. 188). Chin et al (2002) distinguished more precise subcategories of "*comprehension questions* which typically sought an explanation of something not understood" and "*anomaly detection questions* where the student expressed skepticism or detected some discrepant information or cognitive conflict and sought to address this anomalous data" (p. 532). Similarly, Watts, Gould, and Alsop (1997) describe *elaboration questions,* which "are indicative of trying to reconcile competing ideas, the demands of a new theory against the call of experience" (p. 61).

In complement to this expanded attention to questions, some research has focused on students' attitudes and stances towards areas of uncertainty. Chin (2004) argued that fostering inquisitiveness is important to students' development as learners. Recent work by Schinkel (2017) and Gilbert & Byers (2017) argues for the importance of wonder, the state of acknowledging and experiencing the mysterious and unknown and "a heightened awareness that one's knowledge is incomplete or mistaken" (Schinkel, 2017, p. 542). Beyond mere curiosity, which may be satisfied by obtaining facts, wonder is not necessarily resolved or eliminated when an apparent resolution to the uncertainty has been found. Experiencing wonder and being inquisitive are part of what it means to do science and develop as a scientist. Other recent work has highlighted *uncertainty* as central to scientific engagement (Engle, 2012; Watkins, *et al*, 2018). Manz (2015, 2016), for example, showed that students' exploration and development of uncertainties supported their development of new models and conceptual ideas and practices.

To this literature, we have contributed analyses of students' efforts to pin down what has them feeling uncertain (Phillips, *et al* 2017). We refer to these efforts as *problematizing*, the intellectual work of identifying, articulating, and motivating a problem, and we showed students can problematize without particular, explicit instructional support. Consistent with the research in science education we reviewed above, as well as with accounts of professional physics, we argued that problematizing is an important scientific activity. Asking a question can be a significant achievement of extended effort that results in a knowledge product in its own right, one that defines a gap or inconsistency in current understanding. Problematizing can take place as students or scientists begin their inquiry or throughout an extended investigation.

There has been more attention to activity of this sort in engineering education, which has explicit representation in engineers' professional discourse as "problem scoping" (sometimes "framing" or "defining") (Atman, Yasuhara, Adams, Barker, Turns, & Rhone, 2008; Dorst & Cross, 2001; Maher & Poon, 1996; Watkins, Spencer, & Hammer, 2014). Research in engineering education includes analyses of how problems co-evolve with possible solutions, and it emphasizes that defining problems in engineering is an open-ended activity involving extended effort, in a complex interaction with other practices.

That view is reflected in the NGSS. Dimension 1 presents *Asking Questions* as the first of eight practices of science, paired with *Defining Problems* in engineering: "While science begins with questions, engineering begins with *defining* a problem to solve" (NGSS p. 52, emphasis added). NGSS devotes significant attention to defining problems as one of three phases of the engineering design process, acknowledging the intellectual work involved. In contrast, as we show later in the article, the NGSS discussion of *Asking Questions* focuses on the questions, not on the intellectual work students do in composing them.

Next, we briefly discuss problematizing in professional science, drawing on the writings of scientists and those who study them.

Problematizing in professional science

The importance and difficulty of problematizing are apparent in scientists’ writing. One prominent example is in Einstein’s famous skepticism of quantum mechanics. In 1926, he wrote to a colleague that God “is not playing at dice” (Einstein, Born & Born, 1971), and throughout the mid 1920s wrote of his discomfort with the lack of “tangible forms” in quantum mechanics and the apparent “abandonment of strict causality” (Mehra, 1987, p. 467). It was not until much later that Einstein, working with Podolsky and Rosen, was able to articulate a problem, now known as the EPR paradox. In their paper, they detailed conceptual and mathematical arguments that “the wave function does not provide a complete description of physical reality.” In their conclusion, the authors “left open the question of whether or not such a description exists” while asserting a belief that “such a theory is possible” (Einstein, Podolsky & Rosen, 1935, p. 778), Articulating the EPR paradox and motivating the community of physicists to see a problem took extensive time and effort. We present other examples from physics in Phillips, *et al*, 2017.

Elements of problematizing in science have also been highlighted in studies of scientists’ work and thinking. Wertheimer (1982) argued that “productive thinking” requires identifying “gaps, trouble-regions, disturbances, [and] superficialities” in one’s knowledge and identifying the “fitting or not fitting” of one’s knowledge within a broader structure (Wertheimer, 1982, p. 235). Similarly, Henle argued that identifying the “shape of the gap” is a main goal of scientists (Henle, 1986, p.173).

Keller (2002) described how the formulation of questions and problems can define fields and historical eras within fields. For example, she noted that a primary division in fields of biology is in whether one approaches the question “How are living entities formed?” as about *all* living entities (evolutionary biology) or as about a particular entity (embryology and genetics). She argued that synthetic biology in the mid-20th century formulated that question to be largely equivalent to “What is life?” If researchers could create life or life-like entities in the lab, they would have a precise definition of what it means for something to be alive. Keller also traced how different framings of the problem of how an organism develops are related to different eras of genetics. Thus, much of biology, like physics, consists of constructing particular formulations of questions that then inform (and constrict) particular lines of research.

The problems that scientists articulate may or may not be answerable by experimentation or observation. Einstein, Podolsky, and Rosen (1935) knew of no way to resolve their paradox empirically. Experimental approaches did not begin until several decades later, after theoretical work by Bell (1964) and significant advances in technology (Selleri, 2013). In a more recent example, the blackhole information paradox in physics is considered a purely theoretical problem; experimentation to resolve the paradox is generally considered to be impossible (Mathur, 2009). In cosmology and particle physics, there is ongoing debate over whether or not "fine-tuning problems"—cases of inexplicable and statically improbable conditions that exist in the universe—are problems at all. Many argue for so-called "anthropic" solutions: the universe must be as it is, otherwise intelligent observers such as ourselves would not exist (Weinberg, 1987; Perlov & Vilenkin, 2017). Such a possible philosophical explanation does not render the original problems "unscientific," nor the work to articulate them any less important. Rather they provide us with an example of the diversity of ways in which problems in science can be resolved.

We do not argue that problematizing and the nature of problems are the same across fields or even take a single form within them, but rather that problematizing is a central activity across the sciences, analogous to constructing explanations and developing and using models. It is part of scientists' work, and it should be a part of students' experiences in classrooms. In the next section, we present an example from a 5th grade science discussion to show what problematizing can look like in classrooms and motivate the need for standards to target this kind of intellectual activity.

Students doing science

Project background

This article is part of a larger project to study the dynamics of learners' engagement and persistence in science. It was through the study of the data that we came to recognize students' problematizing. We present the methodology of this project in earlier articles (Phillips, Watkins & Hammer, 2017; Watkins, et al, 2018), but to summarize briefly here, there are four steps:

1. Selecting instances for study. For the purposes of this project, we selected only clear examples of students' doing science, as captured in video recordings and written work. We presented candidate episodes to a panel of faculty from biology, chemistry, and physics departments, and we asked: "Do you see these students as doing science?" We limited ourselves to instances in which there was a strong, unproblematic consensus.
2. Close analyses I. We transcribed each instance and, using both the transcript and video, analyzed what contributed to the dynamics, using research methods drawn from interaction analysis (Erickson, 2006; Jordan & Henderson, 1995; McDermott, Gospodinoff, & Aron, 1978) and knowledge analysis (diSessa, 1993). For the first nine cases, to the extent possible, we kept the analyses independent of each other. Each case had a lead analyst, who presented their work to the project staff for critique. There were five different lead analysts across the nine cases, and, during critiques, we disallowed references to other data.
3. Comparison across cases. After we had analyzed the cases independently, we conducted a cross-case analysis to identify themes and patterns across them. Some themes were unsurprising and, we expected, sufficiently developed in the literature (e.g. that students had opportunities to express their reasoning). Three themes seemed worth further consideration, one of which was problematizing.[1]
4. Close analyses II. We re-analyzed the set of episodes looking now specifically for evidence within each of the themes we had identified in our comparison across cases.

The second round of close analysis showed problematizing as prominent in the dynamics of seven out of the nine cases. Phillips et al (2017) presents evidence from four of those cases, showing student problematizing in a 5th grade public school class, two from a college physics course, and one from a seminar for pre-service teachers. In this article, we present a fifth case, from another 5th grade public school class.

Clouds: An example of students' problematizing

We have analyzed this episode elsewhere with respect to affect (Jaber & Hammer, 2016) and to students' positioning themselves as not-understanding (Watkins et al, 2018). Further

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[1] Another theme was the role of social displays of not-understanding (Watkins *et al*, 2018), and the third was evidence of students' affect, in particular of vexation over uncertainties (Radoff, 2017).

excerpts from this episode can be found in those papers, and the full video is available on our project website.[2] Here, we focus on the episode as an instance of problematizing.

It took place in a fifth-grade public school classroom, during a unit on the Water Cycle. On this day, the teacher, Mr. M, had the students sit on the floor in a circle to discuss the question: “How is it that a cloud rains?” We present the conversation that followed in three segments.

Mr. M calls on a student, Alyssa, who had her hand raised.

Alyssa: Well clouds get water-

Mr. M: Ssh (to other students), I’m listening (to Alyssa).

Alyssa: from the air. like the cloud gets the water from the air that has always been there and um the cloud when it get- it holds the water till it--till it turns grey and then it rains, coz it gets too heavy.

Mr. M: It gets too heavy. (Jordan raises her hand.) How does it *do* that? Jordan?

Jordan: Um, I think, I agree with Alyssa, because if a cloud- well, I have a question.

Mr. M: Ok.

Jordan: What's in a cloud that makes it hold the water?

Alyssa: (whispering to Jordan) It just does it.

Student: Nnhhnn? (sounds like “I don’t know”)

Jordan: Like, does it float?

Mr. M: Ooh I see a scrunchy face. (points at Brian, most students turn to look at him) What are you thinking about? Did you listen to her question? Could you say your question one more time, Jordan?

Jordan: Why does- how could water be in a cloud without falling?

Mr. M: What do you think Brian? How does a cloud hold water?

Elea: (quietly) Yeah, cause it's as light as a feather.

(~17 sec pause)

Mr. M: What do you think?

Elea: I don’t think it holds water.

Mr. M: What do you mean?

Elea: It doesn’t hold water.

Mr. M: What do you mean? Talk to us about that.

Elea: It can’t hold water because it’s such (inaudible)

Alyssa responds directly to Mr. M’s question. She describes how water moves into a cloud, concluding that a cloud rains when “it gets too heavy.” The teacher asks how clouds “do that” and calls on Jordan, who is sitting next to Alyssa.

Jordan starts by voicing her agreement, but she interrupts herself to say “well, I have a question.” With permission from the teacher, she asks, “What’s in a cloud that makes it hold the water?” This question is about a property of a cloud that “makes it hold the water,” but a few seconds later Jordan shifts to ask “does it float,” presumably meaning the water in the cloud. A few turns later she asks another, more general question, “how could water be in a cloud without

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[2] www.studentsdoingscience.tufts.edu

falling?” These varied question formulations direct attention to different aspects of the phenomena, but all mark a shift from the teacher asking *how clouds rain* to a student asking *how clouds hold water*.

Several students respond, starting with Alyssa. She speaks in a quiet whisper, but her tone is firm: “it just does it.” Alyssa appears unconvinced that this is a question they need to address. Elea, in contrast, endorses Jordan’s puzzlement and adds something new, that “it” (presumably the cloud) is “as light as a feather.” Elea shifts to challenge the premise of Alyssa’s explanation, saying she does not think a cloud can hold water. Her reasoning is inaudible on the video, but it seems to be about a property of the cloud.

Throughout, Mr. M focuses on students’ reasoning. At one point, he directs attention back to Jordan’s question; at another he presses Elea to elaborate her thinking. Jordan then offers the idea that water is a gas when it is in a cloud.

Jordan: I think if it could, it would be gas that would be in the cloud and the water was already turned into gas. So when it falls out, something happens in it, and it turns back to water.

Ryan: I think like the air is a gas, like one type of gas, and the cloud is one type of gas and like- and the air like slowly goes into the cloud.

Mr. M: And?

Ryan: And then it rains.

Mr. M: And then it rains. Sahara, did you hear what, what Jordan or what-

Sahara: I didn't.

Mr. M: Jordan, could you say what you have said a minute ago, one more time repeat it for us?

Jordan: What thing?

Mr. M: What you just said about the cloud. You think that a cloud is what?

Jordan: I think that a cloud cannot hold all the water because the water would be too heavy for a cloud, and everyone thinks it's light, so, how can it have all the water?

Mr. M: That's what we're asking, isn't it? Alyssa?

Jordan speaks hypothetically, suggesting that the water could be a gas, which seems consistent with her previous suggestion that water could “float.” After Ryan supports this idea, Mr. M again directs attention to Jordan’s thinking, asking her to repeat what she said about the cloud.

Jordan instead restates her question about how clouds can “have all the water.” However, this time she adds that “water is heavy,” as a contrast to Elea’s contribution that a cloud is light. This serves to makes the contradiction explicit: how does a light cloud contain heavy water? While Elea provided evidence in support of her claim that clouds cannot hold water, Jordan develops an argument to motivate her question.

The teacher then calls on Alyssa:

Alyssa: It gets the water- well it can hold as much as it can, and then it turns to grey, and then, and then it just drops it, and that's when it rains, but uhm

Jordan: But what holds it?

Elea: Yeah, how does it hold it?

Alyssa: The cloud.

Jordan: How does a cloud *hold* it.

Elea: *How*? It’s light.

Jordan: It doesn't have a *magical wall* holding it.
Elea: hhh. Yeah hhh like- it doesn't have a patch
Student: Yeah.
Elea: under the cloud so like to keep the water in.
Student: Yeah, I kind of agree.
Alyssa: It just holds as much as it can.
Jordan: But *how*? without a wall or a patch
Elea: How can it hold it?
Jordan: under it. Does it like turn into gas? What does it *do*?
Nikita: How is a black cloud stronger than the white cloud?
Student: It doesn’t hold water, (inaudible)

Alyssa’s statement that a cloud will “hold as much as it can” does not address the problem Jordan and Elea have been working to express. This prompts a change in tenor and animation of the conversation. Jordan and Elea raise their voices, speak without waiting for the teacher, and ask in exasperated tones “what holds it” and “how does it hold it?”

They are arguing that there is a gap in Alyssa’s description, rejecting her reasoning that “clouds do what clouds do.” Both Jordan and Elea elongate the words “how” and “hold” to emphasize the need for a mechanism. Jordan brings in ironic example explanations of a “magical wall” or patch to highlight that there is something missing.

Partway through this exchange, Jordan rephrases her question yet another way, from asking about what is “in a cloud” that holds the water to asking “what does it (the water) *do*?” emphasizing the last word. She brings back her idea of water (or the cloud) being a gas, but phrases it as a question, nested within the overall problem of how water can be in a cloud. A new student joins and contributes still another dimension to the question, taking up Alyssa’s description of a cloud turning grey as it holds more water, to ask “how is a black cloud stronger than the white cloud?” The discussion continues as other students join in and the instructor praises their interactions.

Students’ problematizing

The work Jordan, Elea, and then other students were doing was to identify, articulate, and motivate a gap or inconsistency in their current understanding. There is evidence throughout that was how they framed their activity: at multiple points Jordan and Elea made moves to focus not on providing explanations, but on articulating and rearticulating what they saw as problematic.

The question itself evolves over the course of the conversation. It began with Jordan’s unease: The teacher had asked how a cloud rains, but for Jordan it was not the *falling* that needed explaining; it was the not-falling. She first posed her question in a way that presumed something in the cloud must act to hold the water, but she quickly shifted to wonder if the water can just float. Elea added the idea of weight—clouds are light— and that helped Jordan both argue for and refine her question, focusing on the inconsistency of light clouds holding heavy water. By the end of the episode, Nikita joined in problematizing, asking about different kinds of clouds.

There is evidence as well of several aspects to the problem. First, there is the problem of explaining how anything can be in the sky without falling, because everything falls—everything *heavy,* at least—unless there is something to hold it up. Second, there is the problem that, for us, is essentially conservation of mass: If clouds are light, how can they contain water, which is heavy? Third, perhaps, is the question of the structure or integrity of a cloud: Clouds do not have walls or patches; they are not solid, so by what mechanism could they hold a heavy liquid?

Finally, we note that the students’ work to this point does not involve or point toward any particular experiment. Certainly, one could imagine helping the students develop empirical questions. There are simple experiments or demonstrations that could inform the question of *whether* clouds hold water; *how* may be more difficult. From the students' perspective in this moment, however, the questions are mainly theoretical.

This was one example, which we present to ground the discussions that follow—we refer to this as the *Clouds* case. In our previous article (Phillips et al, 2017), we present four other examples, any of which could serve the same purpose here. As we described above, we selected it as a clear example of students' doing science. Subsequent analyses led us to recognize the students' engagement involved problematizing: Their scientific work did not start with an agreed-upon question but with a student recognizing an inconsistency and then working to articulate and motivate it as a problem worth addressing.

Next, we discuss how the NGSS portrays the practice of *Asking Questions* and argue that it does not give an adequate description of problematizing in science.

Problematizing and Practice 1: *Asking Questions*

Asking Questions in the NGSS

Our purpose in this section is to review *Asking Question* as currently depicted in NGSS and we present our critiques below. For now, we summarize briefly that the performance expectations in the Standards do not clearly include problematizing in the sense we developed above, as the possibly-extended activity of formulating the question to address. As well, they do not clearly include questions, like Jordan's and Elea's about clouds, that are not obviously open to empirical investigation.

There is significant attention to the practice of asking questions in the NGSS, distributed throughout the documents. We begin by collecting examples from the main text of the Standards, where references to *Asking Questions* appear in lists and tables of performance expectations arranged by grade levels and disciplinary core ideas. In each case, there is a specific form of the practice tied to the core idea, in a brief numbered list and a more general form noted in the table.

The first instance is in K-ESS3, with K-ESS3-2 specifying that Kindergarten students "who demonstrate understanding" can "Ask questions to obtain information about the purpose of weather forecasting to prepare for, and respond to, severe weather" (NGSS Lead States, DCI Arrangement, p. 9). The more general expectation in the table is this:

> Asking questions and defining problems in K-2 builds on prior experiences and progresses to simple descriptive questions that can be tested.
>
> - Ask questions based on observations to find more information about the designed world. (NGSS Lead States, DCI Arrangement, p. 9).

The next mention regarding asking questions is in 3-PS2 "Motion and Stability: Forces and Interactions." 3-PS2-3 specifies that students be able to "Ask questions about data to determine cause and effect relationships of electrical or magnetic interactions between two objects not in contact with each other," (NGSS Lead States, DCI Arrangement, p. 23) with the more general description in the table:

> Asking questions and defining problems in 3-5 builds on K-2 experiences and progresses to specifying qualitative relationships.
>
> - Ask questions that can be investigated based on patterns such as cause and effect relationships. (NGSS Lead States, DCI Arrangement, p. 23).

The Middle School performance expectation builds from there, with MS-PS2-3 and MS-ESS3-5 specifying that students who demonstrate understanding can "Ask questions about data to determine the factors that affect the strength of electrical and magnetic forces" (NGSS Lead States, DCI Arrangement, p. 51) and "Ask questions to clarify evidence of the factors that have caused the rise in global temperatures over the past century" (NGSS Lead States, DCI Arrangement, p. 71). For the high school years, the sole example of asking questions is given in HS-LS3-3: "Ask questions to clarify relationships about the role of DNA and chromosomes in coding the instructions for characteristic traits passed from parents to offspring" (NGSS Lead States, DCI Arrangement, p. 91).

There is a range in these expectations for and examples of *Asking Questions* within the lists and tables of the Standards. It includes questions as starting points for investigations—"questions that can be investigated"—as well as questions that seek further information or clarification of information students already have. In many examples, the Standards seem to frame questions as directly in service of the core ideas, such as "to determine the factors that affect the strength of electrical and magnetic forces." The focus, as we noted earlier, is on the questions, rather than on the intellectual work of composing them, in contrast with the NGSS discussion of *Defining Problems* in engineering.

We turn now to the main description of *Asking Questions* as a practice, which is in Appendix F and begins with a quotation from the NRC Framework: "Students at any grade level should be able to ask questions of each other about the texts they read, the features of the phenomena they observe, and the conclusions they draw from their models or scientific investigations." (NRC, 2012, p. 56) The description continues:

> Scientific questions arise in a variety of ways. They can be driven by curiosity about the world, inspired by the predictions of a model, theory, or findings from previous investigations, or they can be stimulated by the need to solve a problem. Scientific questions are distinguished from other types of questions in that the answers lie in explanations supported by empirical evidence, including evidence gathered by others or through investigation….
>
> It is important to realize that asking a question also leads to involvement in another practice. A student can ask a question about data that will lead to further analysis and interpretation. (NGSS Lead States, Appendix F, p. 4)

From there, the Appendix presents tables of expectations for the practices that are not tied to particular core ideas. At the grade 3-5 level, it lists:

> Asking questions and defining problems in 3–5 builds on K–2 experiences and progresses to specifying qualitative relationships.
>
> - Ask questions about what would happen if a variable is changed.
> - Identify scientific (testable) and non-scientific (non-testable) questions.
> - Ask questions that can be investigated and predict reasonable outcomes based on patterns such as cause and effect relationships. (NGSS Lead States, 2013, Appendix F, p. 4)

The list of expectations through fifth grade does not include questions like Jordan's and Elea's in clouds; they fit better in the expectations for 6-8:

> Asking questions and defining problems in 6–8 builds on K–5 experiences and progresses to specifying relationships between variables, and clarifying arguments and models.
>
> - Ask questions
>   - that arise from careful observation of phenomena, models, or unexpected results, to clarify and/or seek additional information.

> - to identify and/or clarify evidence and/or the premise(s) of an argument.
> - to determine relationships between independent and dependent variables and relationships in models.
> - to clarify and/or refine a model, an explanation, or an engineering problem.
> - that require sufficient and appropriate empirical evidence to answer.
> - that can be investigated within the scope of the classroom, outdoor environment, and museums and other public facilities with available resources and, when appropriate, frame a hypothesis based on observations and scientific principles.
> - that challenge the premise(s) of an argument or the interpretation of a data set. (NGSS Lead States, 2013, Appendix F, p. 4-5)

These better capture the students' work in *Clouds*, Jordan's and Elea's essentially theoretical inquiries that were challenging or looking to clarify the premise that "clouds hold water."

Still, as in the main body of the Standards, the description emphasizes that scientific questions support empirical investigation. The focus also remains on the questions, their properties and what they accomplish: They can be investigated; they clarify or refine, determine or challenge. Mostly the list describes questions about what students already have, existing data, models, defined variables; a bullet emphasizes the value of questions that can be investigated with available resources. There is very little attention to how questions come to be, only that they "arise," out of curiosity or careful observation.

In the next section, we argue that these descriptions do not sufficiently capture the extended effort of problematizing that we discussed in previous sections of this article.

Three critiques

We argue that there are three ways in which the descriptions and examples of *Asking Questions* in the NGSS book and supplementary materials overlook problematizing, that is the work learners do to identify, articulate, and motivate a gap or inconsistency in their understanding.

1. *Asking Questions* does not capture the extended activity and effort involved in problematizing. Across the NGSS, questions are mostly described as simply being "asked" or as "arising," in contrast to explanations and models, described as "constructed" and "developed." This language depicts "asking questions" as a simple, one step practice, in contrast to other practices that require extended effort and time. It is not until grades 9-12 that the Standards speak of students' "formulating, refining, and evaluating" questions.

In contrast, in the *Clouds* episode, and in accounts from professional science, the formulation of a question—the identification, articulation, and motivation of a problem—often involves extended effort and time. From the moment Jordan introduced the question, "What's in a cloud that makes it hold the water?" she and then Elea, and then others, worked to revise it. They revised the question multiple times, including to make it more general than asking for a physical feature of a cloud as an object ("How could water be in a cloud without falling?"), to add a concern about weight (water is heavy and clouds are "light as a feather") and differentiate kinds of clouds. These refinements were epistemic achievements, shifting and expanding the students' understanding of "the shape of the gap" (Henle, 1986) in their current thinking.

These students were fifth graders. In our other cases, we observed students problematizing from the elementary years through university courses, and in a myriad of ways:

around observations within a classroom or from everyday life, the solution to a homework question, or a model that students have studied.

It is true that some valuable and meaningful questions may "arise" or otherwise come to be without extended effort and work, but we argue it is an oversight for the NGSS to put such questions at the forefront. Instructional practices should not only anticipate but actively cultivate students’ working toward questions, as forms of knowledge in their own right on a level with explanations and models. As with those forms of knowledge, students and scientists construct and develop questions through discussions and arguments. Indeed, common across all of our cases where problematizing was a primary feature of the dynamic is that students had the freedom to develop their questions (Phillips et al, 2017).

2. Questions are the beginnings of science in NGSS, while problematizing overlaps with other activities. In NGSS, questions are generally described as the beginning of science, leading to the other practices, in contrast to other practices that are described as “overlapping.” This is consistent with how NGSS sees questions as being simply asked, in one step, and other practices as involving extended time and effort, leading one to the other in complex dynamics. There are exceptions: Some mentions in lists, such as 6-8 above, have questions arise within activities of explaining or modeling. Thus, a particular area for refinement is making clear that, as with the other practices, asking questions may occur at any point within scientific inquiry and may overlap with other scientific activities and practices.

In *Clouds*, for example, the discussion moves fluidly between problematizing and constructing explanations. Alyssa’s explanation that the cloud “holds as much as it can” spurs Jordan and Elea to insist they need a mechanism –“how does it hold it?” Jordan shifts into considering how water in the cloud might be a gas and “when it falls out, something happens” so that the gas “turns back into water.” She then shifts back into problematizing, refining the question to focus on the inconsistency between clouds being light and their holding water, which is heavy. In other cases, students interpret data, use mathematical thinking, and propose investigations all as a part of problematizing.

The same is true of problematizing in professional science. In order to articulate their problem to their community, Einstein, Podolsky and Rosen (1935) developed mathematical models and certainly engaged in argumentation. In the process of interpreting data, scientists may problematize as they seek to understand unexpected data. Designing investigations is often an iterative process of problematizing as scientists determine what measurements will help uncover an underlying phenomenon.

3. Questions in NGSS are presented as "empirically testable," while in science they are often theoretical. NGSS predominantly describes questions as empirical, with a priority on questions that can be answered with data students collect in the classroom. Again, in some places, the description affords different interpretation, such as in the 6-8 table above, which includes questions to clarify models or explanations. In other places, however, the text is explicit and emphatic: scientific questions are testable, and questions that are not testable are not scientific. In 9-12, when the Standards speak of students’ “formulating, refining, and evaluating” it is of “empirically testable questions.”

In contrast, the questions in *Clouds* were theoretical, at least for the moment, as the students’ thinking had not progressed to the point of empirical investigation. We contend, however, that they were doing valuable science throughout. In our other cases, we see students problematizing around how to reconcile different representations of phenomena, where the question did not have a "testable" solution, but rather a mathematical resolution.

Of course, this is true as well in professional science. As previously mentioned, Einstein and his colleagues (1935) knew of no way to empirically investigate their paradox. Indeed, at the time of their posing, many seminal problems do not afford empirical investigation, and many are solved either through computational analyses or mathematical proof. Certainly, it is valuable and often essential in science to formulate testable hypotheses, to design and conduct experiments. But it is also valuable and often essential to identify and articulate gaps and inconsistencies in the current state of knowledge, before having a clear sense of how to fill or resolve them.

Across our three critiques, this is the only aspect of the NGSS depiction of *Asking Questions* that we argue is inconsistent with how students and scientists problematize: The explicit criterion that questions must be testable to be scientific. More generally, we are arguing that the depiction is incomplete. In the next section, we offer recommendations for revision.

Recommendations for future standards

Our main, overarching proposal is for significantly greater emphasis on the activity of problematizing, the often-extended work that can go into composing a question. Rather than stating "science begins with a question," we suggest that new standards should allow science beginning with a sense that something is amiss, unknown, or otherwise puzzling. Science education should help students recognize and appreciate the intellectual challenge of identifying and articulating what it is that has them feeling uncertain (Engle, 2012; Jaber, 2014; Manz, 2016; Watkins *et al*, 2018).

We have three specific recommendations, paralleling our previous critiques.

Change *Asking Questions* to *Identifying Uncertainties and Constructing Questions*

Rather than describing that questions are merely "asked," future standards should describe how many good questions are *constructed*, in that an individual may start from a general sense that something is amiss or uncertain and then must do work to refine that uncertainty into a clear question. More often than not, good questions in science need to be refined over time, just as with good explanations and with well-defined problems in engineering.

Reiser et al. (2017) recently pressed in this direction, describing the work of "constructing" and "refining" questions, as well as how students might develop arguments within asking questions. We see this work as an important step, although we disagree with the contrast between questions that arise from students' confusion and those that help students identify what they need to figure out. In our accounts of problematizing, it is students' confusion and uncertainty that is "driving" them to identify, articulate, and motivate a question.

To be clear, we are proposing more than a change in terminology. Future standards should help educators appreciate the need, and design opportunities, for students to grapple with composing problems that articulate their uncertainties. Rather than encouraging prescriptive approaches to helping students learn to ask questions, a future iteration of NGSS should emphasize the importance of encouraging students to identify what has them uncertain or uneasy. In current instructional practice, it is commonplace to ask if students have any questions. We have argued that students and scientists do not simply *have* questions; they work to construct questions. Future standards should help educators frame this work as part of scientific inquiry, supporting students in their efforts to capture in words what they do not understand.

Emphasize that identifying uncertainties and constructing questions does not simply spark science, but rather includes and overlaps with the other practices

Future standards should explicitly describe how students' developing questions may not simply lead to, but also arise from and co-occur with students' engaging in the other practices. In the *Clouds* case, we see students identifying uncertainties and constructing questions while using evidence to argue that they need to develop a model. In our other case studies, we see students' using one model to argue for a problem in another, drawing on mathematical reasoning to communicate their uncertainties, using the facets of their constructed problems to help plan and carry out investigations, and using and analyzing data as part of their constructing questions. Such a change may be mainly expositional, as portions of NGSS do imply that questions arise within the other practices, particularly in developing models. Schwarz, Passmore, & Reiser (2017) describe that questions can arise throughout students' inquiries, not just at the beginning, and as overlapping with other practices. As well, research on problem-scoping in engineering education and text on problems in engineering within NGSS provide guides for future standards' discussion of questions and problems in science.

Include text on the importance of questions and problems that cannot be answered empirically, at least not within the classroom

As we have seen, in scientists' work and in the case studies from our project, many important questions and problems are not immediately amenable to empirical investigations. Yet the Framework and NGSS place a strong emphasis on students' asking questions that can be answered empirically, particularly with tools available within the classroom. Certainly, empirical investigation is central to science, but many important questions in science, both today and historically, cannot be tested with current technology or have no clear means of testing, even with hypothetical future technologies. By emphasizing that only empirically-testable questions are "scientific," the standards may encourage teachers to push a student like Jordan to focus just on what may be testable within the classroom rather than what is puzzling and compelling to her in that moment. Reiser et al (2017) again take a step in this direction, presenting examples of students posing and being driven by questions that do not immediately afford empirical testing in the classroom. By placing value on a broader range of questions, future standards can not only better reflect scientists' problematizing but also encourage practitioners to support students' exploration of their uncertainties, wonder, and interest.

Implications for instruction

With its emphasis on scientific practices, the NGSS already encourages curriculum and instruction that provide students opportunities to pursue and refine their own ideas. Our work similarly encourages instruction to provide students opportunities to pursue and refine their own problems. This is a shift from traditional patterns in which students only solve problems that teachers assign. Here, we consider some specific ways in which instructors can support students' problematizing.

There are efforts already underway to design tasks and learning environments that allow or provoke students to construct questions. An emerging principle in science education research is that students should encounter ambiguities, complexities, and inconsistencies (Engle, 2012; Engle and Conant, 2002; Manz, 2015; Reiser, 2004; Hammer, 1997; Hammer, Goldberg, & Fargason, 2012). In some approaches, students have more freedom to identify, articulate, and pursue their own experiences of gaps and inconsistencies. Sikorski & Hammer (2017) have argued for greater emphasis on the latter, such as happened in *Clouds*, the teacher supporting a line of inquiry he had not planned. Our arguments offer further support for efforts to design learning environments that make space for and provoke student uncertainty.

In similar ways but on a smaller scale, instructors could write homework and exam questions that ask students to articulate problems of their own.[3] Another strategy is to position students as instructors of a given topic and ask that they select or pose problems for their peers to solve; the students are assessed partly by the quality of the problem they choose (Roger Tobin, personal communication, April 6, 2018). These strategies position students' construction of a scientific problem as an important learning outcome in itself.

Emphasizing that problematizing takes real intellectual effort could motivate instructors to elicit and interpret students' participation in new ways. While instructors often ask if students have any questions, students may not ask any because they have not yet succeeded in the work of problematizing. Instructors could make space for and help students appreciate being in the state of feeling confused but not yet knowing what to ask, praising their expressions of uncertainty, and helping them frame problematizing as an essential activity (Watkins *et al*, 2018). This stance toward uncertainty marks a shift from what is often valued in science and in classrooms, in which confidently providing canonical understandings is typically the sole marker of accomplishment, and may promote relational equity (Boaler, 2008) in science classrooms.

Our arguments also motivate encouraging instructors to attend to students' questions or problems that are not immediately empirically testable. There is great opportunity for additional connection to mathematics through discussion of how problems and questions in science can be resolved through mathematical proof or numerical experiments. Such questions and problems are surely "scientific" in the sense that they do lend themselves to falsifiable hypotheses in the Popperian sense (Popper, 2005) even if their resolution lies in mathematics. Instructors could support students' development of mathematical and computational reasoning skills through exploring such problems.

Lastly, we see implications for how instructors conceptualize and support students' progress, within a thread of scientific inquiry and more broadly in their development as scientists. It is progress within inquiry to develop clearer conceptualizations of the nature of an inconsistency or in how they provide support to motivate the existence of a problem. Building on the emphasis on how scientific practices overlap, instructors might see opportunities to support students to engage in argumentation or experimentation to refine a problem. And it is progress for students to develop disciplinary dispositions (Lehrer, 2009) in which they deliberately seek out uncertainties and frame problems as exciting opportunities. For example, Radoff and colleagues (Radoff, 2017; Radoff, Jaber & Hammer, 2016) present a case study of a student shifting in how she framed confusion when learning introductory physics—moving from experiencing uncertainty as anxiety-provoking to exciting. Instructors might start to target these kinds of transformations as worthy learning goals in their science courses.

Conclusion

NGSS and the Framework have set an important precedent that learning science includes engaging in the doing of science. By emphasizing the importance of the scientific practices, NGSS captures what many in the science education research community have argued: science is as much a way of exploring the world around us as it is the knowledge that that exploration has produced. As described in NGSS, the scientific practices are broadly applicable across the

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[3] We provide an example in the online supplement to Phillips et al (2017).

curriculum: students should argue from evidence in their study of literature and develop models in their studies of history. We argue that problematizing—determining what is known and unknown and motivating others to take up questions and problems—is similarly valuable to learners in science and beyond. Clarifying this important and often difficult work will serve to make future standards stronger. Additionally, we see a need for further research on students' framing and abilities for activities of identifying, articulating, and motivating gaps and inconsistencies. From there, research is needed on how best to develop learning environments that support students in this important scientific work. In the meantime, we encourage practitioners to support students' formulating and articulating questions and problems.

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