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Navigating student uncertainty for productive struggle: Establishing the importance for and distinguishing types, sources, and desirability of scientific uncertainties

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Abstract

An essential aspect of scientific practice involves grappling with the generation of predictions, representations, interpretations, investigations, and communications related to scientific phenomena, all of which are inherently permeated with uncertainty. Transferring this practice from expert settings to the classroom is invaluable yet challenging. Teachers often perceive struggles as incidental, negative, and uncomfortable, assuming they stem from students' deficiencies in knowledge or understanding, which they feel compelled to promptly address to progress. While some empirical research has explored the role of scientific uncertainties in driving productive student struggle, few studies have explicitly examined or provided a framework to unpack scientific uncertainty as it manifests in the classroom, including the sources that lead to student struggle and how teachers can manage it effectively. In this position paper, we elucidate the importance of incorporating scientific uncertainties as pedagogical resources to foster student struggles through uncertainty from three perspectives: scientific literacy, student agency, and coherent trajectories of sensemaking. To develop a theoretical framework, we consider scientific uncertainty as a resource for productive struggle in the sensemaking process. We



delve into two types (e.g., conceptual, epistemic), four sources (e.g., insufficiency, ambiguity, incoherence, conflict), and three desirability considerations (e.g., relevance, timing, complexity) of scientific uncertainties in student struggles to provide a theoretical foundation for understanding what students struggle with, why they struggle, and how scientific uncertainties can be effectively managed by teachers. With this framework, researchers and teachers can examine the (mis)alignments between uncertainty-in-design, uncertainty-in-practice, and uncertainty-in-reflection.

KEYWORDS

desirable uncertainty, productive struggle, science learning and teaching, scientific uncertainty, sensemaking

1 | INTRODUCTION

Struggle is essential to learning, as students develop persistence and resilience to pursue and attain learning goals, as well as a robust understanding of science concepts and practices (Fries et al., 2021). To struggle productively, students must actively recognize why they are struggling and persist through their challenges by clarifying, modifying, and refining their approaches to dealing with them (Barlow et al., 2018; Warshauer, 2015). This approach acknowledges that deep learning is a dynamic and often arduous process, and that productive learning experiences often arise from navigating uncertainty. Learning extends beyond the development of scientific knowledge to encompass productive struggle associated with uncertainty and deep engagement in scientific practice.

Uncertainty¹ is ubiquitous in scientific practice and is one of the major factors provoking student struggle (Kampourakis & McCain, 2019; Kirch, 2010). Uncertainty causes students to struggle not only with identifying the necessary understanding to interpret a natural phenomenon under study but also with negotiating how to generate appropriate methods to collect and analyze data to form evidence, how to represent models to convince peers, and how to unpack peer critique to strengthen their work (Chen, 2022; Manz & Suárez, 2018). Students' scientific uncertainty motivates them to identify insufficiency, ambiguity, incoherence, and conflict in their intuitive thinking about a phenomenon and urges them to find potential solutions to explain it and pursue deeper understanding. The resulting struggle arises from students having a psychological need for certainty (Baer & Kidd, 2022), but more importantly, from conceptual and epistemic needs for a better understanding (Kampourakis & McCain, 2019). Thus, struggle induced by uncertainty has the potential to be productive and essential for student learning because it builds their own deeper and better understanding. We use "understanding" instead of "knowledge" to emphasize that the function of scientific uncertainty is not merely to have students go through the information and practices embedded in the task. What's more important is that students, with agency, arrive largely at their understanding of an encountered phenomenon through a meaningful process for them.

Various science instructional methods and curricular approaches have emphasized how scientists conduct science, often overlooking the inherent struggle with uncertainty in scientific practice. This oversight may lead teachers and students to perceive science as a quest for certainty and a final product, rather than an ongoing

process involving grappling with uncertainty in generating predictions, representations, interpretations, investigations, and communications. Having teachers and students recognize that struggling with uncertainty is an essential scientific practice and a valuable resource for sensemaking can have beneficial effects on cognitive and affective aspects of science learning engagement (Hong & Lin-Siegler, 2012) and knowledge-building agency (Zemal-Saul & Hershsberger, 2019).

Pedagogically engaging students in productive struggle with scientific uncertainty requires careful theoretical examination of how scientific uncertainties should be defined and invited in the classroom, and how to support student to navigate those uncertainties responsively, aligning with students' learning trajectories. Despite scholars' increased interest in the role of scientific uncertainty in the science classroom and for productive struggle (e.g., Chen, 2022; Ford & Forman, 2015; Keen & Sevan, 2022; Manz, 2015; Metz, 2004; Watkins & Manz, 2022), the definition of scientific uncertainty and consideration of how it can be used productively remain vague.

The goal of this position paper² is to propose and elaborate on a theoretical examination of (a) the scientific uncertainties that cause student struggles, (b) why students encounter such uncertainty, and (c) how this uncertainty can be managed productively. A theoretical framework (see Figure 1) is introduced to underscore the significance of and differentiate between the types, sources, and desirability of student uncertainty. In this framework, we define learning science as a process of sensemaking (Odden & Russ, 2019), which does not abruptly transition a learner from a state of not-knowing to knowing (Barnes, 1992). Instead, learning unfolds along a prolonged trajectory during which students navigate varying degrees of uncertainty related to newly encountered phenomena and previously-held ideas, aiming for a deeper understanding. We use the term "navigate" to emphasize that uncertainties are not always static and stable (Ha et al., 2024; Starrett et al., 2023; Tiberghien et al., 2014). The state and sources of scientific uncertainty are often dynamically evolving, depending on a student's level of comprehension and approaches to investigating an encountered issue. Furthermore, navigation is a collaborative effort between students and teachers as they work together to identify areas of not-knowing and develop strategies to attain better understanding.

In the following sections, we first define scientific uncertainty from an individual learning perspective. We then narrow our focus to scientific uncertainty and uncertainty navigation for sensemaking, and explore how this

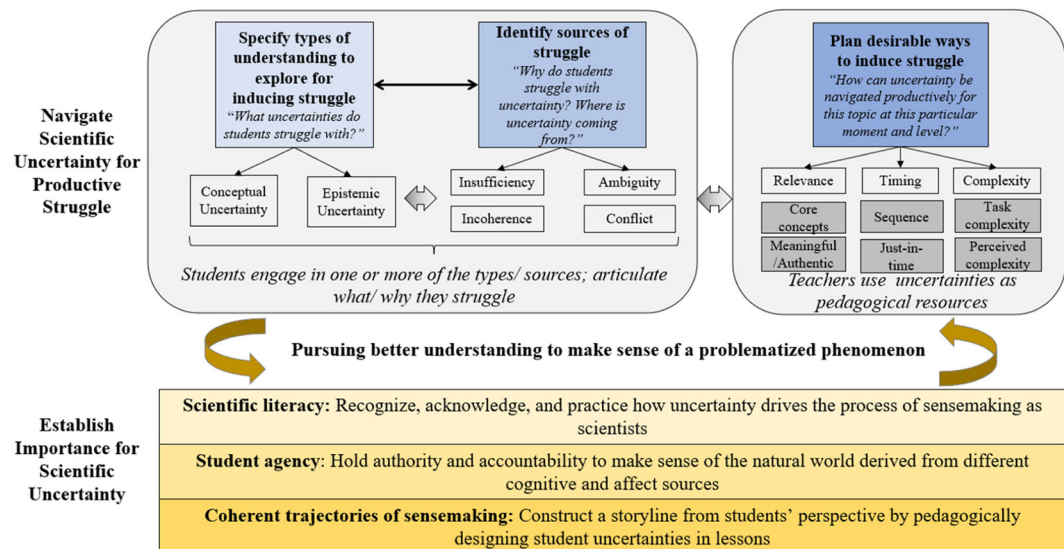


FIGURE 1 Navigating scientific uncertainty for productive struggle: Pedagogical consideration of needs, types, and sources of scientific uncertainty, and desirable ways to induce struggle.



navigation process engages students in productive struggle. We elucidate why researchers and practitioners need scientific uncertainty to promote sensemaking in science classrooms from three perspectives: scientific literacy, epistemic agency, and coherent trajectories of sensemaking. Alongside its definition and rationale, we introduce two types of scientific uncertainty—conceptual and epistemic—and four sources of scientific uncertainty: insufficiency, ambiguity, incoherence, and conflict. We illustrate three considerations related to the desirability of uncertainty to support student productive struggle: relevance, timing, and complexity. Finally, we conclude with a discussion of the pedagogical and theoretical implications of this framework for researchers and educators.

2 | BOUNDING THE FOCUS: UNCERTAINTY, SCIENTIFIC UNCERTAINTY, AND PRODUCTIVE STRUGGLE

In this section, we introduce our definition of uncertainty and scientific uncertainty in the science classroom. We situate the role of scientific uncertainty in the process of sensemaking, which is a “process of building an explanation to resolve a perceived gap or conflict in knowledge” (Odden & Russ, 2019, p. 187). Based on the boundary, we illustrate how scientific uncertainty can be navigated for productive struggle.

2.1 | Defining uncertainty and scientific uncertainty

Uncertainty is manifested as an individual subjective experience of being unsure about using existing understanding to respond to, unfold, and interpret encountered situations (Lamnina & Chase, 2019; Smithson, 1989). Uncertainty may reciprocally engender learning, for example, leading students to identify a gap in current understanding (Henle, 1986), problematize their thinking (Engle & Conant, 2002; Phillips et al., 2018), seek more evidence to justify their claims (Zaslavsky, 2005), and promote deep discussion (Jordan & McDaniel, 2014). This view of uncertainty to learning aligns with Dewey's (1933) reflective thinking, through which uncertainty begets students to define a problem, analyze the problem, tease out possible solutions, and decide the best solution available. Piaget (1972) described the experience of uncertainty as a necessary process of restructuring individual's disequilibrium toward a new understanding. This experience has been described as student puzzlement (Passmore, 1980), confusion (D'Mello et al., 2014), cognitive conflict (Hoyles, 1985), failure (Kapur, 2008), or impasse (Munzar et al., 2021). Uncertainty often accompanies affective reactions, such as overwhelming, anxiety, depression, surprise, interesting, and/or curiosity.

Scientific uncertainty is defined as an individual subjective experience of being unsure about what and how existing scientific understanding can be integrated with new information, predict an unexperienced event, or explain an encountered phenomenon. Scientific uncertainty in science classroom highlights student cognitive focus on foregrounding the substance of student wrestle with scientific disciplinary connections between their ideas, language, lived experience, and culture, as well as pursuing the substance of student ways of thinking.

2.2 | Navigating uncertainty for sensemaking

Navigating the experience of scientific uncertainty in classroom is a process of making sense and articulating the sources of one's uncertainty. Scientific uncertainty is associated with students' “known uncertainty,” meaning students have to be aware of what they do not know and what they need to pursue (Glăveanu, 2022; Greco & Roger, 2003). If students are not aware of or do not recognize the uncertainty, they do not have a reason to seek resolutions and expand their understanding, and thus do not enter the state of disequilibrium. Making students explicitly aware of their uncertainty is the initial step to navigating uncertainty (Jordan, 2015). Students also need to

actively articulate the uncertainty and find strategies to make it become “more certain” (Ancona, 2012). Odden and Russ (2019) argued that this is a process of sensemaking through “building a new explanation for something unknown or not understood—to “figure something out”—using their own ideas, intuitions, and experiences” (p. 193). That is, uncertainty navigation can refer to a sensemaking process in which uncertainty is recognized and evolves, opening a space for students to explicitly explore what and why they do not know.

2.3 | Productive struggle associated with scientific uncertainty

We consider that student scientific uncertainties can be navigated for productive struggle if the uncertainties lead students (a) to acknowledge and accept the existence of uncertainties, recognize the need to pursue a better understanding, and address gaps in their existing understanding (English, 2013; Granberg, 2016); and (b) to maintain engagement in the face of uncertainties inherent in the complex task of finding resources and resolutions (Warshauer, 2015). In contrast, navigating for unproductive struggle refers to students (a) being stuck, conceding, or stopping exploration without reaching a desired understanding; (b) not engaging with further uncertainties critical to their learning after reducing some mundane uncertainties (Beghetto, 2021); and (c) feeling overwhelmed or frustrated when not perceiving the value or relevance of the uncertainty (Barlow et al., 2018; Park & Ramirez, 2022).

Traditional pedagogical practices that emphasize the final form of scientific knowledge often view student struggle with uncertainty as a deficiency in students' existing knowledge that needs to be fixed or removed (Starrett et al., 2024). Students may struggle but are not given ample opportunities to explore gaps in their existing understandings and to use awareness of uncertainty to drive sensemaking. One way to make struggling with science uncertainties productive is to treat student uncertainty as a pedagogical resource to determine the direction of teaching (Chen et al., 2019), decide classroom activities, and drive student practice to achieve better understanding (Richards et al., 2020). When student scientific uncertainty is leveraged as a resource, students' awareness of uncertainty can be articulated, unpacked, explored, and expanded. After students resolve one uncertainty, they realize they have other uncertainties, leading them to collect more data to construct more robust evidence. Hiebert and Grouws (2007) argued that this process, from the perspective of mathematics education, reflects a productive struggle because “students expend effort to make sense of mathematics, to figure out something that is not immediately apparent” (p. 387).

With scientific uncertainty and uncertainty navigation for productive struggle defined, fundamental questions arise: Why is scientific uncertainty important in science classrooms?

3 | SCIENTIFIC UNCERTAINTY IN THE SCIENCE CLASSROOM: WHY IS IT IMPORTANT?

To address this question, we examine the importance of uncertainty in relation to positive science outcomes/consequences for students: scientific literacy, student agency, and coherent trajectories of sensemaking.

3.1 | Importance for scientific literacy: Bridging the nature of scientists' work with student scientific practice

Scientific literacy has been identified as a desirable outcome of learning for science subjects taught in K-12 (NGSS Lead States, 2013). An effective way of promoting scientific literacy is to create an environment for students to learn how to think and practice like a scientist. Scientific uncertainty is one of the major factors driving scientists'



thinking and practices to make sense of the natural world (Kampourakis & McCain, 2019; Watkins & Manz, 2022). Because of the ubiquity and nature of uncertainty in science, scientists continue to pursue better explanations and evidence to understand natural phenomena. Scientists are used to dealing with the uncertain nature of scientific knowledge and its generation process.

In summary, uncertainty is ubiquitous in the purposes, products, and processes of science, and in the positive perceptual responses of scientists. It follows, then, that if we want students to engage in authentic scientific practices to make sense of the natural world as scientists, students need to learn how to wrestle and deal with scientific uncertainty and recognize and acknowledge how it drives the process of sensemaking. The goal of equipping students to think and practice like a scientist does not aim to make all students become scientists. Beyond preparing students for the STEM workforce, the need for scientific literacy extends to helping improve public understanding of uncertainty in science, and its roles and impacts (Chen & Jordan, 2023; Kampourakis & McCain, 2019). Students can develop a productive mindset and positive stance toward uncertainty, as well as skills, mindsets, and capacity for navigating scientific uncertainty that can help them deal with social-scientific issues or make civic and personal decisions in their everyday lives (Bächtold et al., 2023).

However, the role of uncertainty in the development of scientific understanding and how scientists deal with uncertainty are often not authentically addressed in the science classroom. The attitude that “certainty prevails in science education” (Kirch, 2010, p. 312) highlights the inauthenticity of classroom scientific inquiry. Students may learn scientific knowledge but they may not learn how to do science, how to orient to struggle as scientists do for understanding, or how to take agency in pursuing knowledge.

3.2 | Importance for student agency: The need for both cognitive and affective considerations

Transferring how scientists struggle to pursue better understanding to students' productive struggle in real classrooms requires supporting the development of student agency—the power to contribute to, evaluate, and shape knowledge production and inquiry practices (Cherbow & McNeill, 2022; Miller et al., 2018). Having agency, students hold authority and accountability to direct and monitor their own building of knowledge and understanding (Scardamalia, 2002; Zhang et al., 2022). However, the prevailing view of student agency does not sufficiently address what motivates students to make sense and develop a better understanding of a phenomenon, or what makes them struggle. What is the “need” motivating students to take agency for making sense of knowledge critique and construction?

We argue that students' scientific uncertainty creates a need that motivates students to pursue better understanding of scientific practice (e.g., Chen & Techawitthayachinda, 2021; Engle & Conant, 2002; Watkins & Manz, 2022). We agree with Tekkumru-Kisa et al. (2020) that opportunities to experience uncertainty throughout a lesson are critical for student productive struggle and sensemaking. In advocating for this argument, we discuss the importance of uncertainty for agency from two perspectives: cognition and affect.

As to the role of cognition in agency, uncertainty creates an opportunity for students to generate awareness about what they know, what they do not know, and how to address the gaps, inconsistency, and conflicts (Zaslavsky, 2005). This opportunity triggers students to cognitively make connections between existing understanding, new concepts, phenomena, context, and practice. Uncertainty situates students in a cognitive state of struggle so that “not only this [struggle] helps them to identify gaps in their knowledge but also prepares them for subsequent instruction that explicitly connects their prior knowledge to the core concepts and representations of a domain” (Fries et al., 2021, p. 753). In other words, uncertainty-driven struggles allow students to cognitively direct and monitor their learning by reflecting on their current understanding, recognizing what they should explore (i.e., knowledge gaps), seeking information that can possibly address the gaps and gauging usefulness and appropriateness of new information in constructing a better understanding (Ha et al., 2023).

Moreover, uncertainty can help students grasp a better understanding of an unpredictable situation or a phenomenon throughout a science learning process, a science unit. For instance, by exploring 10th-grade students' learning about mechanics in physics, Tiberghien et al. (2014) demonstrated that uncertainty can drive the knowledge building process because student understanding is constantly evolving; new uncertainties occur when students apply their new understanding to explain a target phenomenon. When students solved their uncertainty about "What are the objects that act on the static stone?" (e.g., action equals reaction), another uncertainty was raised about how the action and reaction apply to a moving car. During the continuous process of pursuing better understanding to make sense of the natural world, uncertainty never disappears but rather creates a need for students to assume agency for learning science to effectively cope with the inherent succession of uncertainties.

As to the affective component, Jaber and colleagues (e.g., Davidson et al., 2020; Jaber & Hammer, 2016) suggest that scientific uncertainty can cause students to "feel," as do scientists, "the excitement of having a new idea or irritation at an inconsistency" (Jaber & Hammer, 2016, p. 189). They found that student agency depends on students' feeling they can and should be doing the intellectual work of scientific sensemaking.

Uncertainty can trigger "ah-ha" moments, producing positive affective experiences such as pleasure and satisfaction associated with coming to know, even in the midst of continuing uncertainty about which pathway to pursue (Burton, 1998). Such uncertainty may cause students to experience negative emotions (Vilhunen et al., 2023), depending on their expectations, appraisals, and attributions of the uncertainty (Lamnina & Chase, 2019). While negative emotions, on one hand, might disengage students and stifle their agency (D'Mello & Graesser, 2012), such negative emotions, on the other hand, can be a "developmental resource" that directs students' attention to what are beyond their understanding (Glăveanu, 2022, p. 11). Through teachers' appropriate use of strategies to support student navigation of uncertainty, this uncertainty can also initiate student curiosity that drives and activates a desire to know, emotional states that drive attempts to solve problems, and motivation to learn.

3.3 | Importance for coherent sensemaking: Building coherent trajectories for students' own sensemaking

Recently, researchers have proposed that lesson plans, materials, and activities should support student engagement in sensemaking and be designed "as storylines that are coherent from the students' point of view" (Penuel et al., 2022, p. 151). To make this storyline happen, teachers first need to problematize a phenomenon (Lee & Grapin, 2022). Unfortunately, the problems posed by teachers may not take student perspective into account (e.g., Loughran, 2002). Therefore, students may engage in a teachers' storyline, not one of their own construction. From our perspective, this limits opportunities for students to engage in productive struggle. Uncertainty spurs students to grapple with the need to figure out how to make sense of a problematized phenomenon and thus develop their own coherent trajectory of sensemaking. Like Reiser et al. (2021), we advocate that uncertainty engages students in cycles of incrementally building their own storylines to respond to a target phenomenon and finding ways to revise their developing storylines and models of target phenomena.

Teacher play important roles in supporting students in navigating their scientific uncertainty to develop coherent trajectories of sensemaking. Chen and Techawithayachinda (2021) argued that student uncertainty to construct a coherent trajectory should consider different stages: raise, maintain, and reduce. That is, teachers should raise student uncertainty to create space for discussion, maintain the space through preventing immature closure, and discussing alternative arguments or conflicting ideas, as well as reduce the space by making coherent connections among the raised uncertainty, prior understanding, and students' everyday experience. Teachers can use student scientific uncertainty as a critical resource for positioning students as agents to open, maintain, and close the discussion space. Watkins and Manz (2022) characterized students' uncertainty as pedagogical decision points to construct coherent trajectories of sensemaking at which a teacher decides (a) whether to make space for discussion, (b) how to transform individual student uncertainty into a collective problem, (c) which aspects of

uncertainty can be solved and maintained, (d) how to scaffold the class to evaluate their solutions to solve the uncertainty, and (e) whether to make space for another uncertainty.

Based on the need to promote scientific literacy, epistemic agency, and coherent trajectories, student scientific uncertainty should be considered, elicited, and embraced as a resource for teaching and learning in the science classroom. However, scientific uncertainty is a complex construct that has not been clearly defined and unpacked in the field of science education. It is important to unpack what types of scientific uncertainty can be used to support student struggle, where scientific uncertainties come from, and how uncertainties have the potential to generate desirable, productive struggle for sensemaking.

4 | TYPES OF SCIENTIFIC UNCERTAINTY: WHAT DO STUDENTS STRUGGLE WITH?

As described above, scientific uncertainty can refer to students' awareness of being unsure or doubting as they struggle to utilize understandings of science to solve problems, ambiguities, or discrepancies. Current reform documents (e.g., NGSS Lead States, 2013; Organisation for Economic Co-operation and Development [OECD], 2019) and research (e.g., Ford & Wargo, 2012) suggest there are two types of understandings in science, conceptual and epistemic. Based on the definition of scientific uncertainty and the two types of target understandings for scientific practice, two types of scientific uncertainty can be identified: conceptual uncertainty and epistemic uncertainty. The two types of scientific uncertainty and their roles in sensemaking are summarized in Table 1 and further described in the section below.

4.1 | Conceptual uncertainty

Conceptual uncertainty can be defined as the subjective experience of being unsure of conceptual understanding of a topic or what they know (e.g., what I know about where trees get most of their mass from). Conceptual understanding refers to a state of comprehending, mastering, and practically grasping content knowledge and everyday knowledge/experience related to a target issue. Content knowledge is knowledge that students possess about a particular topic (e.g., photosynthesis, force, and motion) (Papadouris & Constantinou, 2017). It resonates with the core concepts identified in NGSS Lead States (2013). Everyday knowledge/experience is informal

TABLE 1 Types and roles of scientific uncertainty in sensemaking.

	Conceptual uncertainty	Epistemic uncertainty
Definition	Subjective experience of being unsure or unconfident about one's conceptual understanding	Subjective experience of being unsure or unconfident about one's epistemic understanding
Role in sensemaking	Drive students to activate prior knowledge (e.g., content and everyday knowledge), identify the gap within it, or assess limitations of their existing conceptual understanding	Drive students to find a way to generate a tentative hypothesis, claim, evidence, and model for further investigation—to reduce epistemic uncertainty and eventually conceptual uncertainty
Complementary interactions	Conceptual and epistemic uncertainty are neither stable nor independent of each other, but are dynamically evolving and codependent; for example, conceptual (epistemic) uncertainty evolves to another conceptual (epistemic) uncertainty through struggling with conceptual (epistemic) uncertainty as the sensemaking process unfolds	

knowledge that students acquired through observations and interactions during one's daily life (Warren et al., 2001). Content knowledge provides the foundational facts and concepts, while everyday knowledge helps students intuitively grasp complex or abstract concepts. Together, both content and everyday knowledge serve as valuable resources for developing meaningful conceptual understanding of a target topic (Silseth, 2018). Desirably, conceptual uncertainty can lead students to wonder why their existing knowledge cannot explain a phenomenon coherently or sufficiently, or for them to inquire about new concepts they do not yet grasp.

Traditional science teaching often misuses conceptual uncertainty. For example, research on teachers' use of questioning (e.g., Martin & Hand, 2009) and teacher talk (e.g., Mercer, 2019) revealed that those from traditional classrooms often use students' conceptual uncertainty as an assessment tool to evaluate how much of the conceptual knowledge delivered by the teacher students can recite. Once the teacher raises the students' conceptual uncertainty and receives their responses, they quickly feed information to reduce or resolve uncertainty. The use of conceptual uncertainty in the traditional classroom intends to point out students' misconceptions and faulty reasonings (Furtak & Penuel, 2019). Thus, students have limited opportunities to productively struggle, navigate, and resolve their conceptual uncertainty and make sense of why they are uncertain about a target phenomenon.

The excerpt in Table 2 shows how Mrs. Kumari, an eighth-grade science teacher with 10 years of experience, used students' conceptual uncertainty as an assessment tool to lecture on the target concepts. The excerpt begins as she raised conceptual uncertainty by asking what natural resources and renewable energy are and then reducing it immediately by feeding students specific information.

In this excerpt, Mrs. Kumari asked several questions to raise students' conceptual uncertainty (e.g., Turns 1, 3, 5, 9) about the topic of natural resources. However, she did not provide students the opportunity to navigate their uncertainty and connect their everyday knowledge to the topic; that is, students had limited opportunity to engage in struggle. For example, Mrs. Kumari began by asking about what resource means (Turn 1) and that initiated students' struggle with conceptual uncertainty. She did not follow-up on the student's uncertain response (Turn 2) but continued to provide information and self-answer her own questions. She continued to raise conceptual uncertainties (Turns 5, 9) but immediately reduced them without providing time for students to respond, think, and

TABLE 2 Conversation where eighth-grade science teacher, Mrs. Kumari, used conceptual uncertainty to check student understanding of natural resources.

Turn	Speaker	Quote
1	Mrs. Kumari:	First, what is <i>resource</i> ?
2	Juan:	Is resource something coming from nature?
3	Mrs. Kumari:	What happens if we use up all of the resource?
4	Whole class:	[No students responded]
5	Mrs. Kumari:	It is done, right?
6	Mrs. Kumari:	For example, petroleum oil is found between the layers of the Earth's crust, or between the rocks. It forms over several million years. Once we use up petroleum oil, we have to wait another several million years. That is what we call <i>nonrenewable resource</i> . What is a nonrenewable resource?
7	Shelly:	Oil!
8	David:	Gas!
9	Mrs. Kumari:	Right now, we only use 13% renewable energy. Why don't we all use nonrenewable energy? Because it is too expensive! What is a nonrenewable energy?
10	Samantha:	Solar energy?



reason. This conversation is a typical example of what we often observe in traditional classrooms, reflecting a knowledge deficit perspective (Larkin, 2012; Sinatra et al., 2014).

Receiving scientifically correct information does not necessarily reduce or resolve students' uncertainty or ensure that students will fully understand a phenomenon. Even though students can correctly recite new information, they may not remember this information over the long-term (e.g., Pugh et al., 2010). Another problem with this traditional knowledge deficit perspective is that teachers situate themselves within a narrow and limited view by considering only one type of scientific uncertainty—conceptual uncertainty. However, engaging students in authentic science practices and immersing students in a coherent sensemaking trajectory require that science teachers also recognize epistemic uncertainty as a resource.

4.2 | Epistemic uncertainty

Epistemic uncertainty refers to an individual's subjective experience of being unsure or unconfident about the epistemic understanding or how I know what I know and why I believe it (e.g., "How do I know where most of the mass of the tree comes from?"). To reveal what epistemic uncertainty is, it is necessary first to clarify the complex idea of epistemic understanding. Epistemic understanding has been conceptualized in different ways based on researchers' aims, framework, or orientation. Based on the perspective of computer assisted learning, Shaffer (2006) describes epistemic understanding as a frame to guide students on knowing (a) where to begin asking questions, (b) what constitutes appropriate evidence to assess, (c) how to gather that evidence, and (d) when to draw a conclusion and/or move on to a different issue. Building on the Epistemologies in Practice framework, Berland et al. (2016) defined epistemic understanding as students' concerns about (a) what counts as a sufficient answer to their question, (b) how the specific knowledge of a particular phenomenon transfers to other contexts and is applied broadly, (c) how information and raw data are justified and evaluated, and (d) how knowledge can be represented and revised with the consideration of the audience in mind. Rooted in the perspective of assessment, the PISA 2018 Science Framework (Organisation for Economic Co-operation and Development [OECD], 2019) defines epistemic understanding as knowledge consisting of two components that can be assessed as outcomes of learning: (a) knowledge of the constructs and defining features essential to the process of knowledge building in science (e.g., theories, hypotheses, models, arguments), and (b) the role of these constructs in justifying the knowledge produced by science. In summary, epistemic understanding is about students' understanding about how to problematize a phenomenon, unpack complex problems and extract critical variables to investigate, construct a simplified model to simulate a phenomenon, interpret data as evidence to support claims, and negotiate peers' critique to establish consensus (Leung, 2020; Perkins, 1992). It is different from epistemology or epistemological belief, which focuses on disposition on knowledge, such as absolutist, realist, multiplist, and evaluativist (e.g., Kuhn et al., 2000). Therefore, struggling with epistemic understanding, that is, epistemic uncertainty, can lead students to deliberate on how they can pursue more coherent explanation of phenomenon through sensemaking processes that involve acquiring, justifying, evaluating, and communicating their understanding.

The concept of epistemic uncertainty has been not been discussed thoroughly in science education (e.g., Kervinen & Aivelo, 2023; Metz, 2004; Tiberghien et al., 2014), though there are a few notable contributions. Two studies in particular have identified multiple spheres of epistemic uncertainty. Metz (2004) tried to capture what epistemic uncertainties elementary students encountered as they struggled to develop a conceptual understanding about the life cycle, needs, and behavior of insects by designing their own investigations of animal behavior. She identified the following student epistemic uncertainty: (1) how to produce the desired outcome, (2) how to collect and interpret the data, (3) how to identify trends in the data, (4) how to generate meaningful explanations and interpret the trends as evidence, and (5) how to construct a theory based on the data. In a similar vein, Chen (2022) explored how epistemic uncertainties fostered fifth graders' struggle and drove the process of modeling to make sense of how humans breathe. Chen identified a variety of epistemic uncertainties, such as wondering about

framing problems through problematization, building and revising a model to represent the human respiratory system, critiquing and decomposing different arguments to find solutions, and representing final theoretical models to explain the target phenomenon. Efforts such as these open an avenue to understand student epistemic uncertainty and the possibility of using it as a resource for productive struggle.

With the distinction between two types of scientific uncertainty, a question is raised: Are both needed to engage students in sensemaking for productive struggle? If the answer is “yes,” what are the characteristics of conceptual and epistemic uncertainties teachers use to facilitate productive struggle and sensemaking? How do they function complementarily to support student productive struggle for sensemaking?

4.3 | The complementary relationship between conceptual and epistemic uncertainties for productive struggle

Although traditional science teachers often emphasize raising students' conceptual uncertainty to check if students have understood and/or memorized content information, this does not mean that we should not utilize conceptual uncertainty and focus only on student epistemic uncertainty. If we discard conceptual uncertainty, with what concepts would students struggle? If we do not consider epistemic uncertainty, then how would students seriously attempt scientific practices?

Emphasizing only one type of uncertainty thwarts reaching the goal of scientific sensemaking—students “come to an understanding of how science grounds its epistemic status and also an understanding of the conceptual itself” (Ford & Wargo, 2012, p. 388). Meaningful sensemaking through productive struggle should engage students in both conceptual and epistemic uncertainties to advance their scientific understanding, just as scientists do. Conceptual and epistemic uncertainties are often intertwined when students are immersed in discussing and making sense of a problematized phenomenon (Ha et al., 2024). Below, we outline two characteristics to address the complementary relationship between conceptual and epistemic uncertainty.

First, conceptual uncertainty motivates students to explore the limitations of what they know, while epistemic uncertainty drives them to understand how they can fill those gaps. Engaging in scientific sensemaking requires students to activate their prior understanding to explain a targeted phenomenon. This step of sensemaking triggers students' conceptual uncertainty, which facilitates them to actively engage in reasoning and raise awareness of gaps within their existing understanding. This step also further generates epistemic uncertainty about why they cannot coherently explain the phenomenon and how they can. Epistemic uncertainty may also motivate students to form and explore tentative hypotheses/claims/models that help them move along in the sensemaking process. For example, van Zee et al. (2005) demonstrated how three undergraduate students explored an optical phenomenon, the perceived bending of a straw placed in water. They were conceptually uncertain when they tried to use their prior understanding or experience to explain the bending. Through articulating and identifying conceptual uncertainty, they recognize the limitations in their knowledge, leading them to think about how to solve the conceptual uncertainty, such as how to sketch a visual representation, connect the phenomenon to their everyday experience, reason the path of light, and conduct an investigation. They not only engaged in discussing the concept of light and tried to reconfirm their conceptual knowledge about light, but they also made inferences based on the phenomenon, such as explaining observed differences in how the light ray moves through water and air. Conceptual uncertainty drove them to continuously examine the “what,” while epistemic uncertainty drove them to learn “how” to explore. Specifically, conceptual uncertainty continually functions as an evaluation resource to assess if new understanding is coherently integrated with existing understanding. Epistemic uncertainty drives the means of scientific exploration, eventually leading to clarity about the content, thus ultimately reducing conceptual uncertainty.

Second, not only are conceptual and epistemic uncertainties coexisting, they are often intertwined when students are immersed in discussing and making sense of a problematized phenomenon. That is, conceptual and



epistemic uncertainties are not entirely independent and stable but depend on each other and dynamically evolve. Student conceptual and epistemic uncertainties are constantly evolving as students gradually develop sophisticated understanding (Ha et al., 2024). For example, when students learn how much electric power a solar panel generates, they may generally consider that more sunlight will generate more electric power. This is accurate for temperatures up to about 77°F. When a teacher shows that a solar panel in Colorado in fact generates more electric power annually than in Arizona, students' conceptual uncertainty may be raised. To understand and resolve the conceptual uncertainty, students may engage in seeking more information and try to understand why, and this leads them to try different means to determine why, reflecting epistemic uncertainty as they use different methods and examine various data. After experiencing epistemic uncertainty, students may gradually understand that sunlight not only provides a solar panel light but also heat. At this stage, students may be conceptually confused about which feature of sunlight (i.e., light or heat) makes a solar panel work and which feature can cause a decline in panel efficiency. At the same time, student epistemic uncertainty evolves from figuring the problematized phenomena of power generated in Colorado and Arizona to reasoning through their hypotheses/tentative claims and generating an investigation to test their hypotheses/tentative claims. Later, students may also epistemically engage in data interpretation and model building. So, student conceptual and epistemic uncertainties are intertwined as they evolve throughout the process of sensemaking.

Teachers should continuously monitor the status of these uncertainties and maintain an awareness of their relationships and realize that both should be managed (Starrett et al., 2024). Identifying the types of uncertainty in different phases of sensemaking can help teachers offer their support in a most effective manner. However, this does not answer why students struggle with uncertainty. Addressing this question requires researchers to explore the sources of conceptual or epistemic uncertainties—and that has not yet been clearly explored in the literature. The following section focuses on where conceptual and epistemic uncertainties come from, what the existing research says about them, and how they support student sensemaking during productive struggle.

5 | SOURCES OF SCIENTIFIC UNCERTAINTY: WHY DO STUDENTS FEEL A STRUGGLE WITH UNCERTAINTY?

Four sources of scientific uncertainty are identified and illustrated based on research demonstrating that students may experience struggles: insufficiency, ambiguity, incoherence, and conflict. A literature review, combined with our research experience, was conducted to identify appropriate studies to distinguish and explain the meanings of the four sources. Most studies identified in this paper do not explicitly point out or clarify the sources of scientific uncertainty. The examples from identified studies include our interpretations to support the meaning of different sources in the science classroom. Table 3 briefly defines each sources of conceptual and epistemic uncertainties and provides an idea of when and about what sources students are uncertain of during their sensemaking practice. Illustrative examples help to further unpack the meanings and pedagogical implications of the four sources in the sections below.

5.1 | Insufficiency

Insufficiency refers to a condition in which students are aware that they need to pursue more understanding, information, or resources to explain, interpret, or make sense of a phenomenon. What we mean by “aware” is that students can identify from their prior understanding what they already know, what they want to know, and what they need to know to make sense of a phenomenon—if they have sufficient opportunity to unpack their prior understanding. Cognitively, students struggle with an absence of understanding, a recalling of relevant information, or a mismatch between what is recalled and newly presented information about the new target phenomenon.

TABLE 3 Four sources of scientific uncertainty.

	Insufficiency	Ambiguity	Incoherence	Conflict
Definition	A condition in which students are aware that they need to pursue deeper understanding—conceptual or epistemic—to explain, interpret, or make sense of a phenomenon	A condition in which meaning of available understanding—conceptual or epistemic—is vague, unsure, undefined, unclarified, and/or open to multiple interpretations	A condition in which there is inconsistency, disconnect, or lack of clarity between current and new understanding—conceptual or epistemic	A condition in which students cannot integrate contradictory information into an existing understanding—conceptual or epistemic
Cognitive condition	Struggle with an absence of understanding, a recalling of relevant knowledge, or a mismatch between what is recalled and newly presented information about the new target phenomenon	Struggle in distinguishing between one and another meaning or deciding which meaning is intended	Struggle in explaining and integrating newly encountered information and current understanding in a consistent and comprehensible way	Struggle in explaining encountered events as they violate/contradict one's existing understanding
Role in sensemaking	Drive students to problematize an everyday phenomenon and explore the gaps in their existing understanding	Drive students to clarify, elaborate, and discuss which meaning and perspectives work better for supporting their claims, perspectives, and decisions	Drive students to generate coherent connections between current and new understanding across vertical and horizontal curricula	Drive students to explore discrepancy between what they know or believe and the target phenomenon and develop better explanations
Pedagogical use	Conceptual insufficiency: Problematizing everyday phenomena, language, and experience, rather than directly telling what they do not know	Conceptual ambiguity: Creating point-of-need conditions to explicitly articulate different meanings or nuances of language to describe a phenomenon	Conceptual incoherence: Providing opportunities to explicitly compare and integrate current and new understanding to build a coherent knowledge structure, rather than directly giving information	Conceptual conflict: Encouraging students to explore conflicting events and generate alternate explanations to understand and resolve conflicts, rather than merely replacing misconceptions with more accurate scientific knowledge
	Epistemic insufficiency: Providing opportunities to plan (e.g., forming questions to problematize phenomena) and enact investigations and generate argumentation	Epistemic ambiguity: Creating an open space to discuss how to interpret fuzzy and unclear data to make sense of blind spots, and varying evidence to support claims, perspectives, and decisions	Epistemic incoherence: Creating an open space to discuss how to put all evidence and/or epistemic resources together to generate a coherent explanation	Epistemic conflict: Challenging students by providing contradicting ideas/methods/positions or counter-evidence/argument to negotiate conflicts through discussion



Awareness and struggle help students perceive and acknowledge relevant needs or gaps in their existing conceptual and epistemic understanding.

5.1.1 | Conceptual insufficiency

Although we critiqued the traditional teachers' emphasis on conceptual insufficiency, we do not dispute that students come to the science classroom with insufficient conceptual understanding—that is one of the reasons for education. Insufficiency should not be defined by the teacher telling students what they do not know or use simple questions or discrepant events to point out flaws in students' reasoning. Insufficiency should be determined after a teacher frames the discussion of a phenomenon while acknowledging student experiences, existing understanding, and language (Phillips et al., 2018). In the latter scenario, students have opportunities to ask questions, become aware of the insufficiency in their existing knowledge, and identify the “need” to understand relevant concepts.

To illustrate uncertainty about insufficient conceptual understanding, we offer Watkins et al. (2018) notion of “positioning as not-understanding,” in which students have adequate opportunities to ask questions, display puzzlement, or figure out their lack and need of conceptual knowledge about a phenomenon. This notion focuses on raising student awareness of insufficiency by identifying inconsistencies or expressions of confusion about their or their peers' ideas concerning a familiar everyday phenomenon. Watkins et al. provided a powerful example illustrating how a fourth-grade teacher introduced water cycles not by simply explaining the vocabulary and phases of water cycles, but by starting the discussion with a common everyday phenomenon. The teacher positioned students as idea providers and herself as the recipient of these ideas. Circling the students on the floor, the teacher asked them to share ideas about clouds and rain, saying, “How is it that a cloud rains?” When students had the opportunity to express and explore their ideas and puzzlement, they collectively framed several conceptual uncertainties stemming from insufficient understanding, such as “Does it [water] like turn into gas? What does it do?” “Does it float?”

5.1.2 | Epistemic insufficiency

Engaging in productive struggle requires students to not only explore their insufficient conceptual understanding but also their insufficient epistemic understanding. That is, students explore and struggle with how they cannot make sense of a specific phenomenon and form questions as to how to problematize the phenomenon. Consider again the fourth-grade teacher introducing water cycles (Watkins et al., 2018). Students did not just engage in exploring their existing conceptual understanding; most of their time was spent exploring their epistemic understanding by providing evidence to justify their claims (e.g., “when you go through a cloud through an airplane, it's bumpy”), and reason with different ideas (e.g., “a cloud cannot hold all the water, because the water would be too heavy for a cloud; the higher up in the sky, there's not a lot of gravity. So, the clouds are very high, so it's just floating up there. If it were low gravity, why would water fall as rain?”). Because students navigated their epistemic uncertainties, more conceptual uncertainties were raised, such as “How could water be in a cloud without falling?” “How does it go up?” In such situations, conceptual and epistemic uncertainties are entangled with each other, driving the process of sensemaking.

Therefore, productively raising students' uncertainty about insufficiency does not mean directly asking simple questions or feeding them information, just as in the previous example from Mrs. Kumari's class (see Table 1). Rather, teachers need to situate students in a meaningful context in which they have the resources and authority to make tangible connections among their prior understanding, lived experience, the scientific concepts to be learned, and the target phenomenon to identify the what (i.e., conceptual insufficiency) and the how (i.e., epistemic insufficiency) of students' need for more understanding.

5.2 | Ambiguity

Ambiguity generally relates to vagueness and possible multiple meanings or interpretations. Unlike the first source of scientific uncertainty, insufficiency, where relevant information is unknown or unavailable, ambiguity occurs when relevant information is available but overall meaning is undefined or not clarified. Ambiguity often causes students' uncertainty in deciding which meaning is intended or if any of them are legitimate (Sterner, 2022). Ambiguity can productively open the discussion space by leaving room for alternative interpretations of what is being asked or of the referents embedded in a question, or what the alternative viable solution pathways are (Johnson et al., 2022).

5.2.1 | Conceptual ambiguity

In science, conceptual ambiguity may come from multiple sources, such as lexical ambiguity and terminological ambiguity. Each of these is exemplified below.

Lexical ambiguity refers to the potential double or multiple interpretations when the same wording is used differently in science and everyday life (Brown & Spang, 2008). For example, Rector et al. (2013) studied 320 biology undergraduate students' responses to evolutionary change. They identified five key words that have different meaning when used in scientific explanation and students' everyday lives—"adapt," "need," "select," "pressure," and "must"—and found that 81% of students ambiguously use the words in responding to the questions. Although students incorporated the words to explain the evolutionary concepts, they interpreted the words based on their lived experience or everyday uses. For example, students tended to interpret "adaptive" as individuals adjusting to suit a particular environment, rather than as a result of a multigenerational evolutionary process through which the distribution of variation in a population becomes better aligned to a particular habitat.

Terminology is another source of conceptual ambiguity. It stems from students' confusion over definitions and not understanding a non-standard use of a scientific term. For example, in a unit on photosynthesis, students often consider that the dark reaction of Calvin cycle actually takes place in the dark or at night (Loneragan, 2000) and equate the dark reaction with the process of respiration (Yip, 1998). The reality of the situation is that several enzymes in the so-called "dark reactions" do, in fact, occur during the day but are indirectly dependent on the presence of light energy. Researchers have pointed out that the ambiguous meaning often causes students to struggle to understand the scientific meaning of this scientific term.

Terminological ambiguity also comes from ambiguous use in everyday life, misleading students to understand scientific meaning. In Engle and Conant's (2002) study of a fifth-grade unit on classification, they demonstrated how ambiguous terminology raised students' uncertainty when they viewed a video about killer whales (also called orcas) in which the trainer noted that killer whales are not whales, but dolphins. Students argued that "if they're dolphins, why do they call them killer whales, why don't they call them (killer dolphins)" (p. 478). This ambiguous terminology caused student uncertainty about their existing understanding used in their everyday life. Their teacher did not clarify the ambiguity (e.g., killer whale, killer dolphins, or orcas), but leveraged the ambiguous terminology to motivate students to navigate their uncertainty and search for reliable evidence to resolve it. Thus, students not only searched different resources to support their arguments/positions but also learned about how to classify species, genus, family, order, and so forth.

Many teachers ignore or have difficulty recognizing students' lexical and terminological ambiguity. They often interpret students' responses as lacking content knowledge and introduce vocabulary and concepts in response (Schlepppegrell, 2012). As the language used in an everyday setting does not translate well into scientific use, expressed meanings, relationships, and concepts can become conceptual uncertainty remained unaddressed. Supporting students in productively navigating conceptual ambiguity requires that teachers understand how their students use language in everyday situations, recognize the gap or nuanced difference in use between students and



scientists, and create point-of-need conditions for students to explicitly articulate the language in-the-moment to describe phenomena or concepts (Brown & Spang, 2008; Jung & Brown, 2016).

5.2.2 | Epistemic ambiguity

Ambiguity can occur in students' struggle of epistemic understanding, such as ambiguous data leading to multiple interpretations (Johnson et al., 2022), or ambiguity in socio-scientific issues (SSIs) creating an opportunity for multiple perspectives and decision-making (Herman et al., 2022).

Science education research shows that epistemic uncertainty related to ambiguous data leads to multiple interpretations. For example, Chen and Techawitthayachinda (2021) demonstrated how ambiguous data raised students' epistemic uncertainty and opened a space for discussion, debate, and expansion of ideas. In their study of a fifth-grade unit of seed germination, students explored if seeds need sunlight or darkness to germinate. It surprised the students that three out of five corn seeds grew in the sunlight and four out of five grew in the darkness. These varied or ambiguous data caused student uncertainty that initiated different interpretations of the data and vigorous debate, with statements made, such as the seeds do not need sun, the seeds do not need darkness, the seeds died, and the seeds need warmth. The teachers tacitly used uncertainty surrounding the ambiguous data to scaffold students to understand their "blind spot" and recognize that seed germination does not need either sunlight or darkness, but appropriate temperature.

Research on using SSIs as a context, tool, or approach to learn science shows that students often experience ambiguity due to different and sometimes controversial perspective taking, such as in nuclear power building (Wu & Tsai, 2007), genetically modified foods (Lee et al., 2020), or model construction of COVID-19 (Ke et al., 2021). For example, Emery et al. (2015) introduced a scenario about whether to transform an abandoned grassy school yard into a concrete parking lot for cars and bikes to a group of 11th and 12th grade students. Students evaluated and interpreted various evidence to explore and debate how their decisions impacted community water quality and the surrounding ecosystem. Ambiguity comes into play in multiple ways when students epistemically engage in explaining data to support their claims, perspectives, and decisions.

In summary, rather than lecturing students on scientifically sound concepts, teachers should help students navigate issues about what causes ambiguity and provide room for students to articulate their uncertainty related to ambiguity. Ambiguity provides an opportunity to discuss and open a space for students to clarify, elaborate, and bridge how they perceive the ambiguity between their intuitive knowledge and scientific information.

5.3 | Incoherence

Incoherence commonly refers to ideas, explanations, information, and interpretations not holding together (Rosenberg et al., 2006). However, its meaning has often been used interchangeably with ambiguity. While ambiguity refers to multiple meanings, incoherence refers to inconsistency or a disconnection between current understanding and newly encountered information (Reif & Allen, 1992). DiSessa et al. (2004) viewed incoherence from a "fragmentation" or "knowledge in pieces" (KiP) perspective whereby an individual's "conceptual ecology" is composed of multiple fine-grained knowledge sources that connect and interact in complex ways. Incoherent knowledge thus comes from disconnection among pieces of knowledge and inconsistency in the use of intuitive knowledge to explain a problematized phenomenon. Students may struggle in explaining and organizing new and current understandings in a consistent or meaningful way (Schank, 1999). This may be especially true of novices, whose "conceptual ecology" is not as coherent, connected, or complex as experts (Nie et al., 2019). Nonetheless, the uncertainty of incoherence may potentially promote students to be more "disciplinarily productive" (Engle & Conant, 2002), seeking more coherent evidence, pushing to distinguish fuzzy concepts, and requesting clarification of indistinct and disordered relationships.

5.3.1 | Conceptual incoherence

There are two major sources of student conceptual incoherence. The first comes from vertical misalignment, that is, what students learn in one grade level, lesson, or course does not prepare them for the next stage to be able to connect concisely newly learned concepts (Jin et al., 2019; Sikorski & Hammer, 2017). For example, when learning electromagnetism, students usually struggle to connect the concepts of two units (e.g., electricity and magnetism) to develop an understanding of electromagnetism (Anderson et al., 2000). Maloney et al. (2001) found that students in a US college general physics course struggled to distinguish the difference, and relate the two concepts between electric and magnetic field effects. Students were confused about how the flow of electric current produces a magnetic field, and misunderstood the north magnetic pole as being positively charged. In the same unit of electromagnetism, Galili (1995) developed a written test to examine the coherence of the connection between Israeli high school students' ideas about force and motion in mechanics and in electromagnetic situations. He concluded that 67% of students were unaware that Newton's Third Law applies to electromagnetic conditions, and that they struggled to connect ideas about work and energy coherently in the context of electric and magnetic fields.

The second source of incoherence comes from horizontal misalignment. That is, what students learn in one subject (e.g., math, physics, chemistry) does not connect with another subject within the same grade level. For example, students may learn the concept of ratio in a math class. However, when they study the concept of material density in physics, they usually struggle to conceptually understand that density is the ratio between mass and volume or mass per unit volume and what the ratio means in this physics unit (Kiray & Simsek, 2021). In the same unit of density, students also have difficulty comprehending that air and liquid have the property of density even though they have learned the concepts of matter and molecular structure in their chemistry course (Wells et al., 2019).

Anderson et al. (2000) contended that horizontal misalignment is often caused by the disintegration or disconnection between content knowledge in school (e.g., textbooks, teachers), informal knowledge (e.g., museum visit), and everyday knowledge/experience in daily lives (e.g., lighting, refrigerators). By studying two seventh-grade students' learning of electricity and magnetism, they found students developed coherent, sophisticated, and abstract understanding after they had opportunities to visit an interactive science museum and were involved in in-class completion of post-visit activities explicitly connected to specific experiences at the museum and everyday experiences (e.g., measurement of the flow of electricity in the post-visit activities and experiences on a student's uncle's farm which had an electric fence). Students not only developed better sensemaking of electricity and magnetism, but also knew how to apply the knowledge to their everyday lives.

5.3.2 | Epistemic incoherence

Incoherence in epistemic uncertainty can result from a disorganized or unclear explanation of data, information, and experience (Thagard, 1989), or clear understanding of how to find and approach relevant resources (Hammer & Elby, 2003).

Epistemic uncertainty related to incoherent explanation has been substantially studied in the field of argumentation (e.g., Chen & Qiao, 2020) and modeling (e.g., Mendonça & Justi, 2014). Students encountering this uncertainty usually struggle to integrate information, data, or evidence and generate a coherent interpretation. For example, in Manz' study (2015) about third-grade students exploring plant growth in their school backyard, students experienced uncertainties related to incoherent information and evidence. After they engaged in investigation and data collection, they found some plants (i.e., strawberries) grew well in shade but some plants (i.e., cactus, sun plants) grew better under sunny conditions. Students also found that strawberries grew most of the fall but disappeared later. The teacher recognized the incoherence and utilized it to open space for discussion through



engaging students to pull all of the evidence together to understand how plants use different strategies in different environments. Epistemic incoherence was raised due to students considering only part of the data. After holistically reviewing and interpreting the data, students could resolve incoherent explanations and build a coherent one to interpret the results.

Building on a resource perspective, researchers have argued that incoherence may result from student trouble with finding, framing, and organizing epistemic resources (Chakrin & Campbell, 2022; Louca et al., 2004). Watkins and Manz (2022) argued that students experiencing epistemic struggle in developing a coherent explanation is often not about their content knowledge, but about how students coherently discover and put epistemic resources together. For example, in Rosenberg et al. study (2006) of how a group of eighth-grade students explored rock cycles, students experienced epistemic uncertainty related to incoherent use, activation, and framing of epistemic resources. Students discussed how the layers of sedimentary rock can become metamorphic. However, they struggled to coherently explaining where heat and pressure come from to form a metamorphic rock because of their disorganized use of the resources available to them, such as the worksheets, accumulated information, their mental images, lived experience, and casual-effect reasoning.

5.4 | Conflict

Conflict may be the most commonly studied cause of scientific uncertainty, especially in the research on conceptual change (e.g., Chi, 2009; Limón, 2001; Pacaci et al., 2023; Posner et al., 1982). Traditional views of conceptual change are rooted in a knowledge deficit perspective, which assumes that students accept correct scientific views to remove their uncertainty or misconception (Sinatra et al., 2014). We do not take the traditional views to define the source of conflict. Building on utilizing student uncertainty, or “misconception” in this case, as a pedagogical resource to open space for discussing the conflict and gathering more evidence (Larkin, 2012). In contrast, we define conflict as a cognitive condition in which students perceive encountered ideas, information, or phenomenon as contradictory to their existing understanding. Students struggle to explain encountered events as they cannot be effectively processed with one’s existing understanding.

5.4.1 | Conceptual conflict

Conflict often arises when student’s existing understanding is inconsistent with the target phenomenon and scientific concepts to be understood (Pacaci et al., 2023). For example, in a unit about seasons, students often intuitively consider that the Earth’s distance to the sun determines change of season. Studies have shown that students often consider this distance to be greater in winter than summer (e.g., Plummer & Maynard, 2014). However, the distance between the Earth and Sun is shortest in January, and greatest in July. Distance does not cause seasonal change, but the tilt of the Earth does. This fact conflicts with students’ prior understanding or intuition about what causes seasonal change. Teachers may need to raise students’ awareness of the conflict by explicitly address it, engage students in discussing what causes their struggle, and help students seek understandable evidence to resolve it.

Students’ uncertainty related to conceptual conflict should not only be used as a pedagogical resource in the beginning of a unit to make students uneasy or as a source of surprise, but also throughout the unit to drive students to actively work to generate evidence and resolve the uncertainty. Tsai and Chang (2005), for example, compared two groups of ninth-grade students studying a unit on seasons. The first group explored several conceptual conflicts and discrepant events related what caused their uncertainty about global seasonality (e.g., the seasons in the Northern Hemisphere are the opposite of those in the Southern Hemisphere). The teacher used conceptual conflict as a means to explore potential solutions that eventually allowed students to shape a fruitful

and meaningful explanation. Therefore, students had the opportunity to acknowledge and explain conceptual conflicts they had and how to resolve them. Students in the second group received a lecture with the same information and curriculum as the treatment group, but were treated as lacking or having insufficient content knowledge once their conflicting ideas were raised. They did not have the opportunity to explore and explain conceptual conflicts. They found that students in the first group performed significantly better in posttest and delay-posttest than students in the second group. They concluded that students should engage in sufficient struggle to deeply explore their uncertainty about what they are conflicted over and find a way to resolve it, rather than just trying to understand the nuanced interpretation of scientific facts through rote memorization. Tsai and Chang's results showed that students also need to engage in epistemic conflict to understand how to generate appropriate evidence to explain and negotiate their ideas and reasons. That is, students' conceptual conflict is insufficient to engage students in productive struggle and should be utilized to create a space to discuss, explore, maintain, and resolve conceptual uncertainty by engaging students in epistemic conflict.

5.4.2 | Epistemic conflict

As noted, students should engage in considering why the conceptual conflicts occur and how to resolve them. More specifically, they need to experience epistemic conflict when experiencing conceptual conflict. When engaging in epistemic conflict, students struggle with how they can reason about conceptual conflicts, interpret data as evidence to support their claims, and resolve counter evidence.

Epistemic conflict involves situations wherein students are aware that there are two or more contradictory reasons, justifications, explanations, or interpretations of a single data point or phenomenon. However, students usually construct their best interpretation in private and represent it in public. Students themselves (in private) usually do not have two or more contradictory explanations for the same data or issue. Thus, epistemic conflict usually is raised from or after students become aware of or are challenged with contradictory ideas or counter evidence/arguments from peers or teachers (Mercier & Sperber, 2011).

Research in argumentation has demonstrated how epistemic conflict raises student uncertainty and opens debate and discussion space. In the earlier examples from Chen and Techawitthayachinda's (2021) study of fifth-grade students explaining the ambiguous data about whether seed germination requires sunlight or darkness, students initially generated multiple interpretations and reasoning from the ambiguity. However, once students shared and elaborated their varied explanations, they gradually experienced uncertainty about conflicting ideas (need sunlight or not). Students' conversations showed that they supported two contradictory positions and tried to use various examples from their everyday lives to defend their positions. Students who supported the idea that seed germination needs sunlight explained that they saw the phenomenon in their everyday life. Students who held the opposite position considered that seeds may just need warmth. By confronting the epistemic conflict and attempting to solve it together, students clarified the different needs of seeds, interpreted why seeds could germinate in sunlight or darkness, and identified what seeds need to germinate using everyday examples as support their results (e.g., farmers usually do not plant seeds in winter). In this manner, the epistemic conflict was resolved.

5.5 | Characterizing relationships among the four sources of scientific uncertainty

First, the four sources are often interwoven. We propose that the four sources of scientific uncertainty may not occur alone but are frequently interwoven during the sensemaking process. For example, when eighth-grade students learned what characteristics of sunlight contribute to a solar panel's generation of electricity, they encountered conceptual insufficiency (e.g., needing more conceptual understanding of a solar panel or features of sunlight) and conceptual ambiguity (multiple interpretations of the heat and light effect). They encountered



conceptual conflict once they knew that a solar panel in Colorado annually generates more electricity than Arizona, because this information contradicted their prior understanding or belief. They simultaneously experienced epistemic insufficiency once they began seeking to explain the data and were not sure how to interpret the solar power data from Colorado and Arizona. Therefore, while sensemaking, students may encounter several sources of uncertainty simultaneously or sequentially.

Second, the degree and nature of interweaving are decided by how and what teachers design for student struggle. We propose that the nature and degree of sources being interwoven can be determined by how teachers design for student struggle. That is, the interwoven nature of the sources depends on how teachers leverage uncertainty to drive the direction of lessons, what potential struggles teachers design into or anticipate in their activities or lessons, and how students respond to the raised uncertainty based on their existing conceptual and epistemic understandings. For example, when students engage in and discuss data or results from an investigation, teachers may want to emphasize multiple interpretations of the data or results; epistemic ambiguity is the focus when students wrestle with ways to generate different explanations. If teachers want to emphasize developing a holistic and coherent perspective for analyzing and organizing the data, epistemic incoherence is the source to drive students to develop coherent evidence and explanation. By way of contrast, in a traditional classroom, teachers may consider inconclusive data as students' conceptual insufficiency and thus may point out the deficiency of student conceptual and epistemic understanding and then provide all the information and explanation for students to memorize or "learn." Therefore, the degree of intertwining may depend on the goals of the teacher's pedagogy, lesson, and orientation, as well as what struggles teachers intend their students to experience and overcome.

In identifying and distinguishing the four sources, we do not mean to negate the possibility of other sources causing student scientific uncertainty. There are probably more than the four sources identified in this paper. More important is how teachers use or leverage the sources of scientific uncertainty to support student learning and productive struggle to build better understanding and generate desirable outcomes. The following section focuses on the desirability of scientific uncertainty and how teachers can leverage it.

6 | DESIRABILITY OF SCIENTIFIC UNCERTAINTY: HOW ARE SCIENTIFIC UNCERTAINTIES NAVIGATED FOR PRODUCTIVE STRUGGLE?

Not all uncertainties are desirable all the time. Previous research has theorized distinctions between desirable and undesirable uncertainty in classrooms using different language (e.g., desirable and undesirable difficulties; Bjork & Bjork, 2011; productive and unproductive uncertainty, McLaughlan et al., 2021; good and bad uncertainty, Beghetto, 2017). In the current position paper, Weaver's (1949) concepts of "desirable uncertainty" and "undesirable uncertainty" are adapted to differentiate between resources and opportunities to improve students' understanding from noise, irrelevance, and inappropriate information transmission. The goal is to align uncertainty with the teachers' pedagogical goals to drive and support students' agency as they make their own sense of puzzling phenomena, ideas, or issues. This section proposes three considerations to effectively manage scientific uncertainty: relevance, timing, and complexity. Pedagogical and design concerns related to the three considerations for desirable scientific uncertainty are summarized in Table 4 and illustrated in the section below.

6.1 | Relevance

Student thinking may result in unproductive conversation when irrelevant concepts, or meaningless/unauthentic phenomena are introduced. Accordingly, students may then struggle with uncertainties that are not relevant to the core concepts and practices for the lesson, and with uncertainties that have little meaning in relation to their experiences and existing understanding.

TABLE 4 Three considerations for ensuring desirability of scientific uncertainty.

	Relevance	Timing	Complexity
Pedagogical considerations	- Scientific uncertainty is related to core concepts and practice - Scientific uncertainty is situated in meaningful and authentic phenomena	- Scientific uncertainty is appropriately sequenced in a simple-to-complex manner facilitating understanding development in long-term memory while reducing unnecessary demands on working memory - Scientific uncertainty is managed in a just-in-time manner	- Scientific uncertainty involves an appropriate level of complexity - The degree of complexity of scientific uncertainty is perceived differently among individuals
Pedagogical decisions in sensemaking	- Identify what scientific uncertainties are expected and decide which uncertainty will be focused on during an activity or lesson - Consider student prior knowledge, interests, and motivation to design for meaningful and authentic uncertainty about a phenomenon	- Identify an appropriate sequence and pacing of possible scientific uncertainties and design activities or lessons according to the identified sequence - Monitor student uncertainties in real-time and provide just-in-time support for scientific uncertainties	- Identify the level of complexity of scientific uncertainty and adapt it by adjusting the level of element interactivity - Consider students' existing understanding as related to processing conceptual and epistemic understanding and then determine the level of complexity of scientific uncertainty

6.1.1 | Scientific uncertainty related to the target core concepts and practices

Scientific uncertainty can be desirable when it is related to the core concepts (conceptual understanding) and practices (epistemic understanding). Teachers should decide on and design types of scientific uncertainties that are relevant to the activity, lesson, or discussion. Embedding or amplifying only information relevant to the target phenomenon can help students focus on desirable conceptual and epistemic uncertainties. Many students have difficulty in figuring out the important core concepts concerning the target phenomenon, and they struggle with ways to examine the phenomenon (epistemic understanding). Amplifying the desirable conceptual uncertainty related to core concepts will foster student engagement in desirable epistemic uncertainty (e.g., epistemic ambiguity about multiple claims and explanations. This view also consistent with Watkins and Manz's (2022) noting the importance of considering what uncertainties are relevant and irrelevant, whether uncertainties should be open to discussion and elaboration, and which elements and relations to address and which to leave open.

6.1.2 | Scientific uncertainty related to prior experience and meaningfulness/authenticity of the target phenomena

Even when the topic of discussion is directly relevant to the core concepts, student uncertainties could still be irrelevant when a meaningful connection between their prior understanding and the core concepts is not made. When uncertainties do not align with students' prior understanding, meaningful learning might not occur (Ausubel, 1963). Teachers need to consider whether the sources of scientific uncertainty make sense to students.

Relevance in terms of meaningfulness is in part defined by students' perceptions and experiences of the authenticity of phenomena, discussion topics, or tasks, as determined by students' prior understandings,



experiences, interests, motivation, and learning goals (Hernandez-Martinez & Vos, 2018). That is, the relevance of uncertainty concerning core concepts is not guaranteed unless students perceive the uncertainty as relating to authentic phenomena with which they are familiar. For example, when teachers in Florida introduce a unit on animals and natural habitats, they may situate scientific uncertainty in a phenomenon about the sea or tropical environment that is familiar to students, rather than in a desert zone that may be unfamiliar to them. Students perceive learning tasks as relevant especially when they are able to make connections between discussions of the target phenomenon and their personal experience, prior understanding, everyday language.

6.2 | Timing

A desirable uncertainty at one point in a lesson or curriculum might not have the same desirability at another point. Uncertainties can be navigated with timing as a consideration.

6.2.1 | Scientific uncertainty appropriately sequenced in a lesson and/or curriculum

Cognitive load theory suggests that “instruction needs to be designed in a manner that facilitates the acquisition of knowledge in long-term memory while reducing unnecessary demands on working memory” (Clarke et al., 2005; p. 15). The sequence of learning activities or lessons throughout the curriculum can be set in a simple-to-complex or unpacking-complex-for-clarity manners, as this ensure optimal level of cognitive load imposed on students and promotes desirable learning outcomes (Koedinger et al., 2012). On one hand, simple-to-complex sequencing strategies on learning in relation to student prior understanding and cognitive load help students gradually build skills through simpler uncertainties before engage in navigating more complex uncertainties. Clarke et al. (2005) found that such sequencing as more advantageous than concurrent presentation.

On the other hand, unpacking-complex-for-clarity strategies provide students authentic learning environment with complex uncertainties in the beginning, just like what scientists do and struggle. This sequence provides students opportunities for maximizing that struggles to unpack the phenomenon, identify variables to explore, and figure out methods to test their hypothesis. It is important for teachers to thoughtfully allocate time for unpacking complex uncertainties for clarity to avoid cognitively overburdening students. Teachers can (and should) embed phenomenon in authentic science learning tasks, but they still need to unpack the phenomenon. Teachers can engage students in a complex phenomenon associated with multiple types and sources of uncertainty, but it is necessary to help students unpack the complexity and strategically sequence uncertainties for clarity. In these strategies, highly uncertain (complex) task is given to students in the beginning. What is critical to the strategies is to ensure enough time and resources to unpack such complexities (Sinha & Kapur, 2021). For instance, Schwartz et al. (2011) compared learning outcomes for eight-grade students inventing solutions to problems related to density before receiving direct instruction with those who received direct instruction first. They found that sequencing invention activities (i.e., complex first) before instruction (i.e., simple) improved subsequent performance on problems requiring transfer of the deep structure of density. In other words, unpacking-complex-for-clarity better prepared students to learn from direct instruction if teachers scaffold students to unpack the complex for clarity.

6.2.2 | Scientific uncertainty navigated in a just-in-time manner

The just-in-time navigation of uncertainties is closely related to continuously monitor student learning and raise uncertainty closely connect to their current understanding and identify the gaps. Real-time monitoring of students' sensemaking processes and emerging uncertainties is essential for just-in-time support for raising and resolving

uncertainties at an appropriate time (Sayer et al., 2016). This support requires timely processing of the uncertainties presented by the teacher, and also for adaptively responding to uncertainties raised by students in the moment-to-moment unfolding of classroom interactions. For example, when students explore how a solar panel (2 V) works with an incandescent light bulb (1.5 V) and an LED (3.3 V), they found that an incandescent light bulb can be lit but the LED cannot be. For a teacher, it is good to provide just-in-time navigation of uncertainty, conceptual incoherence in this case, to support students in discussing why one light source was lit and not the other and induce students to consider the features of electricity (e.g., voltage, current, power).

Uncertainties that are raised earlier (or later) than appropriate may unnecessarily confuse learners and cause them to fail to acquire understanding of target concepts. For example, when teachers open a space for discussing the phenomenon of why a magnet is able to generate electricity by moving a magnet bar near a solenoid connected to a microammeter, the teachers may first need to engage in exploring more basic concepts or uncertainties about how electricity production affects electrons, and why electricity flows from the negative to the positive (Anderson et al., 2000). Regarding the timing of uncertainties raised, it is assumed that it could have been desirable for students to be encouraged to have uncertainties about the core concept at that point in the unit.

6.3 | Complexity

The complexity of uncertainty is subjective and relative, as is the corresponding complexity of learning tasks, phenomena, or concepts under discussion (Doyle, 1988; Tekkumru-Kisa et al., 2020). It can depend on the multiplicity and interactivity of the involved elements (Sweller, 1994), as well as student ability to grasp and integrate new information into an existing knowledge base.

6.3.1 | Complexity determined by the level of element interactivity

The complexity of uncertainty can be determined by the level of element interactivity in a learning tasks (Barlow et al., 2018; Sweller, 1994). Element interactivity is “a measure for the number of conceptual items that need to be processed simultaneously to understand provided learning material” (Roelle & Berthold, 2017, p. 144). If the level of element interactivity of the task is high, the learning task is considered complex, and when it is low, the task is considered simple. This holds true for the complexity of the corresponding uncertainty.

Students lose motivation and/or show poor performances when tasks are too complex or simple (van Merriënboer et al., 2003). Therefore, the number of elements and interdependencies to be simultaneously processed in working memory should consider students' cognitive load so as not to overwhelm students' information processing capacity or lose students' interests in the activity. For example, when a middle-school biology teacher engages students in discussing what variables may influence guppies' color change, the teacher may not want to throw at students a data table consisting of 20 variables and non-comprehensible methods of data collection. This may increase unnecessary complexity of uncertainty and overwhelm the students, which is not the goal. It is also not an appropriate way to make the data table too easy to generate “correct” and certain answers because it may lose the authenticity of scientific practice.

It may be appropriate to carefully consider with students about what the meaning of data and what data can be included and excluded for the activity, and then to gradually work through the remaining variables with students before engaging them in analyzing, negotiating, and modeling the cause-effect relationships. Considering the level of complexity can engage students in essential and desirable uncertainty through reducing intrinsic cognitive load (e.g., understanding meanings of variables and methods) and minimizing extraneous cognitive load.

6.3.2 | Complexity determined by the amount of scientific uncertainty held by students

The level of complexity is determined by the perceived amount of scientific uncertainty. For example, when learning about seasons, traditional teachers often only consider a conceptual conflict about the tilt of the Earth's rotational axis causing seasonal change. However, students may perceive more than conceptual conflict. Students may hold other uncertainties: why the direct and indirect sunlight or the amount of sunlight effects the seasonal temperature difference (Plummer & Maynard, 2014), how directness and amount are related, or how to represent the Sun's meridian altitude on a globe (Sung & Oh, 2018). Therefore, the differing level of perceived complexity is determined by the extent to which an individual student construct relevant knowledge structure of a learning task.

6.4 | An example of undesirable uncertainties

An example from Ms. Kim's eighth-grade biology classroom in South Korea when students learned about seed germination shows how undesirable uncertainties can occur in a science classroom (Cho et al., 2019). Students were expected to discuss the concept that nutrients (e.g., glucose) stored in a seed are consumed through respiration to cause germination, which results in the germinated seed losing weight. The loss of weight during germination is often counterintuitive to students because the volume of the seed increases as it germinates.

Students in Ms. Kim's class were given a worksheet (see Figure 2) to justify two competing claims about the comparison of the weights of two bean seeds under two conditions: being watered and not being watered. The two beans initially had the same weight and moisture content. Both were placed in no light containers at a similar temperature (75°F). After 3 days, only the watered bean (B) had germinated. Students were invited to debate which one was heavier in the end. To guide the debate, two claims were suggested by teachers.

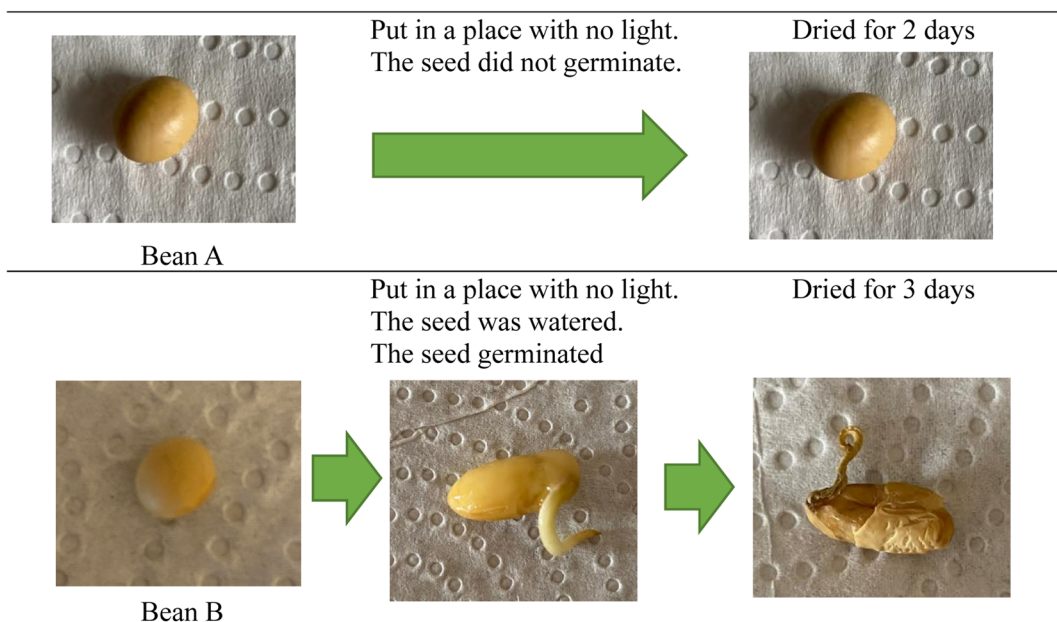


FIGURE 2 Experimental comparison of bean seed germination under two conditions, with no light and with no light but with water. Bean A and Bean B had similar initial weight and moisture content. Core concept to be discussed and learned: Nutrients (e.g., glucose) stored in a seed are consumed through respiration to cause germination, which results in the germinated seed losing weight.

TABLE 5 Conversation where students tried to distinguish photosynthesis and respiration by asking questions.

Line	Speaker	Quote
158	David:	It [the weight of the two beans] is the same, isn't it?
159	Arena:	Ms. Kim, do they [plants] need sunlight to respire?
160	Ms. Kim:	How do you think? Do you think they need sunlight to respire?
161	Arena:	I do!
162	Ms. Kim	You think so? You are saying that they respire only where there is sunlight? To put it in a different way, sunlight...?
163	Arena:	Without it, they can't respire.
164	Ms. Kim:	Without it, they can't respire...?
165	Arena:	But, when they respire, they produce carbon dioxide. Wait, is it oxygen and glucose [they produce]? No, glucose is [produced during] photosynthesis.
166	Ms. Kim:	What is it that they can do with sunlight?
167	Arena:	Photosynthesis... Can they respire without sunlight?
168	Ms. Kim:	Well, think about what we learned last time.
169	Arena:	Oh, because they can respire at night, so they can respire without it [sunlight]...?
170	Ms. Kim:	Now, you remember, right?

Claim A: I think Bean B would be heavier because a sprout was grown.
Claim B: I think Bean B is lighter because it used energy during germination.

Table 5 shows a conversation from Arena's group. In the beginning, students had no idea what to focus on and where to start their discussion to understand the phenomenon. The students tried to retrieve what they had learned about photosynthesis and respiration from previous classes and tried to distinguish the two concepts by asking Ms. Kim questions.

After distinguishing photosynthesis and respiration, students started to share their initial ideas about the weight of the two beans (see Table 6). They drew a couple of interesting analogies from the concept of the density of cotton candy of different volumes, water turning into ice, and falling speeds of cotton candy of different volumes.

6.4.1 | Analysis of Ms. Kim's case

Figure 3 visualizes and encapsulates the discussion paths that the teacher expected and the students experienced, along with the types and sources of scientific uncertainties anticipated by the teacher and those encountered by the students. Additionally, it illustrates why the uncertainties navigated in this case are considered undesirable based on three key considerations.

First, the problematized phenomenon about seed germination was designed and presented by Ms. Kim to facilitate student discussion of two core concepts: (a) water as a necessary condition for seed germination, and (b) seed germination undergoes cellular respiration. However, the students' conversation differed from Ms. Kim's expectation. Students discussed if seeds need sunlight to germinate, and surprisingly, connected this phenomenon to what they learned about density in physics class. Ms. Kim had expected that students would use their prior knowledge of plant respiration, learned in the last class, to complete the task. However, throughout the discussion,



TABLE 6 Conversation where students tried to bring what they learned about density to reason which bean weighed more.

Line	Speaker	Quote
176	Arena:	I think it [the weight] is the same between the two beans.
177	Chris:	Yeah, I mean the things that were inside just came out of it, that's it.
178	Arena:	But, you know, think about cotton candy. This [drawing a big circle with her hands] big cotton candy must be so light. But this small [drawing a small circle] lump of cotton candy must be heavier, isn't it?
179	David:	Is it [the small lump of cotton candy] also light? I mean, it has the same weight, I guess?
180	Arena:	It's been so confusing for me.
...	...	...
183	David:	Well, when water gets frozen, the weight (of the water) remains the same, isn't it?
184	Chris:	Well, the cotton candy thing is so confusing.
185	Arena:	You know, when you crumple the cotton and make it smaller, it falls right away [quickly] whereas the original cotton falls slowly when you drop it.
186	Chris:	Well, isn't it because of the volume?
187	Arena:	But, then...
188	Chris:	You know, the friction by the...the air? What was it?
189	Bruno:	Yeah, that's because of the air. The air resistance.
190	David:	But, the ice has the same weight with the water, doesn't it?

students barely made connections between the target phenomenon and what they had learned about plant respiration. As a result, the uncertainty raised failed to yield a productive discussion relative to the target concept. Students' attention was distracted by another concept, density, as they thought of analogies of cotton candy or water turning into ice. Students did not discuss the teacher's desired core concept, plant respiration.

Students experienced several undesirable scientific uncertainties that were not aligned with Ms. Kim's teaching goals and plan. For example, students encountered conceptual conflict when their beliefs, such as sunlight being the necessary condition for seed germination, contradicted experimental results. Additionally, they faced conceptual ambiguity as they grappled with which concepts to employ in their explanations. Furthermore, students encountered conceptual incoherence as they struggled to connect their understanding of density, likened to cotton candy, with concepts of force and motion, particularly in relation to falling speed. They were uncertain about whether density influences motion generated by a force, such as whether two batches of cotton candy with the same weight but different volumes would fall at the same speed due to gravity. As indicated in Table 6, students discussed weight based on the density concept. Moreover, students experienced epistemic ambiguity because the presented phenomenon introduced numerous points of discussion, including water, weight, sunlight, respiration, and photosynthesis. Consequently, students grappled with determining the validity of claims from various perspectives.

The lack of effective navigation of uncertainty shown in this episode can be understood across three dimensions: relevance, timing, and complexity. Uncertainty is desirable when it is worth maintaining because it may lead to productive thoughts, discourse, or struggle. Regarding the first dimension, scientific uncertainty can be desirable when it is relevant to the core concept being discussed. However, in this episode, students' uncertainty was not focused on the core concept (i.e., plant or seed respiration) but rather diverted toward other uncertainties,

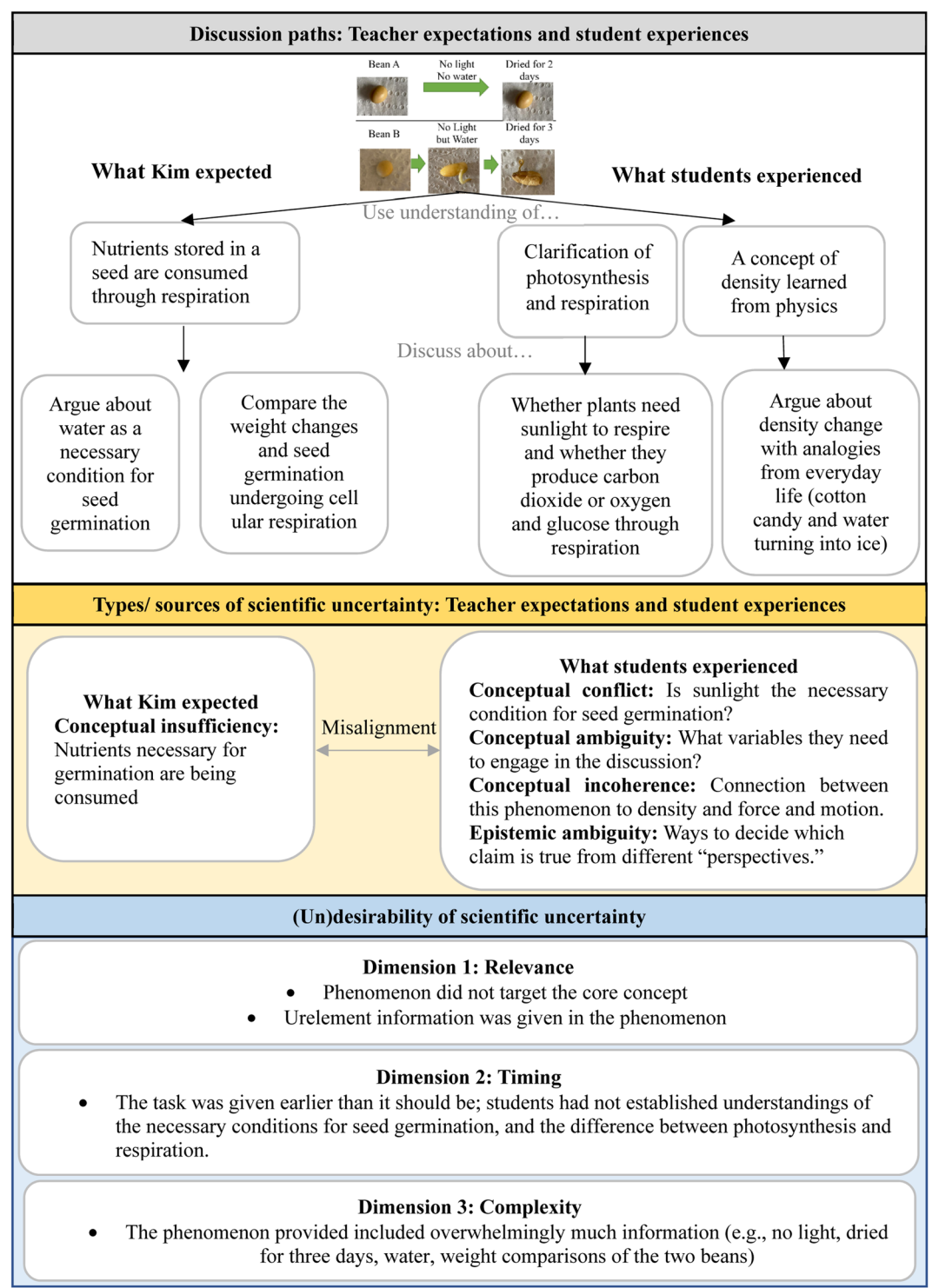


FIGURE 3 Visualization of the analysis for Kim's case based on discussion paths, types/sources of scientific uncertainty, and three considerations of desirable uncertainty.



such as sunlight as a necessary element for seed germination and density. Several factors in the task design could have contributed to this lack of effective navigation of uncertainty. For instance, some irrelevant information provided in the “seed germination” task, such as the mention of two beans without light and the three stages from a healthy seed to seed germination to seed drying for 3 days, seemed to divert students’ attention to plant photosynthesis. Conversely, some information, such as the mention of watering, directly related to the core concept, could have been emphasized by the teacher in the initial presentation of the phenomenon.

The phenomenon of seed germination is suitable for students to explore the nutritional needs of seeds if they have already learned the necessary conditions for germination, such as water, appropriate temperature, and oxygen. This issue relates to the second consideration of desirability, timing. Uncertainty can be beneficial when raised at the appropriate time. However, in this activity, the task was assigned to students with the intention of applying the concept of seed respiration. Unfortunately, students had not yet learned the necessary conditions for seed germination, nor had they established a clear understanding of the difference between respiration and photosynthesis. Consequently, the timing of the uncertainty was not ideal, and students did not engage with it as Ms. Kim had intended.

The timing of the task, coupled with the absence of necessary background information and teacher support, significantly influenced its complexity. The target phenomenon was likely too intricate for the students, given their current conceptual and epistemic understanding. Moreover, the additional information provided about the phenomenon, such as the absence of light, 3 days of drying, watering, and weight comparisons of two beans, was unnecessary for the initial task design at the beginning of the unit. In fact, simplifying the task to focus solely on plant respiration would have likely avoided the uncertainty surrounding analogies, such as the comparison of batches of cotton candy and water turning into ice. Lastly, teacher support is necessary to understand the types and sources of scientific uncertainty students encountered and to help them align the core concepts and student uncertainty. Therefore, uncertainty that surpasses students’ current comprehension levels tends to be challenging to navigate.

6.5 | Summary

Determining the relevance, timing, and complexity of scientific uncertainty is not a simple task with clear standards or criteria that a teacher can apply. The determination depends on various contextual factors, including the curriculum and the authenticity of its elements, the prior experiences and understanding of both students and teachers, the difficulty level, and the interactivity of learning concepts and the target phenomena. Moreover, as it is context-dependent, determination can be influenced by teacher interventions and decision-making, both during the planning phase and through adaptively responding to students during the enactment of lessons.

7 | DISCUSSION

7.1 | Pedagogical implications of the framework for productive struggle in scientific sensemaking

Facilitating classroom activities that center on student uncertainties is complex and can benefit from clear criteria and/or signs and clues from which teachers can make pedagogical decisions. Pedagogically, Figure 1 helps science teachers and educators visualize the relationships between types, sources, and desirability of scientific uncertainty when they use student uncertainty as a pedagogical resource in their lessons, activities, and discussions. We suggest that teachers might think about what core concepts and practices students should engage with in a lesson. Doing so will help teachers (a) decide types of uncertainties (e.g., conceptual and epistemic) to address and

encourage, and (b) recognize, respond to, and intentionally design for possible sources of uncertainties (e.g., insufficiency, ambiguity, incoherence, and conflict) that can produce productive struggle and drive students to engage in desirable scientific practice. Struggle associated with uncertainty can be raised, maintained, reduced, and perhaps postponed. Navigation itself is complex with the options of timing, depth, and direction (raise, maintain, or reduce) uncertainty. With the designed scientific uncertainties, teachers can decide when and how to embed them in their teaching to address the need to facilitate students' scientific literacy, epistemic agency, and coherent trajectories of sensemaking.

This framework will not only help science teachers design lessons or activities, but will support them in reflecting on their teaching, figuring out with what and why students struggle, and adjusting teaching strategies to support students' sensemaking. For example, science teachers often report that students struggle with the tilt of the Earth's rotational axis causing seasonal change even though students engage in discussion and "accept the truth." Studies suggest that students may memorize the "knowledge" but do not develop deeper understanding by solving their uncertainties (Plummer & Maynard, 2014). This framework can help teachers think about what other sources of uncertainties their students may still struggle with, and what strategies can help students navigate the cognitive and affective challenges needed to resolve their uncertainties. Desirability can guide teachers in considering what phenomenon can be introduced to prompt thinking about the embedded uncertainties, in which sequences of uncertainties can productively be discussed and which should be postponed, and whether the discussed uncertainties are too complex for students.

Therefore, exploring different sources of uncertainty can offer substantial insight into why students experience and struggle with uncertainties (e.g., whether their understanding is insufficient, ambiguous, incoherent, or conflicted when they are uncertain). Distinguishing two types of uncertainties (e.g., conceptual and epistemic) helps science educators better understand and redesign lessons around what students struggle with and what practices can help students resolve the struggle (e.g., whether they are uncertain about conceptual understanding or about the way of knowing). Lastly, three considerations of desirability of uncertainties (i.e., relevance, timing, and complexity) inform pedagogical decisions for prioritizing uncertainties during the learning process (e.g., judging which uncertainty is relevant, addressed at an appropriate timing, so as not to be overwhelming with complexity).

7.2 | Implications for future research

This paper introduces a theoretical framework that contributes to an understanding of how to utilize student scientific uncertainty as a resource for productive struggle in the process of sensemaking. However, understanding and implementing the pedagogical roles of scientific uncertainty and how they can be productively adapted in science teaching require more targeted empirical study. For example, although a complementary relationship between conceptual and epistemic uncertainties for productive struggle is proposed in this paper, this relationship has not yet been explicitly unpacked in any empirical study. In addition, if we consider scientific sensemaking as a process or trajectory (see Odden & Russ, 2018), content uncertainties and epistemic uncertainties may play different but complementary roles at different points in the sensemaking process. Teachers may therefore need different strategies at different times to encourage student uncertainty and struggle. It is necessary then for researchers to explore how the two types of uncertainties play out their roles and drive the process of sensemaking.

Furthermore, it is critical that future research seeks to understand how the sources of scientific uncertainty (i.e., insufficiency, ambiguity, incoherence, conflict) are dynamically involved and evolve to impact students' knowledge building across the process of sensemaking. Outlining possible sources of uncertainty in each phase of sensemaking would help teachers prepare possible questions, strategies, materials, and information to provide to students when they struggle. Teachers' increased understanding of different sources of uncertainty can help them adaptively respond to such uncertainty by offering appropriate supports based on students' cognitive needs while working within limited class time.



Another important question for further research concerns how those identified uncertainties can be designed in lesson plans to support student productive struggle, and how they can be adapted as pedagogical resources in a desirable way during the moments of teaching practice. Although three considerations are proposed in this paper, they should be empirically examined and likely expanded upon. In addition, teachers may design their lessons or activities expecting particular uncertainties, but students may not respond in the expected way. It is important to study the alignment and misalignment among teachers' uncertainty-in-design (i.e., planning) and uncertainty-in-practice (i.e., adaptive responsivity), and uncertainty-in-reflection (e.g., reframing and reshaping undesirable uncertainty to desirable uncertainty). As such, translating how scientists struggle to do science in the science classroom will be more meaningful for student learning and science teaching.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

Data is available on request due to privacy/ethical restrictions. The data that support the findings of this study are available from the corresponding author upon reasonable request.

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ENDNOTES

¹ We take uncertainty to be a subjective experience reflecting an individual's of being unsure of using existing understanding to respond to encountered issues, conditions, or phenomena. Uncertainty is distinguishable from ignorance, "the condition of not knowing something" (Birkenholtz & Simon, 2022, p. 156), in that uncertainty requires awareness of being in a state of incomplete knowledge (Smithson, 1989). Firestein (2012) preferred to define ignorance in a social construct, saying: "It [consensus ignorance] is not an individual lack of information but a communal gap in knowledge...where data don't exist...where the existing data don't make sense, don't add up to a coherent explanation, cannot be used to make a prediction" (p. 7). This consensus ignorance in science is a social construct referring to the knowledge constructed within a community. Here, we focus uncertainty as an individual construct reflecting individual's dubiety about using existing understating to respond encountered issues, conditions, or phenomena.

² We call this a position paper because we attempt to (a) provide a framework (see Figure 1) that responds to the goals based on an examination of literature review combined with our research experience, and (b) articulate our stance that student scientific uncertainty can be considered as a resource for productive struggle in the process of sensemaking.

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