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Teacher strategies to support student navigation of uncertainty: Considering the dynamic nature of scientific uncertainty throughout phases of sensemaking

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Abstract

Sensemaking has been advocated as a core practice of science education to support students in constructing their own understanding through a prolonged trajectory. However, the field lacks a discussion of teaching strategies that can better support students as they develop in the trajectory of sensemaking, which includes four phases: initial engagement with a driving question related to a target phenomenon; identification of incoherence and insufficiency in existing understanding; exploration of multiple resources to help develop plausible explanations; and synthesis of solutions and application of new understanding to interpret the target phenomenon. With the view that students' scientific uncertainty, including conceptual and epistemic uncertainties, can motivate or drive the trajectory of sensemaking coherent with students' understanding, this multiple case study examined how two science teachers, one from South Korea and one from the USA, supported students to navigate their scientific uncertainties to shape a trajectory of sensemaking that is coherent to them. Transcripts of video recordings of classroom discourses and student-created artifacts were analyzed. We identified the dynamic nature of students' scientific uncertainties in the four phases and the teaching strategies in each phase. Three main findings emerged from

this study: (1) student uncertainty as a key not only to initiate the trajectory of sensemaking meaningfully but also to continuously develop the trajectory along a coherent pathway, (2) conceptual and epistemic uncertainties having different roles in building different phases of sensemaking, and (3) teaching strategies that support student navigation of scientific uncertainty that drives the trajectory of sensemaking.

KEYWORDS

conceptual uncertainty, epistemic uncertainty, sensemaking, student scientific uncertainty, uncertainty navigation

1 | INTRODUCTION

Sensemaking is described as students' active engagement in generating and developing a coherent explanation of how phenomena occur (Cherbow & McNeill, 2022; Ford, 2012; Krist & Shim, 2023; Odden & Russ, 2019; Quintana et al., 2004; Reiser et al., 2017; Weick et al., 2005), contrasting with the teacher transfer of knowledge to students. It represents a main goal of science education (National Research Council [NRC], 2012), providing explicit opportunities for students to become capable of understanding and processing information about the natural world.

Although sensemaking can be characterized as an "aha!" moment (Conlin, 2013; Haverly et al., 2020; Richards et al., 2020), it is often portrayed as a cumulative, sequential, and ongoing cycle of events occurring over time (e.g., Cannady et al., 2019; Kapon, 2017; Kuo et al., 2020; Odden, 2021). Lowell et al. (2022), Penuel et al. (2022), and Reiser et al. (2021) suggested viewing sensemaking as a trajectory toward a better understanding that is coherent from a student's viewpoint, involving identifying incoherence, seeking solutions, and applying new understanding to new situations. This view of sensemaking as a prolonged process moves beyond fragmentary moments and noncontinuous decision points. This view emphasizes the identification of sequential activities and how those activities consequentially support students in recognizing and resolving gaps in existing understanding, which then develop into a coherent understanding of problematized phenomena (Odden & Russ, 2019; Sikorski & Hammer, 2017).

Previous studies that suggested the idea of sensemaking as a trajectory of grasping better understanding provide a starting point to discuss how to invite students to build a trajectory of sensemaking (Penuel et al., 2022; Reiser et al., 2021). However, two issues remain to be resolved to promote an understanding of how a coherent trajectory of sensemaking can be achieved in science classrooms. First, current research lacks discussion on what drives or motivates the process of developing coherent understanding through a trajectory for sensemaking that extends over a whole class period or even several sessions. Although scholars agree that engaging students to share their ideas plays a key role in developing coherence across experiences, practices, and knowledge (Kloser et al., 2019; Russ, 2018; Warren et al., 2001), merely sharing ideas does not result in the development of coherent understanding. Recently, scholars have suggested that students' scientific uncertainty potentially motivates or drives the process of sensemaking (Chen, 2022; Colley & Windschitl, 2016; Jaber et al., 2021; Watkins & Manz, 2022). Watkins and Manz (2022) suggested that "classroom sense-making conversations necessitate that uncertainty be taken up by the class," because "recognizing uncertainty can motivate students to examine whether and how their accounts fit together" (p. 6). We adapted this perspective and view scientific uncertainty as student struggle, perplexity, or doubt about how to explain a phenomenon or how to integrate new information into their



existing understanding. Yet, there have been only a few studies that have examined how scientific uncertainties drive and shape a trajectory of sensemaking that dynamically develops from its beginning through sustenance and to completion.

Second, there is a limited understanding of teacher strategies that support students' navigation of dynamically evolving scientific uncertainties during sensemaking. Studies have focused on what strategies could create sensemaking moments (e.g., Haverly et al., 2020) or what pedagogical decisions teachers should make to open space for discussion (e.g., Watkins & Manz, 2022). Few studies have explored teaching strategies that support student navigation of uncertainties in and through different phases of the sensemaking. Uncertainties are not always static and stable (Tiberghien et al., 2014) but often dynamically evolve along the trajectory of sensemaking (Kampourakis & McCain, 2020; Sensevy, 2014). For example, when students explore the efficiency of a solar panel, they may be uncertain about what variables determine efficiency in the beginning. Once they develop their hypothesis, they may be uncertain about how to design a valid investigation to collect data and test the hypothesis. Later, students may be uncertain about how to interpret the raw data as evidence to support, reject, or revise their hypothesis to understand the efficiency of a solar panel. From this perspective, student scientific uncertainties are associated with the status of their existing understanding and change and evolve throughout different phases along the trajectory of sensemaking (Tiberghien et al., 2014). Therefore, teachers will likely need different strategies for different phases to support students as they navigate dynamically evolving uncertainties. To date, this issue has not been comprehensively explored.

In this study, we focused on collective discussion (i.e., small group discussion, whole class discussion) in which students collaborated with each other to socially explore a target phenomenon, identify and resolve gaps between what they understand and what they do not understand, and justify the best solution to explain the problematized phenomenon. Therefore, in this study, we view sensemaking as a collective discussion process that starts with the presentation and problematization of a target phenomenon and progresses toward the construction of a reasonable explanation of the phenomenon.

Building on this view of sensemaking, we aimed to contribute to understand (1) how student scientific uncertainties evolve and drive dynamically developing trajectories of sensemaking, and (2) what teacher strategies can support students to navigate the scientific uncertainties and cumulatively develop coherent understanding.

2 | THEORETICAL FRAMEWORK

This study aims to identify teacher strategies that can support students in navigating scientific uncertainties, which evolve and drive a trajectory of sensemaking. Teaching strategies to support student navigation of uncertainty in collective sensemaking refer to teacher actions making an individual student's uncertainties public within a community (e.g., whole class discussion, small group discussion) and supporting students to use the uncertainties as resources for sensemaking to understand and explain a phenomenon throughout the trajectory of sensemaking. In this section, we introduce our view of sensemaking as a trajectory of grasping better understanding in the science classroom. Based on this perspective, we propose a framework of four phases of sensemaking, elaborate on uncertainty, and explain our focus on conceptual and epistemic uncertainties that we identify in the four phases of sensemaking. We end with a review of the literature on teaching strategies to support student uncertainty navigation in sensemaking.

2.1 | Sensemaking as a trajectory of grasping better understanding

Studies that view sensemaking as a process spanning a whole class period, or even several sessions, provide a starting point to discuss how to support students to construct coherent understanding through the trajectory of

sensemaking (e.g., Lowell et al., 2022; Penuel et al., 2022; Reiser et al., 2021; Tekkumru-Kisa et al., 2023). Schwarz et al. (2017) suggested that sensemaking is “the conceptual process in which a learner actively engages with the natural or designed world; wonders about it; and develops, tests, and refines ideas with peers and the teacher” (p. 6). We consider this perspective more powerful than conceptualizing sensemaking as a particular “aha!” moment, because making sense of a phenomenon is an ongoing process “of building an explanation to resolve a perceived gap or conflict in knowledge” (Odden & Russ, 2019, p. 187). This view of sensemaking aligns with Dewey’s (1933) reflective thinking, through which students need to define a problem, analyze the problem, tease out possible solutions, and decide on the best solution available. This view also corresponds to what Quintana and colleagues (2004) argued to be productive sensemaking, which connects to how students reason “about a phenomenon to a process for testing a conjecture and from the empirical data generated in that testing back to the implications for the phenomenon” (p. 344).

Quintana and colleagues (2004) indicated that sensemaking is a trajectory centralized with students’ ideas, aiming to construct a more coherent and consistent understanding. Based on these studies, we consider sensemaking as a trajectory of how student understanding in science lessons is cumulatively developed. Sensemaking consists of classroom activities that are sequenced in such a way that students make sense of them (Cannady et al., 2019; Krist & Shim, 2023; Reiser et al., 2021; Zembal-Saul et al., 2013). Namely, a trajectory of sensemaking is designed in relation to student *need*. It is expected that students are aware of what they are trying to “figure something out” (Odden & Russ, 2019, p. 192) and why they are working on a certain sequence of activities (Penuel et al., 2022).

This perspective on sensemaking raises a critical question: What is the “need” that drives and motivates students to figure something out and navigate their sensemaking? Scholars have argued that unless teachers can design or respond to the “need” to engage students in sensemaking, the practice of sensemaking is likely to have little scientific meaning for students (e.g., Engle & Conant, 2002; Gouvea et al., 2022; Ha et al., 2023; Kang et al., 2016; Manz, 2018). They have advocated that students’ scientific uncertainty is a “need” that establishes a meaningful trajectory of sensemaking. For example, Manz and colleagues (e.g., Manz & Suárez, 2018; Manz, 2015; Watkins & Manz, 2022) showed that students’ scientific uncertainty motivates students to identify the insufficiency and incoherence of their intuitive thinking about a phenomenon and supports them to find conceptual resources to generate their solutions to explain the phenomenon and pursue deeper understanding. Tekkumru-Kisa et al. (2020) concurred that “having students experience productive uncertainty is considered critical for students’ productive struggle and sensemaking throughout a lesson” (p. 613). In studying how 10th-graders learned mechanics, Tiberghien et al. (2014) suggested that “uncertainty is an essential component of the growing of knowledge” (p. 934) and “can drive the learning process of knowledge” (p. 931). Building on these studies, we expand our view of sensemaking as a prolonged trajectory to encompass students’ scientific uncertainty that drives students in grasping better understanding along the trajectory of sensemaking.

2.2 | Four phases of sensemaking associated with scientific uncertainties

From iterative reviews of relevant literature (e.g., Ancona, 2012; Kapon, 2017; Odden & Russ, 2019; Phillips et al., 2018; Reiser et al., 2021; Schwarz et al., 2017; Windschitl et al., 2018), we identified the following four phases of sensemaking: (1) initial engagement with a driving question related to a target phenomenon, (2) identification of incoherence and insufficiency in existing understanding, (3) exploration of multiple resources to help develop plausible explanations, and (4) synthesis of solutions and application of new understanding to interpret the phenomenon (Table 1). The features of the four phases are described based on what students would act to grasp better understanding.

Phase 1 begins when students have an opportunity to explore a target phenomenon (Chen & Jordan, 2023; Chin & Osborne, 2010; Engle & Conant, 2002; Phillips et al., 2018). In the science classroom, the target



TABLE 1 Features of sensemaking phases and sources of scientific uncertainty in each phase.

Phases of sensemaking	Features of sensemaking	Sources of scientific uncertainty
Phase 1. Initial engagement with a driving question related to a target phenomenon	Students explore a natural phenomenon and engage in generating initial ideas and questions.	• Prior knowledge alignment with the phenomenon • Differences among diverse ideas to explain a phenomenon
Phase 2. Identification of incoherence and insufficiency in existing understanding	Students identify the gaps in their existing understanding and frame hypotheses and plans to search resources to further develop better understanding.	Incoherence and insufficiencies that exist in students' understanding
Phase 3. Exploration of multiple resources to help develop plausible explanations	Students explore resources to develop an explanation of the phenomenon.	Ways to resolve incoherence or insufficiencies in the students' existing understanding
Phase 4. Synthesis of solutions and application of new understanding to interpret the phenomenon	Students engage in synthesizing the suggested solutions and constructing a shared understanding of the phenomenon.	Synthesis and application of what students have learned from the previous phase to interpret the phenomenon

phenomenon is observable, complex, and meaningful, aligning with students' everyday life and core concepts to be learned (Penuel et al., 2022; Windschitl et al., 2018). The target phenomenon can be a natural event anywhere in the world, an unexpected experimental result, or a prediction. The goal is to initiate the process of sensemaking through which students can “develop the knowledge necessary to explain or predict the phenomena” (Achieve, 2017, p. 2), while they discuss their uncertainties largely revealed through their examination of their existing understanding. Exploring the target phenomenon, students express their initial ideas about how the phenomenon occurred. In this phase, it is important to ensure that students have equitable opportunities to share their experiences and express their uncertainties to engage in sensemaking of the target phenomenon (Bang et al., 2017; Haverly et al., 2020; Kang, 2022). Students can express their interpretation of the phenomena and bring their everyday experience, everyday language, and cultural background to the joint discussion. The source of scientific uncertainty in this phase will result from not only the process of aligning prior knowledge with the phenomenon (Chin & Osborne, 2010; Engle & Conant, 2002; Penuel et al., 2022) but also differences among the students' diverse initial ideas (Allchin & Zemplén, 2020; Feinstein & Waddington, 2020; Ford & Forman, 2015).

In Phase 2, students identify gaps between what they know and do not know, as well as what they should know to explain the target phenomenon (Ford & Forman, 2015; Schwarz et al., 2017). These gaps, which indicate student scientific uncertainty, can result from students' incoherence and insufficiency of initial ideas for explaining the phenomenon. Here, incoherence means that students' prior knowledge is inconsistent and may conflict with the presented phenomenon (Klein et al., 2006a, 2006b; Odden & Russ, 2019). Insufficiency refers to the need for students to acquire further understanding to explain the phenomenon (Chen, 2020). Students may identify and unpack incoherence and insufficiency when they engage in deep and varied reasoning (e.g., analogical, deductive, inductive) to clarify how their initial mental models can explain the encountered phenomenon (May et al., 2006; Niebert et al., 2012). For example, when students explore a phenomenon about why seeds lost weight when sprouting, they may analogize the weight change in plants to that in the human body. This analogical reasoning not only helps students connect their prior knowledge to the target phenomenon but also supports them to clarify their initial mental models of the phenomenon. During the reasoning process, students may identify gaps in their current understanding, such as whether analogizing the mechanism in plants to the one in the human body is valid. These gaps then prompt students to shape hypotheses and plans to find potential solutions. Identifying gaps in their

existing knowledge, students can co-participate in shaping and developing the subsequent trajectory of sensemaking (Reiser et al., 2021).

In Phase 3, students navigate what resources they need to resolve insufficiency and incoherence and use the collected resources to construct potential explanations. They engage in the investigation of variables and the collection of data that they can use to resolve incoherence and insufficiencies in their initial ideas (Beven, 2016; Reiser et al., 2021; Schwarz et al., 2017). These data could include information from different knowledge sources (e.g., children's dictionary, the Internet), relevant scientific concepts, and their observations of the target phenomenon. During this phase, students are uncertain as to what resources to use and how to make connections between what they have explored from different resources.

In Phase 4, students synthesize their solutions to resolve the insufficiency and incoherence identified in Phase 2 and apply new understandings to explain the target phenomenon (Ford, 2008; Schwarz et al., 2017). With the resources and solutions explored in the previous phase, students engage in constructing coherent understanding to explain the target phenomenon. Thus, it is expected that students can resolve their uncertainties regarding what to choose among the multiple possible explanations and how to apply what they have learned from the previous phase and develop a shared understanding of the phenomenon within their classroom community. In this process, students can develop a sense of caring and respect to address diverse ideas and perspectives and contribute to synthesizing a shared understanding. Specifically, students can discuss how to use various resources gathered in Phase 3 to synthesize a new explanation. This can involve examining the usefulness of each resource through different perspectives that students bring from their diverse sociocultural backgrounds.

This theoretical framework was used in the current study to unpack how scientific uncertainties evolve and drive the trajectory of sensemaking. However, scientific uncertainty is a complex construct that has not yet been clearly defined in the field of science education. In the next section, we expand current understanding of scientific uncertainty and conceptualize scientific uncertainties into two forms in relation to knowledge and knowing: content uncertainty and epistemic uncertainty.

2.3 | Defining scientific uncertainty: Conceptual uncertainty and epistemic uncertainty

Although educational scholars have defined and used scientific uncertainty in different ways based on their research objectives (e.g., Acar et al., 2010; Bateman et al., 2022; Chen, 2020; Kampourakis & McCain, 2020; Ko & Luna, 2023; Manz & Suárez, 2018; Watkins et al., 2018), most agree that it refers to the situation in which students feel a struggle, confusion, and doubt about their state of understanding while trying to explain a phenomenon. To identify and explore scientific uncertainty from classroom sensemaking discourse, it is critical to unpack what understanding students need to explain a phenomenon. If we can address this question, we may better understand what scientific uncertainty is and empirically operate this construct in our research.

Current reform documents (Ministry of Education, 2015; NRC, 2012) and research (e.g., Ford & Wargo, 2012; Osborne, 2014) suggested that conceptual and epistemic understandings are two critical types of understanding that students use to engage in making sense of natural phenomena. Therefore, two types of scientific uncertainties are identified based on the target understandings of science learning: conceptual uncertainty and epistemic uncertainty.

Conceptual uncertainty can be described as students' subjective experience of being unsure or struggling about using existing conceptual understanding to explain a phenomenon (Chakravartty, 2017; Chen & Qiao, 2020; Jordan & McDaniel, 2014; Kampourakis & McCain, 2020; van der Bles et al., 2019). Conceptual understanding can be considered as comprehension, mastery, and practical grasp of content knowledge and everyday knowledge toward a particular topic. Content knowledge is the scientifically established knowledge of facts, theories, ideas, and concepts of the natural world, such as Newton's laws of motion, Darwin's theory of evolution, or Boyle's law of the relationship between pressure and volume. Simply speaking, content knowledge is about *knowing what* and *knowing*



that (Duschl, 2008; Ryle, 1949). It has been emphasized in national standards (e.g., NRC, 2012), assessments (e.g., National Assessment of Educational Progress [NAEP], 2014; Orpwood, 2001), and research (e.g., Klosterman & Sadler, 2010); also, it is an essential component to determine student learning outcomes in science. Everyday knowledge, also called intuitive knowledge, refers to informal knowledge and common sense developed through and used in students' daily lives, experiences, and observations (Eberbach & Crowley, 2009; Warren et al., 2005). When explaining an encountered phenomenon, Barton and Tan (2009), Silseth (2018), and Warren et al. (2001) found that students not only use content knowledge about what they learned from previous lessons but also retrieve their everyday knowledge. Furberg and Silseth (2022) argued that invoking the two types of knowledge helps students productively and conceptually participate in the discussion, coherently test their conceptual understanding about the phenomenon, and promote their authority over uncertainty.

Epistemic uncertainty can be described as students being unsure or struggling about using their epistemic understanding to explain a phenomenon. It emerges while attempting to formulate specific questions, generate data, analyze data to find patterns, interpret data to shape rigorous evidence and explain phenomena, and reason to identify gaps in existing conceptual understanding (Beven, 2016; Kampourakis, 2018; Kirch, 2010; Sensevy, 2014; Tiberghien et al., 2014; Urbanek et al., 2023). Epistemic understanding is the understanding of how to interpret data as evidence and justify claims and solutions to problems (Chen et al., 2016; Kelly & Licon, 2018; Leung, 2020; Ryu & Sandoval, 2012; Yang et al., 2018). Duncan et al. (2018) described epistemic understanding in four aspects: (a) evidence analysis, which includes the understanding of how data and conclusions fit together; (b) evidence evaluation, which includes the understanding of how to critically examine the quality of evidence; (c) evidence interpretation, which includes the understanding of how to derive theoretical claims, explanations, or models from evidence; and (d) evidence integration, which includes the understanding of how to coordinate diverse evidence with alternative claims. Lee et al. (2023) described epistemic understanding as students' abilities to "evaluate the applicability, limitation, uncertainty, and generalizability of evidence based claims from scientific experiments" (p. 11). From an assessment perspective, Osborne (2016) described epistemic understanding as knowledge in several features, such as knowledge of reasoning (e.g., deductive, inductive, abductive, analogic), knowledge of how a scientific claim is supported by data and reasoning, knowledge of the function of a hypothesis in establishing a testable question and prediction, and knowledge of how to represent and communicate models or arguments to peers. Unfortunately, this understanding is generally overlooked or deemphasized in traditional science teaching. The science education literature has largely criticized the traditional classroom that overly focuses on recalling "correct" knowledge and has argued for providing opportunities for students to participate in the process of sensemaking and develop epistemic understanding (e.g., NRC, 2012).

In this study, we consider both conceptual and epistemic uncertainties as important scientific uncertainties necessary for driving the process of sensemaking. The conceptual and epistemic uncertainties have distinguishable and complementary roles, thus requiring their parsing as well as co-consideration. This can be interpreted as a critique of the over-emphasis or distortion (e.g., solely focusing on content knowledge rather than integrating content and everyday knowledge) of conceptual uncertainty in the traditional classroom and an argument for addressing epistemic uncertainty. On one hand, we agree with how conceptual uncertainty has been solely emphasized or distorted in traditional classrooms (e.g., questions focusing on recalling existing content knowledge) and how we need to move away from only focusing on conceptual uncertainty in student learning. On the other hand, without considering the role of conceptual uncertainty, it is unlikely to meaningfully unpack how student uncertainty evolves and progresses across the trajectory of sensemaking when students explore a phenomenon—that is, how conceptual and epistemic uncertainties develop and drive students' sensemaking process.

By considering the two types of uncertainties, we can capture a fuller picture of what teacher strategies support students as they navigate the scientific uncertainties in each phase of sensemaking. This approach is unique in that our review of the literature in science education did not reveal any studies that explicitly examined how the two types of uncertainties mutually support and drive the process of sensemaking. Therefore, based on the framework of sensemaking shown in Table 1, we examine how conceptual and epistemic uncertainties arise, how

they separately and jointly shape and drive the flow of a trajectory in each phase, and what strategies teachers can incorporate to use them as pedagogical resources to help students make sense of a target phenomenon.

2.4 | Teacher support and strategies for student uncertainty navigation

Researchers in science education have implicitly or explicitly investigated teacher strategies to support student navigation of uncertainty for sensemaking. Argumentation is one of the richest areas in science education research on student uncertainty related to sensemaking (McDonald & Kelly, 2012). Scientific uncertainty is inherent in argumentation, because students engage in using their conceptual and epistemic understanding to interpret data to shape scientific evidence, critique peers' arguments, identify knowledge gaps, and collectively generate new solutions to a given problem (e.g., Bächtold et al., 2023; Buck et al., 2014; Chen et al., 2019; Ford & Forman, 2015; Grimes et al., 2019; Lee et al., 2014, 2020; Manz, 2015; Osborne & Patterson, 2011; Rapanta & Felton, 2022). These researchers have identified many sources of students' epistemic uncertainty (e.g., generate scientific evidence and claims, identify incoherence of arguments) and have suggested strategies to develop students' epistemic understanding of argumentation and scientific practices (e.g., using Toulmin's argument structure). This line of studies has implicitly recognized the role of uncertainty in student learning and dialogue, as well as having provided some strategies to deal with uncertainty.

So far, studies that have explicitly explored uncertainty management for sensemaking have focused mainly on making uncertainty tangible for students and using it as a means to make space to discuss, debate, and debunk ideas. From a curriculum design perspective, Manz and Suárez (2018) identified three strategies to help elementary science teachers embed scientific uncertainties in curricula and lesson plans: start with complex phenomena, iterate on relevant investigations, and promote variability in students' thinking. Watkins and colleagues (2018) used "framing" strategies to position students as "not-understanding" by asking questions about a phenomenon. They found that uncertainty can create a space "in which they not only can present claims, but also can articulate what they do not yet understand" (p. 593). Watkins and Manz (2022) identified some teachers' pedagogical decisions as a way to use students' uncertainty for making sense of a phenomenon, such as deciding which uncertainties should be explored or postponed and how to transform individuals' uncertainty into a public problem.

Drawing upon semiotic theory, Oliveira et al. (2012), Tang (2021), and Kirch and Siry (2012) showed that by using hedging expressions (e.g., *maybe*, *might*, and *could*), teachers and students could explicitly communicate uncertainty, leading to the co-construction of shared knowledge. Building on the equitable sensemaking perspective, researchers suggested incorporating students' diverse initial ideas and questions as intellectual resources so that equitable opportunities are provided for them to participate in the subsequent process of sensemaking (e.g., Carlone et al., 2011; Haverly et al., 2020; Kang, 2022; Warren et al., 2001). Kang (2022) contributed to developing teaching strategies to promote equity in sensemaking by attending to students' struggles and needs, interpreting classroom situations with consideration of power dynamics, and taking pedagogical actions to expand equitable opportunities for engagement.

Recently, Chen and colleagues (Chen & Qiao, 2020; Chen & Techawitthayachinda, 2021; Chen, 2022) focused on epistemic uncertainty and described strategies to raise (e.g., note ambiguities), maintain (e.g., discuss alternative or conflicting ideas), and reduce student uncertainties (e.g., making a coherent connection among prior knowledge, current uncertainty, and familiar phenomena). However, their studies focused only on epistemic uncertainty at some specific moments and were limited in unpacking specific strategies to deal with conceptual and epistemic uncertainties throughout different phases of sensemaking.

As mentioned above, current strategies identified to navigate uncertainty for sensemaking have focused on making space for dialogical interaction and discussion. Few studies have explored strategies across different phases of sensemaking to solve students' uncertainties and further develop a better understanding. Although some studies have explored strategies to maintain and reduce uncertainty, very few studies have



investigated strategies to navigate both *conceptual* and *epistemic* uncertainties and the dynamic and evolved nature of uncertainties that drive the trajectory of sensemaking. To support sensemaking in the science classroom, we need to understand how to manage students' dynamic uncertainties that emerge through different phases of sensemaking.

3 | OBJECTIVES AND RESEARCH QUESTIONS OF THIS STUDY

This study examines how the science teacher can support students' navigation of dynamic and evolving scientific uncertainties that emerge and drive the four phases of sensemaking, thus building a prolonged trajectory of sensemaking. In the current study, we consider two types of scientific uncertainty that are navigated in sensemaking—conceptual uncertainty, the uncertainty in using existing conceptual understanding to respond to a certain problem (Chen & Qiao, 2020; Jordan & McDaniel, 2014), and epistemic uncertainty, the uncertainty in using epistemic understanding to explain a phenomenon (Beven, 2016; Kampourakis, 2018; Kervinen & Aivelo, 2023; Tiberghien et al., 2014). Based on the defined uncertainties and the framework (Table 1), we explored how the conceptual and epistemic uncertainties evolved and drove the four phases of sensemaking, and what strategies teachers used to support students' navigation of uncertainties to develop coherent understanding. Specific research questions are as follows:

- (1) How do students' scientific uncertainties, including conceptual and epistemic uncertainties, evolve and drive the four phases of sensemaking?
- (2) What strategies do science teachers use to support student navigation of scientific uncertainties with dynamic and evolving nature in each phase and cumulatively to develop coherent understanding?

4 | METHODS

4.1 | Research design

This study was designed as a follow-up to initial explorations of a teaching intervention focused on argumentation, in which students' ideas were to be used as resources for knowledge development in the science classroom. After the completion of the initial studies that were conducted separately in South Korea (Cho et al., 2019) and the United States (Chen & Qiao, 2020), the first author, who conducted studies in South Korea, and the second author, who conducted studies in the United States, had intensive discussions about what made the argumentative dialogue productive and if there were any commonalities among the teachers from the two countries. We found that students' scientific uncertainty played a critical role in creating a need for them to engage in argumentation and driving trajectories for sensemaking of target phenomena. Therefore, we decided to further examine classroom discourse to understand how student scientific uncertainties drove the discourse and to identify strategies of how teachers used students' scientific uncertainty as a pedagogical resource to help them make sense of a phenomenon.

In the current study, we employed a multiple case study method (Merriam, 1998) to examine various cases of uncertainty navigation in sensemaking and to identify general teaching strategies that support students' navigation of scientific uncertainties during collective discussions (e.g., small group or whole-class discussions). Because the goal of this study was *not to compare the differences* among different classrooms, we took a diverse cases approach (Seawright & Gerring, 2008), aiming to *identify commonalities* among these diverse cases. Therefore, two science classrooms were purposefully selected from East Asian and Western cultures, one in South Korea and one in the United States to represent different cultures and learning contexts.

4.2 | Participants

A Korean teacher, Ms. Kim, was chosen among five teachers who participated in a 1-day professional development workshop that aimed to develop teacher strategies to support student engagement in argumentation for making sense of phenomena. After the professional development, Ms. Kim was selected because she was the most active in collaborating with the first author to discuss lesson plans, worksheets, and activities. At the time, Ms. Kim taught seventh-grade and had 10 years of teaching experience in secondary-level schools.

Similarly, one US teacher, Ms. Ellis, was chosen among three teachers who participated in a similar 1-day professional development workshop held by the second author in the United States. Ms. Ellis was also the most active teacher, collaborating with the second author to design lessons, identify phenomena to be explored, and create worksheets and activities. She was a fifth-grade teacher with 10 years of teaching experience in elementary-level schools. Table 2 presents a description of the two teachers and their classrooms.

The two classes focused, respectively, on *plants and energy* and *human respiratory* system units. Target phenomena to make sense of were developed and/or selected so that students could learn and use core concepts in each unit as suggested in the national curricula for sensemaking (Ministry of Education, 2015; NGSS Lead States, 2013). For example, to support students learn and use the concept of transpiration, an experimental phenomenon was contrived in which a plant with its stoma was blocked with lotion on its leaves and a plant that was not so blocked. The students were to compare the conditions of the two plants (the independent variable) and explain the difference in their consumption of water (the dependent variable). In this specific case, students were expected to explain why the water level of a bottle for the plant without lotion was lower than that with lotion using the notion that the plant without lotion could transpire and lose water inside it through the stoma more easily and absorb water from the bottle.

4.3 | Educational context

Although the two teachers participated in separate professional development workshops in two different countries, both workshops presented several common design principles related to argumentation activities. Below are the key common principles identified through the authors' discussion.

4.3.1 | Design principle 1: Engage students in problematizing a target phenomenon

Teachers were asked to present a target phenomenon and problematize it, that is, identifying incoherence in students' initial explanations of the phenomenon. This was expected to facilitate their recognition of the necessity for further discussion to understand that phenomenon (Benedict-Chambers et al., 2017; Engle & Conant, 2002; Yilmaz et al., 2017).

4.3.2 | Design principle 2: Engage students in generating and revising arguments for the sensemaking of a target phenomenon

Classroom activities were designed to have students generate and revise their arguments to explain the target phenomenon. This principle encourages students to shape their conjectures and hypothetical explanations concerning the phenomenon. It was expected that their arguments in the beginning would be unclear; however, as they explore the phenomenon and collect more data, their arguments would become more robust and evidential (Ford, 2012). In other words, the teachers use students' arguments to drive them to develop scientific knowledge cumulatively.

TABLE 2 Description of participating teachers, their students, and the curriculum.

Teacher participants	Country (language of instruction)	Teaching experience	Type of school	Grade level	Science unit	Student gender and ethnicity	Number of lessons and episodes
Ms. Kim	South Korea (Korean)	10 years	Private	Seventh grade	Plants and energy	14 females, 14 males; 28 Asian,	7 lessons, 7 episodes
Ms. Ellis	United States (English)	10 years	Public	Fifth grade	Human respiratory system	11 females, 13 males; 1 Asian, 1 Latino, 1 Black, 20 White	6 lessons, 11 episodes

4.3.3 | Design principle 3: Engage students in socially negotiating their arguments to reach a consensus

We viewed social discussion as key to developing scientific knowledge in scientific communities, and scientific argumentation encompasses this social aspect (Ford, 2012; Kolstø & Ratcliffe, 2007). It is a process in which various arguments are proposed, evaluated, and revised with the goal of developing an argument that community members can accept. Reflecting this social aspect of argumentation, the activities were designed to provide students with opportunities to share and revise their ideas through collective discussion. Teachers were also asked to encourage students' engagement in collective discussion by, for example, emphasizing that reaching a consensus, rather than finding out "correct" knowledge, is a sound way to validate an argument.

With these design principles in mind, we collaborated with teachers through multiple meetings before and during the implementation of the curriculum. During the meetings, we collaboratively revised teacher lesson plans, designed worksheets and activities, and clarified teacher concerns about implementing argumentation in their classrooms.

Although the four phases of sensemaking were not addressed in both of the workshops, the two teachers showed commonalities in their enactment of argumentation activities. They began each activity with the presentation of a target phenomenon. Then, they asked a driving question that encouraged students to share their initial ideas to make sense of the phenomenon. Classroom discussion followed to develop evidence-based knowledge of the phenomenon. In this discussion, the teachers encouraged students to identify gaps in their initial ideas, generate and evaluate new plausible ideas, and develop an evidence-based explanation. The teachers often joined in students' small group discussions and took the role of a critic to facilitate the identification of scientific uncertainty and further development of a better understanding. The activity usually ended with the students' development of final knowledge that they agreed to be valid.

4.4 | Data collection and selection

The main data sources of this study were video recordings and transcripts of discourse (e.g., small group and whole-class discussions) in the classrooms. Student-created artifacts and writing samples were also collected or recorded in photographs and used as auxiliary data to understand the contexts and processes of classroom activities.

After rounds of reviewing these materials, we decided to analyze data regarding collective discussions in each classroom. Specifically, we selected the whole-class discussion and small-group discussion from the two teachers' classrooms. These data were chosen for analysis because we considered that these collective discussions were where the process of development of explanations to make sense of a target phenomenon occurred. These diverse activities and learning environment helped us unpack and identify general teaching strategies that support students' navigation of the scientific uncertainties during collective discussions (e.g., small group or whole-class discussions). Due to the nature of the two teachers' classrooms described above, we viewed the selected parts as offering the most direct window through which to explore student uncertainty and sensemaking.

4.5 | Data analysis

Our data analysis process consists of five steps. Supporting Information: Appendix A presents an example from Ms. Kim's lesson about osmosis in the plant root's absorption of water. In this lesson, the teacher presented a video clip illustrating a carrot with a hole in the middle (Supporting Information: Appendix B). The carrot was put in distilled water, and water outside the carrot moved into the hole in the carrot as time passed. Students were asked to develop arguments that make sense of how water outside a carrot comes into it. Students' group discussion lasted for about 35 min.



4.5.1 | Step 1: Identification of episodes

We first iteratively watched the video recordings and read the transcripts while referring to the student-created artifacts and writing samples. Then, we divided the transcripts of each lesson into episodes. Based on our theoretical framework, we defined the boundaries of an episode as starting from a teacher's driving question of a target phenomenon and ending when students reached an agreed explanation of the given phenomenon. However, there were some episodes in which students did not reach an agreed explanation and moved to another discussed topic. In such episodes, we viewed that the episode as having ended. We included these episodes that did not reach the last phase in our analysis because there was a possibility of identifying the teachers' strategies that successfully supported students to navigate uncertainty. Episodes lasted from 5 to 40 min, and 18 episodes were identified from the two classrooms (Table 2).

4.5.2 | Step 2: A microlevel analysis of episodes

Once episodes were identified, we conducted a microlevel analysis of the episodes using an ethnographic microanalysis method (Atkinson et al., 2011; Erickson, 1992), which examines how classroom participants socially shape their collective understanding of a discussed issue through interactions. We first developed a tentative framework of phases of sensemaking based on literature review about sensemaking and iterative review of 18 episodes. Specifically, we reviewed video recordings of the classrooms and noticed that classroom discussions progressed in a similar sequence to make sense of a target phenomenon. Then, we refined the tentative framework based on the overall iterative review of data. These inductively derived analyses were revised through an iterative process until a comprehensive framework (see Table 1) emerged that covered the 18 episodes (Lincoln & Guba, 1985).

An example to identify the four phases of sensemaking is provided in Supporting Information: Appendix A. The beginning of Phase 1 was identified as the teachers' introduction of a target phenomenon (see Supporting Information: Appendix B) and the asking of driving questions: "Think of a most valid argument to explain the phenomenon." When students' initial ideas were shared after teachers' questions, an identification of incoherence and insufficiency in their existing understanding followed. Students' identification of their incoherence and insufficiency, which we defined as their inconsistency, differences, and gaps in the shared ideas, signaled to us the beginning of Phase 2. In the episode in Supporting Information: Appendix A, incoherence in students' initial ideas was explicitly shown when a student asked, "How can water go through cell membranes of the carrot?" This indicated that students were struggling to explain the mechanism of the movement of water across cells of the carrot.

The beginning of Phase 3 was identified from the part where students started to search for additional information and discuss how to use that information in relation to their initial ideas. This conversation usually began with a teacher or students' nudging questions and guidance to use other information sources. In the episode in Supporting Information: Appendix A, Phase 3 began with Ms. Kim's additional explanation of scientific knowledge of a student worksheet, which students struggled to understand, facilitating students' identification of scientific uncertainties to gather resources to develop plausible explanations. The new understanding developed in Phase 3 included clarified and expanded conceptual understanding and an understanding of scientific concepts that can be applied in the next phase.

Phase 4 began with utterances that promote the application of the understanding developed in Phase 3, explaining a target phenomenon by applying the understanding developed in Phase 3. In this episode, after exploring potential resources to use in explaining the phenomenon, one student proposed a claim: "Water can go through cell membranes of the carrot. I think this is the answer." Starting from this utterance, students discussed how to use the idea of osmosis to explain how the water was able to go through the cell membrane of the carrot.

The discussion and Phase 4 ended with the students' development of an explanation that water outside the carrot moved through cell membranes of the carrot by osmosis.

After identifying phases of sensemaking from the data sets, we coded students' conceptual and epistemic uncertainties and their sources. During this analysis, we referred to the literature about identifying scientific uncertainty from an individual's discourse. Conceptual uncertainty was identified as students' struggles with using conceptual understanding to respond to encountered phenomena or discussed issues (e.g., retrieving and using specific content and everyday knowledge) (Chakravartty, 2017; Jordan & McDaniel, 2014; Kampourakis & McCain, 2020; van der Bles et al., 2019). Epistemic uncertainty was identified as students' struggles about how to use their epistemic understanding to respond to encountered phenomena or discussed issues (Beven, 2016; Kirch, 2010; Sensevy, 2014; Tiberghien et al., 2014). We referred to these definitions to code conceptual and epistemic uncertainties from video recordings and transcripts of classroom discussions. An example of the coding process at this stage is shown in Supporting Information: Appendix C, and examples of conceptual and epistemic uncertainties that we coded are shown in Supporting Information: Appendix D. Conceptual and epistemic uncertainties identified in each phase from 18 episodes are shown in Supporting Information: Appendix E.

Teaching strategies to support students' navigation of scientific uncertainties were coded across the datasets. To identify teaching strategies, we explored events with the guiding question of how a teacher supported students to identify and resolve uncertainties that drive the progression through sensemaking. For example, in the discourse in Supporting Information: Appendix C, we identified that the teacher was supporting students to *identifying information and knowledge resources that can be comprehensible to students* so that they can use the scientific concept as a resource to develop a plausible explanation. Examples of coded teaching strategies are shown in Supporting Information: Appendix F. The initial codes were revised through discussions among researchers so that the codes could clearly show different strategies.

4.5.3 | Step 3: Generation of figures visualizing the development of uncertainty in the trajectory of sensemaking

After identifying scientific uncertainty and teacher strategies, we generated a figure that summarized the flow of uncertainty development in each episode (see the figure in Step 3 in Supporting Information: Appendix A). In generating this figure, we placed the uncertainties identified in each phase and used arrows to show the sequence of uncertainty emergence and interrelatedness of the emerged uncertainties. For example, Minkyung's questions to understand information written on expert cards on the student worksheet (line 171) showed conceptual uncertainty. This was followed by a conceptual uncertainty of water movement by osmosis (lines 177, 179). We placed the two uncertainties in Phase 3 in Supporting Information: Appendix C and visualized this trajectory of uncertainty development using arrows, as shown in Step 3 in Supporting Information: Appendix A. The generation of this figure helped us to visualize how student scientific uncertainty dynamically evolves and drives the sensemaking. In addition, the visualized uncertainty development helped us compare and contrast the 18 episodes.

4.5.4 | Step 4: A summative theorization of teaching strategies

Next, we developed a summative theorization of teaching strategies for each phase of sensemaking. Specifically, we first generated sequences of uncertainty development through the four phases of sensemaking in the selected episodes. The patterns of uncertainty development and sources of the uncertainties were compared and organized into a framework. For example, in the episode in Supporting Information: Appendix A, conceptual uncertainty was identified in Phase 1 when students attempted to retrieve scientific knowledge that they learned before to explain the target phenomenon. Thus, we presented in the summative figure (Figure 4) that this type of conceptual



uncertainty emerged from students' attempts and struggles to *retrieve content knowledge or use everyday knowledge* to understand scientific phenomena. Through comparison with uncertainties identified during other episodes, we identified an epistemic uncertainty in Phase 2 to have emerged when *identifying the gap in existing understanding of the phenomenon*. In Phase 3, we interpreted that conceptual uncertainty was managed to *develop relevant content knowledge*. In Phase 4, we found epistemic uncertainty in how to apply the new understanding of osmosis to explain the target phenomenon, which corresponds to *comparing new understandings and applying the "best" new understanding to explain to the phenomenon*.

The identified teacher strategies to support the navigation of scientific uncertainties in each phase were organized and added to the framework. In Supporting Information: Appendix A, we identified teacher strategies *eliciting initial ideas to explain a phenomenon; focusing on and/or amplifying specific aspects of a core concept and the ways of thinking; identifying information and knowledge resources that can be comprehensible to students; and synthesizing, evaluating, and applying the "best" new understanding to explain the phenomenon*. These teaching strategies were placed in each phase along with strategies identified in other episodes.

To minimize subjectiveness in our analysis, the three authors independently analyzed the data first and then held meetings at each step to discuss any disagreements and revise the analysis accordingly.

4.5.5 | Step 5: Selection of representative episodes

The final step was to choose representative episodes to present in the Findings section based on three criteria: The first criterion was whether there were four phases clearly shown in the episode. This means that there were episodes in which students did not reach the last phase of developing new understanding to interpret the given phenomenon, and we chose the episodes that showed the four phases clearly to present ample data regarding how teachers and students navigate the uncertainties in sensemaking. For the second criterion, we selected episodes that represented different types of target phenomena, which refer to natural phenomena that are found in a student's everyday life, and investigative phenomena, which refer to phenomena artificially set up for experimentation or investigation (Bobrowsky, 2018). The third criterion included whether the episode contained different types of scientific uncertainties associated with various teaching strategies that we identified in each phase. After repeated viewing of the data sets, we selected two episodes that met these three criteria. The selected two episodes show typical patterns that emerged in the 18 episodes, illustrating how scientific uncertainties developed, as well as what teacher strategies were used to support students' uncertainty navigation in the trajectory of sensemaking.

5 | FINDINGS

We present two representative cases within the framework of the four phases of sensemaking. Then, we unpack how the teachers supported students' navigation of the entangled conceptual and epistemic uncertainties and the development of a trajectory of students' sensemaking. We summarize the two cases and discuss what strategies teachers used to support students to navigate their conceptual and epistemic uncertainties.

5.1 | Case 1: Sensemaking of the everyday phenomenon of human breathing

5.1.1 | Description of the episode

This episode occurred in the second lesson on the human respiratory system, when Ms. Ellis introduced an everyday phenomenon. Before this lesson, students had learned about the structure of the human respiratory

system by searching for relevant information in their school library. The following episode occurred after they had gathered and discussed that information. By the end of this lesson, the students were expected to understand the process of breathing caused by pressure fluctuations within the lungs.

Phase 1: Initial engagement with a driving question related to a target phenomenon

In this initial phase, Ms. Ellis used a variety of questions to engage students in discussing the process of breathing and elicit diverse ideas for debate. In response to these supports, students engaged in brainstorming, activating their prior knowledge. This episode began with Ms. Ellis asking students to breathe in and out. Although breathing is an everyday movement, Ms. Ellis wanted students to deliberate on the question "How do you breathe in by your lung?" by integrating what they found in the school library in the previous lesson and their previous experience and understanding. Students responded to Ms. Ellis's question: "Breathe in by your lungs," "You breathe out, too!" "You inhale," and "The air, carbon dioxide, and oxygen go through your nose and your mouth."

Following students' responses, Ms. Ellis emphasized the interrogative by asking, "How? How did it get through there?" A student, Kristy, responded, "Brain sends messages to your lungs to breathe in and breathe out." Ms. Ellis was not satisfied with students' responses and said: "You're telling me that I do. Did I ask whether I breathed in?" She rephrased her original question and asked, "You keep using this word 'breathe,' but I don't understand how. How? How do your lungs do it? So, they get this message [from your brain], then how do they do it?" This time, students provided more diverse answers, such as "You suck it in," "Like a vacuum. Okay, it's like a vacuum," and "Maybe you vacuum air..."

Ms. Ellis captured the moment and used students' language, saying, "You what? You vacuum?" Use of the word "vacuum" sparked an intense disagreement among students: "You can't vacuum with your mouth" and "Is there a vacuum? ... does it suck stuff..."

Ms. Ellis adopted students' language of vacuum and sucking as an opportunity to engage them in elaborating and debating their ideas of breathing. This intention was shown from her responses to students' different ideas. As such, Ms. Ellis problematized the everyday phenomenon to elicit and explore students' diverse everyday knowledge, which became the source of uncertainty. In this phase, students' uncertainty was identified from their struggle with using existing content and everyday knowledge to understand and explain the phenomenon. Therefore, we coded this as conceptual uncertainty.

Phase 2: Identification of incoherence and insufficiency in existing understanding

With attention to the conceptual uncertainty in which students engaged in Phase 1, their subsequent discussion was driven by the epistemic uncertainty about how to use the concept of "vacuum" to analogically explain breathing. The class continued the discussion of using "vacuum" to describe the movement of breathing. Students delved deeper into their explanation about why they supported it, why they disputed it, and why they were confused. The discussion helped students understand the insufficiency of their existing understanding to explain the everyday phenomenon.

For example, students who supported the idea of vacuum elaborated on the process of vacuum in breathing: "When you get a diaphragm contract, it creates a vacuum that causes, um, drawn air into the nose and mouth," "I think you have a suction in your throat, where it ... it ... when you breathe air, you bring it in. And that ... air is everywhere and you bring it in," "It's something that sucks in."

In contrast, students who did not support this idea expressed confusion and doubt regarding the explanation involving a vacuum: "I'm so confused ... I don't understand what they're saying!" "What do you mean by that?" "I don't, it's like you're trying to make stuff up." One student, Becca, was confused about the analogical reasoning and said, "Your heart pumps it in."

Listening to the students' sharing of their ideas, Ms. Ellis noticed confusion and struggle in the students' use of the terms "vacuum" and "suck" to describe the process of breathing. She said, "So now we're back to sucking. So, creating a vacuum and sucking are the same thing?" In response to this question, students tried to explain the



difference between the two concepts, but they kept repeating the same words. Ms. Ellis attempted to summarize the students' ideas and said, "We've got a couple of different explanations.... We got... you suck it in.... Something about pressure. ... And then the diaphragm's goanna contract and create a vacuum. What's a vacuum?" At this moment, the students' discussion was stagnant and did not move forward.

The discussion in this phase was driven by the epistemic uncertainty (i.e., struggling to analogize "vacuum" and "suck" to explain the breathing process) that was intertwined with the prior conceptual uncertainty (i.e., "How do we breathe?") of the previous phase. Ms. Ellis not only supported students to express their ideas and disagreements but also tried to maintain and increase their uncertainty to identify the incoherent elements of their discussion and the insufficiency of their existing understanding. The incoherence identified in this phase is the idea of using "vacuum" and "suck" to explain the breathing process. That is, the students struggled to use the analogy of a vacuum to provide a coherent explanation of breathing. The insufficiency suggests the students' lack of resources to provide a more evidential explanation of the analogy. Although some students seemed to have comprehended the analogy, they struggled to find evidence in explaining the concept of vacuum-movement to describe breathing. That is, they seemed to have insufficient resources to resolve the gap in existing understanding.

Phase 3: Exploration of multiple resources to help develop plausible explanations

When students started to explore multiple resources to deal with the epistemic uncertainty of the previous phase, two conceptual uncertainties emerged: the definition of "vacuum" and the definition of "suck." This phase started from Betty's suggestion, "Why don't we look it up in the dictionary?," which restarted the dead-end conversation in Phase 2. To find definitions of "vacuum," Maria used an adult dictionary and shared her findings with the classroom: "A perfectly empty space; a space partially exhausted as to the highest degree possible by artificial means as an air pump; a degree of rare action below atmospheric pressure; a device created for utilizing a partial vacuum." However, when Ms. Ellis asked which one can fit into their explanation of the process of breathing, students murmured and hesitated to decide. The three definitions from the adult dictionary seemed too complicated for them, and they raised another uncertainty regarding the definition of vacuum suitable for explaining the breathing process. It showed that the definitions from the adult dictionary did not make sense to students, and thus students could not comprehend them.

Recognizing students' uncertainty, instead of providing them with the answer, Ms. Ellis suggested using a children's dictionary, which could provide definitions in a language that they could understand. The students found several different meanings and struggled to figure out which one was the best. The following are some examples that the students found:

April: A vacuum cleaner is "a machine that takes out dirt from carpets, furniture, etc.; to work a vacuum cleaner reduced the air pressure inside itself. Then dirt is carried into it by outside air, rushing to fill the particle vacuum."

Jim: A vacuum is "the air is carried into it by outside air rushing to fill the particle vacuum."

Jackson: Suction is "the act of sucking; drawing up of food into a tube, by expelling the air so that food fills the vacuum."

Andrea: Suck is "the action or process of drawing something as a liquid or dust, into a space, like a vacuum cleaner or pump, by partially exhausting the air in the space... [inaudible]"

In this phase, two conceptual uncertainties emerged as students made sense of the definitions of "vacuum" and "suck." Ms. Ellis did not halt the trajectory of sensemaking here but asked a series of questions to guide students to distinguish the uncertainty regarding relationships between the two concepts, such as, "Which one of those fits with the one we're trying— you guys are trying to use? You got an empty space. Right, so something's being made empty by removing all of the air from it?" These questions led students to continue sensemaking to Phase 4.

Phase 4: Synthesis of solutions and application of new understanding to interpret the phenomenon

After students made sense of what "vacuum" and "suck" mean, students' uncertainties changed and evolved into two epistemic uncertainties: How to distinguish and explain the relationship between "vacuum" and

"suck" and how to apply their understandings of "vacuum" and "suck" to explain the phenomenon. These two epistemic uncertainties drove students to explore their understanding of how humans breathe in this phase.

Following the information students found in the children's dictionary, Ms. Ellis asked a sequence of questions, including, "Are 'sucking' and 'vacuum' the same thing?," "How do they go together? You have to have a suck to make a vacuum?" Her questions raised an epistemic uncertainty about how to distinguish the two concepts and led students to connect their findings and make sense of the relationship between vacuum, sucking, and air pressure (Table 3).

Through this discussion, Ms. Ellis and the students developed a description of a vacuum using the word "air pressure". "[The vacuum gets air in because] the pressure inside is reduced... [and] the air is carried into it [the space] by outside air rushing to fill [the vacuum]." Once students grasped the idea of a vacuum, Ms. Ellis continued to press students to search the definition of "sucking" and identify the difference between the two concepts. As such, the relationship between "vacuum" and "sucking" was clarified based on the clues that students found in the dictionaries, and the mechanistic explanation of the movement of the air that was described when the phrase "sucking in" was explained.

As students developed an understanding of sucking and vacuum, Ms. Ellis raised another epistemic uncertainty about applying their newly developed understanding to explain the phenomenon of breathing. This epistemic uncertainty evolved from the one in Phase 2, in which the uncertainty emerged from an attempt to explain the breathing process by using the new understanding of sucking and vacuum. The following excerpt shows the conversation among Ms. Ellis and students, focusing on explaining breathing using the ideas of vacuum and sucking (Table 4). Through this conversation, the students constructed an explanation noting that after the lungs press in and make the air go out of the human body (line 204), the diaphragm creates a vacuum to bring the air in (lines 207, 209).

TABLE 3 Excerpt illustrating the whole class discussion in Ms. Ellis's classroom about vacuum, sucking, and air pressure (Lines 130–143).

Line	Speaker	Utterance
130	Ms. Ellis	How's it work? How does the vacuum get air in? Does it suck?
131	Emma	No, it reduces the air in.
132	Ms. Ellis	It reduces what?
133	Several students at once	Pressure.
134	Ms. Ellis	Pressure where? ... Reduces the pressure where?
135	Emma	Um... um... eh, inside itself?
136	Ms. Ellis	Inside. So, the pressure inside is reduced and what happens to the air outside?
137	Sophia	Umm....[unclear]
138		[Long pause]
139	Ms. Ellis	Keep going with the sentence.
140	April	Umm....[unclear]
141	Ms. Ellis	Reduces the air pressure inside itself and...
142	Amy	The air is carried into it by outside air rushing to fill the particle vacuum.
143	Ms. Ellis	So, the outside air, then, once it reduces the pressure inside, the outside air...



TABLE 4 Excerpt illustrating the whole class discussion in Ms. Ellis's classroom about "Vacuum" (Lines 204–209).

Line	Speaker	Utterance
204	Ms. Ellis	Ok, so your lungs press in, and that makes the air go... out. So how does it come in?
205	Adam	[Inaudible statement; he is too quiet to be heard by the camera]
206	Ms. Ellis	[To the table that is closest to the camera, where students have been talking quietly among themselves for about a minute] That group, you'd probably get a lot more out of this if you were listening. Louder.
207	Chris	So, since the diaphragm creates a vacuum, wouldn't you suck it in because it's— it creates a vacuum, so the definition of "suck" is the...
208	Maria	But, it kinda sounds like...
209	Ms. Ellis	So, the definition was to create a vacuum to bring air in.

5.1.2 | Teacher's support and strategies for uncertainty development in sensemaking

Figure 1 illustrates the flow and types of uncertainty developed over the four phases of sensemaking. Specifically, Figure 1 helps us understand which type(s) of uncertainty were raised and discussed in each phase and how uncertainties were intertwined and evolved into one another, driving the process. In Phase 1, Ms. Ellis initially posed a driving question, "How do you breathe in by your lung?" to elicit students' prior knowledge and encourage them to express what they found in the library. She rephrased questions in various ways following students' initial responses to elicit more diverse ideas (e.g., "How do your lungs do it? So, they get this message [from your brain], then how do they do it?", "You what? You vacuum?"). Students' struggles were shown from their attempts to use their content and everyday knowledge to answer Ms. Ellis's question, indicating their conceptual uncertainty. Following students' expression of existing understanding flexibly, Ms. Ellis tacitly and explicitly highlighted students' everyday language and experiences—vacuuming and sucking—to generate an uncertain moment in which students expressed several different ideas. Two strategies were identified: (1) eliciting initial ideas and everyday language to explain a phenomenon and (2) connecting and comparing diverse prior knowledge to explain the phenomenon.

In Phase 2, Ms. Ellis focused on helping students explain their ideas and debate the use of the ideas of "vacuum" and "sucking" to analogize the breathing process. In this phase, Ms. Ellis tacitly amplified the uncertainty by focusing on the two concepts. This epistemic uncertainty intertwined with the prior conceptual uncertainty was identified from students' struggle to understand how to use their understanding of the process of vacuuming and sucking to explain the human breathing process. Specifically, this epistemic uncertainty was caused by students' awareness of the incoherence of their existing understanding and insufficient resources to explain the phenomenon, also called the gap in existing understanding. Two strategies were identified: (1) supporting deep reasoning (e.g., analogical reasoning) to identify the gap in existing understanding and what understanding to pursue and (2) focusing on and amplifying specific aspects of a core concept and the ways of thinking expected by the teacher.

To resolve the epistemic uncertainty in Phase 2, two conceptual uncertainties emerged in Phase 3 regarding the definitions of "vacuum" and "sucking." Ms. Ellis guided students to search a children's dictionary to explore the meaning of a vacuum and sucking, supporting them to expand their understanding of the meaning of the terms. It was expected that this expanded understanding could lead not only to resolving students' uncertainty raised in Phase 1 and Phase 2 but also to deepening student understanding of breathing. One strategy was identified: identifying information and knowledge resources that can be comprehensible to students.

In Phase 4, Ms. Ellis did not ask students to immediately apply what they found from the dictionaries but raised two epistemic uncertainties guiding students to synthesize, compare, and connect the relationship between a vacuum and sucking. The initial one was related to distinguishing and explaining the relationship between a vacuum

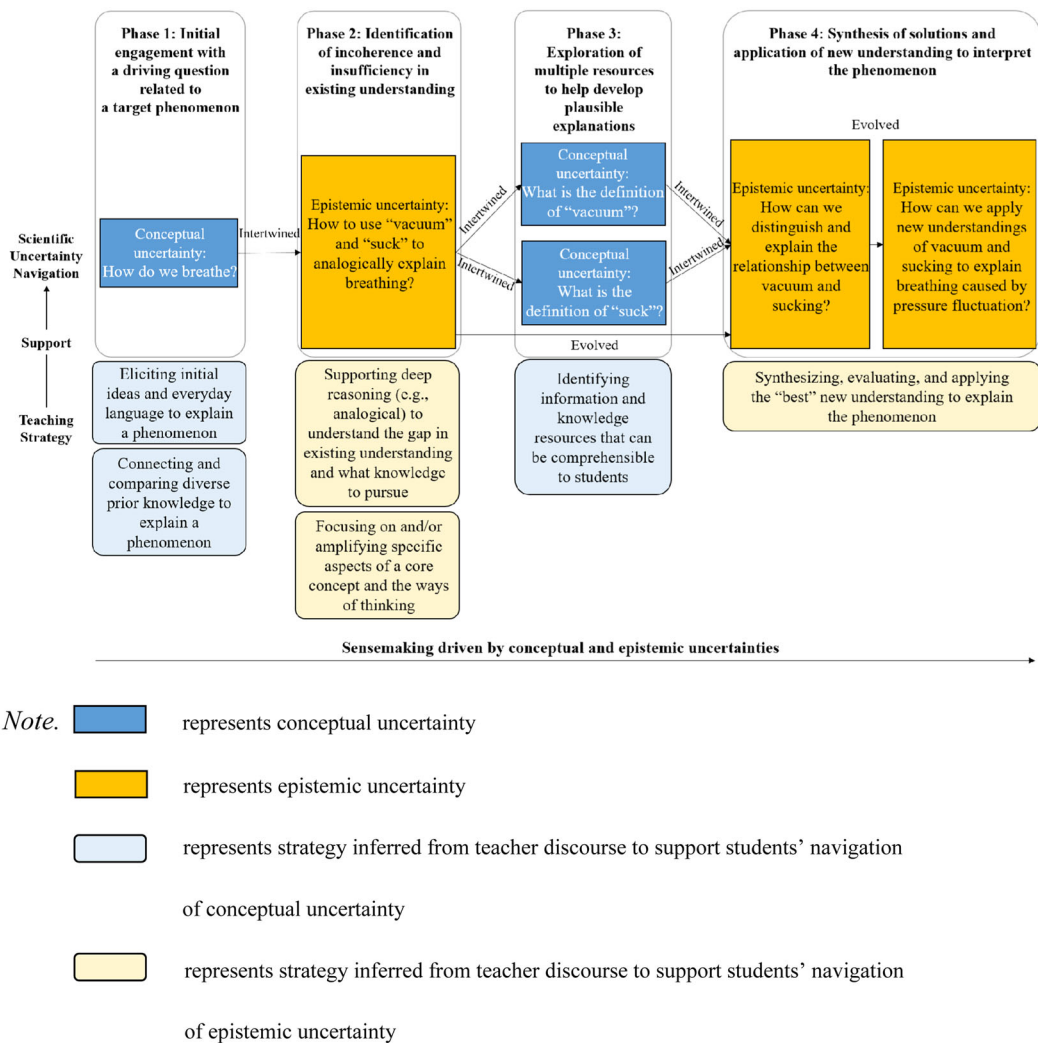


FIGURE 1 The flow of uncertainty development and teacher support in the sensemaking of human breathing.

and sucking. Once students developed an understanding of a vacuum and sucking in response to this epistemic uncertainty, Ms. Ellis raised another epistemic uncertainty and required students to apply what they learned from Phase 3 to explain the human breathing process. In this way, she encouraged students to consider the diverse resources gathered in Phase 3 for the development of an explanation. One strategy was identified: synthesizing, evaluating, and applying the "best" new understanding to explain the phenomenon.

5.2 | Case 2: Sensemaking of a predicted phenomenon of seed germination

5.2.1 | Description of the episode

In Ms. Kim's lesson on seed germination, students were expected to understand that nutrients (e.g., glucose) stored in seeds are consumed through respiration to produce energy for germination, resulting in a loss of weight in the

germinated seed. This weight loss during germination can be counterintuitive for students because the volume of the seed increases as it germinates. Before the episode, students had learned about photosynthesis and cellular respiration in plants. The episode began with Ms. Kim introducing a target phenomenon about seed germination. Specifically, she presented a bean placed in water in a dark environment to facilitate germination (Figure 2). Students were then asked to select an argument they agree with among two claims about the weight change of the bean—whether the germinated bean becomes heavier or lighter. They were also asked to explain the reason for choosing a claim using scientific concepts that they had previously learned. Following the introduction of the phenomenon, Ms. Kim asked students to develop an explanation of the phenomenon through small group discussions. The following episode unfolded within one of the student groups in Ms. Kim's classroom.

Phase 1: Initial engagement with a driving question related to a target phenomenon

The episode began with Ms. Kim introducing the bean germination phenomenon presented in the worksheet, asking students to predict the bean's weight change and construct an argument supporting their prediction. In this initial phase, students grappled with two conceptual uncertainties: which content knowledge is relevant to this phenomenon—respiration or photosynthesis?; and what is the relationship between energy usage and weight change in bean germination? Initially, students struggled to identify which scientific concepts they could use to develop arguments. They asked each other a series of questions: "Is the energy produced through photosynthesis or respiration?" "What do they (beans) need for respiration?" "Are oxygen and glucose produced when they respire? Oh, the glucose is produced when they photosynthesize."

In answering these questions, students retrieved and shared prior knowledge related to seed germination and photosynthesis.

While listening to students' discussions, Ms. Kim noticed that they not only failed to focus on respiration but also struggled with a misconception about respiration. This was shown in a discourse that initiated when Taehee asked the following question: "It's photosynthesis (that needs sunlight in the process). Then, do plants need sunlight to respire as well? I think they need sunlight." To clarify their confusion over the concepts of photosynthesis and respiration, Ms. Kim posed guiding questions, such as "Which one (between photosynthesis and respiration) do the plants do with sunlight?" and "Let's think about what we learned in the last lesson." With the help of these questions, students were able to establish specific scientific knowledge. "It's photosynthesis (that needs sunlight)." Hoping that students could further retrieve relevant prior knowledge and engage in the discussion of the phenomenon, Ms. Kim also suggested students refer to the expert cards containing scientific explanations related to seed germination and respiration (e.g., "It takes a lot of energy when beans germinate.").

The second conceptual uncertainty emerged when the students shared their initial ideas about the relationship between energy usage and weight change in beans. Specifically, this uncertainty arose from Yaena's questioning of the claim that the germinated bean would be lighter: "Well, I doubt that energy turns into weight, doesn't it? I mean, it [energy] is not something... [related] to weight, is it?" With a hint of uncertainty, this utterance initiated the

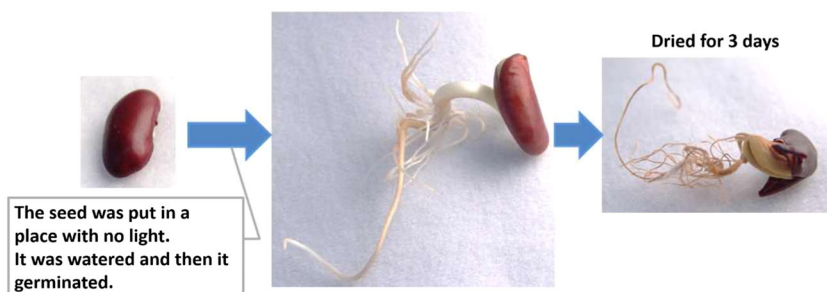


FIGURE 2 The phenomenon of bean germination.

discussion about the relationship between energy and weight. Taehee proposed an idea, "They [Beans] need to respire to produce energy. And they need nutrients to respire. But there are no nutrients produced because the bean did not photosynthesize. So, it cannot use energy," implying that energy should not be considered when discussing the weight change of beans in the first place.

As such, students' discussion in Phase 1 was driven by their attempts to seek relevant prior knowledge about the target phenomenon. At the beginning of their discussion, students' conceptual uncertainties emerged from their confusion over the concepts of photosynthesis and respiration. The uncertainty was coded as conceptual because students struggled to use their conceptual understanding—seeking and retrieving prior knowledge about photosynthesis and respiration. The teacher supported students' navigation of uncertainty by tacitly guiding them to focus on relevant content knowledge (i.e., respiration, not photosynthesis) and to revise any misunderstandings they had. Based on the content knowledge that they attended to, students were then able to share initial ideas about the relationship between energy usage and weight change in beans. The uncertainty was coded as another conceptual uncertainty because students struggled to retrieve their everyday knowledge about the relationship between energy usage and weight change.

Phase 2: Identification of incoherence and insufficiency in existing understanding

As students grappled with their initial ideas concerning the two conceptual uncertainties, they identified incoherence and insufficiency in their understanding, giving rise to two epistemic uncertainties: (a) How could the bean sprout if it did not use energy, and (b) Is the analogy of weight change in plants to the human body valid? The first epistemic uncertainty arose when an incoherence in the initial ideas shared in Phase 1 was identified and challenged. For example, Chaerin evaluated and rebutted Taehee's idea that the bean could not use energy because it had not produced energy: "But it says here [in the worksheet] that this seed sprouted only with water." Thinking that the bean could not have sprouted without using energy, Chaerin pointed out that Taehee's explanation was incoherent with the phenomenon. Taehee then modified her original argument, saying, "Yes, it sprouted because the water was given. Then, perhaps, it used only the energy stored in it [the bean]." Although this modified idea aligns with the core concept that a bean uses energy produced through respiration to sprout, consuming nutrients stored in it, their discussion did not progress further, and no responses followed for a while. Noticing this dead-end conversation, Ms. Kim encouraged students to delve deeper into the expert cards and engage more with the scientific concepts: "What's said in the expert cards might not be easy to understand, but please take enough time to look into the expert cards."

After some time, Yaena resumed the conversation by referring to the expert card: "Look, it says that there are nutrients inside the beans to be used for their growth," indicating her agreement with Taehee's modified idea. The second epistemic uncertainty arose along with this new understanding when Yaena attempted to analogize the energy consumption in human body to justify that spending energy has nothing to do with losing weight: "I think that plants do not lose their weight when they spend their energy. Just like our body not gaining any weight when we get energy. Wait, do we lose weight when we are exhausted? Does 'energy' have different meanings for the human body and plants?" This utterance indicates her uncertainty about whether her analogy between energy in the human body and energy in plants made sense. Additionally, Yaena realized that her current understanding was insufficient; she needed further information about energy in the human body and plants.

As such, students' discussion in Phase 2 revolved around two epistemic uncertainties as students grappled with the conceptual uncertainty from the previous phase. The uncertainties became apparent as they identified incoherence and insufficiency in their understanding. The first epistemic uncertainty arose when Chaerin questioned the incoherence in Taehee's initial idea about the phenomenon. That is, Chaerin wrestled with applying her epistemic understanding of how to explain or rebut an incoherence between Taehee's idea and the phenomenon. It was only when Ms. Kim encouraged students to study the expert cards carefully to resolve the incoherence that Yaena supported Taehee's idea with a reference to the expert cards. The reduced uncertainty then allowed Yaena to attempt an analogy of energy between humans and plants. However, this analogical reasoning led



to the second epistemic uncertainty regarding the validity of the analogy. Students struggled to apply their epistemic understanding of how to generate a valid analogy.

Phase 3: Exploration of multiple resources to help develop plausible explanations

Realizing their uncertainty about the analogy, students initiated a discussion to refine and use their understanding of how weight loss (or fat loss) occurs during exercise, which is a reference of their analogical thinking (Table 5). In this process, two conceptual uncertainties surfaced: (a) in what forms carbohydrates and fats are stored in the human body and (b) whether energy has weight.

Initially, students were confused of in which form—carbohydrates or fats— energy is stored in the human body. Chaerin sought clarification from Ms. Kim, asking, “Isn’t carbohydrate stored [in our body] as fat?” (line 306). Yaena tackled this question and its relevance to seed germination by inquiring, “Why would there be fat in plants?” (line 308). To help students continue discussion with more familiar examples, Ms. Kim challenged Yaena by mentioning peanuts: “There could be fat in plant cells, too. Think about peanuts. They have fat.” (lines 310). Yaena then raised another question, “Do they? If we eat them, do they turn into fat?” (line 312). This question indicates her attempt to connect her everyday knowledge—food as a source of energy—to the scientific knowledge of different forms of nutrients storing energy. Noticing this effort to clarify the conceptual understanding of in which form energy is stored in the human body, Ms. Kim elaborated further by mentioning scientific knowledge that nutrients in diverse forms taken into the human body can become fat (line 320). However, continued to struggle in understanding what roles nutrients play in energy consumption and how they are related to seed germination.

Students then shifted their focus to the second conceptual uncertainty: whether energy has weight. They asked the teacher directly, “Does energy have weight?” (line 322). In response, Ms. Kim provided two useful pieces of information. First, she conveyed that energy is the ability to work (line 323), offering a potential clue for students to support their analogy of human energy consumption during exercise. The second piece of information was an everyday example: “Can we measure the weight of the sunlight?” (line 325). Ms. Kim tried to offer information and knowledge that were comprehensible and familiar to students so that the students can identify and resolve the uncertainty using their knowledge, rather than providing direct answers to their questions.

To summarize, during this phase, students grappled with two conceptual uncertainties. These uncertainties, namely in which form—carbohydrate and fat— energy is stored in the human body and whether energy has weight, emerged as the students sought information to resolve the epistemic uncertainty from Phase 2 regarding the analogy of weight change in plants to the human body.

Phase 4: Synthesis of solutions and application of new understanding to interpret the phenomenon

In an attempt to draw a conclusion based on their acquired understanding, students revisited the epistemic uncertainty of using an analogy between human weight loss through exercise and a bean’s weight change through germination. While grappling with the analogy, students encountered difficulties in applying their newly developed understanding to it. Student struggles were indicated from utterances such as “I can’t figure this out,” repeated use of the phrase “When the bean uses energy ...” without additional ideas, and pauses in the group discussion. After contemplating the teacher’s explanations about how carbohydrates and glucose are stored in the human body, Chaerin presented her final argument: “I will go with the second claim. Because people lose weight when they exercise, and this is because they used energy when exercising. Therefore, because the bean used energy as it germinated, I think the bean would get lighter.” Yaena, agreeing with Chaerin’s analogy, synthesized her thoughts with Chaerin’s by adding relevant scientific knowledge of using nutrients stored in the bean and made a final argument: “The germinated bean is lighter because it used nutrients that it had in it, just like people lose weight after they exercise.”

The epistemic uncertainty that students managed in this phase evolved from the one in Phase 2—whether it is valid to make an analogy of weight change in plants to the human body. In other words, this earlier epistemic uncertainty was resolved, as students no longer doubted the validity of the analogy. Students’ epistemic uncertainty

TABLE 5 Excerpt illustrating the small group discussion in taehee's group about nutrients storing energy in the human body (Lines 292–325).

Line	Speaker	Utterance
292	Chaerin	I've learned that people need things like carbohydrate and (inaudible) to use energy.
...		
295	Chaerin	Hey, when we are hungry, wait, diet (working out) is... Taehee, is the fat what stores energy?
296	Taehee	What?
297	Chaerin	Is the fat what stores energy?
298	Taehee	What are you talking about? Carbohydrates... Glucose is fat.
299	Chaerin	Hey, but doesn't glucose produce energy?
300	Taehee	Right.
301	Taehee	That'll do.
302	Yaena	Ms. Kim...
303	Taehee	Does energy have weight?
304	Ms. Kim	Do you think that energy has weight?
305	Taehee	Please, just tell us, Ms. Kim.
306	Chaerin	Isn't carbohydrate stored (in our body) as fat?
307	Ms. Kim	Fat?
308	Yaena	Why would there be fat in plants?
309	Chaerin	No, I mean, in human body...
310	Ms. Kim	There could be fat in plant cells, too. Think about peanuts. They have fat.
311	Chaerin	Do they?
312	Yaena	Do they? If we eat them, do they turn into fat?
313	Taehee	Ms. Kim...
314	Ms. Kim	Well, we eat them and get energy.
...		
320	Ms. Kim	Plants produce glucose through photosynthesis at first, but the glucose is stored in the form of starch. (inaudible) But this glucose can be converted into fat or protein and stored in plants, too. The same goes for human body. The fat that you eat can remain as fat, and the carbohydrate that you eat can remain as carbohydrate, but if you overeat carbohydrate, it can become fat... and gain weight.
321	Chaerin	(inaudible)
322	Taehee	Ms. Kim, please just give me the answer to this question. Does energy have weight?
323	Ms. Kim	Energy. To put it in another way, energy is the capability of being able to work. Do we say that energy has 2 kg or 3 kg of weight?
324	Taehee	No.
325	Ms. Kim	Can we measure the weight of the sunlight?



now concerned how to apply the new understanding of the analogy to develop a final argument that could explain the phenomenon. In dealing with this epistemic uncertainty, students managed to make connections between “germinate” and “exercise,” and between “get lighter” and “lose weight.” Although not shown from the teacher’s utterance, we inferred from the students’ discussion that they employed the strategy of using the understanding they had developed up to Phase 3 to synthesize an explanation of the target phenomenon.

5.2.2 | Teacher’s support and strategies for uncertainty development in sensemaking

Figure 3 illustrates the types of uncertainties that emerged in each phase and how they are intertwined and evolved over the four sensemaking phases. In Phase 1, conceptual uncertainties were raised as students attempted to gather and use conceptual understanding to develop initial explanations of the given phenomenon. Students attended to different conceptual uncertainties raised by their group members and explored various content knowledge that they deemed relevant to the target phenomenon. Ms. Kim provided support by asking clarifying questions and offering expert cards for reference, guiding students to focus on conceptual understanding relevant to developing explanations of the given phenomenon. Based on the retrieved understanding, students were able to attend to respiration and develop initial explanations of the relationship between energy and weight. One teaching strategy identified was to exclude unnecessary conceptual uncertainties for students to focus on the target concept.

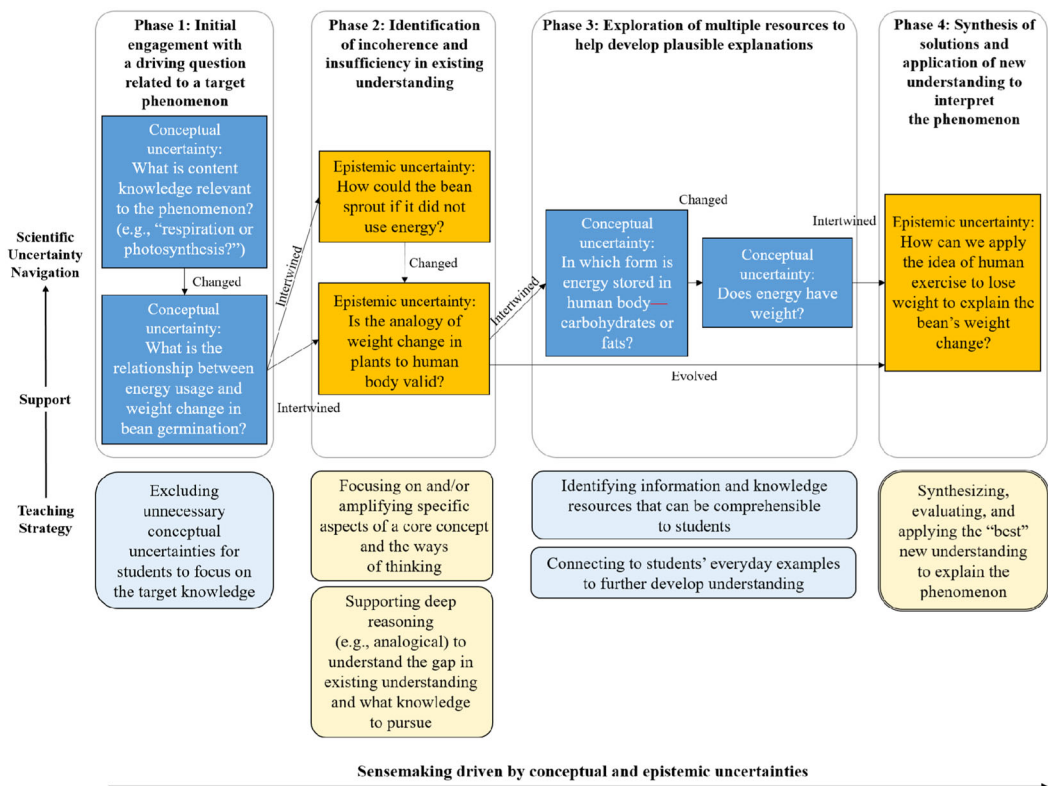
In Phase 2, although not supported by the teachers, it was shown that students engaged in analogical reasoning to understand the incoherence and address the uncertainty derived from it. They identified incoherence in their initial explanations and attempted to form an analogy to everyday experience to develop understanding that could resolve the incoherence. During this process, two epistemic uncertainties arose, intertwined with the last conceptual uncertainty in Phase 1: incoherence in the initial explanation to explain the phenomenon and whether their analogy is valid. Recognizing that their uncertainty about the analogy was rooted in relevant content and everyday knowledge (e.g., beans using nutrients inside them to germinate), Ms. Kim encouraged students to carefully examine the expert cards instead of directly resolving their epistemic uncertainty. Two strategies were identified: focusing on and/or amplifying specific aspects of a core concept and the ways of thinking expected by the teacher, and supporting deep reasoning (e.g., analogical) to understand the gap in existing understanding and what knowledge to pursue.

In Phase 3, students focused on resolving the epistemic uncertainties identified in Phase 2. They explored diverse conceptual understandings and everyday experiences that could be useful in developing a new explanation. During this process, they identified two conceptual uncertainties that needed resolution and sought help from Ms. Kim. She provided various content knowledge that students requested. In contrast to explanations using scientific terms, Ms. Kim’s explanation included information that was comprehensible to students and connected with everyday examples. Two strategies were identified: identifying information and knowledge resources that can be comprehensible to students and connecting to students’ everyday examples to further develop understanding.

In Phase 4, the epistemic uncertainty of how to apply their new understanding to explain the phenomenon—specifically, the weight change of the bean after germination—drove the discussion. Although not identified from the teacher’s discourse, we inferred that students used the strategy of *synthesizing, evaluating, and applying the ‘best’ new understanding to explain the phenomenon*, thus managing the epistemic uncertainty and developing their argument with analogical reasoning.

5.3 | Summary of the findings: The dynamic nature of scientific uncertainty and teaching strategies to support student uncertainty navigation in sensemaking

The two exemplary cases illustrate that uncertainty development drives the process of sensemaking and how teachers can support such a process. The flows of uncertainty development (Figures 1 and 3) show that



Note. represents conceptual uncertainty

represents epistemic uncertainty

represents strategy inferred from teacher discourse to support students' navigation of conceptual uncertainty

represents strategy inferred from teacher discourse to support students' navigation of epistemic uncertainty

represents strategy inferred from student discourse to support navigation of epistemic uncertainty

FIGURE 3 The flow of uncertainty development and teacher support for students to construct understanding of weight change in a bean as a result of germination.

uncertainties were dynamic and evolved across the four phases of sensemaking depending on students' understanding and practice status. Based on the analysis of these cases and the collections of the two figures, in this section, we synthesize teaching strategies to support students' navigation of scientific uncertainties in sensemaking.

Figure 4 presents a summary of the types of uncertainties and the strategies to support student uncertainty navigation for sensemaking in each phase. Conceptual uncertainty pervaded Phase 1. Students were typically inclined to first retrieve their prior knowledge, what we categorize as content and everyday knowledge, to make sense of a given phenomenon. The two representative episodes and the other 16 episodes (see Supporting

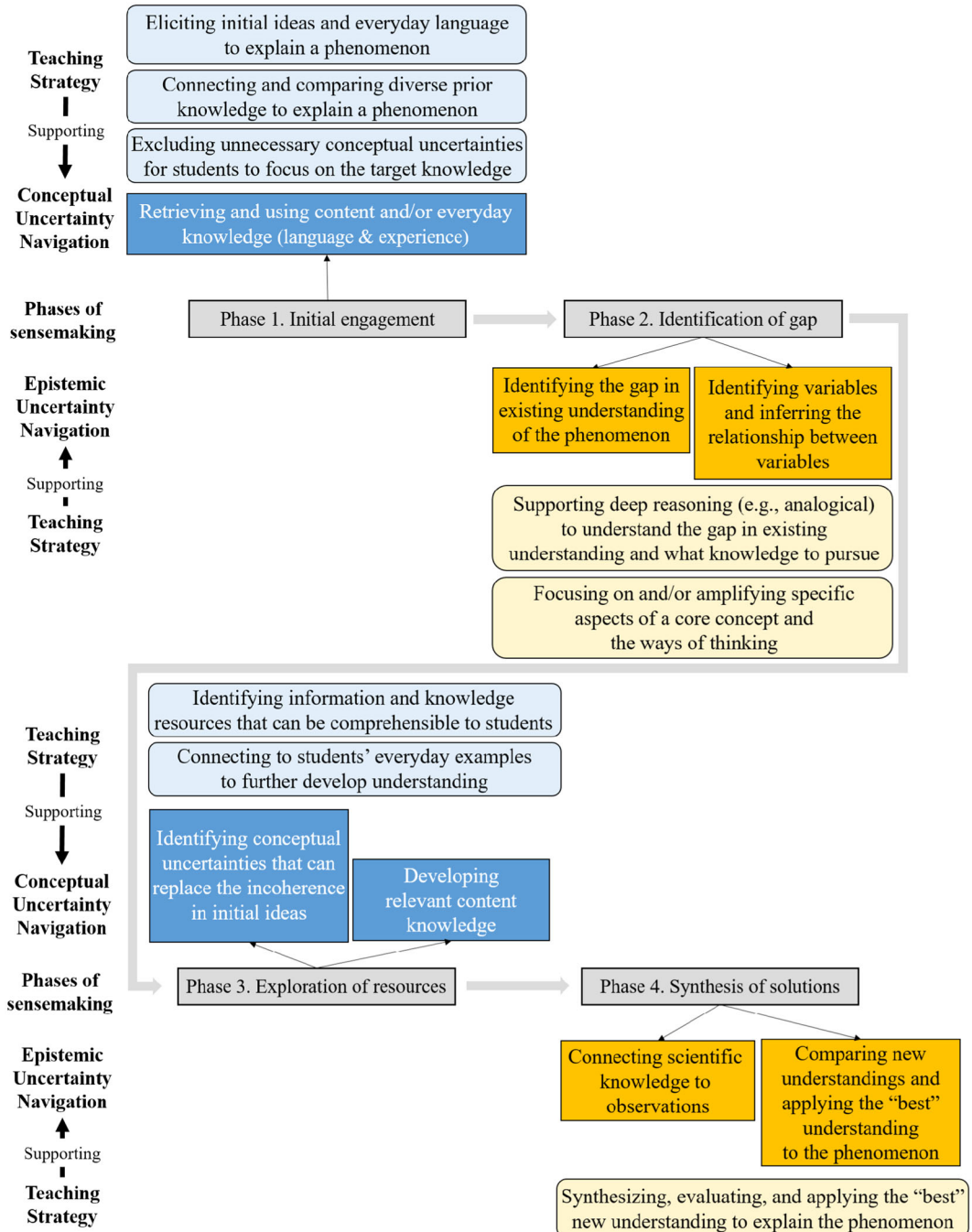


FIGURE 4 Teacher support for students' navigation of scientific uncertainties across phases of sensemaking.

Information: Appendix E) consistently show that students may need to engage in resolving their conceptual uncertainty before engaging in epistemic uncertainty when they encounter a new phenomenon or issue. This trajectory of uncertainty navigation may resonate with what Driver and Oldham (1986) described about the constructivist approach, in which students need to fully explore their prior knowledge or “mini-theories” (p. 106) at the beginning of a unit to prepare for the construction of meaningful understanding. Three strategies were identified to navigate conceptual uncertainty in Phase 1: (1) eliciting initial ideas and everyday language to explain a phenomenon (Case 1), (2) connecting and comparing diverse prior knowledge to explain a phenomenon (Case 1), and (3) excluding unnecessary conceptual uncertainties so students could focus on the target knowledge (Case 2).

We found the two cases consistently showed that teachers supported students' engagement in discussing target phenomena and navigating their conceptual uncertainties by eliciting their initial ideas and by connecting and comparing diverse prior knowledge with the target phenomenon. The first two strategies are necessary and important to help students unpack their prior knowledge to explain the target phenomenon and begin realizing the limitations of their existing conceptual understanding. The third strategy, the exclusion of unnecessary conceptual uncertainties, was demonstrated in Case 2. In this case, the strategy occurred when Ms. Kim guided students to clarify their confusion about photosynthesis and respiration and focus only on respiration, not photosynthesis, in their further exploration.

In Phase 2, incoherence and insufficiency of students' existing understanding were identified. The two figures (Figures 1 and 3) show that epistemic uncertainty predominated in this phase. Once students brainstormed their prior knowledge in Phase 1, they engaged in exploring, arguing, and reasoning about what knowledge resources they needed to pursue and identifying the incoherence of their existing understanding. Two strategies were identified: supporting deep reasoning (e.g., analogical reasoning) to understand the gap in existing understanding and what knowledge to pursue (Cases 1 and 2), and focusing on and/or amplifying specific aspects of a core concept and the ways of thinking expected by the teacher (Cases 1 and 2). To navigate epistemic uncertainties in Phase 2, the teachers consistently supported students' engagement in deep reasoning and repeatedly identified incoherence in students' initial explanations so that they could engage in resolving the incoherence, not merely patching up the initial explanations with small bits of additional information. However, we found that this strategy is not sufficient to prepare students to make sense of complex concepts and determine what they need to pursue for explaining the target phenomena. The second strategy shows that teachers needed to focus on and amplify specific variables, making them visible and useful. With these strategies, students were able to attend to the relationship between variables in the given phenomenon and identify the insufficiency of their existing understanding, facilitating progress to the next phase.

In Phase 3, students explored resources to develop a plausible explanation of the phenomenon. Conceptual uncertainties were shown as students clarified their prior knowledge and developed relevant conceptual understanding. Specifically, students identified conceptual uncertainties that could resolve the incoherence revealed in Phase 2. To support navigating these uncertainties, two strategies were identified: identifying information and knowledge resources that can be comprehensible to students (Cases 1 and 2), and connecting to students' everyday examples to further develop understanding (Case 2). We found that the common ground across the two strategies is to identify knowledge resources that are comprehensible to the students. This depends on how the new information and knowledge can be integrated into students' existing understanding. For example, Case 1 shows that students could not comprehend the definition of vacuum and sucking from an adult dictionary when it is defined in a more sophisticated way. Case 2 shows students struggling with using expert cards to explain the phenomena. These cases indicate that teachers need to guide students to find resources that are comprehensible to them (strategy 1) and scaffold students to connect their everyday examples to develop an understanding of the core concept (strategy 2).

In Phase 4, the solution and application of the new understanding developed in Phase 3 were synthesized to interpret the phenomenon. Epistemic uncertainties were the main type of uncertainties in this phase and were shown when students connected newly developed understanding to explain the phenomenon. The major strategy for this phase is to synthesize, evaluate, and apply the “best” new understanding to explain the phenomenon (Cases



1 and 2). We found this strategy is crucial in helping students incorporate what they learned in Phase 3 and apply it to explain the problematized phenomenon.

6 | DISCUSSION

To support students' sensemaking in the science classroom, previous studies have argued for the necessity of building the trajectory of science activity in a way that is coherent with students' ideas, interests, and motivations (Reiser et al., 2021; Roth et al., 2011; Sikorski & Hammer, 2017). We identified four phases of sensemaking and presented the development of various scientific uncertainties as the key to supporting students as they make sense of a phenomenon. We also identified various teaching strategies that can support student navigation of their scientific uncertainties throughout the trajectory of sensemaking. Three critical themes emerged from our findings related to our two research questions: (1) student uncertainty as a key not only to initiate the trajectory of sensemaking meaningfully but also to continuously develop sensemaking along a coherent pathway, (2) conceptual and epistemic uncertainties having different roles in driving the coherent trajectory of sensemaking, and (3) teaching strategies that support student navigation of scientific uncertainty that drives sensemaking. Below, we discuss how the themes emerged from the results.

6.1 | Student uncertainty as a key to initiate, problematize, and develop sensemaking

Target phenomena are supposed to be puzzling for students, encouraging their engagement in sensemaking. This description suggests that such phenomena are expected to raise student uncertainty to open space for discussion. However, the findings of this study suggest that teacher support is also needed to maintain and resolve student uncertainty. Our findings revealed a sequence of scientific uncertainties managed by the teachers to help students make sense of the given phenomenon. This sequence of navigated uncertainties can be considered the key construct of the trajectory of sensemaking. We further discuss this point in the following two subsections.

6.1.1 | Problematizing a phenomenon in Phases 1 and 2

Several studies suggest that problematizing a phenomenon is the first step in the start of sensemaking (e.g., Haverly et al., 2020; Penuel et al., 2022; Phillips et al., 2018; Rapkiewicz et al., 2023; Reiser et al., 2021). The analysis of our data revealed that students were not aware of the learning goal of the sensemaking activity with the presentation of the phenomenon and did not immediately generate ideas related to the target phenomenon. That is, the phenomenon did not problematize itself nor automatically trigger students' interests. Our results show that only when students were aware of their uncertainty, did they intensively explore their prior knowledge, experience, and misconceptions (Phase 1), and realize the limitation of their existing understanding to explain the phenomenon (Phase 2) so that they might engage in meaningful sensemaking. For example, in Case 1, students neither realized the intention of Ms. Ellis's questions nor engaged in deep discussion of the process of breathing, until Ms. Ellis raised students' uncertainty by comparing the difference among students' ideas and using a vacuum to analogize the breathing process. In Case 2, even though Ms. Kim provided two different arguments for students, students had difficulty providing their reasoning to support an argument they selected and did not realize their misconceptions that they used in developing their explanation. Students did not consider their existing understanding problematic until they realized the conflicts and incoherence. That is, students need to have opportunities to explicitly navigate what they know, which often accompanies conceptual uncertainty, by exploring their existing

content and everyday knowledge before they can meaningfully engage in reasoning about what they do not know, which often accompanies epistemic uncertainty.

Therefore, problematizing a phenomenon is about not only how teachers present the phenomenon but also how teachers raise student awareness of their conceptual uncertainty through intensively exploring their prior knowledge of the phenomenon (Phase 1), identifying the gap within their existing understanding to explain the phenomenon through deep reasoning (e.g., analogical), and understanding what knowledge they need to pursue (Phase 2). Our results in Phase 1 and Phase 2 resonate with recently emerging calls for problematizing a phenomenon as the first step to build a trajectory of sensemaking and for explicitly raising students' awareness of uncertainty to reveal the incoherence and insufficiency of explanation, which is the key to problematizing a phenomenon (Dorst & Cross, 2001; Engle & Conant, 2002; Ko, 2021; Phillips et al., 2018; Suárez, 2020).

In the first two phases, we found that analogical reasoning continuously occurred when students engaged in explaining the target phenomenon and identified the gap in their existing understanding. In Case 1, analogical reasoning was shown when students used their everyday knowledge of "vacuum" and "suck" to explain breathing. In Case 2, students analogized weight change in the human body to that of plants. In these attempts, gaps in students' initial understanding were revealed and became the main epistemic uncertainties that drove subsequent phases. These cases corroborate the literature that analogical reasoning is a main strategy to make sense of phenomena (May et al., 2006; Niebert et al., 2012), and they extend further by showing that supporting such analogical reasoning can be a strategy to reveal the gap in existing understanding and drive the trajectory of sensemaking.

6.1.2 | Building coherent understanding in Phases 3 and 4

After experiencing the problematization of a phenomenon, students need to explore multiple potential solutions to decide which one can best resolve their uncertainties and explain the phenomenon. Our findings indicate that identifying and resolving incoherence in students' initial explanations is an impetus for exploring and developing better explanations of the phenomenon. Specifically, attempts to identify and resolve incoherence raised students' uncertainty that can drive the process of building coherent understanding, which included not only searching multiple resources and generating potential solutions (Phase 3) but also selecting and applying the best solution that makes sense to them to explain the problematized phenomenon (Phase 4). For example, in Case 1, students searched the explanation of sucking and a vacuum from several versions of adult and children dictionaries. They decided to use and synthesize the definitions from children's dictionaries rather than from the adult dictionary that did not make sense to them. In Case 2, there was an occasion where Ms. Kim explained scientific concepts to students but not to the extent their conceptual uncertainties were resolved. Case 2 showed that coherence is "perspective dependent." That is, the students did not realize the relationship of the scientific concepts to the phenomenon in the way that the teacher expected. The students were able to develop an explanation with the usage of everyday examples that they were familiar with, such as "Think about peanuts. They have fat. (...) we eat them and get energy."

These two examples demonstrate that instead of treating uncertainties as deficiencies to be remediated, students' scientific uncertainty can be used as a pedagogical resource for teachers to understand what needs to be emphasized to help students rationalize a better solution to solve their uncertainty. When the teachers noticed and identified students' scientific uncertainty, they shifted to supporting students' exploration of resources and development of new understandings. These instructional decisions made in response to students' scientific uncertainty were critical pedagogical resources for teachers to both shape a coherent trajectory of sensemaking with students and support students' resolution of the scientific uncertainties.



6.2 | Conceptual and epistemic uncertainties having different roles in driving the trajectory of sensemaking

Although several studies (Cannady et al., 2019; Quintana et al., 2004; Reiser et al., 2021; Zembal-Saul et al., 2013) and standards (e.g., NGSS) suggest designing coherent curricula and activities to foster students to develop scientific knowledge, a consideration of what drives or motivates sensemaking with a prolonged sequence has been limited. Building on the findings of this study, we suggest that both conceptual and epistemic uncertainties are critical and play different roles in driving and building the trajectory of sensemaking. The findings suggest that although epistemic uncertainty is important for students to understand how they develop better understanding, conceptual uncertainty also appears to be critical for exploring the limitation of what they know (e.g., prior knowledge) and driving them to examine resources for plausible explanations. Both types of uncertainty were related to one another and evolved into different ones as students progressed through the phases of sensemaking. The phases of sensemaking identified in this study help to parse the differences in the scientific uncertainties along the trajectory of sensemaking.

It is interesting that there are phases in which scientific uncertainties raised are of only one type. We find this to be relevant to the differing natures of the phases. For example, there were only conceptual uncertainties in Phase 1. The introduced target phenomena were not problematized by itself. Students tried to recall and use their prior knowledge to explain the given phenomenon at first, and conceptual uncertainties then manifested in this process. In Phase 2, insufficiency and incoherence of students' initial explanations stemming from prior knowledge were identified. Epistemic uncertainties emerged from students' attempts to generate different explanations with the identified incoherence in the initial explanations resolved. This pattern of conceptual uncertainty being navigated before epistemic uncertainty responds to Ausubel's (1968) theory of meaningful learning. He suggested that only when students explicitly retrieve existing understanding and link it to the encountered phenomenon, meaningful learning may occur. This also echoes what Driver and Oldham's (1986) suggested about the constructivist teaching approach in which students first need to "make their ideas explicit, hence bringing them to conscious awareness" (p. 118) of restructuring ideas. Therefore, in Phases 1 and 2, we suggest that conceptual uncertainty plays a significant role when students initially explore a phenomenon or discuss an issue. Students may need to struggle to explore and unpack their existing understanding, which is conceptual uncertainty, before productively engaging in epistemic uncertainty to identify insufficiencies and incoherence in their understanding toward an encountered phenomenon.

However, this does not mean that the trajectory of uncertainty navigation is linear. Instead, it may dynamically evolve. The conceptual uncertainty in Phase 3 is different from Phase 1. In Phase 3, conceptual uncertainties were managed in an effort to search plausible content and everyday knowledge to resolve epistemic uncertainty identified in Phase 2. As students grasp better conceptual understanding by resolving conceptual uncertainties, epistemic uncertainties followed in Phase 4 to apply the new understanding to develop explanations of the natural phenomenon. The epistemic uncertainties that appeared in the last phase were the ones evolved from the epistemic uncertainties identified in Phase 2 and about applying the understanding developed in Phase 3 to explaining the phenomenon.

This finding suggests that teachers' support through navigating student scientific uncertainties should be differentiated according to the nature of each phase of sensemaking. For example, the identification of Phase 1 indicates that teachers can support students to recall and reflect on their prior knowledge of an introduced target phenomenon first. This will be a foothold for students' identification of gaps in their prior knowledge in Phase 2. In Phase 2, teachers can support students to navigate epistemic uncertainties, which become the motif for students to engage in the next phase. In Phase 3, teachers can use different strategies as shown in our findings to support students to navigate and resolve conceptual uncertainties that can solve the incoherence revealed in Phase 2, such as providing sources to develop conceptual understanding further.

6.3 | Teaching strategies that support student navigation of scientific uncertainty that drives sensemaking

Previous studies on teaching strategies to support the navigation of student scientific uncertainty have largely focused on making uncertainty tangible for students to create a space for their participation in sensemaking (e.g., Watkins & Manz, 2022; Watkins et al., 2018). The current study identifies teaching strategies to support the navigation of students' epistemic and conceptual uncertainties emerging across four phases of sensemaking. This study expands the existing literature in two ways. First, it suggests how different teacher strategies are suitable for supporting the navigation of scientific uncertainty to drive different phases of sensemaking, each with distinctive features. For example, teaching strategies to support navigating epistemic uncertainty varied among different phases due to the distinctive features of each phase. In Phase 2, epistemic uncertainty emerged from identifying gaps in students' initial ideas. In Phase 4, epistemic uncertainties were identified during the synthesis of new understanding of a target phenomenon. Conceptual uncertainties also varied across different phases. While students were involved in conceptual uncertainties to retrieve prior knowledge to use in explaining an anchoring phenomenon in Phase 1, conceptual uncertainties in Phase 3 emerged as students developed conceptual understanding to use in developing plausible explanations.

Second, teaching strategies identified in this study contribute to how to support navigating not just epistemic uncertainties but also conceptual uncertainties that emerge in sensemaking. The cases showed that conceptual uncertainty is another main type of uncertainty that emerged along with epistemic uncertainty in students' discussions, and it needs to be considered to build a trajectory of sensemaking that is coherent from students' perspective. Teaching strategies can be used to support students in navigating these two types of uncertainties, ultimately addressing the next uncertainty, and driving each phase to build a trajectory of sensemaking.

These teaching strategies can be used by science teachers planning to enact sensemaking in their classrooms. For example, our findings can be useful to predict the types of student uncertainties that may emerge and plan how to support using such uncertainties in the construction of a trajectory of sensemaking, taking into account what is desirable for each phase. Additionally, the exemplary cases we reported can be used as resources for developing teacher education materials. Using the description of each phase in an episode, teacher educators can design activities where they identify types of students' scientific uncertainties and discuss how to support students' navigation of uncertainty in a specific phase of sensemaking. This type of teacher education activity can be helpful for enhancing teachers' abilities to build a trajectory of sensemaking with students in the science classroom.

7 | IMPLICATIONS FOR PROMOTING EQUITY IN THE SCIENCE CLASSROOM

There has been an increasing call for promoting equitable learning opportunities in the science classroom (e.g., Bang et al., 2017; Carlone et al., 2011; Grapin et al., 2023; Lewis et al., 2009). Although the main focus of this study is not on equity, the findings of this study contributes to this line of literature by providing various strategies to support students in navigating their uncertainties to develop sensemaking, offering students opportunities to exercise agency and promote equitable learning. For example, in Phases 1 and 2, diverse scientific uncertainties can emerge as students retrieve and use varied prior knowledge to explain a target phenomenon. The teaching strategies identified in this study can be used to explicate and incorporate uncertainties from a diverse range of students in classroom discussions, providing equitable opportunities for students to engage in sensemaking. For example, Case 2 suggests that encouraging students to explore various content knowledge they perceive as relevant to the target phenomenon can be a strategy to promote equity in Phase 1. In Case 1, Ms. Ellis rephrased a driving question in multiple ways after students' initial responses to elicit more diverse ideas. This support aligns with teacher questioning that encourages students to generate ideas based on their prior knowledge (Chin, 2007). The teacher



can then encourage students to engage in deep reasoning with different ideas elicited, revealing and addressing gaps in their diverse initial explanations. Then, in Phase 2, the teacher can support students to focus on specific aspects of a core concept and the desired ways of thinking, guiding students toward meaningful disciplinary learning rooted in ideas reflecting their sociocultural backgrounds and everyday knowledge. This resonates with and expands on previous studies that suggested the incorporation of diverse student uncertainties in sensemaking moments (Haverly et al., 2020) and provides a way to connect student ideas to disciplinarily meaningful sensemaking.

Phases 3 and 4 are where students explore multiple resources and synthesize new understanding to explain the target phenomenon. Based on the current findings, it can be expected that students from different sociocultural backgrounds might struggle in searching for resources comprehensible to them. Possible pedagogical actions could include encouraging students to search for and use different information sources and fostering discussions to incorporate various resources they discover. This type of support was identified in Case 1, where Ms. Ellis encouraged students to explore diverse information sources, such as the internet and children's dictionaries, to find understandable information pieces. In Case 2, Ms. Kim supported students to clarify conceptual understanding related to the information or everyday experience they were attending to, supporting exploration of resources from different perspectives. In this way, in both cases, students were able to form a shared set of resources for developing a new explanation. After gathering resources, the teacher can further support students to consider diverse ideas and perspectives with a caring and respectful mindset as they synthesize a shared understanding (Reiser et al., 2021). An example of this is Ms. Ellis raising of epistemic uncertainties that encouraged students to use the gathered resources together to synthesize a new explanation. By developing a new explanation from shared resources, students from different backgrounds were able to collectively develop an explanation with which they agree (Carlone et al., 2011; Haverly et al., 2020).

Remaining questions persist on developing teaching strategies that promote equity in sensemaking in the science classroom: How can scientific uncertainties be interpreted in terms of power dynamics among students? What other types of uncertainty might emerge when we encompass students' diverse sociocultural backgrounds in the classrooms? For example, Jordan and McDaniel (2014) suggested the possibility of relational uncertainty, referring to students' struggles in navigating a legitimate way of participation in the classroom learning community. Addressing these questions with an equity lens will contribute to expanding the field's understanding of student uncertainty in sensemaking and leveraging moments of student uncertainty to create a space for diverse students to engage in sensemaking in the science classroom.

8 | LIMITATIONS AND FUTURE DIRECTIONS

This study explored how students' conceptual and epistemic uncertainties evolve and drive the progression of sensemaking, identifying teaching strategies to support navigation of scientific uncertainties. However, considering that the current study, as a follow-up design, identified teaching strategies from classroom discourses in argumentation activities reflectively, future studies are needed on how teachers interpret the strategies and use them in their classrooms when the strategies are explicitly introduced to them. Specifically, it would be worthwhile to explore how teachers plan sensemaking activities based on the teaching strategies so that a trajectory of sensemaking can emerge from student uncertainties. However, this requires that teachers have a basic trajectory of sensemaking framework in mind while planning. Addressing these issues can be helpful for teachers in using the findings as resources for implementing sensemaking activities in their science classrooms.

The teaching strategies identified here were derived from exploration of classroom activities that focused on argumentation. While evidence-based development of understanding is a primary feature of sensemaking in scientific endeavors, there can be activities with designs that emphasize other aspects of scientific sensemaking, such as representation and modeling. This indicates the need for further research to investigate sensemaking that progresses in different ways and to identify teaching strategies for diverse sensemaking activities, such as

supporting students' depiction of their ideas in the practice of modeling. We believe that these studies will contribute to a better understanding of how the trajectory of sensemaking can be built on students' uncertainties, thus supporting students' meaningful engagement in sensemaking.

Lastly, although we attempted to identify teaching strategies for supporting students' navigation of scientific uncertainty, we found that students used various strategies in Phase 4 of Case 2 when the teachers were absent from the group. This suggests the exercise of student agency, leading to the formation of a collaborative knowledge development community. This situation arose due to the small group discussion format, where Ms. Kim was unable to provide continuous support to every group. Future studies are needed to explore how students exercise their agency in discursive practices to navigate scientific uncertainty during small group discussions when teachers are absent. We expect that this line of study can contribute to developing students' abilities not only to participate in but also to organize and advance the process of sensemaking through navigating uncertainty on their own.

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DATA AVAILABILITY STATEMENT

Data 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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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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