

Preparing Science Teachers to Teach With and About Uncertainty

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Uncertainty and Scientific Literacy

Not all students will become professional scientists, but all of them will face science-related decisions in their personal, professional, and civic lives. They may need to decide whether to receive a newly developed vaccine, how to interpret reports about contaminants in their local drinking water, how to weigh the benefits and environmental costs of a proposed data center, or how to evaluate policies addressing local public health and environmental concerns. Science education should therefore prepare students to use scientific knowledge and ways of reasoning for problem-solving, critical thinking, and responsible decision-making (DeBoer, 2000). This purpose aligns with what Roberts (2007) and Roberts and Bybee (2014) call *Vision II* of scientific literacy. Roberts and Bybee (2014) distinguished between two broad orientations toward scientific literacy. *Vision I* emphasizes the knowledge and practices defined within scientific disciplines and typically orients student learning toward preparation for more advanced scientific study. *Vision II* emphasizes situations beyond the professional practice of science in which individuals draw on scientific knowledge and ways of reasoning. From the perspective of *Vision II*, school science should “illuminate how science permeates and interacts with many areas of human endeavor and life situations” (Roberts & Bybee, 2014, p. 546).

Using science in real-life contexts, particularly when addressing problems with consequences for individuals, communities, and society, often requires reasoning under uncertainty. In these situations, scientific knowledge can inform decision-making without necessarily providing the single correct answer or solution. Admittedly, not every real-life application of science requires considering uncertainty. However, complex personal and societal issues often demand that people sort out what is known and unknown, assess the limitations of available evidence, weigh the risks and potential benefits of alternative actions, and make decisions while acknowledging what remains uncertain.

Uncertainty in Socioscientific Issues

Socioscientific issues (SSI), such as vaccination, access to clean water, and the environmental impacts of technology infrastructure, make the demands of reasoning under uncertainty particularly prominent. SSI-based instruction offers one approach to enact *Vision II* in science classrooms (Sadler et al., 2019) by contextualizing learning within complex problems informed by science but also involving ethical, political, economic, and other social considerations (Sadler, 2004). In examining these issues, students must draw on scientific evidence while also considering the societal implications.

The uncertainty associated with SSI is critical for several reasons. First, some issues require people to take actions before the underlying mechanisms, long-term effects, and impact of possible solutions are fully understood. For example, when a new infectious disease emerges, public health decisions may be necessary before scientists know which populations face the greatest risks, what the long-term health impacts are, or which interventions are most effective. These decisions must be made using incomplete and evolving evidence (Zeidler & Sadler, 2023). From a nature of science perspective, scientific explanations and conclusions are subject to change. They may be refined as researchers gather additional evidence, develop new theoretical interpretations, or improve the methods and technologies used to investigate the phenomenon (Lederman et al., 2002; NGSS Lead States, 2013). This provisional nature of scientific knowledge is especially prominent in SSI because people may need to respond to the issue while research is ongoing and knowledge is still developing.

Second, uncertainty may persist when established scientific knowledge is applied to a new SSI context that calls for context-specific solutions and decisions. For example, the greenhouse effect as the mechanism for climate change is well-established, but when it comes to local implications, the timing, magnitude, and consequences could depend on local factors including local environmental conditions, human activities, and the interaction among them. General scientific knowledge in this case may not yield precise predictions about how and when a particular community will be affected.

Third, uncertainty in SSI also arises from the generation, interpretation, and communication of data-based scientific evidence, impacting the public's perception and decision making. Variability is a fundamental feature of data. Although researchers can attribute some variation to identifiable factors, some degree of variability always remains unexplained (Rubin, 2020). Researchers also work with limited observations, make inferential claims about broader populations, and use probabilistic thinking to predict future outcomes (Markar & Rubin, 2018). For example, water samples collected at only some locations and over a limited period may not fully represent patterns of contamination across a community or over time. Measurement error introduces noise, datasets may contain missing data, and even sophisticated analytic models simplify complex systems and cannot account for every relevant factor (Jelassi, 2026; Oreskes et al., 1994). Because scientific inferences extend beyond direct observation, they necessarily carry some degree of uncertainty (Lele, 2020), which academic and professional sources often communicate through probabilities, estimated ranges, and confidence levels. However, when scientific evidence is communicated to public audiences, uncertainty is not always made clear (Jensen & Pokharel, 2016); in media and online spaces, it may be oversimplified or presented misleadingly (Watson et al., 2024).

Uncertainty as a Drive for Scientific Practices

To prepare students to make informed decisions for SSI, science instruction must make uncertainty explicit and provide opportunities for students to encounter and respond to it. Manz (2015) describes these opportunities as “productive moments of uncertainty”, through which students can develop scientific ideas and deepen their understanding of science and engineering practices.

Gray et al. (2025) pointed out that uncertainty drives scientific practices. These practices often begin with an unexplained phenomenon or an unresolved question. As students work to make sense of a phenomenon or problem, many aspects of the inquiry remain open for them to decide, such as which entities and processes to represent in a model, how to collect and analyze data, and what evidence to select to support a claim. Engaging in these practices enables students to identify and articulate sources of uncertainty and to determine how to improve the practice to reduce uncertainty, even as they recognize that uncertainty cannot be eliminated completely (Ford & Forman, 2015). Scientific reasoning develops as students explore alternatives, negotiate decisions, and determine which uncertainties they can reduce and which they must acknowledge when drawing conclusions. Such exploration and negotiation are central to student-centered sensemaking, in which students' questions and ideas shape the direction of inquiry through ongoing discussion, investigation, and revision (Ford, 2008; Gray et al., 2025).

Types of Uncertainty

Uncertainty arises from multiple sources, and students' experiences with uncertainty vary extensively. Chen et al. (2024) suggest that unpacking types of uncertainty helps teachers understand what students struggle with and how to respond to support "productive struggle" (p. 1099). The literature has investigated and differentiated multiple types of uncertainty (e.g., Gustafson & Rice, 2019; Spiegelhalter, 2011; Chen et al., 2024). Broadly, uncertainty can be viewed from two perspectives (Blauza et al., 2025). A subject-centered psychological perspective focuses on an individual's first-person experience of being unsure, which may involve confusion, curiosity, anxiety, or a desire for further investigation. An object-centered external perspective, by contrast, takes a third-person view and focuses on what remains unknown about a body of knowledge.

Some scholars distinguish between epistemic and ontological uncertainty (e.g., Bähr et al., 2026; Dewulf & Biesbroek, 2018). Epistemic uncertainty refers to uncertainty that surfaces when a student is aware of their own limitations in abilities and/or underlying knowledge to explain a phenomenon or solve a problem. Epistemic uncertainty can be strategically leveraged as a resource to enhance learning (Chen & Qiao, 2020). When intentionally incorporated into science instruction, epistemic uncertainty can signal to students that their existing ideas do not adequately explain a new phenomenon or solve the problem, prompting them to reconsider and refine those ideas (Manz, 2018). However, epistemic uncertainty is not beneficial by default. Sufficient and timely support is critical for fostering students' curiosity and motivation while preventing frustration and disengagement (Graesser & D'Mello, 2012).

Ontological uncertainty is a result of the inherent variability of phenomena and complexity of the world. It is not a limitation in what people currently know and cannot be eliminated even with additional research and more advanced knowledge (Blauza et al., 2026; Dewulf & Biesbroek, 2018). For example, more data and better models can improve hurricane forecast accuracy, but they cannot determine the exact timing, path, and severity of every hurricane. Teaching students about ontological uncertainty can help them recognize that scientific knowledge is not a fixed collection of facts with the capacity to produce correct

answers in every situation. Scientific knowledge may be updated or even replaced as new data, research methods, and theories become available (National Science Teaching Association, 2020). Such revision reflects science’s capacity to improve knowledge and respond to changing conditions. It should be noted that ontological uncertainty in science and SSI does not weaken the reliability of scientific knowledge. Rather, scientific knowledge becomes more reliable through empirical evidence, logical reasoning, methodological scrutiny, and repeated testing that continually refine scientific explanations. However, the relationship between revision and reliability is not always accepted by the public, especially when updates to knowledge lead to changes in policy and recommendations tied to risks stemming from our individual decisions. Science education should therefore help students distinguish the reliability of a scientific claim from the precision of its predictions. Understanding ontological uncertainty helps students recognize why well-supported science can still produce conditional, probabilistic, and revisable guidance, and use that guidance responsibly in decision-making.

Supporting Students’ Productive Engagement With Uncertainty

Curricular and pedagogical research has examined ways to support students’ engagement with and navigation of uncertainty. For example, Manz et al. (2026) summarize four broad design principles: problematizing scientific ideas and practices to open up meaningful decisions; creating moments in which students encounter puzzles, notice conflicts, or raise disagreements; making uncertainty public as an opportunity to refine practices and update knowledge; and using differences in students’ findings, explanations, and other artifacts for shared sensemaking.

Chen and colleagues have proposed the SUPeR framework as a way for teachers to position uncertainty as a productive resource for inquiry, data practices, argumentation, and reflection (Chen & Jordan, 2024; Heal et al., 2025). The SUPeR approach begins by problematizing a phenomenon, prompting students to activate prior knowledge and recognize gaps in their understanding. Students then plan and carry out investigations to gather evidence. Next, they engage in argumentation by interpreting the data they have collected, grappling with unexpected or ambiguous results, comparing multiple perspectives, and working toward a shared understanding. Finally, students reflect on what they have learned, apply their revised ideas and practices, and generate new questions for further inquiry.

Student collaboration is critical for fostering positive experiences as students engage with uncertainty in science classrooms (Yurdakul & Han Tosunoglu, 2026). Liu et al. (2026) highlight that structured scaffolds for identifying, sustaining, and resolving uncertainty can support effective collaboration and help students recognize uncertainty’s value in the learning process. In addition, Chen and Techawitthayachinda (2021) emphasize keeping discussions of uncertainty open so students can work collectively toward possible resolutions, rather than closing them prematurely and risking negative impacts on learning and students’ experiences with uncertainty. In addition to classroom discussion and collaboration, Pietrocola et al. (2025) highlight the use of local issues to activate students’ prior knowledge from life experiences and further help students reason about uncertainty and evaluate risks. Their study used a risk matrix to analyze the likelihood and severity of possible consequences of the issue.

A growing body of literature has focused on uncertainty as a meaningful feature of students' disciplinary learning. However, this scholarship has largely considered how instruction can help students treat uncertainty as a motivation for questioning, investigation, and further information seeking (Gray et al., 2025). Comparatively less attention has been given to supporting students' understanding of ontological uncertainty and to providing opportunities for them to grapple with uncertainty that cannot be fully resolved through additional evidence or inquiry. Covitt and Anderson (2022) suggest that students need opportunities to explicitly experience ontological uncertainty, while they could do so by examining and quantifying uncertainty in data collection and analysis. Rosenberg et al. (2022) propose a Bayesian approach that invites students to represent their confidence in a scientific claim as a degree of belief rather than as simply true or false. By considering prior knowledge, evaluating new evidence, and revising their confidence accordingly, students can recognize why empirical claims should not be treated as absolutely certain or impossible. This approach can also help students make sense of scientific phenomena that are inherently probabilistic, where additional evidence may sharpen predictions without producing complete certainty.

Implications for Science Teacher Education

Although uncertainty is integral to scientific practice and socioscientific decision-making, teaching about uncertainty is challenging (Bähr et al., 2026). Teachers may view uncertainty as an instructional problem to minimize rather than as a resource for students' sensemaking, or they may lack strategies for recognizing, sustaining, and responding to students' uncertainty during inquiry (Starrett et al., 2025). In the context of SSI, teachers may also be concerned about where students' conversations might lead and how to respond sensitively to the social and political values intertwined with uncertainty in these issues. Therefore, teachers need opportunities to examine how uncertainty functions in these contexts and to develop pedagogical strategies that support students without prematurely resolving their questions.

However, research on teacher learning that addresses teachers' awareness and pedagogical practices for facilitating students' engagement with uncertainty is very limited. Gray and Bryce (2006) argue that because SSI involve irreducible uncertainty, professional development for SSI teaching should help teachers embrace uncertainty. Starrett et al. (2025) found that allowing teachers to shift between their "teacher hats" and "student hats" helped them develop greater awareness of the productive potential of student uncertainty and expand their use of strategies to raise, sustain, and utilize uncertainty in classroom instruction. Miani et al. (2026) described a preservice teacher education module that brought together participants from physics, mathematics, computer science, biotechnology, and natural science to investigate climate change. The module positioned complexity and uncertainty as shared concepts through which participants could compare disciplinary methods and perspectives. The activities helped preservice teachers distinguish between uncertainty that may be reduced through additional data or improved models and uncertainty stemming from the complex interactions within the climate system, which cannot be fully eliminated. By shifting among the roles of explorer, student, and analyst, participants examined these forms of uncertainty and considered how an interdisciplinary learning experience could inform their own instructional design.

Conclusion

Uncertainty is an inherent dimension of science and an especially important aspect of SSI, and individuals and communities must consider it as they negotiate these complex issues. Therefore, understanding uncertainty and competencies for dealing productively with uncertainty is necessary for scientific literacy, particularly the *Vision II* operationalization of scientific literacy (Roberts & Bybee, 2014). Research and theory stemming from science studies and science education have yielded useful frameworks for understanding uncertainty, its varying forms, and the ways in which learners may interact with it. For the purposes of science teaching and learning, we have found classifying epistemic and ontological uncertainty to be a useful conceptualization of the construct. This framing highlights the uncertainty learners feel about their own understanding of a scientific phenomenon (i.e., epistemic uncertainty) and distinguishes it from uncertainty inherent to the accounts that the broader scientific community can generate about a particular phenomenon (i.e., ontological uncertainty). Both forms of uncertainty are natural parts of learning science, and it can be helpful for students and educators to be aware of these possible sources of uncertainty and how they might interact. Recently, science education scholars have explored uncertainty in teaching and learning contexts and advanced ideas and tools to support students' productive engagement with uncertainty. For example, Manz and colleagues (2026) present design principles for incorporating uncertainty as a targeted feature of science learning. Gray and colleagues (2025) show how students can leverage uncertainty to motivate inquiry. Chen and colleagues propose the SUPeR framework for instruction to facilitate inquiry, science practices, and reflection (Chen & Jordan, 2024), and Rosenberg and colleagues (2022) advance a framework for helping students make sense of uncertainty by introducing basic Bayesian concepts. This work has moved the field rather rapidly and creates new opportunities for science teacher education. A few recent efforts have begun to link advances in uncertainty for science learning and teacher education (e.g., Starrett et al., 2025), but much work remains. We contend that teachers need to understand ontological uncertainty as a feature of complex and variable phenomena. They also need to recognize students' epistemic uncertainty and use responsive scaffolding to sustain curiosity, collaborative sensemaking, and evidence-based reasoning. Research that explores how to help teachers develop these understandings is needed, as are strategies and programs that build from research, theory, and praxis for supporting in-service and preservice science teacher learning and competencies in this area. We hope that *Innovations* can become a place where well-grounded strategies and programs for promoting teacher growth related to scientific uncertainty are featured.

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