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ARTICLE

Preservice Secondary Science Teachers' Nature of Science Views, Rationales, and Teaching During a NOS Course Guided by RFN: a Multiple Case Study

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Abstract

This multiple-case study investigated the changes in three secondary science preservice teachers' views of the nature of science (NOS), rationales for teaching NOS, and their NOS teaching at the end of a NOS course guided by the reconceptualized family resemblance approach (RFN). RFN is chosen as a conceptual framework that visualizes science as a cognitive-epistemic and socio-institutional system to guide this study. Data sources included individual interviews as well as each preservice teachers' lesson plan and teaching video from the lesson they enacted within the course at the end of the semester. Findings showed that there was an overall improvement in preservice teachers' views of NOS across all RFN categories, but one preservice teacher continued to hold misconceptions about scientific theories and laws after the course. Two preservice teachers developed multifaceted rationales for teaching NOS that transcend the classroom, while one preservice teacher continued to express mainly affective reasons for teaching NOS. Despite all preservice teachers having accurate views, professing multiple rationales for teaching NOS, and in two cases expressing knowledge of effective NOS teaching at the end of the course, only one of the three preservice teachers enacted explicit and reflective NOS instruction in their lesson. This preservice teacher chose to focus on the social-institutional NOS based on the RFN. This study suggests the need to provide extended NOS exposure and teaching experiences for preservice teachers in teacher preparation programs. Recommendations and implications for further research and science teacher education are discussed.

1 Introduction

Nature of science (NOS) is a complex, yet necessary component of scientific literacy. NOS typically represents "what science is, how it works, how scientists operate as a social group and how society itself both directs and reacts to scientific endeavors" (Clough, 2006, p. 463). Even though the definition of NOS varies (Irzik & Nola, 2011; Lederman &

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Lederman, 2014), NOS has remained widely accepted and argued for in science standards and reform documents for over 50 years (AAAS, 1990, 1994; NGSS Lead States, 2013; NRC, 1996, 2012). For decades, researchers have contended that it is important to teach NOS so that students are prepared to enter society as scientifically literate individuals (Driver et al., 1996; Lederman et al., 2013; Thomas & Durant, 1987; Shamos, 1995). However, research suggests that there are many challenges related to effective NOS instruction (McComas, 2020).

First, research shows that science teachers do not possess adequate views of NOS regardless of the instrument used for assessment, experience in teaching years, grade level taught, and science discipline (Lederman & Lederman, 2014). Preservice and in-service teachers hold some inaccurate views of NOS, such as the idea that hypotheses become theories which become laws, that there is one linear scientific method, and that scientific knowledge is completely objective and absolute (McComas, 1996). This is concerning as preservice and in-service teachers' own views of NOS are understood to have a critical role on students' views of NOS (Akerson et al., 2017; Lederman, 1992). Studies consistently reaffirm that deep understandings of NOS are necessary for effective NOS instruction (Abd-El-Khalick & Lederman, 2023). Secondary science teachers tend to rely more on textbooks to teach science as compared to elementary teachers, and secondary science textbooks tend to both underrepresent and misrepresent NOS (Abd-el-Khalick et al., 2017). However, very few postsecondary institutions offer a NOS course of any variety, and it is estimated that less than 10% of preservice secondary teachers will have taken a NOS course as a requirement (Backhus & Thompson, 2006). Therefore, this study focuses on preservice science teachers within a NOS course as part of a secondary science teacher preparation program.

Research shows that in addition to possessing informed views of NOS, teachers must also personally believe in the importance of teaching NOS (Nouri et al., 2021). Among the factors that mediate translation of NOS understandings into instruction are teachers' rationales for teaching NOS. Yet, a persistent culture of school science that prioritizes traditional content knowledge over epistemic knowledge and processes (McComas, 2020) causes most science teachers to believe that their first and most urgent priority is teaching scientific principles (Lee & Witz, 2009). Previous research has suggested that there is limited translation of NOS conceptions between teachers and students, and there is a need to investigate possible relationships between NOS understandings and behavioral intentions (Abd-El-Khalick & Lederman, 2023). When teachers' intentions to teach NOS are grounded in a well-developed rationale for teaching NOS, they may be able to overcome potential barriers to teaching NOS (Hanuscin, 2013). Few studies have focused on developing preservice science teachers' rationales for why it is important to teach NOS (Wan & Wong, 2016).

To translate teachers' NOS understandings and a well-developed rationale into NOS instruction, it is also imperative to have knowledge of how to teach NOS. This is because the choices made by the teacher within the specific context of a lesson are a key determining factor that influences students' beliefs about NOS (Lederman, 1992). According to McComas (1998), teachers' understanding of NOS and knowledge of appropriate instructional activities are alone insufficient to foster student understanding of NOS, because the actions taken by a teacher are more important. Teachers must know how to effectively implement the activities to target misconceptions. Additionally, many teachers view that NOS will be communicated to students regardless of whether it is done purposefully or accurately through implicit cues during science teaching (McComas et al., 1998). However, empirical research conducted over the past two decades has found that an explicit, reflective approach to NOS instruction is more effective at teaching NOS than is an implicit approach that assumes students will learn about NOS simply by engaging in science (Lederman & Lederman, 2014). To be successful NOS educators, preservice teachers must experience explicit-reflective instruction, reflect upon such instruction, and practice planning and enacting this type of instruction (Demirdöğen et al., 2016; Edgerly et al., 2023; Voss et al., 2023).

In summary, these three challenges, being prevalent and inaccurate NOS views among preservice teachers, a lack of a well-developed rationale for teaching NOS, and the false notion that NOS can be effectively taught without explicit attention and reflection around NOS ideas, act as barriers to effective NOS instruction. The purpose of this study is to investigate how NOS views, rationales, and teaching develop among preservice secondary science teachers during a semester-long NOS course guided by the reconceptualized family resemblance approach (RFN).

The approach to developing secondary science PSTs' views of NOS utilized by the present study is guided by the reconceptualized family resemblance approach (RFN), described by Irzik and Nola (2011, 2014) and later expanded upon and reconceptualized by Erduran and Dagher (2014). Irzik and Nola (2014) suggested conceptualizing science broadly as both a cognitive-epistemic system of thought and practice and as a social-institutional system (see Fig. 1). Presenting NOS as broad categories rather than a list of statements allows for different characterizations of disciplines while showing connections among the categories. RFN guided the NOS course design and was used in this study to analyze the PSTs' changes in NOS views. RFN has been used to design interventions in various contexts, with a growing but limited number of studies conducted specifically in preservice secondary science teacher education (e.g., Cullinane & Erduran, 2022, 2023; Kaya et al., 2019).

Fig. 1 FRA wheel (Erduran & Dagher, 2014, p. 28)

This study seeks to answer the following research questions:

1. What are the changes in secondary preservice teachers' views of NOS before and after a NOS course guided by RFN?
2. In what ways do secondary preservice teachers' rationales for teaching NOS change through a NOS course guided by RFN?
3. How do secondary preservice teachers teach NOS at the end of a NOS course guided by RFN?

2 Theoretical Frameworks and Literature Review

2.1 Reconceptualized Family Resemblance Approach

Although NOS research is often rooted in a consensus view, RFN was chosen to guide this study because many have critiqued the consensus view for being limited in its depiction of NOS. Historically, research in changing preservice teachers' views of NOS has adopted the consensus approach, which lists 7 to 10 aspects that one must know in order to be considered informed: scientific knowledge is empirical, reliable yet tentative, the outcome of creativity, theory-laden, and socioculturally embedded (Lederman & Lederman, 2014). It is the most assessed approach in research, as evidenced by the dominating use of the V-NOS and its versions to measure NOS views (Abd-El-Khalick, 2014). Irzik and Nola (2011, 2014) argued that while there are characteristics that apply to all sciences, they alone cannot define an entire discipline and proposed to instead conceptualize science broadly as both a cognitive-epistemic system of thought and practice and as a social-institutional system. The similarities and differences between sciences can be categorized systematically within the two systems.

Irzik and Nola (2014) identified the following categories within science as a cognitive-epistemic system: processes of inquiry, aims and values, methods and methodological rules, and scientific knowledge. Within science as a social-institutional system, the authors identified categories including professional activities, scientific ethos, social certification and dissemination of scientific knowledge, and social values. Erduran and Dagher (2014) reconceptualized the family resemblance approach for school science and reframed "processes of inquiry" to "practices" as well as included three additional categories of science as a social-institutional system: social organizations and interactions, political power structures, and financial systems. Table 1 displays the categories in the reconceptualized family resemblance approach (RFN) (Erduran & Dagher, 2014).

To illustrate the relationship between science as a cognitive-epistemic system and a social-institutional system and the holistic nature of this relationship, Erduran and Dagher (2014) presented the FRA wheel (Fig. 1). According to Erduran and Dagher (2014), this representation serves as a visual tool to display how the components of both systems are interrelated and impact scientific activity. Presenting NOS as broad categories rather than a list of statements allows for different characterizations of disciplines while showing connections among the categories. The approach to developing secondary science preservice teachers' views of NOS utilized by the present study is guided by the reconceptualized family resemblance approach (RFN) (Erduran & Dagher, 2014). RFN will guide the NOS course design, which has potential to support PSTs'

Table 1 Categories of science within RFN (Erduran & Dagher, 2014)

Science	Category
Cognitive-epistemic system	Practices
	Aims and values
	Methods and methodological rules
	Scientific knowledge
Socio-institutional system	Professional activities
	Scientific ethos
	Social certification and dissemination of scientific knowledge
	Social values
	Social organizations and interactions
	Political power structures
	Financial systems

development of their views of NOS and will also be used to analyze the PSTs' changes in NOS views.

2.1.1 Research on NOS Views Guided by RFN

RFN shows promise as a conceptual framework to ground intervention studies that aim to improve PSTs' views of NOS (Cullinane & Erduran, 2022, 2023; Erduran & Kaya, 2018; Kaya et al., 2019). When preservice teachers are exposed to and instructed to create their own visual representations of RFN, their views of the cognitive-epistemic system of science may improve. Studies within secondary science teacher preparation have found significant positive increases in preservice teachers' views of NOS based on RFN across both the cognitive-epistemic and social-institutional systems when measured quantitatively and qualitatively. Erduran and Kaya (2018) found in a qualitative study that elementary preservice teachers exhibited a large, positive difference after an RFN-based intervention in respect to their understanding of scientific knowledge (mainly the role of theories, laws, and models); however, there was more variation in the quality of representations of scientific practices, suggesting that PSTs may have struggled to understand scientific practices or to visually display their understanding of scientific practices. Kaya et al. (2019) used a mixed-methods approach to investigate PSTs' views of NOS based on RFN and found that in terms of each RFN category, PSTs' views in all categories except scientific practices were significantly improved after an intervention guided by RFN, possibly due to previous exposure in this category that led to a higher pre-test score. In one case study, results showed that for two secondary PSTs, NOS views improved from before to after an intervention guided by RFN, most markedly in the cognitive-epistemic aspects of scientific methods, scientific practices, and aims and values (Cullinane & Erduran, 2022). In a separate case study, Cullinane and Erduran (2023) explored NOS views and lesson planning of two secondary PSTs participating in an RFN workshop, finding that one PST had more informed views at the beginning compared to the other, and while both displayed greater NOS knowledge at the end, there was limited translation into lesson planning, even more so for the PST whose views improved significantly.

The aforementioned studies (Cullinane & Erduran, 2022, 2023; Erduran & Kaya, 2018; Kaya et al., 2019) provide insight into the use of RFN in teacher education contexts to support the development of accurate NOS views; however, more research is needed to understand how preservice teachers develop accurate NOS views across all RFN categories and within a NOS course. No one quantitative or qualitive assessment method is being consistently utilized to measure changes in NOS views regarding RFN. Considering this emerging line of research, the current study will contribute by qualitatively exploring PSTs' views of NOS relative to each RFN category before and after a NOS course.

2.2 Teacher Rationales for Teaching NOS

Driver et al. (1996) explain how science teachers often have well-established notions about how and what science should be taught, including a prioritization of science content over NOS. It is suggested that the constraints of time as well as the presentation of curriculum in policy documents and textbooks of science as a body of established knowledge prevent teachers from portraying the epistemology and socio-institutional aspects of science in a sophisticated manner, such as that portrayed by RFN. Driver et al. (1996) expressed why understanding NOS matters from a science curriculum viewpoint that aims to spread scientific literacy. They articulated five main arguments (Thomas & Durant, 1987) positioned in the literature for promoting public understanding of science and described how understanding NOS is integral for each case. The arguments that drive the need to equip students with a firm understanding of NOS as to promote public understanding of science and increase scientific literacy are as follows: (1) NOS has a utility value, (2) NOS aids in socio-scientific decision-making, (3) NOS encourages people to appreciate and support science as an endeavor, (4) knowing and embodying the moral values of science are valuable traits to society, and (5) NOS can motivate students to learn science while seeing themselves as contributors to science. See Table 2 for an expanded description of each argument.

Many teachers believe they have a responsibility to focus on science content, and when they do believe teaching NOS is important, it is mainly due to the belief that teaching NOS will support students in science content learning (Mulvey & Bell, 2017; Wan & Wong, 2016). A recent meta-synthesis (Nouri et al., 2021) of the literature examining what competencies are required for teachers to be effective NOS educators found that a motivation and rationale to teach NOS are key factors among teachers who do choose to incorporate NOS in science instruction.

Table 2 Arguments for why understanding NOS matters (Driver et al., 1996)

Argument	Description
Utilitarian	To make practical use of scientific knowledge, people must understand the grounds for having confidence in scientific knowledge (by understanding how that knowledge came to be) and in sources of scientific knowledge (such as experts)
Democratic	Socioscientific decision-making relies not only on understanding the basic science content relating to the issue but also in understanding that science is tentative yet negotiated and agreed upon, rather than certain
Cultural	To appreciate and therefore support the aims of the scientific enterprise, people must understand and share the aims and values of science and its societal benefits
Moral	Learning about and embodying the institutional norms of science, such as organized skepticism and freedom of thought, are of general value to society as a whole
Science learning	Understanding that science is theory-laden and dynamic helps students to see themselves as contributors to science, and not become demotivated or affixed to the view that science depends solely on memorization

2.2.1 Research on Teacher Rationales for Teaching NOS

Literature has shown that when science teachers hold a deep-rooted rationale for why they believe NOS educational outcomes are valuable, they are more likely to teach NOS. For example, Lederman (1999) found that among in-service biology teachers, the reasons provided by teachers for teaching NOS impacted their tendency to teach NOS. Herman et al. (2017) also found that the reasons provided for teaching NOS were ultimately related to the degree at which secondary science teachers taught NOS in their individual classrooms. All high and medium NOS implementers expressed high utility value by clearly describing far-reaching outcomes for teaching NOS that included and extended beyond the immediate value of NOS teaching and learning in the classroom. In contrast, low NOS implementers only provided general statements about how NOS is relevant and related to everyday life. Those teachers that did teach NOS at a high level emphasized the value of NOS for citizenship and in socio-scientific decision-making, rationales that transcends the concerns of schooling, including success in the course and on exams (Herman et al., 2017).

Unfortunately, such transcendent NOS rationales are uncommon. For example, in Lederman's (1999) study, the few teachers who did intentionally plan to teach NOS provided only affective reasons, such as it being fun, and bringing science confidence and enjoyment to students. Mulvey and Bell (2017) also found that among preservice secondary science teachers who had experienced two secondary science methods courses with explicit emphases on NOS, the most common rationale expressed was that NOS supports teaching what science is and/or teaching science content. Similarly, Wan and Wong (2016) found that among in-service secondary science teachers, most reasons for teaching NOS were pertinent to science learning, including facilitating the study of science content, increasing interest, supporting engagement in scientific inquiry, and meeting the needs of exams, and that NOS is fundamental to science learning. Fewer teachers discussed that teaching NOS can develop students' thinking abilities, cultivate scientific ethics, and support decision-making on socio-scientific issues (Wan & Wong, 2016).

Importantly, developing the strong rationales that result in implementing NOS instruction takes time to develop. When preservice teachers have repeated and extended engagement with NOS and NOS pedagogy, their rationales become more multifaceted. Kruse et al. (2017) found that preservice teachers who were engaged with NOS and NOS pedagogy in a science methods course prior to taking the NOS course tended to have rationales that transcended improving science content learning when compared to students who were not engaged with NOS prior to the course.

While many studies find that belief in the importance of teaching NOS is a factor that impedes the translation of accurate NOS views to practice, few studies explicitly seek to develop preservice teachers' beliefs about the importance of teaching NOS (e.g., Mulvey & Bell, 2017; Kruse et al., 2017). Teachers' belief in the importance of teaching NOS is not a main focus in many studies but is rather found during analysis to be a factor that impedes the translation of research-aligned NOS views and pedagogy to practice (e.g., Herman et al., 2017; Lederman, 1999). While there has been much research on NOS views, there has been less of a research focus on the beliefs of preservice teachers about why they should teach NOS. However, it is clear from the studies reviewed above that valuing the teaching of NOS can be a significant predictor if and how teachers will plan for and enact NOS instruction. This present study will address these gaps by exploring the topics and reasoning for what secondary preservice teachers declare they would teach in their classrooms and will do so before and after a NOS course to shed light on the development of these ideas as preservice teachers learn more about NOS and how to teach it.

2.3 Explicit-Reflective Approach

The explicit-reflective approach to NOS instruction is used to guide the exploration of the third research question. The term "explicit" is used to emphasize the idea that NOS understandings are cognitive outcomes of instruction and must be purposely targeted and planned for, similar to when teaching abstract scientific principles (Abd-El-Khalick & Akerson, 2004). Explicit approaches should be adopted to teach about NOS in the same manner they are utilized to support students developing their own understandings of complex and abstract science concepts. The second term "reflective" in the descriptor "explicit-reflective" is used to highlight specific instructional moves that allow students opportunities to analyze their activities from a NOS perspective, making connections between what they are doing and what scientists do and how this is related to scientific epistemology. An explicit-reflective approach considers student metacognition of certain cognitive-epistemic and socio-institutional aspects of NOS in relation to their classroom tasks and student reflection on these activities from a NOS framework.

A key component of effective NOS instruction guided by the explicit-reflective conceptual framework is the role of questioning. Student-centered questioning guides students to accurate views of NOS (Clough, 2018). Some types of NOS questions (i.e., general, specific, divergent, or convergent) are more appropriate for some educational outcomes than others (Kruse et al., 2022; Voss et al., 2022). General, divergent NOS questions are more open-ended and can elicit students' current thinking about NOS at the beginning of a lesson or at the end to assess student learning about certain NOS aspects (Kruse et al., 2022; Voss et al., 2022). Specific convergent questions are more useful for guiding students to respond with a specific, accurate position about NOS or to challenge students to further explain accurate, but perhaps oversimplified views of NOS (Voss et al., 2022). In this study, the explicit-reflective approach is used to guide the course instruction about effective NOS teaching and the analysis of NOS teaching by preservice teachers.

Edgerly et al. (2023) identified provisional codes for identifying NOS instruction within elementary teachers' enactment of a video recorded science teaching episode after a NOS professional development. "Implicit" NOS instruction indicates that an activity accurately reflects NOS but does not draw students' attention to NOS ideas, while "explicit" NOS instruction refers to instances where explicit statements are made about NOS by the teacher without prompting student reflection. "Explicit-reflective" is represented by instances where students' attention is drawn to NOS explicitly and includes a reflective component such as asking the students a question. The present study used a modified version of these codes to identify the level of NOS instruction (none, implicit, explicit, or explicit-reflective) enacted by each preservice teacher.

2.3.1 Literature on NOS Teaching Among Preservice Teachers

Teachers with accurate NOS conceptions are prone to downplay the importance of NOS instruction and fail to enact explicit NOS instruction (Duschl & Wright, 1989; Abd-El-Khalick et al., 1998; Bell et al., 2000). This is because they believe that if they plan science instruction such as labs that reflect accurate NOS views, students will gain an understanding of NOS implicitly, which has been refuted by a large amount of research (Abd-El-Khalick & Lederman, 2000; Khishfe & Abd-El-Khalick, 2002; Lederman, 1992). According to Clough (2006), years of learning science and experiencing science in and out of school repeatedly misrepresent NOS in a simplistic and inaccurate manner, both explicitly and implicitly, leading students to possess deeply held misconceptions that are resistant to change.

Several studies guided by the explicit-reflective conceptual approach to NOS instruction have investigated the development among preservice teachers of either their instructional planning for NOS teaching (Abd-El-Khalick, 2005; Voss et al., 2023) or enactment of NOS teaching (Lotter et al., 2009; Mesci et al., 2020) with varied success. Abd-El-Khalick (2005) studied the impact of a two-science methods course sequence on preservice secondary science teachers' NOS instructional planning and found that the translation of participants' NOS views into planned instruction related to NOS was minimal and lacked any explicit or reflective components to address NOS aspects; however, a substantially greater portion of participants also enrolled in a philosophy of science course translated their NOS understandings into explicitly planned instructional sequences. Lotter et al. (2009) found that early teaching experiences including repeated teaching and reflection during teacher education programs are needed to help preservice teachers revise their perceptions of teaching and apply the explicit-reflective techniques learned in methods courses. The enactment of explicit-reflective instruction among preservice teachers is related to their understanding of NOS. For example, Mesci et al. (2020) found that preservice teachers who did not have informed views of NOS had difficulty integrating NOS aspects into their lesson plan, and after a first lesson plan, almost no participants effectively integrated NOS; there was a progressive development as preservice teachers planned and enacted their second lesson plan; however, some continued to struggle. Voss et al. (2023), in a study guided by FRA, found that at the end of the semester, preservice teachers had shifted their instructional views from an implicit to an explicit-reflective approach and were more likely to use specific NOS questions. It was found that preservice teachers more commonly used less contextualized instruction and more concrete approaches for the inner ring of the FRA wheel when compared to the middle and outer rings (Voss et al., 2023).

It is clear that a complex interaction of factors impacts the teaching of NOS, and more information is needed about how to support the development of effective and research-based NOS teaching practices. Many studies have investigated preservice teachers' lesson plans or instructional views, but because these do not always translate into enactment, it is helpful to understand the enactment of NOS teaching by preservice teachers, Additionally, while some research has investigated the integration of isolated NOS aspects into lesson plans, fewer studies have investigated how the reconceptualized family resemblance approach can be used to support preservice teachers in planning and enacting explicit-reflective NOS instruction. The current study will address these gaps by using the lens of the explicit-reflective conceptual approach and RFN, will add to this emerging research area, and will investigate both the enacted NOS teaching and lesson plans of preservice teachers.

2.4 Summary

This study contributes to the literature in several ways. As RFN is a relatively new conceptual framework, it has not yet been used extensively in the NOS literature in developing

PSTs' views of NOS. Additionally, while many studies find that rationales for teaching NOS are a factor that impedes the translation of accurate NOS views to practice, only one study was found to explicitly seek to develop preservice teachers' rationales for teaching NOS (Kruse et al., 2017). Teachers' rationales for teaching NOS are not a main focus in many studies but are rather found during analysis to be a factor that impedes the translation of research-aligned NOS views and pedagogy to practice (e.g., Herman et al., 2017; Lederman, 1999). Finally, there is a need to further explore in what ways preservice teachers attempt to enact explicit-reflective NOS instruction in a NOS course guided by RFN.

3 Methods

A multiple case study approach (Yin, 2003) was used to explore the three research questions in this study. Each of the three participants constitutes a case. This approach provides a rich description of how each PSTs' views of NOS and rationales for teaching NOS change from before to after a NOS course and how they plan and enact NOS teaching at the end of a NOS course.

3.1 Participants

Four preservice teachers were enrolled in the semester-long NOS course, and 100% consented to participate. However, because one of the four preservice teachers missed 5 out of 15 of the in-person sessions, they were not included as a case. The remaining three preservice teachers each became a case in the study. Each of these three preservice teachers had previous experience volunteering with children in educational settings, but had no classroom teaching experience and no prior exposure to NOS in their coursework. Participants' information is described in Table 3.

3.2 Context

This study was conducted at a large southeastern public university in the United States. The NOS course was offered as an elective that would count toward the required number of elective course hours for secondary education majors and science education minors. The focus of the course is to provide a knowledge base on the nature of science (NOS) and the major historical developments of science and their implications on science teaching and learning. The course lasted for one semester and was taught by the first author of the study. Class meetings occurred once weekly, face to face, for 2 h and 50 min over the course of

Table 3 Participants' information

Preservice teacher	Gender	Race	Program	Level within program	Age range
Ben	Male	White	Secondary education, biology concentration	Junior	20–25
Valentina	Female	Latina	Environmental studies major with science education minor	Senior	20–25
Michael	Male	White	Secondary education, biology concentration	Senior	20–25

15 weeks. Preservice teachers were assigned readings that corresponded with online discussion post questions that were due every other week. Table 3 provides an overview of the course.

After an introductory class during the first week, each class session from weeks 2 through 12 consisted of 3–4 activities that required preservice teachers to unpack each RFN category (see Table 4) as well as have multiple experiences with instructional tasks meant to teach the targeted concepts. Types of activities included discussing the assigned readings, group tasks, video and reading reflections, and peer presentations. After engaging in sample instructional tasks each week, such as the "Bengal tiger activity" (Erduran et al., 2020) during week 3, preservice teachers reflected on the benefits and limitations of using the activity with secondary students and discussed why it would be important for students to understand the targeted NOS idea. Preservice teachers were asked to identify where on a continuum (Bannerman, 2008) activities fell in terms of decontextualized vs. contextualized and implicit vs. explicit. Weeks 13 and 14 were dedicated to the NOS lessons, and week 15 consisted of reflection and post-course individual interviews.

3.3 Data Sources

Three data sources (individual interviews, lesson plans, and teaching videos) were used to answer the research questions. At the beginning and end of the course, the researcher conducted a 25-min interview over Zoom with each preservice teacher to understand the preservice teachers' views of NOS related to each RFN category, rationales for teaching NOS, and ideas about how to teach NOS. To explore preservice teachers' views of NOS, one or more questions were asked pertaining to each RFN category. For example, to uncover ideas about the socio-institutional NOS, each participant was asked, "Is science affected by society? How?", and "Is society affected by science? How?" Preservice teachers were also asked to explain what they wanted their future students to understand about NOS and why, as well as how they would teach NOS. The interviews were transcribed using the help of built-in Zoom transcription software.

At the end of the course, the preservice teachers were required to plan and teach a 40-min lesson that includes NOS within the context of a chosen disciplinary core idea in science. These lessons were taught in class, with each preservice teacher teaching to the class, while the other PSTs adopted the role of students. The lesson plans that preservice teachers created as their final assignment were collected to be analyzed. These lessons were video recorded while enacted during week 14 and were transcribed using the help of built-in Zoom transcription software to be used as a data source.

3.4 Data Analysis

3.4.1 NOS Views

To answer the first research question, the interview transcripts were read to identify changes in preservice teachers' views of NOS from before and after the course. For each interview, responses were coded by their respective RFN category, comparing the pre and

Table 4 NOS course calendar

Week	Class topic	Representative session activity	Required readings
1	General introduction to NOS in science education	Introduction of course objectives, syllabus, and assignments	McComas & Clough, 2020 (pp. 3–10)
2	The family resemblance approach and explicit-reflective instruction	Photograph activity (from Erduran & Kaya, 2019, pp. 90–91)	Continuum: Selecting Inquiry-Based Experiences to Promote a Deeper Understanding of the Nature of Science (Bannerman, 2008) Erduran and Dagher (2014) Chapter 2, Sections 2.1 and 2.4
3	Aims and values	The Bengal tiger activity (Erduran et al., 2020)	Erduran and Dagher (2014) Chapter 3
4	Aims and values	Nonhistorical science drama roleplay (McComas, 2020)	
5	Scientific practices	States of rugby activity (Erduran et al., 2020)	Erduran and Dagher (2014) Chapter 4
6	Scientific practices	Interview with nonscientist to reflect on aspects of their life/career that may be science oriented	Appendix F (NGSS Lead States, 2013)
7	Methods and methodological rules	Brandon's matrix (Brandon, 1994, p. 3) activity (from Erduran & Kaya, 2019, pp. 92–93) Scientific methods activity (from Erduran & Kaya, 2019, p. 92) Introduction to Benzene Ring Heuristic (Erduran & Dagher, 2014, p. 164)	Erduran and Dagher (2014) Chapter 5
8	Methods and methodological rules	Discussion about different types of investigations	
9	Scientific knowledge	Theories, laws, models, and paradigm shift task (from Erduran & Kaya, 2019, pp. 94–95)	Erduran and Dagher (2014) Chapter 6
10	Scientific knowledge	Curriculum material production on the evolution of a scientific discovery	
11	Science as a social institutional system	Rosalind Franklin historical narrative (adapted from Dai & Rudge, 2018)	Erduran and Dagher (2014) Chapter 7
12	Science as a social institutional system	Historical short story (Clough, 2018) production	
13	NOS lessons	Instructor models NOS lesson	
14	NOS lessons	Students teach NOS lessons to class	
15	Summary of course	Post-intervention interviews	

post interview of each participant for each category (see Appendix Table 7). This process allowed the researcher to determine how accurate views were pertaining to each category.

3.4.2 Rationales for Teaching NOS

The individual pre and post interviews were also used to explore preservice teachers' rationales for teaching NOS in order to answer the second research question. Each preservice teacher was asked, "What would you teach about NOS?" and "Why?". RFN categories (Table 1) that related to each preservice teachers' intentions for what they would teach about NOS were identified. Driver et al.'s (1996) arguments for why understanding NOS matters were used as a priori codes in analysis and in categorizing the reasons that preservice teachers believed teaching NOS is important (Table 2).

3.4.3 NOS Teaching

To answer the third research question, the lesson plans and NOS teaching video transcripts were analyzed to explore how preservice teachers taught NOS at the end of a NOS course guided by RFN. The RFN categories were used as a priori codes in analysis to uncover which RFN categories were addressed by each preservice teacher. Instances of NOS instruction within each lesson plan and enactment were coded as either "implicit," "explicit," or "explicit-reflective" using the framework put forward by Edgerly et al. (2023). Descriptions and examples of the codes are described in Table 5 below.

After all data analyses had been conducted to create the three case profiles, gathering the data regarding changes in views of NOS, rationales for teaching NOS, and NOS teaching separately for each participant, a cross-case analysis was performed to examine the similarities and differences within each research question of all the preservice teachers.

3.5 Trustworthiness

To ensure the trustworthiness of findings, a second and third experienced science education researcher reviewed the findings to identify any instances in which the conclusions did not align with the data. For example, a discussion occurred between the three researchers to compare their interpretations of each preservice teachers' NOS teaching within the coding schema to that of the first author. This process helped to refine and add confidence in the interpretation of results (Cohen et al., 2007).

4 Findings

In this section, each case profile will be described to answer three research questions, followed by a cross-case analysis to example similarities and differences among cases.

4.1 Ben

Ben had a moderate understanding of NOS based on RFN at the beginning of the course but to different degrees when considering each RFN category. Ben's understanding of scientific methods and scientific knowledge was less informed compared to his understanding of the socio-institutional NOS and the aims and values of science. After the course, Ben's views had become more accurate and developed related to all RFN categories. Prior to the course, Ben expressed a utilitarian argument for why understanding NOS matters. At the end of the course, Ben's rationale for teaching NOS was more deeply developed. Ben restated the utilitarian argument but shifted to more of a democratic and moral rationale for why students should learn about NOS. In his end of course lesson plan, Ben identified several ideas about NOS that he wanted his students to learn, including aspects of the cognitive-epistemic system of NOS and of the socio-institutional system of NOS. Ben implicitly addressed both RFN categories of scientific knowledge and scientific practices in his lesson, areas in which his views improved during the course. His lesson required students to engage in scientific practices and reflect on which science practices they engaged in and required students to make inferences based on observations. Ben did not prompt students to consider how either behavior is reflective of the nature of science, and did not move beyond implicit NOS teaching.

4.1.1 NOS Views

Ben had a moderate understanding of NOS based on RFN at the beginning of the course but to different degrees when considering each RFN category, as evidenced by his pre-course verbal interview data. The categories in which his views were weakest and thus improved the most were scientific knowledge and scientific methods, with examples of these provided below. After the course, Ben's views had become more accurate and developed related to all RFN categories, especially within the cognitive-epistemic system.

For example, in his pre-course interview, Ben described the scientific method as "the process of experimentation."

> Well, when I think of the scientific method, I think of the like 7 or odd steps that I can't exactly think of right now, you know, like, observe, hypothesize, problem is, I can't even remember the exact steps right now. But you know generally the process of experimentation, and tricky thing is that not all science involves experimentation, like I always forget which one is the one with like star signs, astronomy like that one purely is almost an observational thing, because you can't perform experiments on the universe, you just kind of have to see what the stars are doing.

While Ben does refer to the scientific method as the set of seven or so traditional steps, he goes on to say that some science does not involve experimentation, such as astronomy. In his post-course interview, Ben again acknowledged the limitations of the lockstep scientific method, with more specific examples.

> Well, we want to go with the scientific method. It's the oh, you think of something. You get hypotheses, you test it, etc., etc. But you know the better version of the scientific method is that everything is, sometimes you're going to be talking to people. Sometimes you're going to be experimenting. Sometimes you're going to be publishing those results, but you know…The scientific method is more just, I'll use the phrase again, the day to day of the operations of being a scientist, right? And the exact procedures in that day to day…I mean the stereotypical example that we've been going with is astronomy, right? Because astronomy is almost purely observa-

Table 5 Examples and descriptions of codes used to analyze NOS teaching (Edgerly et al., 2023)

Code	Description of NOS instruction	Example from implementation
None	NOS was implicit and inaccurate	Valentina showed a 4-min video about flower structure and functions
Implicit	Students' attention was implicitly drawn to NOS ideas	Ben asked students to identify what science practices they engaged in during the lesson
Explicit	Students' attention was explicitly drawn to NOS ideas	Michael described how negative impacts of oil spills have both environmental and economic costs
Explicit-reflective	Students' attention was explicitly and reflectively drawn to NOS generally	Michael's worksheet included one free-response question inquiring about NOS and the role data has in society relative to environmental concerns

> tional. You can't exactly follow experimentation, which is what the scientific, the lockstep scientific method heavily implies.

Ben rephrased the commonly taught steps of the scientific method but then acknowledged that there is a better version that is not so limited. Ben again brought up astronomy as a counterexample to the "universal" scientific method, explaining that in astronomy, scientists cannot follow the typical scientific method.

4.1.2 Rationales for Teaching NOS

When first asked what NOS ideas he wanted his students to know, Ben's response related to the cognitive-epistemic system categories of scientific methods, scientific practices, and scientific knowledge.

> Definitely like, the basic concepts of the stereotypical, this is the scientific method, here's how you perform an experiment, here's how you think critically.

After the course, he repeated these ideas as examples of what he wanted students to know about NOS. While he newly mentioned "science and society" in his response, he was describing the need for public confidence in science and ability to identify false science as opposed to teaching students explicit ideas about this relationship.

> I guess the two things would be, you know, emphasizing that you can be a scientist, even if you're a non-scientist… And also, I mean, if we want to go back to science and society, being able to, you know, think critically, and be able to understand what is pseudoscience or not science, and what is science. Although there's also the, you know, the problem of how do you get students to think critically in the correct ways, and not say, oh, I don't trust the mainstream. I'm going to go to the fringe theory.

Ben's statement of wanting students to understand that they can "be" a scientist reflects that he values the ability of students to recognize and engage in scientific practices generally. He also finds it important for students to understand the criteria for science and the signals that something is pseudoscientific.

Prior to the course, Ben expressed a utilitarian argument for why understanding NOS matters.

> I'd also argue that you know, knowing science in general is useful, just because pretty much everything else that we said, how science affects technology, how society, then it affects science, which will then affect society. Basic skills like, do I need to go to my doctor, if X, Y, and Z are happening, or is this a normal biological process? Let's see, similar stuff on medication in a certain sense of knowing that antibiotics will not help your cold virus and stuff like that. And…while you can rote memorize those things, it's always going to be more useful for understanding if you know the basic nature of science principles.

This pre-course quote illustrates that Ben found the connectedness between science and society as a reason that it would be useful to teach NOS but does not describe this with much specificity or depth. Ben also believed that an understanding of NOS would be useful for students in personal decisions, such as their medical health, emphasizing the utilitarian argument for teaching NOS in that "people would feel more 'at home' with the products of science if they had a better understanding of the ideas involved" (Driver et al., 1996, p. 16).

At the end of the course, Ben's rationale for teaching NOS was more deeply developed and had expanded to include a moral and democratic argument. Ben restated the utilitarian argument ("thinking critically, and having scientific thinking, is a good skill for life generally") but shifted to a rationale that further transcends the classroom for why it is important for students to learn about NOS.

> Hmm. Well, partly because you know, being able to have the society have some trust in science at the very least, is important because the alternative to not trusting science is just lull, which isn't exactly the best practice to put in place, and you know you also want students to think critically, because outside of the stereotypical thinking critically, having scientific thinking is a good skill for life generally. And also like I want to go back to this Tuskegee. Not all scientists do science well, so… being able to be somewhat of a watchdog, assuming you were not just immediately falling into the wrong rabbit holes. That's important for society.

He described that in the interest of scientific progress, society must have confidence in science, which is needed for socioscientific decision-making. Such trust will only be gained if society understands how scientific knowledge is built and validated. Ben also argued that in reference to Tuskegee, not all scientists "do science well," so it is important for citizens to "be somewhat of a watchdog" and monitor science to ensure it is upholding and embodying the institutional norms, instead of "immediately falling into the wrong rabbit holes."

4.1.3 NOS Teaching

The lesson planned and taught by Ben at the end of the course was designed within the context of a high school biology course during a chemistry unit. The science content idea that Ben targeted was the unique properties of water that contribute to Earth's suitability as an environment for life: cohesive behavior, ability to moderate temperature, expansion upon freezing, and versatility as a solvent. Ben included an ambitious and unrealistic number of NOS ideas in his lesson plan, considering that this was a single, maximum 45-min lesson. In his lesson plan, Ben identified several ideas about NOS based on the RFN framework. He wanted his students to learn aspects of the cognitive-epistemic system of NOS (what characterizes scientific methods, how similar investigations result in the same outcome, how inferences are drawn from observation in science, and the function of models in science). He identified four science practices (NGSS Lead States, 2013) that would be a focus of the lesson, which included developing and using models, analyzing and interpreting data, constructing explanations and designing solutions, and obtaining, evaluating, and communicating information. He also planned for his lesson to address aspects of the socio-institutional system of NOS (weighing costs and benefits for solving specific societal problems). Ben's lesson seemed to mostly focus on the inner ring RFN categories of scientific knowledge and scientific practices, which he had misconceptions about prior to the course but had a significantly improved understanding about at the end of the course. In enactment, Ben briefly addressed the socio-institutional system category of social values. Ben showed a video about the scientific cause of potholes and the economic and public safety impact of potholes and then prompted students to consider other solutions to fix potholes (the social value of addressing human needs). Ben did not explicitly make the connection between this example and the idea that one social value of science is to address human needs. Any NOS instruction both in Ben's lesson plan and in the lesson enactment were implicit.

One example of Ben's implicit NOS instruction pertaining to the RFN category of scientific knowledge occurred when he introduced the lesson.

> Today we are going to be working with models. Specifically, we're going to be modeling properties of water. The properties of water you're going to be modeling today are its cohesive behavior, its ability to moderate temperatures, its tendency to expand upon freezing, and its versatility as a solvent, although we're more modeling cohesive behavior and solids.

Ben does not explicitly connect the practice of modeling to the work of scientists in this example.

While Ben did not enact any explicit-reflective instruction in his NOS lesson at the end of the course, he did express an understanding of explicit-reflective NOS pedagogy in his post-course interview, which was not the case in his pre-course interview. At the beginning of the course, Ben was asked how he might teach NOS to his future students. Ben responded, "Yeah, I would not know other than like experiments in which the nature of science is ingrained, but specifically teaching nature of science, I would not know." Although NOS teaching must be explicit and reflective to be effective, Ben explained that he would teach NOS implicitly such as through experiments; however, these experiences often lead students to interpret NOS in ways that are not intended.

When Ben was asked in his post interview how he would teach NOS, he described both explicit and implicit ways that he would do so. Ben went into detail about how he would teach NOS, referring to the course instruction.

> I'm gonna reference the first document that I'm not remembering correctly with the 4 sliders of, oh, how much you want to teach explicitly vs. how much you want to teach implicitly... Yeah. The continuum, so probably just make sure that I'm not necessarily teaching nature of science in one way, is probably going to be the best approach....One way it [NOS instruction] could look [explicitly] like it's just... you know, 'scientists come from different backgrounds. What backgrounds can scientists come from? Explain.' That's the literal approach to teaching explicitly. But you know...I mean the Mendel thing where you know we're talking about a scientist and their life and sprinkle in various bits of the [NOS] standards in there, or the engineering practices, you know, have those types of questions, or simply just make sure you're clearing these misconceptions, as in you know what is a theory, what is a law.

Ben referred to the NOS teaching continuum (Bannerman, 2008) that shows how NOS instruction can be thought of as a scale in terms of contextualized vs decontextualized and implicit vs explicit and said he would "just make sure that I'm not necessarily teaching nature of science in one way, is probably going to be the best approach." By saying he will avoid "one way" of teaching NOS, Ben is highlighting the strategy of using a mix of implicit and explicit NOS instruction and embedding explicit and reflective NOS questions in his lessons. Ben wrote his curriculum material using the history of science to teach about a scientific discovery on Gregor Mendel and included personal facts about his life, such as that he came from a low socioeconomic background, and embedded explicit-reflective questions into the story he wrote for the assignment. Ben's ideas about how to teach NOS, and the use of explicit-reflective questions during his course assignments, were not represented in the lesson that he taught, as the lesson only included implicit NOS instruction.

In summary, Ben had a moderate understanding of NOS based on RFN, with underdeveloped views related to the scientific knowledge and scientific methods categories, which were improved after the course. Ben continued to express the same ideas about what students should learn about NOS (scientific methods, scientific practices, and the development of scientific knowledge), but his rationale for teaching NOS expanded from a utilitarian argument to include both democratic and moral arguments. Ben's lesson focused on the inner circle category of scientific practices, and he taught NOS at an implicit level.

4.2 Valentina

Valentina's pre-course interview revealed that she had a moderate understanding of NOS based on RFN before the course. After the course, her views of NOS were improved, and she was able to more accurately and specifically articulate ideas related to all RFN categories. During her pre-course interview, Valentina expressed only one type of argument for why understanding NOS matters, which was the science learning argument. Valentina believed NOS aids in science learning and had mainly affective reasons for wanting to teach NOS. After the course, Valentina expressed a deeper rationale for the importance of teaching NOS, elaborating on the argument that teaching NOS supports science learning, and she also expressed a utilitarian argument, expressing that scientific practices are useful in every career and for students' lives beyond the classroom. Valentina struggled to implement NOS in her lesson at the end of the semester, planning to address some NOS ideas, but implicitly. There was no explicit or explicit-reflective NOS instruction in Valentina's lesson plan or lesson enactment.

4.2.1 NOS Views

Valentina had several misconceptions about NOS at the beginning of the semester, as evidenced by her pre-course interview. After the course, Valentina's views of NOS were more sophisticated, and she was able to more accurately and specifically articulate ideas related to all RFN categories, most notably in scientific practices and scientific knowledge, examples of which are provided below. For example, before the course, Valentina knew that science is tentative, and that scientific progress occurs when ideas are evaluated and revised; however, she held misconceptions about the relationship between theories and laws in science.

> I know law is more confirmed around the science community with a lot more evidence, and it's almost like...It is accepted, as you know, like universally true, whereas a theory is...I know it's supported by lots of evidence, but it's not as high up as a law.

This quote illustrates that Valentina believed laws were more "high up" and evidence based than theories. Valentina's understanding of laws and theories improved during the course, as shown by her post-course interview statements.

> Theory is the why and laws are the what, and I know that you said that, like theories are often I think backed up by hypothesis or hypotheses, and then, like laws, are more like a lot of like formulas, and…things like that. But the most important thing is that neither one is more reliable than the other, neither is more accurate, like a theory doesn't become a law.

After the course, Valentina accurately articulated basic distinctions between theories and laws, which is that theories explain phenomena, whereas laws describe them (the "why" and the "what"), and that theories develop from hypotheses and laws can be formulas. She corrected her previous beliefs regarding hierarchy between the two terms, explaining that neither are more accurate or reliable, and a theory does not become a law.

4.2.2 Rationales for Teaching NOS

When asked at the beginning of the course what she would teach about NOS, Valentina's response related to the cognitive-epistemic system.

> I would want everyone, all the kids to come out feeling like a scientist… to feel that they can do it…I want the kids to understand that science is not just like oh, knowing the definition of this big fancy science word, there's a lot more to science and each one of them could do it if they wanted to.

Valentina expressed that she wanted students to know that science is more than a collection of facts, which relates to the scientific practices and scientific method categories that expand the epistemology of science beyond established knowledge to include its processes.

> Just kind of make science less of a step-by-step process, and more of like understanding it. And let them have fun while they're just using their curiosity to be able to understand something or answer a question. I just don't want them to just think that science is like this, like hard thing that only specific people can do. I want to be able to show them everyone could do it and bring in different examples of different role models and different scientists that have done it and do it.

In her post-course response, Valentina was more specific regarding what she wanted students to know about science, especially concerning the scientific methods category. She emphasized that she wanted to teach students that science is a process as well as a product.

During her pre-course interview, Valentina expressed only one type of argument for why understanding NOS matters, which was the science learning argument.

> I think science can be a little intimidating for some, and I feel like understanding the nature of science would help settle some anxieties and help kids feel like they could do it.

Valentina believed NOS aids in science learning and had mainly affective reasons for wanting to teach NOS. After the course, Valentina expressed a deeper belief in the importance of teaching NOS during her post-course interview.

> I think it's important because I think I like, I can even say, from my own experience, like when I was younger, like I didn't pick myself as like someone who would grow up to have a STEM major. So, because of how I felt like it was very limited, for, I don't know just like I'm like a first generation. English is my second language,

> I'm female…So sometimes it was, it feels like extra barriers for different kinds of students, and it could be very intimidating, so I think it's very nice to…humanize science a little bit by talking about the scientists and understanding the process a little bit more and just kind of understand science as a whole, as like a whole concept, and just understand it better. And then maybe, if we understand science better, and we allow our students to, maybe they could learn to love science and feel like they can do it too.

After the course, Valentina elaborated on the science learning argument mentioned initially and described that as a first-generation immigrant and English learner, she never saw herself as someone who would grow up to have a STEM major because of a lack of representation and the presence of extra barriers for herself and students like her. Valentina also provided a second argument for why teaching NOS is important during her post-course interview.

> Science is like in everything. And there's like, for example, the practices of science are like in every kind of career so, and every kind of, even if you don't have a career, a stay-at-home mom, you're using a practice of science. So I think that it's very important. Theres also different aspects of science, like the economic side, the societal side, and these are all things that are very important even when they leave the classroom so I think that if they can understand that, then they can have a better mindset and idea of how the world works.

This demonstrates that Valentina had developed a utilitarian argument for teaching NOS, believing that scientific practices are useful in every career and for students' lives beyond the classroom.

4.2.3 NOS Teaching

Valentina's lesson taught at the end of the course targeted the content of pollination, plant structure, and function, as well as the interdependence between bees and humans, and was designed for a 7th grade life science class. In her lesson plan, Valentina specified that students would be engaging in the scientific practices of developing and using models and asking questions and defining problems. This planned instruction relates to the scientific practices category in the cognitive-epistemic system of NOS. She also included as part of her procedure to "emphasize the importance of pollination for the environment and human life," indicating that she wanted her lesson to address the category of social values (addressing human needs) within the socio-institutional system.

Valentina's lesson included instances of implicit NOS instruction but did not include any explicit or explicit-reflective NOS instruction. For example, Valentina instructed students to work as a group to complete a matching worksheet in which students labeled the parts and function of each part of an angiosperm using a word bank. In this sense, Valentina was engaging students in developing a model to represent an angiosperm and the form and function of its parts, but did not explicitly relate this to the work of scientists. Another instance of implicit NOS instruction occurred when Valentina referenced the social-institutional NOS, specifically the social values subcategory.

> Let me establish why we're learning about the anatomy, because it's very important for what happens after a pollinator lands… let's talk about why we ... learn pollina-

> tion in the first place. Without pollination, there would be basically no plant diversity in the world because there's two types of pollination: there's self-pollination... and cross pollination… So, without these things, there would be, if you remember the Bee movie, if you have seen the Bee movie, then you remember what happened when they removed all the bees. All the flowers and the plants started doing really poorly because without bees there would be no diversity at all.

Valentina is implicitly using the example of bees as a way to address her stated learning goal to "emphasize the importance of pollination for the environment and human life," which relates to the societal relationship with science, but does not make this relationship explicit and does not ask students to reflect on what this means about how science and society interact.

Valentina's implicit NOS teaching aligns with her expressed understanding of NOS pedagogy during his post-course interview. At the end of the course, when asked how she would teach NOS, Valentina lists many strategies, including concept maps, discussions prior to a lesson, using models, using roleplay to teach more about the "societal side of science," and bringing in scientists from underrepresented groups such as people of color and women. Valentina did engage students in modeling when she taught her lesson, but did not utilize any of the other approaches that she brought up in her post interview as ways she would teach NOS. These strategies, i.e., concept maps and discussions, can be considered supports for teaching science or teaching in general, are not specific to NOS, and do not include any explicit or explicit-reflective activities to teach NOS.

In summary, Valentina had a moderate understanding of NOS based on RFN possessing some misconceptions related to the scientific knowledge and scientific methods categories, whereas after the course, her views were more accurate and developed related to all RFN categories. Valentina believed, both before and after the course, that it was important for students to learn about scientific methods, scientific practices, and scientific knowledge. Her rationale for teaching NOS expanded from a science learning argument to additionally include a utilitarian argument. Valentina's lesson implicitly focused on the inner circle category of scientific practices, and she did not explicitly teach NOS.

4.3 Michael

Michael's views of NOS based on RFN at the beginning of the course were advanced. While he did begin with a strong understanding of NOS, his views improved for each category through the course according to the interview data. Michael continued to hold some misconceptions pertaining to the category of scientific knowledge at the end of the course, as he still had the idea that theories are more empirically based than laws. Michael's rationale for teaching NOS before the course was related to how NOS understanding supports science learning and supports students in socioscientific decision-making. This rationale became more fully developed by the end of the course, as he expressed more types of arguments that transcended science learning in the classroom. In his post-course interview, Michael restated the science learning argument, elaborated on his previously stated democratic argument for teaching NOS, and newly described a moral argument. Michael's end of course lesson revolved around the socio-institutional NOS, specifically the subcategories of financial systems, social values, and social organizations. The content ideas that were targeted were the effects of oil spills and the consequences of biodiversity loss. Michael explicitly planned to teach NOS, as illustrated by his stated learning goals and lesson materials, and implemented explicit-reflective NOS instruction in the enactment of his lesson.

4.3.1 Views

Michael's views of NOS based on RFN at the beginning of the course were advanced, as revealed by his pre-course interview responses. While he did begin with a strong understanding of NOS, his views improved for each category through the course according to the interview data, except for continuing to hold some misconceptions pertaining to the category of scientific knowledge at the end of the course. Michael's views were notably improved in the category of scientific methods, and his views about scientific knowledge, specifically the nature of theories and laws, were resistant to change. For example, at the beginning of the course, the pre-course interview revealed that Michael understood how scientific knowledge changes over time, and understood the role of scientific models, but held misconceptions about scientific theories and scientific laws. In his pre-course interview, Michael stated that "theories are less reinforced laws because they don't always work all the time, but they mostly work a lot of the time." After the course, Michael's post-course interview description of theories and laws was more sophisticated but still reflected this misconception.

> Theories essentially seek to provide explanations that are backed up with evidence or hypotheses that have been tested and tested, such as climate change. And then we have laws which are more empirically based that seek to, 'this is how it works, because this' and it's not necessarily seeking to say why it happens, just what happens, I throw the ball this way, it goes that far because I threw it this hard.... Most of the time [laws are more empirically based than theories]. You can make a, well because a lot of scientific laws in physics are mathematical formulas. So that's what I meant.

This quote illustrates Michael's understanding that a distinction between theories and laws is that theories provide explanations, whereas laws provide descriptions of what happens. However, his response suggests that he incorrectly believes theories are supported by less evidence (are less empirically based) than laws.

4.3.2 Rationales for Teaching NOS

At the beginning of the course, Michael described what he wanted students to know about NOS.

> We're talking about… middle schoolers, I don't think they need to know about how the government impacts how science is done. But I think they should know about the scientific method, that laws and theories can potentially change in the future…I think it should be emphasized that not everything in science is set in stone: It's constantly being revamped, being updated. New things are being found out all the time. But if we're talking high school is, I think they can know basically everything about the nature of science if they really want to. Especially how society right now affects science and climate change and all that.

In his response, Michael distinguished between what he wanted lower secondary students to learn about NOS, compared to what he thought was appropriate for upper secondary students to learn about NOS. He mentions the socio-institutional category of financial systems as something he does not think middle school students need to learn about. He also specifically mentions the cognitive-epistemic categories of scientific knowledge and scientific methods as things that students should know. After the course, Michael's response regarding what he wanted students to know about NOS expanded to include the socio-institutional system.

> I wanna especially hammer in the whole honesty aspect. The fact that a trusted scientist will have been peer reviewed multiple times, have lots of credited sources. and of course, the statistical data and research methods are accurate and ethical, and of course they don't use wording that is intentionally made to throw you off…I think statistical data is very important, especially when examining scientific studies, because there are scientific studies. And then there are scientific studies that are just someone standing outside a parking lot with a clipboard.

Michael newly discussed the category of aims and values in his response, bringing up the scientific value of honesty. He also discussed the professional activities of scientists, a category within the socio-institutional system, stating that it was important for students to understand how scientific information is verified in the scientific community such as through peer review.

Michael's rationale for teaching NOS at the beginning of the course was in part related to how NOS understanding supports science learning, explaining that teaching NOS is "how you create scientists and people that think." Michael described how NOS can support students in becoming excited about science, recalling "I have had volunteer experiences where…seeing kids get excited about science is awesome, it really is…And so I guess, seeing that, like that glimmer in their eye that they're starting to get it." Prior to the course, Michael also brought up a democratic argument for why teaching NOS is important. He stated students should learn "especially how society right now affects science and climate change and all that, because I definitely learned about that in high school, so why can't they?" He recalled a guest speaker coming into his high school to teach about the extent of climate change and melted polar ice caps and said, "that's just sad that it's been this many years, and nothing's really like changed or adapted."

After the course, Michael's rationale for teaching NOS was more fully developed, and he identified more types of arguments for teaching NOS that transcended science learning in the classroom. Michael did restate the science learning argument, saying in his post-course interview that he hoped teaching NOS would help students when it was time for their end-of-course exams. However, Michael also newly described a moral argument for why teaching NOS is important, saying that he especially wants to teach about values of science such as honesty, empirical adequacy, and accuracy, "for their own benefit as free thinkers." In his post-course interview, Michael also elaborated on his previously stated democratic argument for teaching NOS.

> If they're not too interested in the content, I can at least teach them well, in society, because that's somewhere you're going regardless of what field you're going into, you're gonna have to deal with people that are giving you the right information, people that are giving you the information as best they know it, and people that are giving you information that's coming from nowhere in particular. and I want them to be able to catch the difference… like make decisions on their own, because… I don't want to teach them how I feel about a thing, I want to present to them the topic, the scientific knowledge, and have them come to their own conclusions.

Michael further articulated the argument that NOS will support students in making practical decisions and choices that involve scientific knowledge (the democratic argument).

4.3.3 NOS Teaching

Michael's lesson was mainly focused around the outer ring of the FRA wheel (the socio-institutional system), specifically addressing the categories of financial systems, social values, and social organizations. This is evidenced by two of his stated learning goals within the lesson plan, stated below:

1. Explore the relative costs associated with cleaning up an oil spill, describe the impact of cost on decision-making to clean up oil spills, and explore and evaluate alternative oil spill cleaning strategies and their merits based on costs and benefits.
2. Students will be able to describe and evaluate the pros and cons of real-life decisions related to the environment.

Michael also chose, less dominantly, to include the inner ring (cognitive-epistemic system) category of scientific practices, identifying four NGSS science practice (NGSS Lead States, 2013), such as obtaining, communicating, and evaluating information. This can be seen in another of his learning goals: "Students will communicate their results or proposed solutions clearly to others, using mathematical data, logical reasoning, and relevant evidence." The content ideas that were targeted were the effects of oil spills and the consequences of biodiversity loss, and the lesson was planned for a high school biology class.

When Michael taught his lesson at the end of the semester, he included implicit, explicit, and explicit-reflective NOS instruction. Michael's lesson included explicit NOS instruction pertaining to social values. Throughout the lesson, students were learning about and considering the environmental impacts of oil spills. After students had completed their tables, they were asked to share their results, while Michael summarized pros and cons of different solutions on the whiteboard. This prompted one of the students to ask, "who is paying for all this cleanup?", and Michael replied, "that's the funny part, is it the government or the companies? BP is a company that didn't step up, and the government had to step in at a certain point, but the question remained, did they do a good enough job?" Michael's response explicitly emphasizes both the environmental and economic costs at play in the situation, and the need to act against environmental wrongdoing, but did not require students to reflect on the way social structures interact with science.

In addition to implicit and explicit NOS instruction, Michael also enacted explicit-reflective NOS instruction at one point in his lesson. At the end of the lesson, he instructed each student to complete a five-question exit ticket, consisting of one true/false question, three multiple choice questions, and, in his words as seen in the lesson plan, "one free-response question inquiring about the nature of science and the role data has in society relative to environmental concerns."

> Free Response: In the real world, scientists have to gather data, conduct experiments, and construct arguments for or against certain methods about societal responses to environmental problems. When considering which strategies to utilize, what factors can affect the decision-making process that government offi-

cials or independent companies have regarding Oil Spills? Minimum 10 Word Response.

This NOS question can be classified as divergent, as no particular perspective is specified within the question. Divergent NOS questions tend to yield highly descriptive results (Voss et al., 2022) and have potential to reveal misconceptions. This question targets several possible ideas related to the socio-institutional NOS and builds on several cognitive-epistemic aspects in leading up to the question. For example, the question prompt brings in practices of scientists that are used to build scientific knowledge, including conducting investigations and engaging in argumentation from evidence.

In summary, Michael had an advanced understanding of NOS based on RFN before the course which was further developed through the course but continued to hold a misconception about the nature of theories and laws. Before the course, Michael expressed that it was important for students to learn about scientific methods and scientific knowledge and articulated this importance again at the end of the course but also included that it was important for students to learn about scientific practices, aims and values of science, and the professional activities of scientists. His rationale for teaching NOS expanded from a science learning argument to additionally include a moral and democratic argument. Michael did demonstrate NOS teaching that was explicit-reflective.

4.4 Cross-Case Analysis

Similarities and differences that were found across the cases for each research question will be described in sections that follow.

4.4.1 NOS Views

Overall, Ben's, Valentina's, and Michael's views of NOS based on RFN improved from before to after the NOS course guided by RFN (see Appendix A). Specifically, they were able to describe a more sophisticated understanding of aims and values, scientific methods, scientific practices, scientific knowledge, and the socio-institutional NOS. Michael was the only PST to still articulate misconceptions about scientific knowledge, specifically the role of theories and laws after the course.

4.4.2 Rationales for Teaching NOS

When asked what they would teach about NOS at the beginning of the course, Ben, Valentina, and Michael had similar responses at the beginning of the course. All three participants described ideas they wanted to teach that were only related to the cognitive-epistemic system of NOS based on the RFN, such as how to "think critically" (scientific knowledge category), and stated that students should learn how science is done through scientific methods. Michael described that he did not think middle school students should learn how the government affects what science is done but said that high school students should learn "everything" about NOS, without providing more specifics. At the end of the course, both Ben and Valentina described that they wanted students to know that they could "do science," wanting to teach the epistemic practices of science to help students feel capable of participating in the endeavor. Michael did not mention this as something he wanted students to know about NOS, and instead described that he wanted students to know about the professional activities and epistemic practices of scientists not to ensure that students felt they could participate in science, but because it will help them in socio-scientific decision-making.

Both Ben and Michael developed a strong democratic argument to support their rationales for teaching NOS, believing that it was essential for students to develop the understandings needed to evaluate credentials of a knowledge provider and of the knowledge provided. Michael and Ben also both described the public's distrust in science, for example, in Michael saying that "people that can use that [scientific] knowledge can either choose to do something about it or not do something about it." Valentina did not make this same argument. While she developed a more developed rationale for teaching NOS, her argument remained mainly utilitarian, in that NOS was important because understanding NOS is necessary for practical reasons, i.e., "if people are to make sense of the science and manage the technological objects and processes they encounter in everyday life" (Driver et al., 1996, p. 16). Valentina fervently believed that learning NOS would benefit students on a personal level, saying "maybe, if we understand science better, and we allow our students to, maybe they could learn to love science and feel like they can do it." Ben also believed it was important to teach NOS so that students would know they could do science but had other reasons that were more tied to benefiting society as a whole. At the end of the course, Valentina's passion for wanting students to love and feel capable of doing science was the dominant reason for her rationale for teaching NOS, unlike Ben and Michael. The RFN categories that preservice teachers expressed they feel students should learn, as well as the arguments for why, are displayed in Table 6. Ideas and arguments that were newly present after the course are in bold.

4.4.3 NOS Teaching

Despite all PSTs having accurate views of NOS and rationales for teaching NOS at the end of the course, there were differences in how much NOS instruction they enacted in their lesson. The lesson plans written by Ben, Valentina, and Michael at the end of the course all intended to target aspects within the scientific practices category and socio-institutional system of NOS by including these as learning goals. However, the lessons varied in how explicitly and reflectively these aspects were taught. All three preservice teachers planned to address the socio-institutional NOS, specifically the social values subcategory, and implicitly enacted this in their lessons. Ben and Valentina both primarily touched on social values by directly explaining to the class how the content is related to the aim of addressing human needs. In comparison, the social values of science were a focal point of Michael's lesson. He emphasized, as he stated in his lesson plan, "the economic costs of solutions, weighed against the environmental cost of inaction." Michael addressed this concept explicitly and reflectively by embedding a contextualized NOS question into his lesson.

All three preservice teachers also planned to engage students in scientific practices in their lesson and did so in an implicit manner. In Ben's lesson, he implemented station activities that engaged students in carrying out investigations, using models, analyzing and interpreting data, constructing explanations, and designing solutions. Valentina's lesson engaged students in developing a model to represent angiosperm structure and function.

Michael's lesson involved students analyzing and interpreting data, engaging in arguments from evidence, and obtaining, evaluating, and communicating information. In all three cases, preservice teachers did not explicitly connect the scientific practices to the work of scientists or require students to reflect on how these practices are the major activities of scientists and how their engagement in them is similar or different to how science is done.

4.4.4 NOS Views, Rationales, and Teaching

A few similarities and differences emerged in analysis of the preservice teachers' changes in NOS views, rationales, and their end-of-course NOS teaching. As Ben, Valentina, and Michael's NOS views improved, their rationales for teaching NOS expanded to include more types of arguments for why students should learn NOS ideas. However, only Michael, whose NOS views were the most sophisticated at the beginning of the course, effectively translated accurate views and a strong rationale into teaching NOS in an explicit-reflective manner, whereas Ben and Valentina's NOS teaching stayed at the implicit level.

It can be noted that unlike Valentina, Ben and Michael both developed rationales that transcended beyond teaching NOS for student interest or practicality. When comparing the level of NOS instruction enacted, Ben more accurately communicated NOS ideas, such as the nature of scientific practices, compared to Valentina. While at the end of the course, despite all three preservice teachers being knowledgeable about NOS and cognizant of why they should teach it, only Michael planned for and implemented explicit-reflective NOS instruction.

5 Discussion

In the following section, findings will be discussed based on each research question.

5.1 Changes in Preservice Teachers' NOS Views Guided by RFN

Overall, Ben's, Valentina's, and Michael's views of NOS based on RFN improved from before to after the NOS course guided by RFN. After the course, they articulated a more

Table 6 Rationales for teaching NOS

Preservice teacher	Ideas about what students should learn (RFN)		Type of argument for why students should learn ideas (Driver et al., 1996)	
	Before	After	Before	After
Ben	Scientific methods Scientific practices Scientific knowledge	Scientific methods Scientific practices Scientific knowledge	Utilitarian	Utilitarian **Moral** **Democratic**
Valentina	Scientific methods Scientific practices Scientific knowledge	Scientific methods Scientific practices Scientific knowledge	Science learning	Science learning **Utilitarian**
Michael	Scientific methods Scientific knowledge	Scientific methods Scientific knowledge **Scientific practices** **Aims and values** **Professional activities**	Science learning	Science learning **Moral** **Democratic**

sophisticated understanding of the aims and values of science, scientific methods, scientific practices, scientific knowledge, and the socio-institutional NOS. Prior to the course, all preservice teachers believed there was one universal scientific method, but after the course, they demonstrated knowledge of a diversity of scientific methods in the post-course interviews. After the course, Ben, Michael, and Valentina had an improved understanding of scientific practices as evidenced by their post-course interviews, in which they each described several of the scientific practices outlined by the NGSS. For example, while Ben identified using mathematics and communication with other scientists as scientific practices in his pre-course interview, he elaborated in his post-course interview to include other practices such as planning investigations, recording observations, and communicating with different types of audiences. Additionally, all preservice teachers' understanding of the scientific knowledge category increased from before to after the course, apart from Michael's retained misconception about a hierarchical nature of theories and laws. A more sophisticated understanding of the final category, socio-institutional NOS, was also revealed by preservice teachers' post-course interview responses. For example, Ben and Valentina both discussed political power systems within science only in their post-course interview and not in their pre-course interview.

This study aligns with other research exploring the learning of NOS within a RFN framework that similarly found NOS views based on RFN among preservice secondary science teachers were overall improved. For example, Cullinane and Erduran (2022) found that an RFN workshop improved views of NOS, and Kaya et al. (2019) found that an RFN-based intervention significantly improved views of NOS in the RFN categories of aims and values, scientific methods, scientific practices, and the socio-institutional NOS. The present finding that preservice teachers' understanding of scientific practices increased is inconsistent with Kaya et al.'s (2019) study which found that preservice teachers' understanding of scientific practices stayed the same. It can be noted that in Kaya et al. (2019), preservice teachers had already been exposed to scientific practices in a previous course and thus had informed views in this category at the start of the course. The present study's finding that understanding of scientific practices improved among preservice teachers is also inconsistent with Erduran and Kaya (2018), who found that preservice teachers struggled to understand scientific practices after an RFN workshop incorporating visual tools, such as the Benzene Ring Heuristic. This might be because the course for the present study may have taken a different approach to conceptualizing the scientific practices category, because while the Benzene Ring Heuristic was introduced like in Erduran and Kaya (2018), the primary teaching of scientific practices was within the context of the NGSS (NGSS Lead States, 2013), due to this being a dominant force shaping curriculum and practice in the United States. It is possible that the scientific practices of the NGSS are easier for preservice teachers to understand than the more philosophical conceptualization of scientific practices presented by Erduran and Dagher (2014). Future research may investigate how these conceptualizations impact preservice teachers' understanding of this category.

The idea that theories are less empirically supported than laws is a widespread belief (McComas, 2020). According to Michael's post-course interview, Michael still incorrectly believed laws were more "empirically based" than theories, which aligns with Mesci and Schwartz (2017), who also found that the theories and laws aspect of NOS is harder to change than other aspects.

5.2 Development of Rationales for Teaching NOS

Ben, Valentina, and Michael had similar thoughts about what they wanted to teach about NOS prior to the course, such as “the scientific method” and critical thinking. The specific ideas they discussed wanting to teach were restricted to the cognitive-epistemic system of NOS based on RFN. After the course, only Michael described specific ideas that related to the socio-institutional system of NOS, stating that he wanted students to be aware of professional activities of scientists such as peer review. Before the course, preservice teachers’ rationales fell into the science learning or utilitarian argument or both. The pre-course interview responses revealed that preservice teachers believed it was important to teach NOS because it can get students excited about science (i.e., the science learning argument), and that understanding NOS is practical (i.e., the utilitarian argument). For example, Ben said in his pre-course interview, “it’s always going to be more useful for understanding if you know the basic nature of science principles.” This initial reasoning that learning NOS would be useful for students in their lives was not particularly guided. Prior to the course, both Valentina’s and Michael’s reasons for teaching NOS were that it would support students in science learning, and these reasons were primarily affective in nature, as both preservice teachers believed that NOS would help students feel excited and motivated to learn science.

Over the course of the semester, Ben, Valentina, and Michael developed deeper beliefs in the arguments they had initially stated for why it is important to teach NOS. For example, Valentina was able to list more persuasive reasons as justification for her belief that teaching NOS would support students in learning science. In her pre-course interview, Valentina stated, “I want them [students] to understand that science is not just like oh, knowing the definition of this big fancy science word, there’s a lot more to science and each one of them could do it if they wanted to.” In her post-course interview, Valentina described specifically that the act of humanizing science by teaching about NOS, talking about science as a process, and showing that people from all types of backgrounds are scientists can help students understand science as a whole concept and be more confident in learning science. All three preservice teachers were able to further elaborate on why it is important to teach NOS, describing new types of arguments that were not stated initially. At the end of the course, Ben developed a democratic argument for teaching NOS, and Michael developed a moral argument for teaching NOS. For example, in his post-course interview, Ben explained “being able to have the society have some trust in science at the very least, is important because the alternative to not trusting science is just lull.” This quote illustrates his development from believing NOS is important for students in the classroom to believing NOS is important for society. While both Ben and Michael developed arguments that moved beyond the immediate value that NOS has for teaching and learning in the science classroom, Valentina’s main reason for teaching NOS at the end of the course remained that it would support students in science learning. Additionally, all preservice teachers communicated an intention to teach NOS at the end of the course.

The findings echo Bell et al. (2016), who found that the most common rationale for teaching NOS reported by preservice teachers was that it improves science content understanding. Similarly, Mulvey and Bell (2017) found all but one participant planned to teach NOS for reasons beyond student engagement and enjoyment. These findings also align with Wan and Wong (2016), who found that teachers were more sensitive to different values of NOS instruction that were relevant to learning science within the classroom. Kruse et al. (2017) found that the preservice teacher who believed teaching NOS would help all students view science as accessible, particularly groups underrepresented in the sciences, also expressed this rationale again at the end of a methods course. It is possible that this argument is especially relevant and motivating to some preservice teachers when considering why it is important to teach NOS. The positive finding that multiple rationales were developed aligns with the findings of Kruse et al. (2017), who found that preservice teachers' NOS rationales become more multifaceted and transcend classroom learning with extended exposure to NOS and NOS pedagogy ideas. Like Mulvey and Bell (2017) and Bell et al. (2016), the preservice teachers in the present study expressed multiple rationales that moved beyond affective reasons to teach NOS, such as cultivating scientific ethos in students (Wan & Wong, 2016).

5.3 NOS Teaching After a NOS Course Guided by RFN

The level of NOS instruction by preservice teachers varied. Valentina taught NOS in an implicit, mostly inaccurate manner. Ben taught a lesson that accurately sent implicit messages about NOS, but only Michael began to utilize explicit and explicit-reflective NOS instruction. During their post-course interviews, Ben and Michael both described how they would teach NOS explicitly and reflectively. For example, Michael said in his post-course interview when asked what type of discussion questions he would use with his students, "Well, they need to be explicit if they're nature of science questions, which I want to have at least one in every assignment." Ben explained that he would use a mix of explicit and implicit NOS instruction, and when asked how the explicit teaching may look, he replied, "I guess one way it could look like it's just…you know, scientists come from different backgrounds. What backgrounds can scientists come from? Explain." This is an example of an explicit-reflective NOS question he wrote for the historical short story course assignment. While Ben's understanding about how to teach NOS improved (toward explicit-reflective), this was not yet evident in the lesson implementation. Unlike Ben and Michael, Valentina did not discuss teaching NOS explicitly or reflectively when asked how she would teach NOS. Instead, she described implicit approaches such as having students act out NOS. For example, in her post-course interview, Valentina said, "So maybe kind of putting this idea of like environmental injustice, kind of like the abstract concept a little bit, and then, like putting it into that activity, and like having them by acting it out." While Valentina valued NOS instruction and had accurate views of NOS at the end of the semester, this was not especially reflected in either her planning for or enactment of NOS instruction.

This echoes the findings of Herman et al. (2017), who found that the level at which preservice teachers understand effective NOS pedagogy is associated with their level of effective NOS instruction. Like Abd-El-Khalick (2005), where the translation of participant preservice teachers' acquired NOS understandings following NOS instruction into instructional planning related to NOS was minimal, overall explicit-reflective NOS instruction in lesson enactment was minimal. The finding that Ben and Valentina struggled to explicitly and reflectively integrate the socio-institutional NOS in their lessons echoes that of Voss et al. (2023) and Cullinane and Erduran (2022), who also found that preservice teachers had difficulty teaching the socio-institutional NOS. This study's findings also aligned to Voss et al. (2023), in that when planning for socio-institutional NOS, preservice teachers tended to take a topic approach, whereas the inner ring (i.e., scientific practices) was more embedded. Michael selected a topic (oil spills) that provided a clear context to teach the socio-institutional NOS.

Positive changes in these preservice teachers' understanding of effective NOS instruction brings further support to Lotter et al.'s (2009) claim that explicit modeling of NOS teaching and practice creating instructional materials are important to gradually build capabilities to teach NOS. Additionally, Lotter et al. (2009) also found that coursework within a science methods course, combined with practicing teaching NOS during the course, helped move preservice secondary science teachers toward effective, explicit-reflective NOS teaching. Like Voss et al. (2023), in the present study, most of the activities for teaching NOS that the preservice teachers described reflected activities they had participated in themselves during their NOS course.

Like Lotter et al. (2009) who found that the teachers' enactment of NOS teaching was still a work in progress, with some groups reverting to PowerPoint notes to cover most of the content standard, Valentina relied heavily on videos and a worksheet to cover her chosen content standard at the expense of including NOS. In Kruse et al. (2017), of the participants who were enrolled for the first time in a course covering NOS like those in the present study, all expressed more accurate NOS views at the end of the course, but not all came to understand the importance of the explicit and reflective framework for teaching NOS. Echoing the findings of Herman et al. (2017), Michael, who implemented NOS at a higher level, expressed a greater utility value for NOS teaching and learning, and a stronger understanding of explicit-reflective NOS instruction, compared to Valentina. This might be attributed to Michael having beliefs for the importance of NOS teaching that relate to specific far-reaching desired outcomes for science education, such as a public that trusts science. This brings further support to Herman et al.'s claim that while teachers who work to implement accurate and effective NOS instruction obviously value it, valuing it in merely a general sense does not mean teachers will work to implement such instruction and further improve their NOS teaching.

5.4 Relationship Between NOS Views, Rationales, and Teaching

The development of NOS views and rationales as related to NOS teaching at the end of the course brings further support to research that finds views and rationales as factors that mediate, but do not guarantee, translation of NOS understandings into instruction. Cullinane and Erduran (2023) similarly found that the improvement of NOS understanding is not necessarily an indicator that it will translate into teaching. In Ben's case, although he was able to accurately describe explicit-reflective NOS pedagogy in his post-course interview, he needed further support to implement it himself. While Valentina had accurate NOS views and was enthusiastic about teaching NOS, and stated ways she would teach NOS, the strategies she described were implicit, and the reasons she listed for teaching NOS remained at the student level, rather than society. This echoes the claim of Nouri et al. (2021) that teachers who effectively teach NOS have specific motivations for doing so, so it is important to teach rationales for teaching NOS.

5.5 Implications

This study contributes to the field as other studies who have investigated how preservice teachers develop their NOS views guided by RFN did not investigate how preservice teachers' views of NOS were related to their NOS teaching (Cullinane & Erduran, 2022, 2023; Erduran & Kaya, 2018; Kaya et al., 2019). Additionally, this study contributes to an emerging line of research investigating preservice and in-service teachers' rationales for teaching NOS, how rationales can develop during a NOS course, and how these may relate to what preservice teachers choose and choose not to teach about NOS. By analyzing the enactment of the three preservice teachers' NOS teaching, this study helps to address a gap in the literature because while many studies (Abd-El-Khalick, 2005; Cullinane & Erduran, 2022; Erduran & Kaya, 2018; Voss et al., 2023) offer glimpses into preservice teachers' NOS teaching through their stated pedagogical views or written lesson plans, there is a need to observe the enactment of NOS teaching because intentions do not always translate into enactment (Lederman, 1999). This study reaffirms research that shows teachers can develop more informed NOS views with explicit-reflective instruction of RFN. This study contributes to the emerging literature that uses RFN as a conceptual framework to guide preservice teacher courses, workshops, and professional developments and supports the need for further research exploring the factors that influence the transfer of NOS knowledge and rationales to NOS instruction. Further research is needed to evaluate the usefulness of this NOS conceptualization in preservice teacher education. Future research should also explore how preservice teachers develop accurate views of scientific practices and if a difference in conceptualization of scientific practices impacts the changes in preservice teachers' views of this category. New studies might investigate how preservice teachers' explicit-reflective NOS teaching develops during a NOS course by measuring it multiple times throughout the course.

This study also provides further empirical support for the need to explicitly include opportunities within secondary preservice teacher preparation for preservice teachers to develop the accurate views, rationales for teaching, and effective pedagogy for NOS, if they will be expected to teach NOS once entering the classroom. This study adds further support to the claim that one exposure to NOS within one teacher education course is not enough to prepare preservice teachers to effectively teach NOS (Akerson et al., 2006; Kruse et al., 2017). This study also adds further support to the argument that preservice teachers must first develop accurate NOS views prior to learning how to teach NOS (Demirdogen et al., 2016; Voss et al., 2023). Findings also indicate the importance of extended engagement with NOS to develop strong rationales for teaching NOS. While Michael did implement explicit-reflective NOS instruction, it was limited and mainly focused on the outer ring of the FRA wheel, without including many interconnections. This suggests that these connections should be more visible in the course design. Courses with NOS learning outcomes should be required elements of secondary science teacher education programs, rather than offered as elective coursework. Preservice teachers might need more support in planning and enacting explicit-reflective NOS instruction that focuses on the inner wheel of the FRA wheel (cognitive-epistemic system), as they tend to teach these ideas more implicitly. Additionally, preservice teachers struggled to articulate many ideas related to the socio-institutional system that they believed were important for students to know at the end of the course. As the present course design treated the socio-institutional system as one category, future NOS course designs may allot time for specialized instruction related to each of the categories within this system (i.e., professional activities, scientific ethos).

Even though some NOS views were more resistant to change, and only one preservice teacher effectively taught NOS explicitly and reflectively, these difficulties can inform future NOS course design to support preservice teachers in these areas. More opportunities to plan for and enact explicit-reflective instruction should be embedded into teacher education coursework. The present course would likely have benefited from more frequent discussions about NOS pedagogy, as the preservice teachers were not yet able to enact NOS instruction at a high level. This provides further support to the idea that an instructional sequence of addressing views first prior to pedagogy can support preservice teachers who are learning both, and that more than one course addressing NOS is necessary to expect the ideal level of NOS instruction. Because preservice teachers often refer to the NOS activities and teaching strategies they experience themselves in their teacher education coursework, they may need more opportunities to develop their own NOS instructional material types during their teacher education courses. Addressing NOS ideas explicitly and reflectively should be made a clear requirement of science teacher lesson plans written as coursework, since this increases the possibility, but does not guarantee, that the lesson will include NOS.

6 Conclusion

All three preservice teachers had overall improved views of NOS at the end of the course guided by RFN and demonstrated a sophisticated understanding of NOS. The three preservice teachers also developed more multifaceted rationales for teaching NOS. However, the informed views and strong rationale for teaching NOS did not fully translate to practice. Only one preservice teacher, Michael, moved beyond an implicit approach to teaching NOS in his lesson enactment at the end of the course. Further research might explore the translation of and complex interactions between the development of NOS views, rationales, and explicit-reflective NOS teaching.

6.1 Limitations

Some limitations in this study must be acknowledged. Although a multiple case study is a time-intensive methodology and contributes rich insight into the phenomena under investigation, this study examined three preservice teachers in one NOS course and thus has limited transferability to theoretical propositions and other preservice teacher populations. A second limitation concerns the fact that this data did not investigate the relationship between the course design and preservice teacher outcomes. Such an investigation could have provided valuable insights regarding how aspects of the course supported preservice teachers' NOS views, rationales for teaching NOS, and NOS teaching. Additionally, even though the first author was careful to interpret the results from the perspective of a researcher, they were also the sole instructor of the course.

Because there was no measure of teaching at the beginning of the semester, it was not possible to relate the change in NOS teaching to the change in views or rationales for teaching NOS. This information would have been useful to see if and how changes in these three areas develop synergistically. Preservice teachers taught their lessons to their peers as it was not possible to observe preservice teachers teaching secondary students. A more authentic context to practice NOS instruction could influence the approaches preservice teachers take to teaching NOS. Lastly, it is unknown whether and for how long preservice teachers will maintain the views, rationales, and NOS teaching demonstrated at the end of the semester without following up.

Appendix

Table 7 Coding examples of NOS views before and after course

Code	Ben		Valentina		Michael	
	Pre	Post	Pre	Post	Pre	Post
Aims and values	"Having the virtue to be able to communicate with other people, I guess, and maybe the virtue of trying to be patient of trying to do other things, if stuff doesn't work. Yeah, honesty, maybe… being honest when you publish"	"It really depends on what type of science you're doing, but you know, generally aims of science would have to be trying to add on to scientific knowledge. An aim could be, you know. trying to solve a problem of some sorts. I mean the value of science of could be trying to stay as neutral or on as unbiased as possible… Ultimately the end goal is consensus, but in order to eventually get to that consensus well, you need to argue with evidence"	"Good ethics, like good at collaborating, valuing other people's opinions, flexibility with other disciplines"	"Authenticity, not having bias…I'm trying to think of the short story we did. How like I incorporated some aims and values, just justice, and like for a society so like creating, I guess, like equal opportunities for everyone… communication and trust, and just making sure your work is like accurate, and being able to share your data or discoveries with the public and not, you know, hiding anything"	"Honesty… because if you flub some numbers just to make your hypothesis correct, then that's a null and void experiment, and you're just lying to people"	"Ethics of you know, intellectual equality, honesty, empirical data, empirical adequacy, accuracy… like knowing science history as opposed to you know, obscuring it. That's more of a value [than an aim]"

Table 7 (continued)

Code	Ben		Valentina		Michael	
	Pre	Post	Pre	Post	Pre	Post
Scientific practices	"I assume in physics you're going to be using, you have to be good, really good at a certain type of math. But then you might be a biologist, and you really need to know statistics. Math is probably one of the stereotypical skills you need to know how to do, once again going back on general observation skills, or critical thinking, creativity perhaps, being able to communicate with other scientists. Stuff like that"	"Sometimes a scientist's day to day not only involves talking to other scientists, but, you know, talking to once again non-scientists, but the exact, whether that be through trying to communicate your findings to the public, in like a radio interview, or trying to get a senator to understand something, and 'please give me money'… And then the other day-to-day is just, you know, doing whatever they're supposed to be observing"	"I think you're [scientists are] doing, let's see, experimentation, that's usually what people think right, I think, like people think like scientists and lab coats. But there's also like social sciences. So, I feel like also like working with people doing surveys, and just I feel like it depends on the kind of science you're doing"	I know you said there's 8 practices…There's like asking questions, analyzing data like you're using mathematics, communicating with other scientists, constructing experiments and explanations, that's a couple. Oh, investigations is one, so planning and carrying out investigations… and then engaging with others, and too with, so to like, talk about evidence and stuff"	The experiment conducting and recording… What I assume scientists do is they enter a sort of scientific journal discourse, and they'll go and read other people's research on research that they know something about. and they will either corroborate their findings or go, huh! That's interesting, and maybe start their own research in their own experiment. And then they'll publish something"	They observe, they ask questions, they seek to answer questions about the world that either they form, or other people ask. They seek to solve problems, all that good stuff, you know, all those lovely practices of science making and using- or designing and using models, analyzing and interpreting data is the easy one, but it's the … obtaining, evaluating and communicating evidence is the last one"

Table 7 (continued)

Code	Ben		Valentina		Michael	
	Pre	Post	Pre	Post	Pre	Post
Scientific methods	Well, when I think of the scientific method, I think of the like 7 or odd steps that I can't exactly think of right now, you know, like, observe, hypothesize, problem is, I can't even remember the exact steps right now. But you know generally the process of experimentation, and tricky thing is that not all science involves experimentation…astronomy, like that one purely is almost an observational thing, because you can't perform experiments on the universe, you just kind of have to see what the stars are doing"	"It's the oh, you think of something, you get hypotheses, you test it, etc., etc. But you know the better version of the scientific method is that sometimes you're going to be talking to people. Sometimes you're going to be experimenting. Sometimes you're going to be publishing those results…I mean the stereotypical example that we've been going with is astronomy, right? Because astronomy is almost purely observational. You can't exactly follow experimentation, which is what the scientific, the lockstep scientific method heavily implies"	A process of doing, I don't know, doing science of experimentation… Just go and make a discovery, do an experiment, find something out, how you would look into something that you are trying to get the answer for"	"Someone says scientific method, it's more of like everyone thinks like the universal like, observing a phenomenon, ask a question about it, creating data or analyzing data, creating models and conclusions. And you know it's like these like certain steps. But I think we learned that the scientific method is not a linear set of a specific linear set of steps. In fact, it could, depending on disciplines, it could be very different, or the sciences. So, I think we just learned that it's just not universal"	"Well, from a strictly formulaic perspective of what was taught in school, the scientific method was, build your hypothesis so it's ask a question, design an experiment, conduct an experiment, record observations, and then make a conclusion. That's the direct academic scientific method. But I prefer to think of it less in that sort of box and more, you ask a question… and then you try to figure out a way to test that issue. So, create an experiment. Then you obviously have to conduct that experiment"	"There is no "the" scientific method except for the one that's taught about in schools, unfortunately… what I mean by unfortunately, is that in schools it's commonly taught. Or I don't know if it's still taught that way now, but hopefully not …not every experiment needs a hypothesis. Not every field of science conducts itself to an experiment, like psychology, for example…There is no one concrete frame of the scientific method"

Table 7 (continued)

Code	Ben		Valentina		Michael	
	Pre	Post	Pre	Post	Pre	Post
Scientific knowledge	“Scientific law being general explanations that are kind of just put out there, but there’s no real explanation for it… And stuff like Einstein’s theories versus like Newton’s laws, there’s generally lots more evidence to support it, than any evidence the law would have”	“If we want to go for an example, Newton did laws for gravity, and Einstein did theories for gravity and tried to explain it more… Newton’s law of gravity attempted to model in a sense gravity…Because you know there is, you know, he formulated equations… By definition no [a theory cannot become a law]. Going back to Newton, where we have to add that, like extra variable G for gravitational constant. Sometimes you’ll modify the law. Sometimes you create a new law entirely”	“I know law is more confirmed around the science community with a lot more evidence, and it’s almost like, it is accepted, as you know, like universally true, whereas a theory is, I know it’s supported by lots of evidence, but it’s not as high up as a law”	“Theory is the why and laws are the what, and I know that you said that, like theories are often I think backed up by hypothesis or hypotheses, and then, like laws, are more like a lot of like formulas, and…things like that. But the most important thing is that that neither one is more reliable than the other, neither is more accurate, like a theory doesn’t become a law”	“Theories are less reinforced laws because they don’t always work all the time, but they mostly work a lot of the time”	“Theories essentially seek to provide explanations that are backed up with evidence or hypotheses that have been tested and tested, such as climate change. And then we have laws which are more empirically based that seek to, ‘this is how it works, because this’ and it’s not necessarily seeking to say why it happens, just what happens, I throw the ball this way, it goes that far because I threw it this hard”

Table 7 (continued)

Code	Ben		Valentina		Michael	
	Pre	Post	Pre	Post	Pre	Post
On the relationship between science and society	"Society decides what it wants to fund, and sometimes it doesn't fund all the possible science stuff that can be done…We would not be having this conversation if the space race did not exist, right? So, in a certain sense, new scientific technologies affect our day to day"	"Science in a sense, can influence how you know politicians act in the sense of…scientists complaining about, 'Hey? Climate change is a thing. Can we fix this, please?'. That's the obvious example, and you know, likewise, politicians can impact how scientists work, of 'Oh you won't get that grant money, you'll do something completely different…So the interactions between science and society has the tendency to be complex in those regards. The interactions between science and society probably depends on how much society trusts science"	"Science works, together with society, to be able to improve… society and science do work together constantly, whether it be pairing up for the patient or trying to improve or embark on continuing to learn something, because sometimes the study will put a stop to something…I think science impacts society. You could see that like a lot in politics, how science can be, can lead to very divisive opinions between people, for example, the topic of climate change"	"They [science and society] build off each other. They're always working with each other. Kind of like ethics and values of society also impact the scientific process and scientific community and the scientific communities is also impacting society as a whole…. Science can impact society by creating new laws and theories that help people. There is that barrier a little, the obstacle of societal judgment… Rosalind with Watson and Crick, like she was maybe treated differently because of the time period, so that, like hindered her a lot, and had to make her more, not secretive, but more protective of her work, because of society, and like the situation between, like, I don't know just not being treated equally"	"The science community that's its own little subsection of society, but also science impacts society in very direct ways, sometimes like with what happened at the end of World War 2. That was a very big impact on society. But the way that society views how science is used or scientists in general, it can be a little weird, because you have some people that won't listen to reason over anything… in order for science to get done, it needs the proper funding and time. The two things that are not often given plenty of, when science is conducted"	"Well given that science is a medium which is meant to be shared with not only other scientists, but also just the general populace, it's how the general populace reacts to it. For example, the people that can use that knowledge can either choose to do something about it or not do something about it, or you have. You know the popular opinion, how they change around science, or how their beliefs are, you know, will change how they interpret that data…. it's when we have cell phones, if we didn't have somebody programming over at apple computers, figuring out how to make calculators even better, we don't have a as much communication between each other"

Declarations

Conflict of Interest The authors declare that they have no conflict of interest.

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