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ARTICLE

Distinguishing Nature of Science Beliefs, Knowledge and Understandings

Towards Clarity and Coherence in Educational Goals Related to the Nature of Science

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Abstract
Whilst teaching about the nature of science (NOS) is a significant goal of science education, there remains debate about specifying the NOS and appropriate pedagogies and approaches to researching the NOS. A neglected, but conceptually and practically significant, problem is the proliferation of NOS-related learning goals such as NOS beliefs, views, understandings and knowledge. In this theoretical paper, we argue that such goals are often poorly defined, and different goals cohere with different pedagogical and research strategies. We propose a novel three-part taxonomy of NOS learning goals (as NOS beliefs, knowledge and understandings) and contend that different approaches are appropriate for teaching and assessing NOS beliefs, views and knowledge. An NOS belief refers to a positive attitudinal stance towards some proposition that lacks justificatory support or cannot easily be judged true or false. NOS knowledge indicates justified true beliefs related to the NOS. NOS understanding denotes a grasping of how a collection of NOS knowledge is related. The goals vary by the extent to which they can be judged true or false and the degree of justification they require. For NOS beliefs, a range of stances is acceptable; NOS knowledge must be a true and justified belief; in the case of NOS understanding, teaching and assessment should focus on the appreciation of relationships between justified true beliefs. The novel taxonomy brings needed clarity to a confused aspect of NOS research and may lead to the development of NOS pedagogies and assessment tools more precisely targeted to well-defined learning goals.

Keywords Epistemology · Nature of science · Pedagogy · Philosophy of science · Secondary science education

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1 Introduction

An understanding of what science is, how scientific knowledge is generated, and what scientists do has long been pursued as a goal of science education. Jenkins (1996) traces the history of nature of science (NOS) education back to J. F. W. Herschel's remark that highlighted the value of understanding, not only scientific concepts, but 'the domains of social conduct [of science], … its philosophy and its logic' (BAAS, 1846, xi). Today, many science curricula and policy documents across the world include some elements of the NOS as important learning goals (Leden & Hansson, 2015; NGSS Lead States, 2013; Olson, 2018; Park et al. 2020). The *PISA 2025 Science Framework* also emphasises that students should be 'both knowledgeable about science and scientifically literate too with a deep understanding of the nature of science, its limitations and the consequences of its application' (OECD, 2021, p. 5). In recent years, attention to the NOS has been heightened as scientific misinformation has arisen as a serious social problem, particularly owing to the heavy reliance of the public on social media as a way of acquiring knowledge (Kaufman & Kaufman, 2018; Sinatra & Hofer, 2021). A growing number of science educators believe that an understanding of NOS is crucial for distinguishing reliable scientific claims from those that are not (Höttecke & Allchin, 2020; Osborne et al., 2022). In addition to educators, leading scientists and philosophers of science have emphasised the role of understanding the NOS in combatting misinformation and pseudoscience (Mahner, 2013). The increasing focus on the NOS as a key element of scientific literacy in the literature and education policy calls for considering the types of NOS learning goals which can guide effective instruction. This article contributes to the research programme by proposing clear definitions of the target concepts of teaching related to the NOS and presents guidance on pedagogies to achieve them.

In reporting teachers' and learners' responses to research tools, classroom activities and assessments related to the NOS, researchers have made use of a range of different epistemological concepts including attitudes, views, knowledge, beliefs and understanding. This proliferation of concepts creates confusion, both for researchers and teachers, about the targets of NOS teaching. Moreover, implications about the factualness of concepts (that is, the extent to which their truth status can be determined) potentially impact how the concepts are taught and assessed. For example, when aspects of the NOS are conceptualised as *knowledge*, the implication is that judgements of truth are possible, by contrast with reference to NOS *views*, where it might be assumed that a plurality of positions may co-exist. The invocation of a range of NOS epistemic goals (knowledge of the NOS, beliefs about the NOS, views about the NOS etc.) raises questions about the appropriateness of different aims for research and teaching, the evidence that would be required to indicate the achievement of different states and the consequences of adopting particular constructions for teaching and research. In a speech, *On Rearing Scholars*, Lakatos commented that, '[t]o train students … to demand exact thinking… is the basis of scientific education' (Lakatos, 2000, p. 379). In this paper, we propose that 'exact thinking' about NOS concepts can address questions about appropriate goals for NOS teaching and research and resolve a significant incoherence in the field. Our conceptual investigation has three parts. First, we argue, from an epistemological point of view, that there exist some confusions in how NOS learning goals have been presented in the literature. Phrases like 'NOS knowledge', 'NOS understandings', 'NOS views' and 'NOS conceptions' have been used interchangeably without precise distinction, and we discuss why such confusion is problematic, both for teaching and researching the NOS. Second, we propose a distinction between 'NOS beliefs', 'NOS knowledge' and 'NOS understanding' to clarify the differing truth statuses and degrees of justification that can exist for aspects of the NOS. Finally, we consider the consequences of that division for research, teaching and assessment of the NOS.

Our focus in this paper is on the epistemological goals and outcomes of teaching about the NOS (that is, the acquisition of beliefs, knowledge and understanding), rather than on the application of such epistemic states to contexts (for example, in conducting scientific investigations, analysing scientific information, making decisions on socio-scientific issues and taking actions). Whilst we acknowledge that application is an important educational goal, our aim here is on the definition of epistemic states that precedes their application.

2 The Lack of Clarity in Learning Goals Related to the NOS

Since the emergence of the NOS as a goal of science education, there has been considerable debate about its meaning and the practical realisation of NOS pedagogy. For example, researchers have argued over how the NOS can be effectively taught, either by explicitly highlighting the NOS or allowing learners to engage in scientific enquiry experiences (Akerson et al., 2000; Duschl & Grandy, 2013). A more intense line of controversies about teaching the NOS relates to the constructs of the NOS, whether to adopt a list-based or more open-ended profile of the NOS or to include the aspects of scientific inquiry besides those of scientific knowledge (Allchin, 2011; Matthews, 2012; McComas et al., 1998). Whilst we acknowledge the fruitful results of these debates on the NOS, rather than engaging in such discussion, our aim in this article is to rethink the goals of education about the NOS from an epistemological point of view. In other words, our main aim is not to consider what the *NOS* consists of but to question and articulate what *NOS learning* can consist of.

What appears to be missing in the current debates around the NOS is the question of how objectives related to the NOS should be stated. A particularly problematic aspect of this question is the diversity of statements of the desired NOS learning goals as, for example, views, beliefs, conceptions, knowledge and understandings. These terms are often used interchangeably in everyday language, as well as in the NOS literature, and no clarification between the terms, in the context of the NOS, has been made thus far. We can make the definitional task somewhat easier by excluding the terms 'NOS attitudes' and 'NOS skills', since currently there seems to be a broad agreement that the NOS is not an attitudinal but a cognitive outcome (Allchin, 2011; Schwartz et al., 2012). In the early years of NOS research, there existed a conflation of the NOS as knowledge and the NOS as skills and attitudes (Lederman, 2007). Nowadays, science education researchers agree that an understanding of the NOS is distinguished from the ability to engage in scientific practices as an educational goal (Lederman et al., 2012; NGSS Lead States, 2013). In other words, researchers now agree that provoking one's emotional or attitudinal reactions to science and carrying out scientific activities does not constitute an immediate NOS learning goal in itself.

Although there seem to be few objections to considering the NOS as a cognitive learning objective, rather than an affective one (Abd-El-Khalick & Akerson, 2004; Allchin 2012; Lederman et al., 2002), there remains a persistent confusion in the usage of terminology. For example, Akerson and Donnelly (2008, p. 46) apply three different NOS constructs to the same target in a single paragraph: 'students … improved their NOS views … may be more successful at achieving adequate NOS understandings … [a model] entails how

Table 1 Examples of concepts cited in NOS assessment instruments. The concepts are highlighted in bold

Year	Author	Instrument
1961	Klopfer and Cooley	Test on **Understanding** Science (N.B. not understanding NOS)
1973	Aikenhead	A Measurement of **Knowledge** About Science and Scientists (Project Physics: Form 1)
1975	Hillis	**Views** of science
1976	Rubba	Nature of science **knowledge** scale
1977	Billeh and Malik	Test on **Understanding** the Nature of Science
1981	Cotham and Smith	**Conceptions** of Scientific Theories Test
1987	Aikenhead, Fleming and Ryan	**Views** of Science-Technology-Society
1990	Lederman and O'Malley	**Views** of Nature of Science – Form A
1997	Aldridge, Taylor and Chen	**Beliefs** About Science and School Science Questionnaire
1998	Abd-El-Khalick, Bell and Lederman	**Views** of Nature of Science – Form B
1998	Abd-El-Khalick	**Views** of Nature of Science – Form C
2002	Abd-El-Khalick	**Perspectives** on Scientific Epistemology
2005	Tsai and Liu	Scientific Epistemological **Views**
2006	Chen	**Views** on Science and Education Questionnaire
2006	Liang et al.	Student **Understanding** of Science and Scientific Inquiry
2013	Chen et al.	Students' **Ideas** about Nature of Science
2014	Lederman et al.	**Views** about scientific inquiry

practically useful or "actionable" new [NOS] knowledge is to the learner'. Similarly, in the influential article by Lederman et al. (2014), *Meaningful assessment of learners' understandings about scientific inquiry—The views about scientific inquiry (VASI) questionnaire*, the title includes both 'understandings' and 'views', which are used interchangeably in their article without differentiation. Osborne et al. (2003, p. 696) referred to developing students' 'knowledge and understandings about science' as the aim of NOS education, but the two concepts are not differentiated. A troubling range of terms has been used in the titles of NOS assessment instruments, as set out in Table 1. Given the differing natures of understanding, knowledge, beliefs and so on, it might be imagined that the designers of assessment tools would discuss how their probe was designed to access and assess different epistemic states, for example, views or knowledge. Such crucial discussion is usually not included in descriptions of these instruments. Cases like the examples we have discussed within the NOS literature highlight that epistemic terms with precise and distinct meanings are, as in everyday language use, commonly used interchangeably.

Conflation of learning goals related to the NOS is found not only in the research literature but also in science curriculum documents. The US *Benchmarks for scientific literacy* (AAAS, 1994) implies that the NOS is a set of beliefs, by stating that the NOS 'is not something that working scientists spend a lot of time discussing. They just do science. But underlying their work are several *beliefs*' (p. 5, italics added). However, in the performance expectations presented in the same section, it is argued that 'students should *know* that', for example, some scientific knowledge is very old and yet is still valid today (p. 6, italics added). An exception is the US *Next Generation Science Standards* (NGSS Lead States, 2013), which is fairly consistent in its use of 'understanding' as the aim of NOS education. It states that 'One fundamental goal for K-12 science education is a scientifically literate person who can *understand* the nature of scientific knowledge' (Appendix H, p. 96, italics added) and also emphasises 'the basic *understandings* about the nature of science' (Appendix H, p. 97, italics added). Despite this consistency, however, the NGSS do not specify anywhere what it means to understand the NOS or what is acceptable evidence of NOS understanding. The standards do, however, make it clear that NOS understanding does not consist of rote memorisation of NOS tenets without considering the historical or hands-on investigations from which the NOS is derived.

The use of terms such as views, attitudes and understanding of the NOS without distinction may not seem a serious issue if one assumes that they point to a similar target and that students will learn something about the NOS regardless of the terms used to describe learning goals. However, we argue, the ambiguous usage has led to at least two problems. The first concerns the epistemic achievements that teachers and researchers desire as a result of education about the NOS. Understanding the NOS may, at least in some theories of understanding in epistemology, be seen as distinct from knowing some facts about the NOS, which in turn may occur in isolation from having views about the NOS, and so on. Moreover, the specification of educational goals impacts the instructional approaches used to achieve those aims (Eisner, 1969), and, as we will discuss, different pedagogies are likely to be applied if supporting students to acquire NOS knowledge or to develop views about the NOS. Given the role of learning goals that 'help us to focus our attention and our efforts' (Anderson & Krathwohl, 2001, p. 3), establishing a clear meaning of educational objectives and research targets relating to the NOS will be essential to designing NOS curricula, instructional interventions, assessment and research projects.

The second issue relates to the assessment of the NOS, both for research purposes and in the classroom. The lack of clarity in terminology poses a challenge to the validity of NOS research instruments and assessment tools. If understandings refer to a different construct from views, the validity of assessing the former with a framework about the latter would be questionable. Allchin (2013) noted that many existing instruments to assess the NOS focus on 'NOS as a set of beliefs or personal perspectives' and stressed that 'knowledge, not personal belief, is the goal' of NOS education (p. 153). To avoid ambiguity in teaching and assessment, NOS researchers need to consider how, and indeed if, terms such as understandings and views are defined and differentiated. The proliferation of terms describing students' and teachers' NOS epistemic states in classroom assessment and research instruments suggests that a reconsideration of the categories applied is overdue. One potential route forward is the observation that the terms suggest differing epistemic statuses—knowledge implies a truth component and a degree of justification that is not required in a belief. A precise description of how each learning goal relates to truth and the degree of justification it requires has implications for teaching and assessing the NOS. The contribution of this article is a three-element taxonomy of epistemic states related to the NOS: NOS beliefs, knowledge and understandings.

The problem becomes evident from an analysis of the existing NOS instruments. An examination of widely used instruments for assessing the NOS (Table 1) suggests that at least seven words have been associated with learning about the NOS: *views, perspectives, beliefs, conceptions, ideas, knowledge* and *understanding*.

Three of the terms in Table 1 are epistemological concepts that have somewhat consensual definitions:

Belief: the mental state of accepting a proposition (BonJour, 2001)

Knowledge: (in the Platonic model) a belief that is both justified and true (BonJour, 2001)

Understanding: a cognitive achievement related to grasping the coherence of a body of knowledge (Kvanvig, 2003)

In addition to these three epistemological terms, the literature refers to NOS views (Lederman et al., 2002), NOS conceptions (Bell et al., 2000) and NOS ideas (Chen et al., 2013). Whilst criteria have been proposed to delineate belief, knowledge and understanding (Grimm, 2006), the terms view, conception, perspective and idea have not been well specified. Definitions of views, conceptions, perspectives and ideas share an aspect of acceptance of some position with models emphasising some differing features. Most generally, a view has been described simply as a species of belief (Habib & Lehrer, 2004). A conception has the additional constraint of referring to an individual's interpretation of a formal concept (Taber, 2009). By contrast, a perspective has been described as a compound concept that combines both beliefs and values and is deployed to make sense of a context (Cuppen, 2012). Perhaps most nebulous of all the terms is the idea, a network of related meanings (Carstensen, 2011). As the terms perspective, conception, idea and view often do not have clear truth statuses or requirements on the degree of justification they entail, we will assume that they can be lumped together with beliefs and that their application does not imply any additional features beyond that of an attitudinal stance that a proposition is the case. In our view, the inconsistent use of the terms is reflective of a more fundamental problem—researchers lack a shared understanding of epistemic goals related to the NOS, that is, the epistemic state that students are expected to reach after learning the NOS.

One route to clarity arises from an analysis of three well-defined epistemic terms (belief, knowledge and understanding), which vary across two axes: first, the truth status of a proposition, that is, whether it can be judged to be true or false. Whilst knowledge, by definition, refers only to true beliefs, beliefs in general include false propositions. Second, the concepts vary by the level of justification that a possessor requires—beliefs do not require the justification that is necessary for knowledge. For the convenience of presentation, let us, for the moment, focus on the concepts of belief and knowledge as they occupy extreme positions on these two axes, before analysing understanding.

3 Towards a Clarification of Learning Goals Related to the NOS

The ambiguous usage of terms related to the NOS has consequences for classroom practice and research. We aim to support the progression of the NOS research programme by clarifying the targets of research and teaching via a taxonomy that separates NOS beliefs, knowledge and understanding. In this article, when it comes to knowledge, we limit our discussion to propositional knowledge or knowledge-that. Therefore, when we say that a student has knowledge of the NOS, we do not consider the possibility of her merely being acquainted with the NOS (acquaintance knowledge) or knowing how to design experiments, conduct observations or interpret data (knowledge-how). The exclusion of knowledge-how from the NOS is sensible also in the light of the broad agreement amongst NOS researchers that the development of scientific inquiry and practice skills are not identical to learning about the NOS (Lederman & Lederman, 2012).[1] It is

[1] Although we recognise that this view has been challenged, and the two are closely linked (Hodson & Wong, 2017; Matthews, 2012), it would be still useful to conceptually distinguish between, for example, being able to conduct an experiment and knowing the role of experiments in science.

widely accepted that whilst truth and justification are necessary conditions on knowledge, they are, by themselves, insufficient. Whilst a consensus on an alternative model of knowledge has yet to emerge, knowledge as justified true belief is still widely used and discussed by epistemologists and science education researchers (Bigelow, 2006; Brock, 2018; Gettier, 1963).

The terms belief and knowledge are widely used to refer to humans' epistemic achievements. We aim to provide conceptual clarity to the confused field of NOS concepts by applying these epistemic concepts to research and teaching about the NOS. Beliefs are propositional attitudes, mental states associated with an assumption that what a sentence expresses is the case (McCain, 2016; Sosa, 1980). By contrast, knowledge is a form of belief with two additional criteria, the belief must be both justified and true. Whilst we acknowledge the limitations of this definition (BonJour, 2001; Gettier, 1963), the lack of a widely agreed upon alternative (Bigelow, 2006) and its taxonomic usefulness in the context of the NOS means that we will adopt the classical definition, knowledge as justified true belief, in this paper. The separation of knowledge and belief by two conditions, truth and justification, will be central to the categorisation of the NOS concepts we introduce below; hence, we now set out two criteria for distinguishing the two. First, though debate continues about the most appropriate manner of determining if a proposition is the case, in general, truth refers to whether a proposition corresponds with the facts (Blackburn & Simmons, 1999). In the context of NOS beliefs, we propose that there is some consensus over the truth of some propositions. For example, the claim that what is argued to be scientific knowledge has changed over time can be shown to be true by reference to historical facts (for example, several models of atomic structure from different periods exist in the historical record). Hence, if a student believes that what is argued to be scientific knowledge has changed over time, we can say that the believer has NOS knowledge. Other aspects related to the NOS have a less clear truth status, particularly when a proposition is directed at science in general rather than a specific branch or tradition in science. For example, the claim that science characteristically attempts to develop explanations (McComas et al., 1998) might be argued to be, in general, false—some scientific work is descriptive, for example, classificatory research in biology or astrophysics (Casadevall & Fang, 2008; Grimaldi & Engel, 2007). The proposition that science is an explanatory project, we argue, does not have a clear truth status; it can be considered true in some contexts, but false in others. Therefore, the general claim that science is explanatory can be better classified as a simple belief, rather than NOS knowledge.

Second, we assume that the justification of NOS beliefs can occur to differing degrees (Hawthorne & Logins, 2020). This assumption allows for more justified and less justified beliefs about NOS and avoids a dichotomy between 'justified' and 'unjustified' beliefs. However, it also creates a 'threshold problem' concerning the level of justification required for a belief to be considered knowledge (Hannon, 2017). Though epistemologists are pessimistic about the existence of a clear specification of adequate justification (BonJour, 2010; Hetherington, 2001), one proposal is that the threshold for a belief to be considered knowledge is determined by features of the context to which the belief is applied (Fantl & McGrath, 2002; Hawthorne & Stanley, 2008). This 'impurist' strategy (Hannon, 2017) is useful in the context of considering knowledge and beliefs about the NOS. Pedagogic models of scientific concepts, including those related to the NOS, are typically not identical to those of expert scientists or philosophers as they have been simplified to some optimum explanatory level (Taber, 2000). Within an impurist conceptualisation of the boundary between belief and knowledge, the threshold of justification may be determined by, and differ depending on, the teaching context such as the level of students and the learning objective of a particular activity. To take one example, it might be felt that a school student has a well justified, true belief concerning the tentative nature of scientific claims if they can cite a couple of historical cases of development (for example, the transition from geocentric to heliocentric understandings of the solar system and the development of atomic models). For a higher education student on a philosophy of science course or for preservice teachers, a higher justificatory bar is likely to be appropriate. The design of novel teaching and assessment approaches focused on NOS beliefs might adopt the assumption that the justification of NOS beliefs is a matter of degree, rather than a dichotomy.

In our clarification of the definition of epistemic concepts in the context of NOS teaching and research, we propose a continuum of aspects of the NOS between two poles. At one end is NOS knowledge, true beliefs which have strong justificatory support and typically have high levels of consensus over their truth in the science education community. For example, the knowledge that what is accepted as scientific knowledge changes over time can be judged to be true, and justified, by reference to the historical record. Similarly, the claim that 'People from all cultures contribute to science' is also a true belief that has good justificatory evidence from the history and sociology of science and therefore can be categorised as knowledge. Knowledge has a truth status (for example, in the case of the claims above, by comparison with data related to the practice of current or historical scientists), suggesting that pedagogy and assessment of NOS knowledge can refer to a truth standard.

By contrast to NOS knowledge, at the other end of the continuum are NOS statements that are hard to categorise as true or false (as in the case of metaphysical beliefs, such as a stance on the mirroring of scientific knowledge and reality), and aspects where consensus is lacking, or have varying truth statuses depending on the context to which they are applied. To distinguish them from NOS knowledge, we refer to these aspects as NOS beliefs. For example, the claim that scientific knowledge is socially constructed might be considered, at least in its strongest form, an epistemological claim whose truth cannot be established with certainty. Where the truth status or the degree of justificatory support of a NOS proposition is unclear or contentious, we argue, the proposition should be categorised as a NOS belief. NOS beliefs are not readily falsifiable and may be aspects about which students can legitimately take different stances. For example, many writers on the NOS have argued that students and teachers should be discouraged from adopting scientistic positions (Abd-El-Khalick, 2001; Korte et al., 2017), the belief that science provides the only or best route to accessing reality. By contrast, others argue that some considered and well-justified versions of scientism are legitimate stances (Ladyman et al., 2007; Peels, 2017).[2] To acknowledge that some NOS beliefs cannot be or are difficult to categorise as true or false is not to suggest that these beliefs should be eliminated from learning objectives related to the NOS. Rather, the truth status of NOS beliefs should be acknowledged and inform the approaches used to teach about them (see below).

We propose that there are, at least, three significant categories of NOS beliefs:

a) Metaphysical beliefs related to the NOS that cannot be judged true or false (for example, the ontological claim that scientific knowledge is a social construct).

[2] Note that we make no assumption about a link between consensus, justification and truth. Consensus is neither a necessary nor a sufficient aspect of justification of beliefs to support a knowledge categorisation (Tucker, 2010). See, for example, the numerous instances in which scientists reached consensus on models which are now rejected (for example, aether theories, the phlogiston model and spontaneous generation).

b) Beliefs about the applications of NOS knowledge to contexts where it is difficult to determine their truth status. This difficulty may arise in the context of claims about domains where appropriate empirical tools are lacking or controversial (for example, the claim that the string theory research programme is scientific). Alternatively, truth determination can be difficult in cases where the status of a claim is contingent on the context (for example, the claim that science seeks to develop laws might be true for some domains of physics, but not be the case in some biological research).
c) Interpretive beliefs about the history or sociology of science, that can be, to some extent be justified by historical or sociological evidence, but whose truth is hard to determine (for example, the claim that scientific knowledge progresses through revolutions).

We will now examine these three categories of NOS beliefs. First, NOS beliefs can relate to metaphysical beliefs, claims relating to the nature of what exists and the features of those entities (Van Inwagen, 2018). Metaphysical claims are seen as an aspect of the NOS (Clough, 2006; Matthews, 1998; Rudolph & Stewart, 1998), and their teaching and assessment should acknowledge this categorisation. Whilst claims about what metaphysicians have written may be true or false, metaphysical beliefs themselves, at least in some interpretations of metaphysics, cannot be marked as true or false because there are no consensus approaches to falsifying such claims (Van Inwagen, 2018). Examples of metaphysical NOS beliefs include 'the success of science arises because scientific knowledge mirrors an existing external reality' and 'scientific constructs, such as forces, are abstractions rather than physical entities'.

Second, NOS beliefs can relate to the extent to which NOS knowledge applies in different contexts. For example, whilst the assertion that scientific knowledge claims are tentative might be considered, in general, justified and true, and hence potential NOS knowledge, individuals may hold beliefs about the degree of tentativeness of knowledge in specific contexts. One interpreter might feel that the scientific community's knowledge of dark matter is relatively tentative and in a period of flux, whilst another assumes that the knowledge, whilst retaining an inherently tentative nature, is robust. Such positions may be held with higher or lower levels of justification. Contextual qualifications related to general NOS knowledge we categorise as NOS beliefs.

Finally, a third category of beliefs relate to historical and sociological descriptions of the processes of science. Students may legitimately adopt different constructions of a historical event, for example, the claim that Galileo's research was a revolutionary break from earlier work (Shapin, 1996), or the processes by which scientific claims were produced, perhaps the significance of the contributions of individual scientists to some discovery. Some interpretative beliefs might be more knowledge-like when the claims are well-justified and their truth status verifiable, for example, the claim that the geocentric model of the universe has largely been rejected by the scientific community since the 16th century. Such beliefs might be thought of as NOS knowledge. By contrast, positions on the extent to which science progresses through evolutionary or revolutionary processes (or some combination of the two) might be thought to be beliefs where a range of positions with differing degrees of justifications can be held but the ultimate truth status of the claim is hard to determine.

In addition to NOS beliefs and knowledge, we include the goal of NOS understanding as the third element of the taxonomy as it acknowledges that the acquisition of NOS knowledge is a necessary, but insufficient, step in the development of NOS expertise. Statements about the NOS are succinct and contextualised, so do not have much educational value if acquired in isolation. In the same way as simply memorising that 'the acceleration of an object is proportional to the net force acting on it' has limited value if a student does not integrate the proposition with their knowledge of acceleration and force, rote learning the claim that 'basic laws of nature are the same everywhere in the universe' (NGSS Lead States, 2013, Appendix H, p. 100) lacks meaning if a student cannot relate the knowledge to the behaviour of particular scientific laws. As with scientific content knowledge, ideal learning about the NOS goes beyond knowledge acquisition to the appropriate integration of concepts into a meaningful structure that encompasses considering the NOS across contexts, which we will refer to as NOS understanding.

Whilst understanding has been used ambiguously in the literature, a recent research programme in the philosophy of science has renewed discussion of the term (Baumberger et al., 2017; de Regt et al., 2009). Though controversy remains over the extent to which knowledge and understanding are distinct concepts (Grimm, 2006), there is some consensus that understanding involves an appreciation of the connection between knowledge propositions (Elgin, 2007; Kvanvig, 2003) and confers an ability to appropriately apply knowledge across contexts (de Regt, 2009; Woodward, 2003). A recent movement in the NOS research programme has seen researchers acknowledging that NOS expertise involves the possession of an interconnected conceptual NOS knowledge structure, rather than just the acquisition of isolated propositions (Bartos & Lederman, 2014; Mulvey et al., 2021; Peters-Burton et al., 2019). We propose that NOS understanding refers to a grasping of the relationships between NOS knowledge and beliefs that supports the ability to transfer learning across contexts. Given the relational aspect of this definition, the assessment of NOS understanding is unlikely to be validly achievable by a single multiple-choice prompt but requires more open-ended forms of assessment, for example, interviews, extended pieces of writing or concept maps, that allow an examination of the structure of NOS knowledge and beliefs that a person holds. The notion of NOS understanding is additionally useful in teaching and assessment as models of understanding typically acknowledge that the state can be attained to differing degrees (for example, partial or deep understanding) (Strevens, 2008). A higher level of NOS understanding can be characterised as not only the acquisition of propositional knowledge but also the formation of appropriate connections between NOS beliefs and knowledge and, ultimately, historical and scientific knowledge related to the NOS in question.

We assume that the NOS belief-knowledge-understanding model has a structural similarity with Irzik and Nola's (2011) family resemblance model of the NOS. In our model, we assume that a definitive demarcation of the boundary between NOS beliefs, knowledge and understanding is not possible. Claims can have higher or lower degrees of belonging to the categories—some claims are better examples of NOS beliefs, knowledge or understanding than others. We assume that category membership is graded—both justification (that demarcates knowledge from beliefs) and inter-conceptual relationships (that separate understanding from knowledge) can occur to varying degrees. The key novel feature of our model is the distinction between NOS belief, knowledge and understanding, which suggests guidance for NOS pedagogy and research as we articulate below. For example, an important affordance of the distinction between beliefs, knowledge and understanding is that it can be used to indicate aspects of the NOS where acceptance of consensus NOS knowledge might be an expected outcome of teaching (for example, students coming to believe that scientific knowledge is, in general, durable) against areas of the NOS where students can have agency over the beliefs they adopt (for example, the durability of scientific knowledge about string theory or interpretations of the nature of scientific revolutions).

A number of attempts have been made to specify consensus NOS claims, many of which might be considered NOS knowledge (for example, McComas et al., 1998; NGSS Lead States, 2013; Cleminson, 1990, see Table 2). Consensus models of the NOS typically take the form of a list of propositions that are, in many cases, true and well justified. For example, the proposition 'Scientific knowledge is tentative and should never be equated with truth. It has only temporary status' (Cleminson, 1990, p. 437) might be thought of as NOS knowledge. Note that we assume that there is a difference between what is presented as scientific knowledge in public representations (such as textbooks), which may not meet the criteria placed on knowledge (for example, where pedagogic simplifications which are not true are introduced without qualification), and scientific knowledge per se. This distinction contrasts with the position implied by some of the statements in Table 2. Cleminson's proposition about the tentativeness of scientific knowledge claims can be considered a justified true belief because evidence from the history of science (for example, cases of revision of scientific knowledge that was well-established) justifies the claim and it is true. However, our view is that statements in the consensus models of the NOS are not restricted to only justified true beliefs. As Allchin (2011) has remarked: 'One must … abandon the notion that NOS can be expressed in unambiguous declarative statements of the form, "Science is X." Properly viewed, the concept of Whole Science accommodates the complementary, sometimes contrasting perspectives' (p. 527). Consensus statements about the NOS are predicated on a number of supporting assumptions and beliefs which have differing degrees of justificatory support and truth statuses (Duhem, 1954; Henderson & Horgan, 2000). The statements in Table 1 are useful pedagogic summaries but can cohere with a range of positions. For example, the claim that '[s]cientific knowledge is based on empirical evidence' (NGSS Lead States, 2013, p. 97) might be considered knowledge (that is, a justified and true belief) in some contexts (for example, in the context of claims about natural selection) but a belief (i.e., having a lower degree of justification and harder to verify) in other contexts (for example, claims about galactic formation developed through digital simulations). The usefulness of consensus models has been critiqued on a number of grounds including the incompleteness of the models, the lack of consensus amongst experts on elements of the models, the observation that some NOS positions are non-propositional and the existence of different practices in scientific subdomains (Allchin, 2011; Dijk, 2011; Hodson & Wong, 2017; Irzik & Nola, 2011; Matthews, 2012). Whilst consensus models may have some usefulness as pedagogic models, we argue that not all aspects of the NOS can be fully expressed in unambiguous declarative statements of the form, 'Science is X'.

In addition to the criticisms described above, we propose a significant but neglected critique of consensus models of the NOS—the implicit assumption of categorical uniformity of the elements in the lists, that is, that the claims have similar truth statuses and degrees of justification. This assumption can, as we set out below, lead to a uniform approach to teaching and assessing the NOS that has potentially negative consequences. That is, an excessive focus on 'consensus' might lead to missed opportunities for teaching aspects of the NOS that are not fully 'true' or 'justified' in an epistemological sense but still can be valuable educational goals. Just as the differing epistemic goals of disciplines (for example, history and mathematics) suggest different

Table 2 Four examples of consensus models of the NOS

Cleminson (1990, pp. 437–439)	**McComas, Almazora, & Clough** (1998, p. 513)	Lederman (2007, pp. 833–835)	**Next-generation science standards** (2013, p. 97)
• Scientific knowledge is tentative and should never be equated with truth. It has only temporary status.	• Scientific knowledge, though durable, has a tentative character.	• Observation and inference are different.	• Scientific investigations use a variety of methods.
• Observation alone cannot give rise to scientific knowledge in a simple inductivist manner. We view the world through theoretical lenses built up from prior knowledge. There can be no sharp definition between observation and inference.	• Scientific knowledge relies heavily, but not entirely, on observation, experimental evidence, rational arguments, and scepticism.	• Scientific laws and theories are distinct forms of knowledge.	• Scientific knowledge is based on empirical evidence.
• New knowledge in science is produced by creative acts of the imagination allied with the methods of scientific inquiry. As such science is a personal and immensely human activity.	• There is no one way to do science (therefore, there is no universal step-by-step scientific method).	• Scientific knowledge is empirical, as it is based on and/or derived from observations of the natural world.	• Scientific knowledge is open to revision in light of new evidence.
• Acquisition of new scientific knowledge is problematic and never easy.	• Science is an attempt to explain natural phenomena.	• Scientific knowledge involves human imagination and creativity.	• Scientific models, laws, mechanisms, and theories explain natural phenomena.
• Scientists study a world of which they are a part, not a world from which they are apart.	• Laws and theories serve different roles in science; therefore, students should note that theories do not become laws even with additional evidence.	• Scientific knowledge is subjective.	• Science is a way of knowing.
	• People from all cultures contribute to science.	• Scientific knowledge influenced by the cultural contexts in which it is developed.	• Scientific knowledge assumes an order and consistency in natural systems and material world.
	• New knowledge must be reported clearly and openly.	• Scientific knowledge is never absolute or certain but tentative and subject to change.	• Science is a human endeavour.
	• Scientists require accurate record keeping, peer review, and replicability.		• Science addresses questions about the natural and material world.

Table 2 (continued)

Cleminson (1990, pp. 437–439)	**McComas, Almazora, & Clough** (1998, p. 513)	Lederman (2007, pp. 833–835)	**Next-generation science standards** (2013, p. 97)
	• Observations are theory laden. • Scientists are creative. • The history of science reveals both an evolutionary and revolutionary character. • Science is part of social and cultural traditions. • Science and technology impact each other. • Scientific ideas are affected by their social and historical milieus.		

pedagogies and approaches to assessment, diversified approaches are required for teaching NOS knowledge, beliefs and understandings.

4 The Benefits of a Division Between NOS Belief, Knowledge and Understandings

A distinction between NOS beliefs, knowledge and understandings has several affordances for teaching and research. First, the categorisation can assist teachers and researchers in assessing their students' achievements more effectively. A learner who has acquired a simple NOS true belief, without justification, another who has NOS knowledge, and a third who can relate multiple justified true beliefs, an epistemically more valuable position, can be distinguished. The use of the three learning goals (belief, knowledge and understanding) supports a move away from simplistic assessment criteria (such as naïve, informed and mixed views) of the NOS and enables the production of more sophisticated assessment approaches and learning progressions (Park 2021). Our graded model emphasises that two individuals can possess the same true belief, for example that 'scientific knowledge is tentative', and both have good justifications for that belief, whilst at the same time, possessing contrasting related beliefs. For example, they might disagree about the extent of the tentativeness of knowledge in different cases. The epistemic ascent from NOS beliefs to NOS knowledge to NOS understanding presents a useful model of learning progression as increasing levels of justification and appreciation of relationships between beliefs. The impurist conceptualisation of demarcation between belief and knowledge (Hannon, 2017), introduced above, proposes that the line between belief and knowledge is determined by the teaching context, for example, the age of learners and the learning aims. Researchers, curriculum designers and teachers can specify the degree of justification that they feel is appropriate in separating NOS beliefs and knowledge, and similarly the degree of interconnectedness that represents adequate understanding, in a context.

Second, the specification of NOS understanding emphasises, in addition to simply acquiring discrete NOS knowledge elements, the value of developing connections and coherence between justified true beliefs. The NOS understanding construct is based on the model of understanding as interconnected knowledge (Davis, 1995; Elgin, 2007; Kvanvig, 2003). This view is increasingly acknowledged in the emerging NOS epistemic network research programme (Mulvey et al., 2021; Peters-Burton et al., 2019). The kind of compound structure described here is unlikely to be easily assessable based on responses to Likert scale probes, and more expansive approaches to the assessment of NOS understanding, for example, case-based open-ended response are likely to be helpful (Allchin, 2011). Given the criticism that most studies have assessed students' knowledge of different NOS aspects separately (Peters-Burton et al., 2019), the use of task and project-based assessments will be essential for facilitating, as well as assessing, the interconnectedness of students' NOS understandings.

Third, the separation of beliefs, knowledge and understanding acknowledges that, like science itself, the NOS is often flexible and open to interpretation, and teachers and researchers can use the tripartite division to indicate their assumptions about the truth of and degree of justifications that exists for different beliefs about the NOS. Given that teachers and students often struggle with teaching and learning about the NOS because it contradicts with their perception that the goal of science teaching is to convey objective truths and 'facts' about nature (Höttecke & Silva, 2011), a clear understanding that the NOS consists of what we believe, know and understand about science, and is open to interpretations, will guide teachers to deal with the controversial, indefinite and changing aspects of the NOS in the classroom. This in turn points to the potential benefits of considering the theories of humanities, social studies and history education in facilitating learning related to the NOS in science education (Kötter & Hammann, 2017).

Finally, although our approach sheds light on the lack of clarity in NOS learning goals and proposes a novel system for distinction, it coheres with existing models of the NOS, including the consensus (Lederman, 2007), family resemblance (Irzik & Nola, 2011), whole science (Allchin, 2011) and features of science (Matthews, 2012) approaches. It suggests that the statements about the NOS in the consensus lists can be categorised into NOS beliefs, knowledge and understandings. Considering beliefs, knowledge and understandings as gradable and interrelated constructs allows us to acknowledge memorisation of declarative statements is an unsatisfactory goal in NOS education. We understand the distinction between epistemic states in a family resemblance-like approach. For example, the 'scientific methods' and 'scientific knowledge' categories in the model can include more knowledge-like claims about the NOS, whereas categories like 'scientific ethos' and 'aims and values' are likely to include belief-like claims. A teacher can use different instructional strategies based on the distinction, which will help them decide how to manage different NOS beliefs and views that students bring to the classroom. Based on such distinctions, curriculum makers and teachers can plan and design learning experiences and assessments to cohere with the target NOS goals of an activity.

5 Implications for Teaching and Assessment of the NOS

The belief-knowledge-understanding distinction suggests approaches to improving NOS pedagogy and assessment. Pedagogical approaches to the NOS often fail to highlight aspects where students are expected to acquire knowledge statements about the NOS (for example, scientific knowledge is tentative but durable) from contexts in which students can adopt a range of different stances (for example, on the degree to which scientific knowledge is socially constructed). This lack of clarification is significant as the acquisition of knowledge and supporting students to develop well-justified beliefs require different pedagogies. Whilst the former can be achieved through approaches such as retrieval practice and spaced repetition, the later involves pedagogies that resemble approaches applied in subjects like history or religious education where the aim of teaching focuses on developing argumentation for particular positions, without the requirement that learners accept a predetermined stance (Guilfoyle et al., 2020; Park et al., 2020). Students can assume that the rigid epistemology of science classrooms allows limited space for them to express their own beliefs (Billingsley et al., 2016), a perception that may deter some students from enjoying school science (Osborne & Collins, 2010). Emphasising aspects of the NOS where students can develop and argue for individual beliefs may then support greater enjoyment of science and the development of responsible citizenship for decision-making (Yacoubian & Khishfe, 2018).

In addition to different approaches to teaching, different forms of assessment are appropriate for NOS understanding, knowledge and beliefs. For example, a question related to NOS knowledge, by definition, tends to have a correct (i.e., true) answer, whilst a question related to a NOS belief often does not. The assessment of NOS knowledge is then relatively straightforward and can be achieved through, for example, multiple choice probes. Nonetheless, care needs to be taken that such probes are phrased in a suitably caveated manner that allows for the respondent potentially possessing some NOS beliefs related to the knowledge proposition that do not cohere with the general statement. For example, the probe 'Scientific knowledge is tentative. Select either: Agree / Neutral / Disagree' might, as Allchin (2011) has observed, evoke a response of 'it depends' (p. 528). A carefully worded probe of NOS knowledge allows for the existence of NOS beliefs that may contradict the main knowledge claim in some contexts by indicating a general agreement:

- In general, scientific knowledge is tentative, that is, in principle open to revision in the light of new data.
  Agree / Neutral / Disagree

In this case, as the question focuses on NOS knowledge, a response of 'disagree' indicates a false belief and might prompt pedagogic intervention. This example can potentially be a valid test of NOS knowledge from an epistemological point of view. However, since the learner with NOS knowledge needs to have good reasons to hold the belief, the question must be accompanied by an additional probe to check the justification, for example, by asking them to explain their answer. Such a probe will be needed not only when students are tested on their NOS knowledge (i.e. summative assessment) but also when the teacher attempts to informally collect evidence of student learning during the class (i.e. formative assessment).

When it comes to beliefs, the less clear truth status of NOS beliefs makes their assessment more challenging than for NOS knowledge and suggests different forms of pedagogic interventions, for example, approaches focused on the development of nuanced forms of argumentation rather than changing belief. Content related to NOS beliefs (e.g. metaphysical aspects, applications to contexts where truth status is hard to determine and historical interpretations) can be better assessed with probes that elicit open responses, which are not judged as true or false (Allchin, 2011). For example, we can use the probe 'To what extent is scientific knowledge cumulative? Elaborate your answer with examples'. However, educators currently lack a pragmatically useful consensus model for assessing philosophical arguments (Schönwetter et al., 2010), and assessment of NOS beliefs, by definition, will involve a degree of subjectivity.

Turning to understanding, whilst it is often cited as a particularly valuable epistemic state (de Regt, 2009; Grimm, 2012; Smith & Siegel, 2004), perhaps because of ongoing debates about the nature of the concept itself (de Regt et al., 2009; Grimm et al., 2017), there is a lack of consensus about how understanding in general, and therefore NOS understanding in particular, might be assessed. If a model of understanding as an appropriately connected conceptual structure (Elgin, 2007; Kvanvig, 2003) is adopted, NOS understanding assessment approaches might examine the inter-relationship of knowledge elements elicited from multiple choice probes (Mulvey et al., 2021; Peters-Burton et al., 2019), open-ended responses (Koksal & Cakiroglu, 2010), comments in interviews (Zimmermann & Gilbert, 2010) or essays (Allchin, 2011). Given the graded nature of understanding, when reporting NOS understanding, students' achievements might be described on a continuum, for example, shallow, partial or deep understanding. NOS understanding assessment may be effectively contextualised within the history of science, student-led inquiry activities or through discussion of socio-scientific issues (Allchin et al., 2014).

Table 3 A summary of the tripartite model of learning goals related to the NOS

Goal	Definition	Example	Appropriate teaching approaches	Appropriate research and assessment approaches
NOS beliefs	A mental state of accepting an NOS proposition which does not have a clear truth status or high degree of justificatory support.	Science is successful because scientific knowledge mirrors external reality.	An introduction to a range of different beliefs and the arguments for and against each position. Students are encouraged to develop arguments for their beliefs and critique alternative positions.	Beliefs may be elicited but not judged as true or false. Assessment may focus on the degree of justification an individual possesses.
NOS knowledge	A justified true belief related to the NOS.	Scientific models develop over time.	May be taught similar to scientific content knowledge. The propositions are introduced and their application to different situations discussed. False beliefs should be corrected.	Assessment can focus on both the truth of propositions and the degree of justificatory support a student possesses.
NOS understanding	A grasping of the coherence of a body of NOS knowledge.	Understanding of the Kuhnian model of scientific progression.	As with supporting scientific understanding in other contexts, teaching might focus on supporting appreciation of the relationship of multiple justified true beliefs and their appropriate application to novel contexts.	The relational element of understanding suggests that probes should elicit students' appreciation of the connections between multiple elements (hence a single multiple-choice question is unlikely to be a suitable probe) and the use of those elements in different contexts. For example, through extended writing, concept maps and discussion.

6 Conclusions

This article arose from the observation that educational objectives related to the NOS have often been used without distinction and a sensitivity to the problems arising from such confusion. The novel taxonomy which separates NOS beliefs, where the truth status of NOS claims is difficult or impossible to determine, NOS knowledge, justified true beliefs, and NOS understanding, which relates to interconnected NOS knowledge, we hope, will bring clarity to pedagogy, assessment and research about the NOS. The distinctions between the three learning goals are summarised in Table 3.

Currently, the literature on the NOS contains ambiguities in relation to the way terms such as belief, knowledge and understanding are applied to the domain. We hope to add clarity to the research programme and that the model set out in Table 3 leads to greater precision in the specification of learning and research goals related to the NOS. We recommend that, when authors use terms such as NOS beliefs, knowledge and understandings, they explicitly state their definition of the learning goal and use the terms consistently. Where researchers make a case that they are assessing some target state, an argument needs to be made for the coherence between the learning goal and the assessment tool. For example, assessment of understanding conceptualised as a grasping of relationships requires the production of evidence related to how multiple elements relate. Similarly, proposed teaching interventions should be designed so that the activities cohere with the nature of the learning goal. The more precise specification of learning goals related to the NOS, we hope, will inform the development of more focused and effective approaches to NOS assessment and pedagogy.

Declarations

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

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