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Teaching and Learning Nature of Science in Elementary Classrooms

Research-Based Strategies for Practical Implementation

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Abstract
Our goal in this article is to provide research-based strategies for embedding Nature of Science (NOS) into science instruction at the elementary level. We thus intend to aid researchers, professional developers, and teachers in noting that not only is it important and possible to teach NOS at the elementary levels, but also that elementary students can learn ideas about NOS. The manuscript reviews research from the past two decades on what students of ages 5 to 12 understand about NOS after appropriate instruction. Research-based teaching strategies are then shared to provide methods for researchers, professional developers, and teachers to improve students' NOS understandings. These strategies include embedding NOS into existing curricula, using classroom interactions, using visual representations, and using students' written work.

Keywords Nature of Science · Elementary · Teaching strategies · NOS learning

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1 Introduction

Nature of Science (NOS) is considered an important educational goal by science education researchers (e.g., Allchin et al. 2014; Lederman 2007; Olson 2018). However, it is rare to see effective NOS instruction taking place in an elementary science lesson. There are numerous reasons for this lack of NOS instruction, including elementary teachers' own conceptions (or misconceptions) about NOS and the fact that NOS is not necessarily part of science curricula. There may also be a misperception that elementary students are not "ready" to develop understandings about NOS. Olson (2018) conducted a review of nine international standards documents, and found that only four included NOS in student expectations, as well as that only one included NOS consistently across the document. In some cases, the NOS that was included was also less than accurate, or was phrased in ways that could lead to misconceptions about NOS.

In this article we focus on the USA, where NOS had been previously explicitly included in standards documents, such as the Benchmarks for Science Literacy (AAAS 1993). However, we now have the Next Generation Science Standards (NGSS Lead States 2013), where unfortunately, there are no strongly stated expectations for students to conceptualize NOS ideas within the body of the document. Without including NOS expectations and practical suggestions in the standards document, there follows that science curricula do not emphasize NOS. Therefore, there is a need to provide some practical suggestions that are based on research for how elementary teachers can effectively include NOS in their instruction. Despite no expectations for NOS included within the main NGSS document, there are descriptions of NOS ideas in Appendix H of the document, indicating that there is still some attention to NOS in science education instruction in the USA.

Conceptualizing NOS is a component of scientific literacy. A scientifically literate person can ask, find, or determine answers to questions derived from curiosity about everyday experiences; describe and predict natural phenomena; understand articles about science in the popular press so as to engage in social conversation about the validity of the conclusions; identify scientific issues underlying national and local decisions and express positions that are scientifically and technologically informed; evaluate the quality of scientific information on the basis of its source and the methods used to generate it; and pose and evaluate arguments based on evidence and to apply conclusions from such arguments appropriately (NRC 1996, 2013). These characteristics of a scientifically literate person are directly related to NOS components. For example, Allchin (2014) has argued that the ability to assess the reliability of a scientific claim is relevant to personal and social decision-making. Conceptualizing the aspects of NOS is directly related to this ability, as individuals will be able to understand the kind of knowledge that science develops. This would be the demarcation of science vs. ways of knowing that are not scientific. Allchin similarly described approaches to contextualizing NOS education, which include being embedded in scientific inquiry. Also, conceptualizing NOS enables students to recognize why they need to understand the nature of the discipline in order to be able to apply the content they are learning (Smith and Siegel 2004).

Our goal in this article is to provide research-based strategies for embedding NOS into science instruction at the elementary level in order to aid researchers, professional developers, and teachers in noting that not only is it important and possible to teach NOS at the elementary levels, but also that elementary students can learn ideas about NOS.

2 Literature Review

The first two authors of the present article conducted independent literature searches for research on how to develop elementary students' conceptions of NOS. They searched ERIC, Google Scholar, and volumes of *Science & Education*, for terms related to NOS and elementary students, such as "Nature of Science" and "elementary" or "primary." Much of the literature found was analytical and/or theoretical and discussed the NOS understandings of teachers (preservice or in-service), or of K-12 students and not just elementary ones (e.g., Smith and Siegel 2004). Further, Deng et al. (2011) examined an impressive 105 research studies about students' views of NOS, and it appears that only seven of the articles they found and reviewed addressed the NOS ideas of K-6 students, three of which were from the first author of the current manuscript (see Deng et al. 2011, pp. 984–988). Although we focused on research published within the last decade, much of what was found was published earlier. These earlier articles were also included because we believe that they are still relevant and because only a few articles have been published more recently. Thus, for the purposes of this paper, we focus our review on studies that examined elementary students' conceptions of NOS published within the last two decades.

Teaching and assessing NOS is a complex endeavor (Clough and Olson 2008); however, a key goal of science education should be developing in students a rich understanding of NOS (Smith and Siegel 2004). Prior research on what elementary students are able to conceptualize about NOS shows that instruction tends to follow aspects that have previously been in standards documents, and/or follow a consensus list of NOS aspects (however, research also shows they should not be taught as a declarative list, but as ideas to summarize deeper understandings; see Lederman and Lederman 2014). Table 1 presents these ideas about NOS.

Though these aspects of NOS are embedded within the NGSS for all Kindergarten through high school grade levels, there are those who question whether elementary (grades K-6 in the USA, or ages 5–12 years old) students can develop sophisticated understandings of NOS. Others have argued that expectations influence the idea that students cannot develop these understandings, but actually with proper instruction, elementary students can learn NOS (e.g., Metz 1995, 2004). Indeed, Ford and Forman (2006) emphasized that students can learn about science and how knowledge develops through scientific investigations. They noted that if

Table 1 Aspects of Nature of Science students can conceptualize

Scientific investigations use a variety of methods (e.g., there is no one scientific method).
Scientific knowledge is based on empirical evidence (e.g., requires evidence)
Scientific knowledge is open to revision in light of new evidence (e.g., scientific knowledge is tentative)
Science models, laws, mechanisms, and theories explain natural phenomena (e.g., through observations of data and inferences about those observations)
Science is a way of knowing (e.g., science is only one way of knowing, and is different from other ways of knowing, such as philosophy, art)
Scientific knowledge assumes an order and consistency in natural systems (e.g., this assumption enables scientists to search for patterns in the data, draw conclusions and develop scientific knowledge)
Science is a human endeavor (e.g., though science seeks to be objective, scientists are human and therefore there is an element of subjectivity, scientific knowledge is embedded in human culture, and is also a product of human creativity)
Science addresses questions about the natural and material world (e.g., science cannot answer all questions, such as those that are religious or metaphysical)

(Lederman and Lederman 2014; NGSS Lead States 2013) students are to conceptualize a discipline, they then need to “grasp” how it works. We agree, and therefore believe it is important to teach NOS to students of all ages.

2.1 Research on What Elementary Students Can Learn About NOS

We were able to identify prior research on what elementary students can learn about NOS, and the teaching strategies that contributed to their understandings. As was found by Deng et al. (2011), there are a limited number of research articles on elementary students’ conceptions of NOS, so our review is top heavy with our prior research. However, we did identify a few others’ work and they are included in this review.

Smith et al. (2000) conducted a long-term analysis of elementary students’ epistemological development as a result of their school science experiences. The researchers compared groups of students taught through a constructivist pedagogy against those who were taught through traditional pedagogy. The authors wished to determine if elementary students were capable of developing complex scientific epistemological understandings, exploring different such levels. Level 1 indicated students who believed that science consists of a collection of facts. Level 2 indicated students who believed that scientific knowledge consists of tested ideas that develop explanation and hypothesis testing. At level 3, science was thought to consist of well-tested theories about the world that are useful in explaining events and making predictions of new events. Students in two sixth-grade classes participated in that study and were interviewed about their ideas of NOS using an open-ended protocol. The students of the one class had been with the same constructivist science teacher for 6 years. In the other class, the students had been with their more traditional teacher for 5 years. The constructivist teacher explicitly had students reflect on their scientific knowledge, and how they knew it, for 6 years. The results indicated that the students in the constructivist classroom developed sophisticated epistemology of science understandings, up to level 2. Immersion in a constructivist classroom that explicitly emphasized ideas about NOS over the 6 years of elementary school seemed to have aided the students in developing these sophisticated understandings.

Conley et al. (2004) studied how epistemological beliefs changed over the course of a 9-week science unit in a diverse sample of 187 fifth-grade students. Epistemological beliefs were measured along four dimensions, using a 26-item Likert scale instrument that measured students’ ideas about the source, the certainty, the development, and the justification of knowledge. This measure was given before and after a unit on chemical properties of substances. Instruction took place from a kit-based science program and was the same across classes. Teachers engaged students in discussions of their investigations and how the latter had aided them in developing their understandings of science concepts. The researchers found that the fifth-grade students’ epistemological understandings had changed over time, but those changes were not large. The researchers stated that the hands-on NOS teaching contributed to epistemological awareness. They did find that higher-achieving students had developed greater epistemological understandings.

Khishfe and Abd-El-Khalick (2002) investigated whether including explicit-reflective NOS instruction is the key to increasing students’ NOS understandings. They compared two sixth-grade classes taught by the same teacher using inquiry methods. One class received explicit-reflective instruction in NOS, while the other received only implicit instruction. Pre- and post-testing of both groups of students showed gains in NOS for those who had been given explicit-reflective NOS instruction, but not for those who had been taught implicitly. This study indicated that even in an inquiry setting, students do not make gains in NOS understanding on their own. Rather, they need to receive explicit-reflective instruction in order to make gains in their NOS understandings.

Walls (2012) examined the NOS views of third grade African-American students in two Midwest urban settings. He used an open-ended questionnaire coupled with interviews and a Draw-A-Scientist test with a photo-eliciting activity. The study also sought to capture their views of themselves as users and producers of science. Their views of NOS were unique, and filled with traditional stereotypical views of what science is and is not, such as science being done by men in lab coats. Walls did not include methods for improving NOS conceptions in his investigation, but it is clear that the students did hold misconceptions about NOS in the absence of explicit intervention.

Huang et al. (2005) explored 6000 Taiwanese fifth- and sixth-graders' views about Nature of Science. Their focus was on three dimensions of Nature of Science in their investigation: (1) scientific knowledge is invented and changing, (2) scientific knowledge is negotiated with other scientists, and (3) cultural context impacts development of scientific knowledge. They developed a 15-item scale that was a forced choice Likert scale questionnaire to explore these dimensions. They recommend instructional strategies to promote accurate understandings, as most students held misconceptions about NOS in the absence of explicit intervention.

In their work that included an overview of several studies, Akerson et al. (2011) emphasized that early childhood students (those of age 5 through about 8) were highly capable of learning appropriate ideas about NOS if they were taught through explicit-reflective strategies, regardless of context (which included an urban, a suburban, and an informal science setting). They reiterated the importance of beginning appropriate explicit-reflective NOS instruction at early elementary ages. We share some of that work in the section below.

In a study on fourth graders' understandings about NOS, Akerson and Abd-El-Khalick (2005) explored what those students understood about NOS at the end of a school year after having been taught by an elementary teacher with appropriate understandings of NOS. As noted by the authors, it was not possible at that time to find prior research on elementary student understandings of NOS. Though the teacher in the study was experienced and taught science through inquiry methods, she did not explicitly teach NOS in her science lessons. The fourth graders did not have acceptable conceptions of NOS by the end of the school year, and the researchers postulated that this occurred because, despite having ample science instruction through inquiry, the NOS concepts were not explicitly taught in connection with the lessons.

In a study conducted with a preservice teacher in her first-grade internship teaching, Akerson and Volrich (2006) found that at the beginning of the semester, the students held uninformed ideas about the targeted NOS aspects of tentativeness, creative and imaginative science, and the distinction between observation and inference. By the end of the semester, students' ideas about NOS had improved substantially, and they had realized that scientists use evidence to make claims, but also create understandings through extrapolating from incomplete data, and change their minds due to new evidence. The explicit-reflective instructional approaches used by the preservice teacher with the first-grade students comprised three main strategies. The first was an introductory lesson wherein she introduced the target NOS aspects. This was a class discussion that required students to discuss their ideas about what science is. She asked them to think about observations in terms of senses, and then the kinds of meanings that they could make from those observations as inferences. After she introduced the ideas about NOS, she continued to embed them in the content that she was teaching. For example, in a unit on plants she asked students how scientists know that plants get water through their roots, and directed students to think about observations and inferences. Finally, she debriefed each science lesson with a concluding discussion that engaged students in thinking about how and what they did in their investigation was similar to what scientists did. Through these discussions, the teacher leads them to think about the data, about observations and inferences, and about how scientists created an understanding from these investigations. The conclusion from this study was that even a new teacher who used appropriate explicit-reflective NOS instruction could improve her first-grade students' understandings of NOS.

In a study that included research on improving elementary teachers' practices for teaching NOS, Akerson and Hanuscin (2007) explored the influence of NOS instruction on elementary student understandings in three classes. It was found that the elementary students' conceptions of NOS improved through the teachers' explicit-reflective NOS instruction. The kindergarteners were asked to reflect on how and what they were doing in their inquiry, for example, on which surface cars rolled best, was like what scientists do. Prior to instruction, the kindergarteners held very poor understandings of NOS. By the end of the school year, it was clear that the kindergarteners could identify the distinction between observation and inference, three of the students had developed an informed understanding of scientific creativity. However, the kindergarteners retained uninformed ideas about tentative NOS. In the first-grade classroom, the students held inadequate views of NOS at the beginning of the school year. The first-grade teacher also provided explicit-reflective NOS instruction to her students, through children's literature, drawing students' attention to tentative NOS by asking them to think how their own ideas changed about the growth of plants, and in using a NOS poster to introduce and debrief NOS ideas. She also incorporated observation and inference charts and student journals. By the end of the school year, the students had improved their ideas about empirical NOS, the distinction between observation and inference, scientific creativity, the tentativeness of science, and the subjective and social-culture embeddedness of NOS. Finally, there was a fifth/sixth-grade teacher who participated in the professional development. This teacher used explicit-reflective instruction, including observation and inference charts to debrief her students' science lessons, as well as a handout of NOS terms for students to reflect on after science investigations, including a trip to the challenger center. Her students held very good views about the targeted NOS ideas as a result of being in her classroom for a year. They improved their conceptions of all NOS aspects and retained few misconceptions. Therefore, students in all grades had improved their NOS ideas due to the explicit-reflective instruction of their teachers.

In a study of K-2 students in an informal science education setting, Akerson and Donnelly (2010) found that explicit-reflective teaching strategies were effective at improving students' NOS conceptions. These strategies included explicitly introducing students to the aspects of NOS, engaging them in scientific inquiries and investigations, and then debriefing them on their NOS ideas orally following the investigations. They then kept a NOS journal, as well as completed worksheets that explicitly focused on NOS through writing. After the NOS journals and worksheets were read, they were used to debrief NOS ideas with students a second time, in a type of "double debrief" to continue emphasizing NOS conceptions. Prior to engaging in this program, students held inadequate conceptions of NOS aspects. Following instruction, it was clear that students of all grade levels had improved in their understandings of all NOS aspects. The results of this study indicated that students of all grade levels can improve their NOS understandings when they are provided appropriate explicit-reflective NOS instruction.

Quigley, Pongsanon, and Akerson (2010) conducted a follow-up study in a similar informal science program with K-2 students. In this case, NOS was embedded in the content of scientific inventions. Each week, there was a focus on a different NOS aspect, which was taught explicitly through investigations connecting to scientific inventions, such as moving cars, and to what contributes to helping them move the fastest and most smoothly. From the explicit NOS instruction embedded in the science content, it was clear that students of all ages improved their NOS conceptions of all aspects. Therefore, whether NOS is taught as an objective or embedded in content, students as young as kindergarten can improve their understandings of NOS as long as explicit-reflective instruction takes place.

Akerson et al. (2014) conducted a study to determine what third-grade students could conceptualize about NOS after a full year of explicit-reflective NOS instruction by student ability level. These explicit-reflective teaching strategies varied. One strategy included a discussion following all investigations, during which the investigations were debriefed to identify the NOS aspects that were embedded in them. Another strategy was the use of scientific notebooks through which students explicitly reflected on writing about their NOS ideas in investigations. Children's literature was used to emphasize NOS aspects to students. These strategies were used across an entire school year, within all science content taught that year. Through comparison of pre- and post-NOS conceptions, it was clear that all students in the class improved their ideas about NOS. Regarding NOS conceptions and ability level, students of all ability levels improved their NOS ideas. The low achiever was able to interact in class and share his ideas about NOS, and while his ideas improved, he retained misconceptions about tentative NOS believing scientists never changed their claims, as well as those about scientific creativity. The medium-achieving student did not like science but enjoyed writing, which enabled her to be especially reflective and interactive through writing in the science notebooks. She engaged in discussing her ideas through the class discussions based on her writings. By the end of the school year, she held adequate ideas of all NOS aspects. The high-achieving student excelled in all subjects, and was highly engaged during investigation debriefs as well as writing. He was the only student in the class who was able to develop an informed understanding of the role of subjectivity and culture in the development of scientific knowledge, and also integrated his NOS ideas. It was clear that students of all achievement levels developed in their NOS understandings from the explicit-reflective NOS instruction, but to varying levels, with high-achieving students able to provide examples in science, beyond identifying the concept in their own investigations.

Fouad, Masters, and Akerson (2015) explored the use of including history of science into explicit-reflective NOS instruction in elementary classes at an Islamic school in an urban area in the USA. The study included two groups of students, one taught NOS explicitly through inquiry and one taught NOS explicitly through history of science. The inquiry instruction included use of debriefing strategies connected to investigations, such as discussions with students about NOS ideas through the content. The history of science group entailed the teacher developing stories from history of science designed to illustrate content as well as NOS explicitly to students. Gains in NOS understandings took place in both groups, with gains in the history group being slightly larger. It was clear that for this group of Muslim elementary students, regardless of being in history or inquiry focused lessons, explicit-reflective instruction was effective at helping improve student conceptions, through debriefing discussions as well as the use of stories.

Through our own research, and reviewing the research of others, we have found that elementary students can conceptualize aspects of NOS, and that this occurs through the use of appropriate explicit and reflective teaching strategies that enable teachers to help elementary students improve their conceptions about NOS. In this article, we share general research-based teaching strategies that can help teachers improve K-6 students' conceptions of NOS. A review of several studies that focused on improving students' conceptions of NOS shows that students as young as 5 years old are able to conceptualize NOS ideas (Akerson et al. 2011). Prior research shows that some NOS aspects, such as observation and inference, creativity, tentativeness, and the empirical NOS are likely more readily accessible to students than subjectivity or the socio-cultural aspects of NOS possibly because these elements are less abstract. However, school age students are able to improve their understandings of all NOS aspects through instruction (Akerson et al. 2014).

2.2 Types of Research-Based Teaching Strategies

So what kinds of strategies are effective in improving students' conceptions of NOS? In designing NOS instruction for K-12 students, we know from prior research that we should use explicit-reflective instruction (Lederman 2007). Indeed, according to the research reviewed, all outcomes support the inclusion of explicit-reflective instruction to improve elementary students' NOS understandings. Though some debate the type of explicit reflective instruction that should take place, there is an agreement that explicit reflective instruction improves student understanding (Duschl and Grandy 2013). In fact, we argue that the consensus list that has been part of previous research is particularly useful for elementary students as it helps them develop ideas about NOS at their developmental levels. While it appears to be simplified, it provides a label for deeper conceptualization of ideas. Explicit-reflective NOS instruction draws students' attention directly to the emphasized NOS aspects through teachers' questions and by asking students to reflect on the science investigations in which they were involved, in other words directly connecting students' NOS understandings to the science content. NOS aspects need to be explicitly connected to the science investigations that the students are conducting, thus contextualizing NOS through scientific practices and disciplinary core ideas. Black box activities, where students need to make observations of a hidden item and then infer what is inside, can be used to introduce NOS aspects so students can conceptualize these ideas and then connect them to science content knowledge development. These kinds of activities enable the teacher to draw attention to NOS aspects using familiar and concrete examples, and provide a foundation upon which content-embedded instruction can occur. Using a variety of these activities enables the teacher to draw connections to NOS aspects across different examples so students can see aspects of NOS through various contexts.

Research has shown that in the absence of intervention through instruction, elementary students retain misconceptions about NOS (e.g., Huang et al. 2005; Walls 2012). Research has also shown that teaching K-12 students about NOS aspects can take place as part of regular classroom science instruction, through explicit-reflective instruction (Akerson et al. 2014). To begin, it is important to familiarize students with the particular NOS aspects addressed in the lesson, as well as any other science content being covered. To be able to conceptualize NOS, students need to be aware of the NOS elements, and these introductory activities highlight these aspects in ways that students can conceptualize these ideas. These introductory activities can include reading children's literature, presenting a short demonstration or inquiry project, or using a K-W-L chart (what we Know, what we Want to know, and what we Learned). Once the concepts have been introduced, research has shown that NOS is best taught through inquiry (Akerson and Donnelly 2010). Following the introductory activity, the students should be engaged in a hands-on inquiry activity that enables the teacher and the students to connect the NOS aspects to the investigation. For example, students can make observations and inferences about a toy car as it is pushed across a variety of surfaces. Students record observations and test different surfaces; they can then generate explanations about the scientific phenomena and share their results with one another. They can reflect on how they are making observations and inferences (through their evidence-based explanations), and developing their understanding of the kinds of surfaces on which cars move best. The teacher can lead them to conceptualizing scientific creativity by noticing that they are creating an understanding of which surfaces cars move best on.

Finally, NOS instruction has been shown to be most effective when taught not only explicitly, but also reflectively (Akerson et al. 2000). Thus, it is imperative to debrief the inquiry so that students can engage in metacognition about their understandings of NOS. Debriefing should include a discussion of NOS aspects present in the inquiry and questioning that allows students to reflect on how science is practiced. For instance, the teacher can either direct the students to think about various NOS aspects present in the inquiry, or ask students to discuss the aspects they noted (with examples) that were present in their inquiry.

Using these strategies of explicitly introducing NOS within the lessons, teaching the lessons, and debriefing the lessons for students to reflect on aspects of NOS within science practice should not be thought of as something done only once, but as part of all science lessons within the curriculum. A one-shot lesson about NOS will have limited, if any, success (Akerson and Volrich, 2006). We describe specific examples of these strategies in subsequent sections of this article.

3 Teaching NOS

To teach NOS aspects, it is generally necessary for teachers to embed them into existing science curricula that may not contain explicit prompts, instruction, or assessments of students' NOS understandings. It is certain that most students may not have heard of scientific inferences (however, they may have heard of, and be able to connect it to, a reading comprehension skill), or terms like "empirical evidence" and "subjectivity," or even Nature of Science itself. Therefore, these terms need to be introduced to students initially, in a way that connects to their former ideas, or through a science lesson that connects the NOS aspects through investigations. It is also critical to engage students in scientific inquiry when teaching NOS, either before or after introducing students to the NOS aspects. If students do not have an opportunity to actually investigate phenomena, it will be difficult for them to connect the terminology to experiences that are similar to the work of scientists (Allchin 2014). Thus, contextualizing their learning in actual science investigations is important. After engaging in an inquiry-based activity, debriefing is a key component in aiding students to develop appropriate understandings about NOS concepts. Research indicates that NOS instruction is most effective when it is explicit and reflective, and debriefing is the perfect way for students to reflect on their NOS ideas (Abd-El-Khalick and Lederman 2000). In the sections below, we will describe strategies that can be used for introducing, engaging, and debriefing NOS ideas in elementary science lessons. These strategies are organized into sections on embedding NOS into existing curricula, using classroom interactions, using visual representations, and use of students' written work.

3.1 Embedding NOS Teaching into Existing Curricula

As described previously, in the USA, most elementary science curricula do not explicitly embed NOS in the lessons. Therefore, teachers need to be able to connect NOS to the lessons within the unit, making connections and designing assessments for student understandings. For instance, we have had experience teaching through the FOSS 1–2 Balance and Motion unit (Full Option Science System [FOSS] 2017). This hands-on, kit-based unit leads students through many interactive explorations of balance and motion that help them understand forces related to what makes things balance, and what puts them into motion. However, teachers would need to help the students identify the components of the investigations that connect them to NOS, such as their engagement in the tentative NOS in how they are modifying their designs or the empirical NOS through the identification of their ideas of what contributes to items being balanced based on evidence. Similarly, teachers can connect the creative NOS by asking students to note that as they are creating designs for what contributes to something spinning, they are creating an understanding for what initiates an item to spin (and to spin the longest, for example). Teachers can ask students to make observations of their designs, and inferences for factors that contribute to making things roll (and roll "best"). Furthermore, as an example of the subjective NOS, teachers can also ask students to think about what they have learned about balance and motion that influence how they would subsequently design their roller coasters (e.g., that their background knowledge influences how they design their roller coasters). We recommend that teachers ask students to make records of their science content knowledge as well as their NOS aspect knowledge on worksheets or in science notebooks. In these (and other) ways, teachers can embed NOS into existing science curricula, enabling them to contextualize their NOS instruction into content that their students will learn in their classrooms, in this case literacy content. Below we share some ideas for embedding NOS into existing curricula.

3.2 Classroom Interactions

Interactions are an important part of every classroom. Engaging in social interactions can support students' understanding of science (Ford and Forman 2006). Through class discussions, seeing a teacher model thinking aloud, teacher questioning, use of NOS terminology, and having students work in teams, the teacher can capitalize on classroom interactions to emphasize accurate NOS conceptions. We share some of these strategies found effective through research below.

3.2.1 Class Discussion

To engage students in explicit discussions of NOS, teachers can design or use a NOS poster that includes the targeted NOS aspects, along with definitions and cartoon drawings, in order to introduce the NOS terms in a manner that is accessible to elementary students (see the Appendix Fig. 1 for an example of such a poster that was developed with elementary teachers in a research-based professional development program; Akerson et al. 2009). This poster can support teachers in introducing the NOS terms, as well as to continue to reference the NOS terms throughout subsequent science lessons by referring to the poster at various points in the lesson. To initially use the poster, the teacher can hold a conversation with students regarding "the nature of science." The teacher can ask students, "What do you think science is? What makes science itself, and not called something like math?" The teacher can then allow responses, and states, "The nature of science really is what makes science 'science.' It is the characteristics of science that make it unique to itself." Though a simplified demarcation is possible for elementary classes, this statement should not be construed to mean that there can, and would be possible to define a sharp demarcation between science and non-science. Then the teacher can read each aspect and definition from the poster, and talk about the terms in "kid friendly" language. Of course, this is simply an introduction to the terms, and certainly the students should not be expected to fully conceptualize the ideas. This introduction can come before or after a science investigation. If it comes after a science investigation, we recommend that the teacher uses examples from that lesson to reinforce conceptual understanding and label the concept with their scientific terms. If the introduction to NOS comes before a science investigation, the teacher can ask students to think about these aspects as they conduct their investigations. The teacher can then use the poster to ask the students to reflect on their investigation (an example of explicit reflective NOS instruction) as the teacher draws students' attention to the NOS aspects before and after a hands-on investigation.

Explicit-reflective instruction can also be facilitated through class discussions during and after inquiry activities. For example, Akerson and Donnelly (2010) asked students how their models of fossils demonstrated subjective NOS, and noted that one student indicated that he thought that "scientists do not always come up with the same idea" (p. 17). Akerson et al. (2011) asked students to identify how they were thinking like scientists during their inquiry investigations and made explicit reference to specific NOS aspects. For example, after students made their own model fossils using clay and then made observations and inferences about each other's fossils, Akerson and Donnelly (2010) asked students how they were being creative and "whether scientists were creative while doing their work" (p. 15). Akerson and Donnelly (2010) also engaged in a "double debrief" process in which we read written responses from each week's debrief, identified any misconceptions, and then orally debriefed the activity again at the beginning of the next activity. This "double debrief" promoted explicit-reflective NOS instruction by allowing us to reteach and address any misconceptions that the students still held.

3.2.2 Modeling Thinking about NOS

From the class discussions' section above, it is clear that the teacher can play a strong role in emphasizing NOS through interactions with students. The teacher can also use a "think-aloud" strategy to model ways to think about NOS within science inquiry lessons, as has been found successful with mathematics lessons (Henjes 2007). For example, the teacher can model the think-aloud strategy in an investigation where students explore a mystery material to determine whether it is a solid or a liquid: Oobleck, a material that actually has characteristics of both solids and liquids. The teacher can say, "Well, I think this material has elements of both solids and liquids. It makes it tough to figure out and put it in one category. I am going to think about NOS ideas. Hmm…I can see that I was making observations that the material (Oobleck) takes the shape of its container, which is my empirical evidence! First, I inferred it was a liquid, because a characteristic of a liquid is that it takes the shape of the container. Then, I inferred it was a solid because I couldn't poke my finger through it and I know solids are hard. Finally, I inferred it may somehow be a solid and a liquid at the same time because it has characteristics of both. I am using the tentative nature of science because I am changing my mind about the evidence. I am also being creative like a scientist because I am creating an understanding of what this stuff is—I think it may be a solid AND a liquid. Now I have to create a new category because it won't fit in the original categories. This is another example of the tentative and creative nature of science! I knew it had characteristics of a solid AND a liquid because I had background knowledge of solids and liquids, which is my subjectivity coming out. Science is amazing!" The teacher could then point out that scientists created a category for fluids like Oobleck they call "non-Newtonian."

By reflecting aloud along with the students (the students can also be asked to join in on these reflections and add their own ideas) the teacher thus models thinking about NOS in connection with the content and science investigation that the students just completed. Then, in later investigations, the teacher gradually releases the modeling and asks the students to do more of the reflecting aloud and on their own.

3.2.3 Teacher Questioning

Teachers can use questions phrased in ways such that they draw attention to NOS aspects in connection with science investigations, as they do when helping students learn other science content (Harlen 2015). For example, while students are observing phenomena, the teacher can ask, "What are your observations? Are you able to make any inferences right now based on your observations? Do you think that your ideas about what is occurring might change? What might make them change?" These kinds of teacher questions can draw students' attention to their investigations as well as to how their investigations are connected to NOS. For example, in a unit on air resistance and forces, the teacher can ask students to explore different whirlybirds to determine what influences them to stay aloft and make them spin. Students can design whirlybirds and test them. The teacher can then ask questions such as, "What are your observations about the whirlybirds we have so far? Can you make any inferences about what might contribute to keeping the whirlybirds in the air longer? What forces are working on the whirlybirds? What changes might you make based on what you see?" Then students can make these changes in their designs, and re-test their whirlybirds. The teacher can then raise more questions, such as, "So, how did your ideas change after you tested your whirlybirds? Do you think scientists change their ideas after they conduct investigations? Would you make more changes based on your second test? Do you think you can ever find the "best" design? Why or why not? How have you been creative like a scientist during your investigations of your whirlybirds?" These questions can be embedded during the time students are investigating, or even raised after the investigation as a debriefing activity. Connecting these questions directly to aspects of NOS is a further illustration of explicit reflective NOS instruction.

3.2.4 NOS Terminology

Including NOS terminology during class discussions can reinforce accurate NOS conceptions and model the use of NOS language for students (Akerson, Buck, Donnelly, Nargund, and Weiland 2011). It is important to refer specifically to the investigation when engaging students in discussion, for example, "Where do we see scientific tentativeness illustrated in our investigation?" These discussions can be facilitated to increase the students' responsibility for identifying aspects of NOS independently by asking a more open-ended question, "Which NOS aspects do you see illustrated in our investigation?" If students would then state, for example, "tentativeness," the teacher can ask, "Where is an example of scientific tentativeness in your investigation?" A student may respond, "We changed our minds about what these (jumping) beans were. We saw them move, and then figured out there had to be something alive and moving in them." Akerson and Volrich (2006) debriefed every NOS activity with an even more open-ended prompt: "How is this like what scientists do?" to promote students' understanding of science practices as well as NOS aspects.

3.2.5 Work in Teams

When students work in teams, they can share and discuss ideas about science and aspects of NOS (Flick 1993). Having students work together in teams also allows the teacher to draw their attention to the fact that all students in their group have different knowledge bases they bring to the discussion, and therefore their viewpoints about the investigations may be slightly different. This difference in understanding can be explicitly and reflectively discussed as part of the subjective NOS. Further, it can allow students (and scientists) to look at data and investigations differently and more holistically than if just one person were investigating a phenomenon. Through sharing ideas in "research teams," students can recognize the tentative NOS—because they may hear one of their peers interpreting data in a different way, they may also see a difference in the data and change their own ideas. This change in their ideas highlights that subjectivity can influence the tentative NOS. Working in teams can also help students see science as being creative as they create various understandings of their scientific investigations in teams—from designing, carrying out, interpreting, and reporting their results, students can see that they are being creative like scientists.

3.3 Visual Representations

Visual representations of NOS aspects can be helpful for students to introduce, and reinforce accurate NOS conceptions. Children's literature can be an engaging way to emphasize NOS ideas. The use of other visual aids can also enable teachers to explicitly emphasize NOS in a way that helps improve elementary students' NOS conceptions.

3.3.1 Children's Literature

Elementary students are accustomed to having stories read to them by the teacher, and children's literature can be used to teach about NOS and reinforce NOS concepts (Akerson and Donnelly, 2010). For example, a teacher can use *The Skull Alphabet Book* (Pallotta and Masiello, 2002) during an activity on fossils. This book cleverly connects the letters of the alphabet to skulls of animals whose names begin with each letter. While the book does not directly emphasize NOS, the teacher can make explicit where NOS can be illustrated by the story. Through making observations of clues in the text and in the accompanying drawings, the reader infers the animal that the skull belongs to, thus leading directly to a discussion of scientific observation and inference. This kind of book also lends itself to a discussion of the role of empirical evidence in the development of scientific knowledge because the skulls represent the data source about which we are making observations and inferences.

Indeed, this book also lends itself to a discussion of the subjective NOS, as people are not likely to infer animals with which we are unfamiliar. This aspect can be illustrated by animals in the book that may be unfamiliar to students, such as the Narwhal whale. Students are often familiar with whales, but not specifically with the Narwhal, and therefore do not infer a whale, which then leads to a discussion regarding the reliable, yet tentative, NOS because not all whales have similar characteristics. The teacher can then provide background knowledge regarding the Narwhal whale and discuss with the students how their inferences may change when they are given more information about this particular whale. This procedure is just like a scientist that may change an inference by reconsidering all the evidence they have or when they obtain new evidence. Indeed, this story can also be used to explore scientific creativity as the teacher can lead a discussion of how scientists create an understanding of an animal based on its skull. The students can be led to discuss how scientists infer missing data, such as those about skin color and coverings, and still create a reasonable and reliable, but tentative, picture of the animal.

This book can also be used during an investigation. For example, after making observations and inferences about skulls, a teacher can read *The Skull Alphabet Book* and ask the students "to make observations of the skulls and the surroundings in the book in order to infer the kind of animals that would have such a skull." In this case, *The Skull Alphabet Book* provided students with contextual information (where skulls may be found) that the classroom investigation could not offer. The book therefore served to support their understanding of the investigation, and allowed for explicit reflective NOS instruction.

Finally, the use of children's literature can reinforce NOS aspects and provide an interdisciplinary connection to literacy (Akerson, Nargund-Joshi, Weiland, Pongsanon, and Avsar 2014). During an activity that emphasizes observations and inferences, students can determine what might be inside an opaque sealed bottle. Students can make various observations, and come back together as a group to discuss the inferences they made and the observations that led them to those inferences. This lesson can be concluded with the book *Seven Blind Mice* (Young 1993) and students can note observations and inferences, as well as the role of subjectivity. The storyline of this book lends itself well to a discussion about observation and inferences given that it is about seven blind mice who use their sense of touch to determine the nature of a "something," which, if they could see, they would know was an elephant. For instance, a student might say, "They bring their data together and compare it. They heard the other mice's inferences so they had more background knowledge and had different ideas." Another student may agree, stating, "You need background knowledge to make inferences." Akerson and Donnelly (2010) also used children's literature to draw connections to specific aspects of NOS in the investigation.

3.3.2 Visual Aids

The use of visual aids to support students' understandings of NOS can be effective (Akerson et al. 2009). As noted previously, a NOS poster can be placed in the classroom for the teacher and students to refer to throughout the science lesson or unit. The teacher can use the poster to introduce the NOS ideas at the beginning of a lesson, and also to explicitly identify aspects of NOS throughout debriefing (reflection) discussions, first by providing examples to the students to model how to notice NOS in their work. As students begin to develop understandings of the NOS ideas, they can then be asked to describe the NOS aspects evident in their investigations on their own, without any scaffolding by the teacher. The students can refer to such a poster while engaging in science lessons, or while recording data in their science notebooks. A reduced copy of the poster can be inserted into the students' science notebook for them to reference independently.

3.4 Students Recording and Reflecting in Writing

An important part of explicit-reflective instruction includes written reflection of explicit NOS ideas. A variety of written methods can support students' development of accurate NOS conceptions, such as through the use of science notebooks, observation and inference charts, and the use of charts, graphs, and classifying.

3.4.1 Science Notebooks

Science notebooks are an excellent tool to promote science learning (Morrison, 2005). Students can use these notebooks to record data, ideas, questions, and reflections. The teacher can also use science notebooks to aid in their students' understandings of NOS. These reflections can connect to disciplinary core ideas as well as to student understandings of NOS aspects. For example, the teacher can ask students to describe in their own words what they believe the NOS aspects mean and then hold a class discussion. Students' responses can be listed on a chart paper that hangs in front of the room. They can then be asked to record the terms with the definitions generated by the class in their notebooks, using the chart to guide them with spelling, if needed. Also, if students are not writing yet, teachers or classroom helpers can record students' ideas in their notebooks, while they are instructed to illustrate their ideas. These notebooks can then be used as an individual assessment of students' conceptions of various NOS aspects.

Teachers can ask students to reflect on the NOS aspects in their science notebooks after investigations, supporting reflective NOS instruction. Indeed, students' responses to NOS prompts following investigations can be listed on chart paper in front of the classroom and they can be instructed to record in their own notebooks ideas with which they agree, or other ideas that they have regarding NOS aspects that were present in their investigations. Again, the use of notebooks to emphasize NOS aspects is another example of explicit-reflective NOS instruction.

The teacher can provide students with writing prompts to encourage them to reflect on their content knowledge as well as their NOS understandings. Following a class discussion about the same topic, the teacher can ask students to write, using prompts such as, "Did anyone make any observations or inferences in this investigation? [allow discussion] Please record those in your notebooks." Or "What was your empirical evidence in this investigation?" Or "How were you creative like a scientist in this investigation?"

During investigations, students can record data as the teacher points out the importance of collecting empirical evidence in the development of scientific understandings. For instance, in a unit on electric circuits, students can draw and write their initial ideas for how to light a bulb using a battery and a wire. As they investigate the problem, the teacher can ask students to record other ideas they try, and finally, different ways in which they are able to light the bulb. The teacher can also ask students to reflect in their notebook recordings on how their ideas changed as they collected more data regarding how to light a bulb. Students can reflect on their writings for how they were being scientifically creative in their investigations, and for instances of where they were using observations and inferences in their explorations. Further, they can record their ideas of where NOS aspects were present in their investigations on how to light a bulb. In this unit on electric circuits, for example, students can continue to record and reflect on their changing ideas as the teacher helps them understand the importance of evidence, the role of observation and inference, and the tentative NOS as their ideas develop through investigations. This example of explicit reflective NOS instruction suggests how teachers can continue emphasizing NOS using science notebooks with students.

Science notebooks can be used to debrief NOS activities in a fashion similar to how they are used during introductory and inquiry activities. They can be used to formatively assess students' understandings of NOS, thereby informing the teacher's NOS instruction by allowing the teacher to identify misconceptions and enabling the teacher to reinforce concepts throughout subsequent inquiry lessons. Additionally, science notebooks can be used to summatively assess not only understandings of individual aspects of NOS but also a holistic view of NOS. For example, by asking students to draw/write a response to the question, "How were we acting like scientists?" students have the opportunity to share in their notebooks their thoughts related to all aspects of NOS.

3.4.2 Observation and Inference Charts

Teachers can ask students to record observations and inferences of phenomena on a chart or in their notebooks. These observations and inferences can be reported to the class for discussion. We have seen teachers successfully use an observation and inference chart that students can use in many different investigations (Akerson, Townsend, Donnelly, Tira, and White 2009). This chart consists of two columns. In one column, students list the observations they are making and in the next column, they make complementary inferences. For example, during an investigation, to determine whether Oobleck is a solid or a liquid, students can list their observations (e.g., it is green, it does not pour, it takes the shape of its container) and their inferences of those observations (e.g., it is a solid, it is a liquid, it is both). In this way, the teacher facilitates explicit-reflective NOS instruction as the students make distinctions between observations and inferences during a hands-on investigation.

3.4.3 Charts/Graphs/Classifying

As is common with scientific investigations, teacher can ask students to use charts, graphs, and methods of classifying data in order to represent their scientific observations (Bowen and Roth 2005). The teacher can help students see that they need to actually collect, organize, and analyze data in order to make scientific claims. For example, during an investigation on what makes the best roller coasters, students can collect data on how far toy cars travel across the floor based on the height of the ramp. With the teacher's help, they can chart the height of the ramp and the distances the car traveled, and also graph this relationship. The teacher can draw students' attention to the importance of collecting and representing these data so they can make better inferences for what contributed to the distance the car traveled. Students can then use this information to design their roller coaster, further illustrating the role of background knowledge, or subjectivity, in the development of scientific knowledge. Teachers can use explicit and reflective instruction to direct students to notice that they are being scientifically creative in designing, carrying out, recording, and interpreting the data that then influences how they design their roller coasters.

3.5 Engaging Students in Inquiry-Based Activities

As previously mentioned, for students to be able to explicitly reflect on NOS aspects as part of scientific investigations, they must be engaged in such investigations. These investigations will enable them to experience scientific explorations, and then explicitly connect NOS ideas to the activities. These investigations should be hands-on, and can move from guided to open inquiry.

3.5.1 Hands-On Activities

It has been long known that students must engage in hands-on, minds-on science investigations, as opposed to only learning through teacher demonstration (Flick, 1993). These activities allow students to raise questions, collect data, and make observations and inferences of phenomena. It is through manipulating materials themselves that students can engage in the practices of science, and then later (or even during that) reflect on when they were making observations and inferences, how they were being creative like scientists, when they were changing their minds about data or because they collected new data, and how their own or the background knowledge of those in their group influenced their interpretations.

For example, during an activity in which students make playdough fossils, they can actually create themselves the impression of an item as a fossil. Then, students can share these self-made fossils with their peers, who can work to determine which item likely made the fossil impression. Students can be asked whether and how they are being creative during such an investigation. They may certainly agree that they are being creative when making the fossil, but they can also be directed to notice that they are being creative like scientists when they are determining what item was likely to have made the impression in a peer's fossil. The teacher can also direct students to notice the kinds of evidence the students are using to make observations and then infer what item was likely used to create the peer's fossil. Teachers can point out that they may not know for sure what item was used to create the impression, yet they can make reasonable inferences based on their observations of the data and on their background knowledge (subjectivity) of items that could possibly make such impressions. In this way, the teacher is using hands-on investigations to directly connect NOS elements for the students—this is another important example of explicit-reflective NOS instruction.

3.5.2 From Guided to Open Inquiry

Students should engage in a variety of inquiries from guided (mostly teacher-led) to open (mostly student-led) as they are exploring science and connecting NOS to science content. For example, teachers can use guided inquiries to help students conceptualize how to design and carry out an investigation by planning the investigation along with them. The teacher can use a think-aloud strategy and/or help students connect their investigations to NOS ideas by using the NOS poster described earlier. When students have experience engaging in guided inquiry, the teacher can gradually allow students design their own science investigations, and with the teacher's supervision, carry them out. Then, similar to the guided inquiry, teachers can ask students to think about how and where NOS aspects were present in their work. Further, the teacher can ask students to reflect on these NOS aspects through the use of the NOS poster and/or record their ideas in their science notebooks. If the students are struggling to connect their ideas, the teacher can use a think-aloud strategy to model how to think about NOS ideas in connection with an investigation.

For example, as part of a unit on buoyancy, students can be asked to design an investigation that enables them to determine whether popcorn floats. This inquiry can build on a unit on floating and sinking, and therefore the teacher can facilitate a class discussion surrounding what the students already know about floating and sinking that may influence their inquiry designs. The teacher can also discuss with the students what they know about scientific investigations, for example, the characteristics of a fair test. After the students design an investigation, they can then carry it out, and the teacher can draw their attention to the data through questioning. Some example questions include the following: Did the popcorn float and sink? Did it matter if they put it in salt water or plain water (for those groups who planned a comparison)? Did it matter if they used popped or unpopped corn (for those who planned a difference)? The teacher can also use the NOS poster to hold a discussion and have students elaborate on how they were scientifically creative in designing the investigation and in interpreting evidence. Students can discuss how they were using their background knowledge to design the investigation as well as interpret data, and also making observations of what occurred and inferences about whether popcorn floated. The teachers can ask students to notice that their results were tentative because if, for example, they had used salt vs. plain water, or popped vs. unpopped corn they may have had different outcomes. In this way, the students can both design their own scientific inquiry as well as connect NOS elements to the investigation.

4 Discussion

In this article, we presented research-based ideas for "what works" in teaching elementary students about NOS. Again, we recommend emphasizing NOS explicitly and reflectively through repeated instruction using the methods we describe in this paper, as through research, these strategies have been found to improve elementary students' ideas about NOS. We also recommend teaching in a cyclic fashion, using introductory activities, NOS instruction embedded in hands-on inquiries, and debriefing activities for most, if not all, science lessons. Activities that emphasize NOS aspects through class discussion (Akerson and Volrich, 2006; Akerson et al. 2014), visual representations (Akerson and Hanuscin 2007), students recording and written reflection (Akerson and Donnelly 2010; Akerson et al. 2014), and being embedded within inquiries and investigations (Smith et al. 2000) have been found to support development of elementary students' conceptions of NOS.

These strategies were developed through research on effective practices to help elementary students improve their NOS conceptions. Though there have been questions regarding whether elementary students are capable of developing appropriate conceptions of NOS aspects, research shows that through appropriate instruction, elementary students can, and do, develop sophisticated understandings of NOS as young as 5 years old (Akerson and Donnelly 2010). Indeed, child psychology researchers such as Metz (1995, 2004) and Carey (1986; Carey and Smith 1993) have long indicated that children are able to develop sophisticated understandings of many science concepts given appropriate instruction. Therefore, we advocate using these strategies in elementary classrooms to improve students' conceptions of NOS.

The explicit-reflective strategies that introduce NOS aspects, reinforce them through scientific investigations, and then debrief these NOS aspects after the investigation, have been shown to improve elementary students' conceptions of NOS aspects (Akerson et al. 2014). These strategies can be repeated throughout different science investigations and science content areas, allowing the teacher to continue emphasizing NOS aspects that students are familiar with, while introducing new NOS aspects that are logically connected to the content. While the strategies can be repeated, it is not necessary to use every strategy within every investigation. While research suggests that the strategies described in this article have worked with elementary students, we are not purporting that these are the only strategies that can be effective, as we know that it is critical to plan your instruction based on the unique needs of students. We suggest using these strategies as a starting point for exploring further the kinds of instructional strategies and approaches that best help elementary students conceptualize NOS. We imagine that there are many different strategies that can be used to effectively teach NOS to elementary students. These strategies can be used to differentiate among students across varies ability and grade levels, to best support their individual developments of NOS conceptions.

To that end, we believe that using a variety of strategies to use NOS can allow for flexibility in instruction based on students' needs and interests. Further, students may need different levels of scaffolding to support their engagement in these strategies, such as younger elementary students may need more modeling and/or sentence frames and sentence starters to engage in writing about NOS. While the variety of strategies presented in this article provide various opportunities for which teachers can embed NOS into their curricula, we recognize that research suggests the importance of explicit-reflective NOS instruction (Duschl and Grandy 2013; Khishfe and Abd-El-Khalick 2002; Lederman 2007), regardless of the strategy.

Although there are many ways to embed NOS instruction into elementary science curricula, including those that connect to literacy (e.g., writing and communication), it is still rarely the case that we see NOS embedded in science lessons in elementary classrooms. Of course, coupled with research on effective strategies is also research on how to best prepare elementary teachers to teach about NOS. That is a subject for a different article, but it is clear, once teachers are convinced that elementary students are capable of learning sophisticated understandings about science and NOS, and have strategies to do so, the elementary students can, and do, develop appropriate understandings of both science content and NOS.

Compliance with Ethical Standards

Conflict of Interest The authors state that they have no conflicts of interest.

Appendix

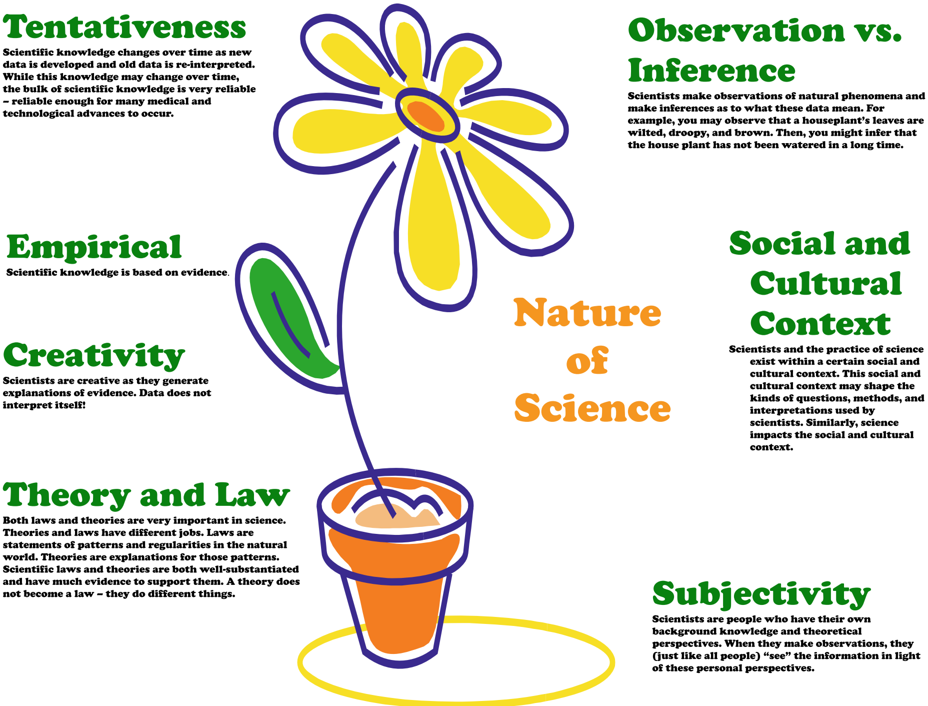

Fig. 1 Sample of poster to be used with science lessons to introduce and debrief NOS aspects

References

Abd-El-Khalick, F., & Lederman, N. G. (2000). Improving science teachers' conceptions of nature of science: a critical review of the literature. *International Journal of Science Education, 22*, 665–701.

Akerson, V. L., & Abd-El-Khalick, F. S. (2005). "How should I know what scientists do—I am just a kid": fourth grade students' conceptions of Nature of Science. *Journal of Elementary Science Education, 17*, 1–11.

Akerson, V. L., & Donnelly, L. A. (2010). Teaching nature of science to K-2 students: what understandings can they attain? *International Journal of Science Education, 32*, 97–124.

Akerson, V. L., & Hanuscin, D. L. (2007). Teaching nature of science through inquiry: the results of a three-year professional development program. *Journal of Research in Science Teaching, 44*, 653–680.

Akerson, V. L., & Volrich, M. (2006). Teaching nature of science explicitly in a first grade internship setting. *Journal of Research in Science Teaching, 43*, 377–394.

Akerson, V. L., Abd-El-Khalick, F. S., & Lederman, N. G. (2000). The influence of a reflective activity-based approach on elementary teachers' conceptions of the nature of science. *Journal of Research in Science Teaching, 37*, 295–317.

Akerson, V. L., Townsend, J. S., Donnelly, L. A., Tira, P., & White, O. (2009). Scientific modeling for inquiring teachers network (SMIT'N): The influence on elementary teachers' views of nature of science, inquiry, and modeling. *Journal of Science Teacher Education, 20*, 21–40.

Akerson, V. L., Buck, G. A., Donnelly, L. A., Nargund, V., & Weiland, I. S. (2011). The importance of teaching and learning nature of science in the early childhood years. *The Journal of Science Education and Technology, 20*, 537–549.

Akerson, V. L., Nargund-Joshi, V., Weiland, I. S., Pongsanon, K., & Avsar, B. (2014). What third grade students of differing ability levels learn about nature of science after a year of instruction. *International Journal of Science Education, 36*, 244–276.

Allchin, D. (2014). From science studies to scientific literacy: a view from the classroom. *Science & Education, 23*, 1911–1932.

Allchin, D., Andersen, H. M., & Nielsen, K. (2014). Complementary approaches to teaching nature of science: Integrating student inquiry, historical cases, and contemporary cases in classroom practice. *Science Education, 98*, 461–486.

American Association for the Advancement of Science. (1993). *Benchmarks for science literacy*. New York: Oxford University Press.

Bowen, M., & Roth, W.-M. (2005). Data and graph interpretation practices among preservice science teachers. *Journal of Research in Science Teaching, 42*, 1063–1088. *Psychologist, 28*(3), 235–251.

Carey, S. (1986). Cognitive science and science education. *American Psychologist, 41*(10), 1123–1130.

Carey, S., & Smith, C. (1993). On understanding the nature of scientific knowledge. *Educational Psychologist, 28*(3), 235–251.

Clough, M., & Olson, J. (2008). Teaching and assessing the nature of science: an introduction. *Science & Education, 17*, 143–145.

Conley, A., Pintrich, P. R., Vekiri, I., & Harrison, D. (2004). Changes in epistemological beliefs in elementary science students. *Contemporary Educational Psychology, 29*, 186–204.

Deng, F., Chen, D. T., Tsai, C. C., & Chai, C. S. (2011). Students' view of the nature of science: a critical review of research. *Science Education, 95*(6), 961–999.

Duschl, R. A., & Grandy, R. (2013). Two views about explicitly teaching nature of science. *Science & Education, 22*, 2109–2139.

Flick, L. B. (1993). The meanings of hands-on science. *Journal of Science Teacher Education, 4*, 1–8.

Ford, M. J., & Forman, E. A. (2006). Redefining disciplinary learning in classroom contexts. *Review of Research in Education, 30*, 1–32.

Fouad, K. E., Masters, H., & Akerson, V. L. (2015). Using history of science to teach nature of science to elementary students. *Science & Education, 24*, 1103–1140.

Full Options Science System. (2017). *Foss Third Edition Balance and Motion Complete Kit 1–2*. Nashua: Delta Education.

Harlen, W. (2015). *Teaching Science for Understanding in Elementary and Middle Schools*. Portsmouth: Heinemann.

Henjes, L. M. (2007). The use of think-aloud strategies to solve word problems. Summative Projects for MA degree, 11, https://digitalcommons.unl.edu/cgi/viewcontent.cgi?referer, https://www.bing.com/&httpsredir=1&article=1014&context=mathmidsummative. Accessed 15 Sep 18.

Huang, C. M., Tsai, C. C., & Chang, C. Y. (2005). An investigation of Taiwanese early adolescents' views about the nature of science. *Adolescence, 40*(159), 1–10.

Khishfe, R., & Abd-El-Khalick, F. (2002). Influence of explicit and reflective versus implicit inquiry oriented instruction on sixth-graders' views of nature of science. *Journal of Research in Science Teaching, 39*, 551–578.

Lederman, N. G. (2007). Nature of science: Past, present, and future. In S. K. Abell & N. G. Lederman (Eds.), *Handbook of research on science education* (pp. 831–879). Mahwah: Erlbaum.

Lederman, N., & Lederman, J. (2014). Research on teaching and learning Nature of Science. In Handbook of Research on Science Education, Volume II. Lederman, N., & Abell, S. (Eds.) pp. 600-621. New York, NY: Routledge

Metz, K. E. (1995). Reassessment of developmental constraints on children's science instruction. *Review of Educational Research, 65*(2), 93–127.

Metz, K. E. (2004). Children's understanding of scientific inquiry: their conceptualization of uncertainty I investigations of their own design. *Cognition and Instruction, 22*(2), 219–290.

Morrison, J. A. (2005). Using science notebooks to promote preservice teachers' understanding of formative assessment. *Issues in Teacher Education, 14*, 5–21.

National Research Council. (1996). *National Science Education Standards*. Washington, DC: National Academy Press.

National Research Council. (2013). *Monitoring progress toward successful K-12 STEM education: a nation advancing?* Washington DC: The National Academies Press.

NGSS Lead States. (2013). *Next generation science standards: for states, by states*. Washington, DC: The National Academies Press.

Olson, J. K. (2018). The inclusion of nature of science in nine recent international science education standards documents. *Science & Education, 27*, 637–660.

Pallotta, J., & Masiello, R. (2002). *The skull alphabet book*. Watertown: Charlesbridge.

Quigley, C., Pongsanon, K., & Akerson, V. L. (2010). "If we teach them, they can learn" Young students' views of nature of science aspects during an informal science education program. *Journal of Science Teacher Education, 21*, 887–907.

Smith, M., & Siegel, H. (2004). Knowing, believing, and understanding: what goals for science education? *Science & Education, 13*, 553–582.

Smith, C. L., Maclin, D., Houghton, C., & Hennessey, M. G. (2000). Sixth-grade students' epistemologies of science: the impact of school science experiences on epistemological development. *Cognition and Instruction, 18*, 349–422.

Walls, L. (2012). Third grade African American students' views of the nature of science. *Journal of Research in Science Teaching, 49*, 1–37.

Young, E. (1993). *Seven blind mice*. New York: Scholastic.