Chapter 15
Framing and Teaching Nature of Science as Questions

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15.1 The Importance of Framing and Teaching the NOS as Questions

More than a decade ago, I put forward serious concerns about framing nature of science (NOS) issues as tenets for science teaching and learning (Clough 2007). I made clear that while general agreement may, for the most part, exist among science educators regarding particular NOS issues, rendering NOS learning outcomes as tenets ignores, or at the very least does not promote, attention to context, nuance, and complexity. My misgivings are shared by many other science educators (e.g., Allchin 2011; Eflin et al. 1999; Elby and Hammer 2001; Erduran and Dagher 2014; Hodson 2008; Matthews 2012; Rudolph 2000). The issues that I and others have raised about NOS tenets include, but go beyond, what NOS content should be taught and learned. Central to my concerns about NOS tenets are the purposes of education and how tenets do not promote meaningful NOS understanding. For instance:

> …tenets, like established scientific knowledge, become something to be taught rather than investigated in a science classroom. For students the tenets become something to know rather than understand. (Clough 2007, p. 1)

Let me be clear that this is not the intent of those who put forward and support NOS tenet statements. But as Duschl (1990) noted in referring to the presentation of science content knowledge in its final form, "When the structure and role of theories are oversimplified, there is little need to accurately portray the processes of theory change" (p. 69). Similarly, the simplified structure of NOS tenets conveys little need to accurately address accompanying arguments, counterarguments, context, and

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nuances to promote a NOS understanding that can be thoughtfully applied in a variety of contexts. Advocates of NOS tenets optimistically maintain that teachers will accurately translate them, but tenets are easily seen as learning outcomes that establish a low ceiling for teaching and learning.

Framing NOS issues as questions deliberately avoids two extreme positions that have fundamental weaknesses. Tenets reflect a mode of thought that McKeon (2016) labels *construction* and Owen (2003) calls *atomism*. This mode of thought is pervasive in schooling and is reflected in detailed learning outcomes and aligned assessments. This perspective has tragically often resulted in the narrowing of schooling to value only those things that can be clearly described as "outcomes" and measured. At the other extreme, some maintain that the NOS is too complex and varied to establish a position on precisely what students should learn, a mode of thought called *discrimination* (McKeon 2016) or *perspectival* (Owen 2003). My view is that the discrimination/perspectival mode of thought is not practical for much of schooling, and the construction/atomism position is antithetical to *education*. My position regarding framing and teaching the NOS via questions reflects McKeon's *resolution* mode of thought whereby problems and the inquiry into those problems are at the forefront of NOS teaching and learning. This entails extensive use of arguments, attention to context and important nuances, and the development of reasoned positions regarding important NOS questions. Framing the NOS as questions calls for and encourages both teachers and students to more deeply think about NOS issues, and promote thinking, the understanding of arguments, and the contextual nature of claims regarding the NOS.[1]

15.2 NOS Questions to Explore in Science Education

The kinds of NOS questions that I maintain ought to guide science education efforts appear in Table 15.1. While not an exhaustive list, the questions encompass the NOS elements that frame this book, but go well beyond them and ideas appearing in other popular NOS tenets lists. They do so in two ways.

First, the questions are phrased in a way that simple responses are unsatisfactory. For instance, rather than a tenet that merely states scientific knowledge is tentative (but also durable as later tenets have noted) or that scientific knowledge has an inventive character, the questions associated with those NOS issues encourage deeper thinking, the use of multiple examples, and reasoned arguments in support of positions (i.e., the reflective thinking that research makes clear is crucial in effective NOS teaching and learning). For example, while the reality of atoms was not firmly established until early in the twentieth century, today that idea is more than durable and now reflects the way we think nature really is. So, a viable argument can

[1] I am indebted to Dr. Joanne Olson for insights into McKeon's work regarding modes of thought. See McKeon, R. (2016). *On knowing: The social sciences*. D. B. Owen & J. K. Olson (Eds.). University of Chicago Press, Chicago, IL.

Table 15.1 Example NOS questions for science education

How are basic science, applied science, engineering, and technology similar and different? How do they impact one another and how does this illustrate that all are needed?
How does the notion of a universal step-by-step scientific method distort how scientists actually work? In what ways are particular aspects of scientists' work guided by existing knowledge and protocols?
Why is well-established science knowledge often so durable and enduring? Regardless of how durable well-established science ideas may be, why is all science knowledge still potentially open to revision or even rejection by the scientific community? How is the possibility of revisiting and revising previously established ideas a strength of science?
In what sense is scientific knowledge invented? In what sense is it discovered?
To what extent is scientific knowledge based on and/or derived from observations of the natural world? In what ways is it based on reasons other than observational and experimental evidence?
How are observations and inferences different? In what sense is an observation an inference?
How has science at times been advanced and hindered by religion? What range of perspectives regarding religion and faith do scientists bring to their work? How does complex interaction rather than persistent warfare better account for the relationship between science and religion?
How is the private work of scientists similar to and different from what is conveyed when they publicly share their work with the wider scientific community? What accounts for these differences, and how does public science mitigate personal bias and other subjective factors?
To what extent are scientists and scientific knowledge objective and subjective? To what extent can subjectivity be reduced or eliminated?
To what extent is scientific knowledge socially and culturally embedded? In what sense does scientific knowledge transcend particular cultures?
In what ways are scientific laws and theories different types of knowledge? How are they related to one another? How does each guide research directions, methods, and the analysis of data?
What purposes do scientific models serve in science? What are the strengths and limitations of scientific models?
To what extent is scientific research and knowledge the product of human imagination and creativity? What factors moderate imagination and creativity in the development and justification of science ideas?

be made that scientists have discovered something about the natural world that was not previously apparent. That does not mean the idea of atoms can never be overturned, and this important issue is reflected in the question appearing in Table 15.1 regarding the potential for revisiting and revising of established science ideas being a strength of science. Of course, NOS tenets are more straightforward than questions, but that is precisely why the content of those statements is problematic. For example, the claim that scientific knowledge is tentative is well-intentioned but also easily misunderstood and open to misuse. An editorial in the March 9, 2017, issue of *Nature*, lamenting anti-science bills that have been introduced in several states, laid some of the fault for the distrust of science at the way NOS is being presented in schools:

> Perhaps a more pressing criticism of the way NOS is taught in schools is that it encourages rather too much doubt over scientific ideas. Many findings, after all, are well established… . Not all science is tentative… (Editorial, p. 149)

Second, the questions in Table 15.1 raise several NOS issues that have surprisingly not been included in commonly advocated NOS lists for science teaching and learning. For example, addressing the differences, similarities, and interdependence between basic science, applied science, engineering, and technology is important for informed decision-making regarding governmental support for each area, and this issue takes on even greater importance given STEM education efforts that can easily exacerbate misunderstanding of these areas (Clough and Olson 2016). Another essential NOS question addresses the complex interaction between science and religion, the common misconceptions that science and religion are in constant conflict and that religion always interferes with science (e.g., Ferngren 2002; Lindberg and Numbers 1986; Olson 2004; Stanley 2007, 2015), and the perspectives that scientists bring to their work regarding religion and faith (Ecklund 2010). Given the way these issues impact the teaching and learning of science, they deserve attention in NOS instructional efforts. Another important NOS issue absent from popular NOS lists is how and why private science differs from public science. The many erroneous and sanitized views of science held by the public and the impact they can have on socio-scientific decision-making (e.g., the backlash to "climate-gate") can be traced to a lack of sufficient attention to this question.

Framing the teaching and learning of NOS issues as questions like those appearing in Table 15.1 will greatly assist in avoiding simplistic and problematic generalized NOS statements, but will require that science teachers understand NOS content and pedagogy at a level where they can effectively teach the NOS through an inquiry approach—having at their disposal general NOS statements simply won't suffice! While advocates of NOS tenets may maintain that teachers must unpack the tenets in the way I have put forward, tenets do not promote that effort and, like most learning outcome standards, appear as a checklist of ideas students must know. Despite the well-intentioned nature of NOS tenets, like all statements of final form knowledge in universal schooling, they inadvertently set and support a low ceiling for teaching and learning.

15.3 Exploring NOS Questions with Students

McKeon's (2016) resolution mode of thought structures content as problems to be explored. The following two examples illustrate the framing and teaching of NOS as questions, and how questions can draw students' attention to important NOS issues and assist them in developing more informed NOS understanding. Both are more extensive and detailed accounts of what appeared in Clough (1997) where I wrote about how I explicitly and consistently incorporated the NOS when teaching high school science. The first example demonstrates how I engaged students in comparing private science to public science, and the second example shows how I had students explore the similarities, differences, and interdependence of basic science, applied science, engineering, and technology. Both examples illustrate how framing the NOS as questions to be explored guided my NOS pedagogy and the way students learned about the NOS.

How is the private work of scientists similar to and different from what is conveyed in sharing their work with the wider scientific community? What accounts for these differences, and how does public science mitigate personal bias and other subjective factors?

Effectively teaching science through inquiry not only mentally engages students in learning science content at a deeper level, but it also creates many opportunities for addressing the NOS. In the classroom example presented here, my students worked in small research teams to determine the products of a chemical reaction. Plausible tests, what lab equipment to use, whether a mathematical approach would be helpful, and what data would be meaningful or not for determining the reaction products were just a few of the questions that students had to consider in their efforts. While some research teams' initial work reflected elements of trial-and-error thinking, that approach soon gave way to using the chemistry knowledge previously learned in class to make reasoned speculations about possible products. For instance, using their understanding of the well-established idea that atoms are not created or destroyed in chemical reactions, students limited the possible products to those that contained elements appearing in the reactants. Prior nomenclature and chemical bonding knowledge was also used in putting forth possible products. Groups attempted to create balanced equations with their speculated products, drawing from their chemistry knowledge that if an equation cannot be balanced, then such a reaction could not occur.

Students soon began making extensive use of the Merck Index, a compendium of information about chemicals, to determine what physical and chemical properties were associated with their speculated products. Much investigation ensued as students wrestled with how to separate the products and test their chemical and physical properties. Some students had the insight that applying stoichiometry could provide quantitative evidence for or against particular products. Data collected required analysis, and issues of ambiguity often arose. Small research teams began working with other research teams, sharing ideas, data, and interpretations. Data at times was deemed not credible. Procedures were reassessed, multiple trials were conducted, and students' satisfaction with results increased when coherence was achieved. But disagreements occurred within and among groups, and these were often, but not always, settled to everyone's satisfaction. Over the several days that their inquiry took place, many approaches were begun, modified, and abandoned. Other approaches were deemed fruitful and maintained. Much debate occurred regarding viable paths to answer the research question, what data was meaningful or trustworthy, how confidence could be achieved, and so on. General agreement often resulted, and some years students became very confident in their conclusions.

Prior to this activity, I assigned students to keep a journal regarding their efforts and include everything related to their work—where they were when their ideas emerged, issues that arose when working with others in and outside their research team, who raised ideas, how ideas were received by others, what ideas were immediately rejected and why, ideas that were abandoned through the process and why, ideas that were abandoned and later resurrected, personality conflicts, etc. In addition to ensuring students were making such entries in their journal, my role during the activity was to pose questions that maintained student engagement in the laboratory investigation and redirect their questions to their laboratory procedures, evidence acquired, and interpretations made. I never told students what data to collect, what tests to run, how to interpret their data, or what conclusions were valid or invalid. Rather, I asked questions that directed their attention to the decisions they had made or were struggling to make to bring to the forefront their thinking. Students experienced a great deal of the frustration, enjoyment, success, and uncertainty inherent in doing science.

At the end of this extensive inquiry experience, I told students to presume I was the editor for a research journal, and each research team was to submit to my journal a paper regarding their work. I provided students the requirements for publication that are found in typical research journals. After their research papers were turned in, I reminded students to complete their personal journal entries regarding their work and bring those to the class the following day. That night I reviewed their research journal submissions and made comments regarding the clarity of their writing and reasoning for their conclusions. The following day I began by having students individually review their personal journals for approximately 5 min and then get together with their research team and share with each other entries of their choosing. After 10 min of sharing, I then returned their submitted research journal papers with my comments and asked questions like the following:

- How is the description of your work appearing in your personal journals different from what appeared in your submitted scientific paper?
- How is the work described in your personal journals similar to what appeared in your submitted scientific paper?
- What accounts for these differences and similarities? What do other scientists need to know and want to know about your research work? What is likely not important to them? Given all this, what are the purposes of scientific papers?
- How does your submitted scientific paper compare with the "scientific method" that is commonly taught in science classes? How does this compare to your actual work?
- What subjective factors appear in your personal journal entries that do not appear in your scientific papers?
- Given the many subjective factors that you note appear in your personal journals, how were these subjective factors reduced? How was confidence in your work eventually achieved?
- In what sense do the work, data, and conclusion appearing in your submitted scientific paper come across as objective knowledge? In what sense is your final thinking far less subjective, yet not totally objective?

I ask many more questions to draw students' attention to other NOS issues in Table 15.1 that are linked to private and public science. Knowing that students may be skeptical regarding how their work compares to the actual work of scientists (Clough 2006), I then had students read "Is The Scientific Paper a Fraud?" (Medawar 1963). Medawar, a co-recipient of the 1960 Nobel Prize in Physiology/Medicine, argued that scientific papers sanitize (by omission rather than deliberate design) how science research actually works, making it appear to be a fairly straightforward inductive and objective process. How private science compares to public science can be further emphasized by showing portions of the *Mechanical Universe and Beyond* program that presents Robert Millikan's oil drop experimental work, data, and efforts to make sense of those data (https://archive.org/details/The_Mechanical_Universe_and_Beyond_12_The_Millikan_Experiment). This and many other examples (e.g., Watson's (1969) *The Double Helix*) are useful for convincing students how private science differs from public science, but how subjective factors in private science are mitigated as research is shared with and evaluated by the wider scientific community. Finally, asking the following kinds of questions is important to help students think about how science journal articles serve a different purpose than conveying all that goes into private work of scientists.

- What information do scientists want to see in research published in journals? Why is that information crucial?
- What information do scientists unlikely want to see in published journal articles? Why is that the case?
- What purpose do science research publications serve and what purpose do they not serve?

Framing and teaching the NOS in this manner promotes a deeper understanding of scientists' work that would assist in more accurately interpreting socio-scientific issues such as the unfortunate climategate public controversy (Allchin 2011).

How are basic science, applied science, engineering, and technology similar and different? How do they impact one another and how does this illustrate that all are needed?

Careful and overt attention to the characteristics of basic science, applied science, engineering, technology, and their interactions is necessary for understanding how each is important and deserving of funding. To engage students in the questions above, I first provided them a brief description and rationale for nine research projects that I selected. Unbeknownst to students, three of the nine were basic science research projects, three were applied science research projects, and three were engineering research projects. The nine projects appeared in no particular order. I instructed students to carefully consider each research project and prioritize them from most deserving to least deserving of public funding. I then asked them to decide what percent of the total available funds should be directed to each project. Unsurprisingly, most students prioritized the three engineering research efforts to create technologies, followed by the applied science research projects, and the basic science projects last. When asked to explain their preferences for funding, students overwhelmingly argue that the projects they rank most worthy of funding will likely improve human life while the research efforts ranked at the bottom have no practical utility. Students' allotment of funds followed this same trend, and many students refused to provide any funding to what they would later learn is called basic or fundamental research. Students' thinking conveys that they value engineering and applied science, but not basic science.

I then had students read a newspaper article (Bednarek 1993) showing how a particular research project they had strongly supported was dependent upon the research projects that they claimed were a waste of money. After students completed this reading, I asked questions such as:

- Had the research projects you claimed were a waste of public money not been supported in the past, how would that have impacted the research projects you now wish to fund?
- If we were to place the nine research projects into three groups, which projects would be grouped together? Comparing your three groupings, what is different in what they seek to accomplish? What is similar in what they seek to accomplish?

When I have taught this lesson more recently, at this point I show a portion of an interview with astrophysicist Neil deGrasse Tyson (2011) where he addresses what science seeks to accomplish and how basic science research impacts technological development in ways that cannot be anticipated. In the interview, he states:

> This notion that science is the path to solve your problems; I think that misrepresents what drives scientists. Do you think when you speak with Brian Green he's going to say, "I am trying to come up with a coherent understanding of the nature of reality so that I can solve people's problems?" Do you think that's what driving him? Do you think I'm being driven when I look at the early universe or study the rotation of galaxies or the consumption of matter by black holes, do you think I'm being driven by the lessening of the suffering of people on Earth? Most research on the frontier of science is not driven by that goal—period! Now, that being said, most of the greatest applications of science that *do* improve the human condition *come* from just that kind of research. Therein is the intellectual link that needs to be established in an elective democracy where tax-based monies pay for the research on the frontier. …The purpose of science is to understand the natural world. And the natural world has, interestingly enough, built within it forces and phenomena and materials that a whole other round of clever people—engineers, in the case of the magnetic resonance imager—these are biomedical engineers basing their patents and their machine principles on physics discovered by a physicist, an astrophysicist at that. So I take issue with the assumption that science is simply to make life better. Science is to understand the world. Now you have a utility belt of understanding. Now you access your tools out of that, and use those, that ever increasing assortment of power over nature, to use that power in the greater good of our species. You need it all.

I then provide three historical examples (i.e., Manhattan project, Race to the Moon, and the War on Cancer) illustrating the role that knowledge gained from basic science plays in engineering efforts and vice versa. I emphasize that building an atomic bomb and landing a human on the Moon were both accomplished within a decade because the fundamental knowledge of nature necessary for accomplishing those two ends was already in hand. In contrast, when United States President Richard Nixon in 1971 declared a war on cancer, such knowledge was not available, and the effort to cure cancer, while making progress, continues today. I then return to the three groupings put forward by students and label them "Basic Science," "Applied Science," and "Engineering." The table appearing in Fig. 15.1 is presented to students, and they are instructed to think about each empty box as they read articles like the following.

- Feynman, R.P. (1955). The Value of Science. In Feynman, R.P. (1988) *What Do You Care What Other People Think?* New York: Norton.
- Medawar, P.B. (1973a). The Cost-Benefit Analysis of Pure Research. In Medawar, P.B. (1990) *The Threat and the Glory: Reflections on Science and Scientists*. New York: HarperCollins.
- Medawar, P.B. (1973b). The Pure Science. In Medawar, P.B. (1990) *The Threat and the Glory: Reflections on Science and Scientists*. New York: HarperCollins.
- National Institute of Health (2017). Curiosity creates cures: The value and impact of basic research. https://www.nigms.nih.gov/Education/Documents/curiosity.pdf
- National Institute of Health (2011). Why do basic research? https://publications.nigms.nih.gov/basicresearch/

Together as a class, we begin the process of filling in each blank box appearing in Fig. 15.1. Students will at times suggest simplistic answers, so additional questions that play off students' suggestions are required throughout the process to tease out important nuances. Through this process, something like what appears in Fig. 15.2 results.

What appears above reflects an initial effort exploring with students the questions regarding how basic science, applied science, and engineering are similar, different, and mutually dependent upon one another. These questions are revisited in a variety of contexts during the school year along with issues regarding the nature of technology (Clough et al. 2013). Again, framing and teaching the NOS as questions encourages a richer understanding of issues that is important in personal and societal decision-making.

	Goal/Product:	**Undertaken to:**	**Direction affected by:**	**Affects:**
Basic Science				
Applied Science				
Engineering				

Fig. 15.1 Characteristics of basic science, applied science, and engineering

	Goal/Product:	Undertaken to:	Direction affected by:	Affects:
Basic Science	Knowledge about the natural world	Understand the natural world. Satisfy curiosity.	Scientists' curiosity. Questions scientists find most important.	Basic science Applied science Engineering Society
Applied Science	Knowledge about the natural world.	Understand the natural world and apply to a perceived technological need. Satisfy curiosity.	Perceived relation to a technological outcome. Society, industry, defense, government.	Basic science Applied science Engineering Society
Engineering	Technology (Artifacts and processes as well as knowledge regarding their development)	Develop products & procedures that are useful in society/ business /military. Satisfy curiosity.	Desires of business, society, defense, & government.	Basic science Applied science Engineering Society

Fig. 15.2 Characteristics of basic science, applied science, and engineering

15.4 Standards as Cues for Teaching and Learning

The NOS questions appearing in Table 15.1 strike an important balance in NOS instruction efforts. Because NOS tenets put forth comprehensive claims that ignore context, nuance, and complexity, they are problematic at best. And NOS tenets may easily be interpreted by teachers, few who have sufficient NOS understanding, as expected learning outcomes. Thus, in seeking to correct common NOS misconceptions, NOS tenets run the risk of creating different and perhaps more dangerous misconceptions regarding science and scientists. Earlier in this chapter I noted the mistaken view that easily follows from teaching that science is tentative and how this can fuel disregard for well-established science ideas important in socio-scientific decision-making. The same can be said regarding the NOS tenet emphasizing subjectivity. Other common NOS tenets appearing in the science education literature compromise an accurate and robust understanding of NOS that can and should promote more informed personal and societal decision-making.

Of course, vague and wildly open-ended NOS questions would also be problematic. Research has made abundantly clear that science teachers and their students possess inaccurate and incomplete NOS understanding. Proponents of NOS tenets rightfully argue that teachers and students need guidance regarding the NOS. The NOS questions appearing in Table 15.1 are designed to be educative! They assist teachers and students by (1) delineating important NOS issues and ideas; (2) drawing attention to more informed ways of thinking about the NOS; and (3) raising exceptions and nuances. For instance, while the second question in the table overtly casts doubt on a universal step-by-step scientific method, it is immediately followed by a question that addresses how scientists *are* guided in their work. On inspection, the questions appearing after each bullet point in Table 15.1 purposely raise an important NOS idea/issue, provide guidance in thinking about that idea/issue, and cue attention to thinking, arguments, and reasoned responses.

Thus, framing the teaching and learning of NOS as questions is not merely a personal preference regarding semantics. Standards are a kind of technology in that they are a manufactured artifact designed to accomplish a particular end. Like all technologies, inherent in their design are cues on how they should be used. Kruse (2013) notes that

> the claw end of a hammer can be used as a flat-bladed screwdriver, but the very design of a hammer sends clear messages that it *should* be used to strike something. …although textbooks can be used as a valuable tool in classrooms, the bolded words cue students (and teachers) to place emphasis on vocabulary acquisition over deep conceptual understanding.

In the same way, the simplified nature and structure of NOS tenets cue teachers and students to particular declarative claims rather than reasoned positions and deep understanding that take into account context and complexity. Like with much schooling, a *training* often ensues rather than an *education* (Eisner 2002), and more harmful NOS misconceptions may result. Framing NOS instruction in terms of questions like those appearing in Table 15.1 sends different cues that would assist in efforts to promote NOS understanding that can be flexibly used to make more informed personal and socio-scientific decisions.

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