Understanding how science works: the nature of science as the foundation for science teaching and learning

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ABSTRACT The nature of science (NOS) is a phrase used to represent the rules of the game of science. Arguably, NOS is the most important content issue in science instruction because it helps students understand the way in which knowledge is generated and validated within the scientific enterprise. This article offers a proposal for the elements of NOS that should inform classroom science teaching and learning, including the distinction between law and theory, the shared methods of science, the role of creativity and subjectivity, the idea that scientific knowledge is tentative, long-lasting and self-correcting and the important reality that science has limits.

The history of science curriculum development reveals countless suggestions for the facts and principles that students should learn to gain an appreciation of the scientific enterprise. Often, these encyclopaedic proposals for content are joined by recommendations that students should have opportunities to engage in the 'doing' of science (i.e. enquiry instruction) and other calls that students must also understand the implications of those discoveries on society (i.e. socio-scientific decision-making). It is clear that science instruction should feature a combination of process and product.

Accompanying these important trends in the field of science teaching and learning are increasing thoughts that perhaps the most essential element to include in science instruction is the nature of science (NOS). As we will see, NOS is a distinct kind of science process and product. Even though there remains some discussion about what this domain of knowledge should be called (i.e. nature of science studies, history and philosophy of science, ideas-about-science, nature of sciences, nature of scientific knowledge, etc.), there is little doubt that having students understand how this discipline functions is vital. While useful distinctions are made between each of the various labels mentioned, it is probably best to continue to use the traditional name 'NOS' to represent the broad issues related to an understanding of the rules of the 'game' of science, its tools, products and methods as they apply in educational settings. In short, we are talking about an understanding of science as a way of knowing, but simply making such a statement is most certainly not enough to guide learning, curriculum development or even the discussion found here. As shall be seen, it is necessary to agree on what elements of NOS we want instructors to weave into science lessons and students to understand.

To set the stage, we must recognise that, for more than a hundred years, countless studies and expert opinion (Central Association of Science and Mathematics Teachers, 1907; Lederman, 1992; McComas, 1998; Matthews, 2014) have demonstrated the importance of including elements of NOS in school science programmes. This foundational understanding is just as important as 'traditional science content', such as lessons about the phases of the Moon, the products and reactants in chemical reactions, and Newton's laws of motion. In fact, NOS is so vital that even making a distinction between 'traditional science content' and an understanding of the rules and products of the game of science that characterise NOS seems odd to those who have considered the relative merits of classroom science content. Yet many educators do make the distinction between NOS and other science content – and in doing so fail to provide students with opportunities to learn the rules, products and limitations of the game of science.

Many who have examined the importance of NOS in the curriculum would agree with Driver, Leach, Millar and Scott (1996), who suggested that NOS provides students with the foundation to understand how science is done and engage in it themselves, shifting the emphasis from simply learning about science to doing and understanding science. Their rationales for NOS in school science include five conclusions about its importance:

- **Utilitarian:** NOS is necessary to make sense of science and technological objects and processes in everyday life.
- **Democratic:** NOS is necessary for informed decision-making on socio-scientific issues.
- **Cultural:** NOS is necessary to appreciate the value of science as part of contemporary culture.
- **Moral:** NOS helps develop an understanding of the norms of the scientific community that embody moral commitments that are of general value to society.
- **Science learning:** NOS facilitates the learning of science subject matter.

With these NOS rationales in mind, it would be hard to imagine a compelling argument against the inclusion of goals and practices that enable students to understand how science works, appreciate how science knowledge is created and validated, explore how scientists do what they do and distinguish science from non-science. This is very timely content. In various nations, it has recently become clear that large numbers of individuals fail to distinguish between news and 'fake news', facts and 'alternative facts'. Understanding how knowledge is generated and validated in science can help. There has never been a more crucial time for students – on their road to becoming reflective citizens – to understand how science functions. This understanding, in turn, will enable our future citizens to evaluate and judge science knowledge claims and act appropriately. It is vital that citizens recognise that the results of science are essentially neutral and apolitical. This is true even in this current political situation in which many want either to ignore the findings of science, criticise its methods or simply to believe that one can choose or not to accept widely shared conclusions and recommendations. At this time, how ironic it is to note that the author of *Brave New World*, Aldous Huxley (1927), said, '*facts do not cease to exist because they are ignored*'. He could have offered this view yesterday! He would likely agree with those who state that there is no time like the present to do whatever is necessary to help students understand knowledge generation and validation in science.

What we know about NOS in schools: a quick review

We are aware that most students and teachers don't know much about science as a *way of knowing*. However, before turning our attention to other kinds of misunderstanding worthy of discussion, it is useful to share the following conclusions that have been revealed by six decades of NOS research regarding what teachers and students think about NOS. There are hundreds of references that could be cited, but the following summary by Lederman (2007) does an excellent job outlining the situation while identifying some of the challenges with respect to NOS in science instruction:

- pre-university students do not typically possess 'adequate' conceptions of NOS;
- pre-university teachers do not typically possess 'adequate' conceptions of NOS;
- conceptions of NOS are best learned through explicit, reflective instruction as opposed to implicitly through experiences with simply 'doing' science;
- teachers' conceptions of NOS are not automatically and necessarily translated into classroom practice;
- teachers often do not regard NOS as an instructional outcome of equal status with that of 'traditional' subject-matter outcomes.

These statements, which come from a review of the science education literature, point out many of the challenges associated with the incorporation of NOS into plans for science learning. I would add to this list that we also do not have a firm notion of how to teach NOS but a few thoughts about that issue will be forthcoming. What we do know, however, is what aspects of NOS should be the focus of instruction in the school science arena. As will be pointed out, these NOS learning goals come from a consensus of the science education community and generally may be grouped into these broad categories: how science generates knowledge (i.e. the philosophical processes that are acceptable within the practice of science) and the philosophical products of science (i.e. the idea that laws and theories are related but not the same).

Considering a consensus view of NOS for school science purposes

When making decisions about what to include in school science, it is vital to consider a multitude of issues, including the readiness of students to learn at a given age, how packed the curriculum is with other content, how particular content might be supported by packaging it with other content, and so on. For instance, at some point, biology educators decided that students should learn about photosynthesis (for good reason, I might add). Hence, life science and biology books are filled with descriptions of photosynthesis that are typically first qualitative (carbon dioxide is taken into plants during the day and is transformed into oxygen through chemical processes resident in chlorophyll). Later, those descriptions become much more mechanistic and quantitative as the structure of chloroplasts and the chemical reactions are added to the discussion. Ultimately, we hope that students learn about photosynthesis and, as a result, understand and perhaps even value the roles of plants in the environment. Countless decisions and discussions have resulted in the biology curriculum that we have today. Clearly, we have reached consensus regarding the inclusion of photosynthesis as a worthy goal of instruction.

Not surprisingly, this process has also occurred in NOS studies. Since the advent of advocacy for the inclusion of NOS in the science curriculum, many proposals have been offered for what elements of NOS we should teach. Lederman (1992, 1998), Lederman and Lederman (2004), McComas (1998, 2004, 2008), Osborne *et al*. (2003), and others, have all provided quite similar recommendations for robust sets of elements regarding what should be the NOS focus in school science. These are sometimes called the 'key NOS aspects', 'general NOS aspects' or the 'NOS consensus view'. In a study comparing various definitions of NOS in school science, Al-Shamrani (2008) found large degrees of overlap. That realisation, coupled with the similar recommendations for NOS goals found in the *Next Generation Science Standards* (NGSS Lead States, 2013), suggests that most in science education are no longer questioning what we should teach about NOS. There is no clear advantage of one set of NOS aspects over another but a widely-shared consensus proposal of such elements is provided here as Figure 1. In this set of recommendations, related issues (sub-elements) are found together so, for instance,

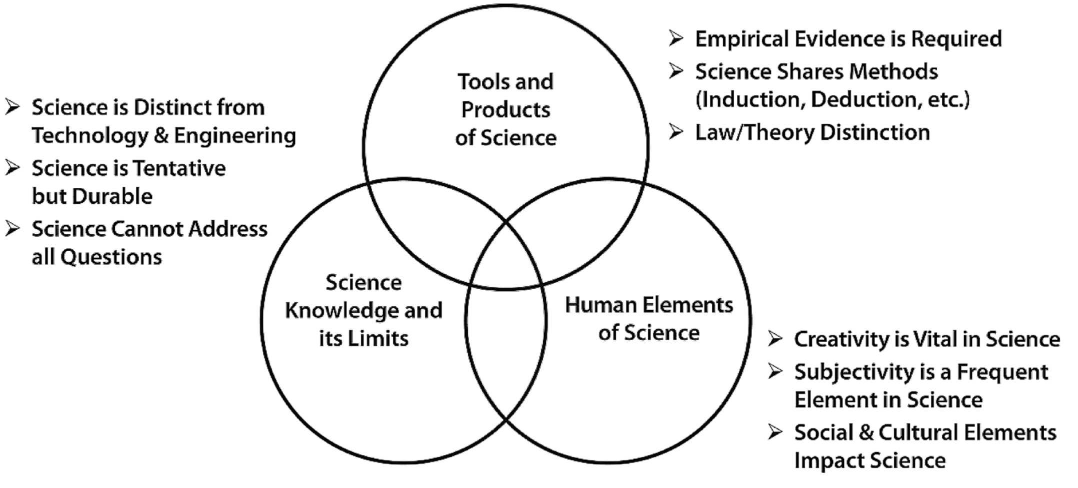

Figure 1 One consensus view of the major aspects of NOS that should be included in science instruction, arranged in three clusters with related sub-elements; reproduced from McComas (2015a) based on McComas (2008) and generally reflected in the US *Next Generation Science Standards* (NGSS Lead States, 2013)

those NOS issues that are related to what are called the '*Tools and Products of Science*' are shown near that circle. The same is true for the sub-elements associated with the other two larger NOS domains.

It is true that a few contributors to the literature of education question whether a set of statements about knowledge generation in science can even be produced (van Dijk, 2011, 2012) and others (Erduran and Dagher, 2014) have offered an alternative to the dominant consensus view. However, the vast majority who support the enhancement of science teaching and learning are ready to put recommendations into action. We have moved on from general NOS advocacy and have agreed on NOS learning goals. Thus, the new focus should be on how to teach and assess NOS for the variety of audiences in the school science realm. Given the attacks on science, which seem to be born out of politics and misunderstanding, perhaps there has never been a more opportune and vital moment to do just that.

What should all citizens understand about the nature of science?

The debate regarding what to teach about NOS in school science settings has been productive in two ways. First, the challenges to the consensus have caused a reconsideration of our assumptions and positions; this is always a healthy ingredient in high-quality scholarship. Second, those of us who have embraced and even added to the consensus list should be heartened that we have it 'right' – at least as correct as those who have defined the science content in biology, chemistry and physics texts. Yet we realise that this is a fluid conversation and new knowledge from the fields of history, philosophy and sociology of science will cause us to reconsider current recommendations. After all, just a generation ago, many were describing science (quite inaccurately) in positivist terms. Therefore, let us end with a quick examination of one of the consensus lists that shares a wide number of features with those offered by others. Please recognise that these descriptions are necessarily brief here but more detail can be found in a variety of sources (e.g. McComas, 2004, 2015b).

In Figure 1, the suggestions for what we should be teaching about NOS in school science settings are clustered in three domains of related sub-elements designed to cover the landscape of important but introductory NOS notions. As stated earlier, this 'list' was never designed to be given to students and memorised; rather, it is a set of benchmarks for teachers, curriculum developers and assessment experts. The first cluster of related NOS ideas is called the '*Tools and Products of Science*'. This domain contains the related ideas of empiricism, the law/theory distinction and the notion of shared methods in science. The first idea is basic: scientific conclusions are based on evidence – an idea that even the youngest learners seem able to appreciate. Next, readers will note a very important tool and product of science, the notion of the roles and nature of laws and theories. Entire books could be written on either of these notions but, in their most basic form, laws are the generalisations or principles (i.e. Newton's law of gravity), while theories are the explanations (i.e. the germ theory of disease) for laws. Many individuals believe in a hierarchical view of laws and theories and falsely think that, with time, a good theory will turn into a law. That misconception is pernicious and potentially damaging, particularly when some use it to reject important scientific ideas such as evolution by declaring them 'only theories'. Finally, this domain includes the idea of shared methods in science as a tool of science. This is a large sub-element and involves issues such as induction and deduction, inference and observation, and all the other commonly accepted ways that scientists collect and analyse data to reach conclusions. Even though there are shared methods, there is no one step-by-step approach that all scientists use; this is a common misconception in the USA and perhaps elsewhere.

In the domain of '*Human Elements of Science*', educators will encounter recommendations that students should come to understand that many aspects of science are as creative as those in the arts (i.e. the selection of problems and methods of investigation) and that subjectivity and bias are inherent in the fact that humans are the ones engaged in science. This idea of bias is often seen as negative. To be sure, sometimes when scientists 'see' only what they 'want' to see, important evidence or findings may well be missed. At the same time, however, the experiences that scientists have after years of work in a field can help them move more quickly to potentially fruitful avenues of research. Finally, this domain contains the idea that social and cultural forces guide the direction of investigations in science, particularly in nations that actively fund research. Many students believe that scientists work on what is of most interest or importance. In reality, much research is encouraged and discouraged primarily by the lines of funding available to support it. In the USA, recently, some administrations supported stem cell research with funding while others cut funding so dramatically that such research slowed considerably. Students must understand that scientific work occurs within a socio-cultural context.

The last domain, '*Science Knowledge and its Limits*', includes the vital notion that there are limits imposed by the rules of science itself as to what science can investigate and speak about with authority. Here, too, we see the often-misunderstood notion that scientific conclusions are long-lasting but ultimately tentative. This idea introduces students to the reality that we can never prove anything in science and that any conclusions reached are liable, but not likely, to be replaced when more evidence demands that science paint a different picture. Finally, one idea that is rarely mentioned in NOS recommendations is the distinction between science and engineering/technology. Many in the science education community have adopted a preference for STEM (science, technology, engineering and mathematics) as a reference for best practices in teaching, and new standards documents across the globe frequently embrace such a view. Certainly, these four areas of inquiry work together, but it is very important that students understand how each contributes and how each is distinct philosophically and in practice from the others. The *Next Generation Science Standards* (NGSS Lead States, 2013) include practices in science and engineering in lists on the same page, potentially leading to two unfortunate conclusions: that science has a stepwise method and so does engineering, and that science and engineering are essentially the same. Of course, neither is a valid conclusion. Thus, it is vital in the STEM education world in which we live that distinctions between the disciplines of science and engineering are clarified for students.

Teaching the nature of science

It will likely be frustrating to note that I end this article with only a brief set of suggestions on what is a highly important aspect of NOS in science instruction, but the fullest account might occupy a book. Certainly, the most important hurdles have now been crossed: we have strong rationales for the inclusion of NOS in the classroom and equally robust and thoughtful suggestions for what must be taught in this domain. In addition, we are beginning to see science standards documents more frequently including guidelines for what to teach about the nature of science. With those thoughts in mind, I will offer some thoughts about NOS instruction.

First, let us begin with a firm rejection of a common mischaracterisation of the 'list' of suggestions regarding NOS content. The list as it is commonly illustrated (Figure 1) is often just a shorthand way of showing the important ideas; much more detail about the meaning of the labels is often contained elsewhere by those offering such lists. No matter what set of NOS principles one adopts to guide science teaching and learning, there is no implication that it simply be memorised by students as if doing so would satisfy the wide range of important NOS understanding that we collectively support. Rather, these sets of recommendations must be unpacked and understood by instructors, and transformed into the basis of material in textbooks, standards, classroom lessons and assessment. Also, we need much more work on the development of engaging and NOS-accurate curriculum projects that will translate these learning goals into classroom practice.

Second, the implication is clear that if any of the interesting and important philosophical notions related to the practices of science are to be included in the classroom, teachers must both embrace and understand for themselves NOS content. This is easier said than done because most teacher education programmes offer little in specifics of NOS and its instructional methods. Likewise, the courses that gave teachers their knowledge of the facts and principles of science likely failed to share any of the detail provided about how knowledge is generated and tested. It would be unfair to suggest that teachers have no understanding about the NOS domain, but studies have shown that teachers may know far less than they do about the traditional science content they teach. In recent years, increasing numbers of teacher education programmes include extensive NOS content or even an entire semester (approximately

14 weeks) of instruction and conversation about the nature of science. This trend must increase because only NOS-knowledgeable teachers can provide effective and interesting NOS learning experiences for students. Another trend that must accelerate is the treatment of NOS in textbooks, with a strong recommendation that this content not be relegated only to the first chapter of the book as is often the case.

Students must have opportunities to learn about NOS in every science discipline or topic they are studying. The strong conclusion from research studies is that it is best if students encounter NOS in context related to traditional science content. Furthermore, it is vital that students encounter NOS explicitly. It is not possible for students to learn 'how science works' by engaging in laboratory or some other practical activity, even though such environments provide incredible examples if pointed out explicitly by teachers. We also know that learners frequently fail to see NOS in traditional science content – such as the dual nature of evolution as a natural principle on one hand and its theoretical mechanism of natural selection on the other. In a classroom of attentive NOS biology teachers, no student would ever say that 'evolution is just a theory'. That statement simply makes no sense to anyone with a firm understanding of the nature of science. To conclude, aspects of NOS must be taught explicitly, must be found across the science curriculum, must be facilitated by knowledgeable teachers and must have equal status with the usual science content. In fact, blending NOS content with traditional science content may be the best way to include these important ideas in an already-packed science curriculum.

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