Beyond the Consensus View: Whole Science

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Abstract. The "consensus view" nature of science (NOS) is now outmoded. To help frame an enduring alternative, one should attend first to the "why" of NOS education. Functional, or civic, scientific literacy is foundational. Acknowledging a need for consumers and citizens to assess the reliability of scientific claims in personal and public decision-making leads to an expansive, open-ended and inclusive list of contextualized NOS elements--experimental, conceptual, and social--known as Whole Science. Any enduring reform also needs to consider practicalities, such as the challenge of assessment, the inevitable role of epistemic dependence (and lessons about expertise, trust, and science con-artists), NOS education beyond the classroom, and the development of concrete lessons based on inquiry learning.

Ironically, the “consensus view” about the nature of science (NOS) no longer enjoys consensus. Criticisms have come from all quarters (Allchin, 2011, 2013; Clough, 2007; Deng, Chen, Tsai, & Tsai, 2011; Elby & Hammer, 2001; Erduran & Dagher, 2014; Rudge & Howe, 2013; Rudolph, 2000; Settlage, Southerland, Johnston, & Sowell, 2005; van Eijck, Hsu, & Roth, 2009). In addition, as Hodson and Wong observe, there are many ambiguities in that characterization, including the unresolved tension between tentativeness and durability, the relationship between knowledge (product) and inquiry (process), the contextuality of an observation/inference distinction, the relevance of law versus theory terminology, the internal versus external nature of the social and cultural embeddedness of science and, finally, the context-dependence of many supposedly domain-general features of the nature of science (2016, pp. 5-14/XX-XX). They justly claim that “It is time to move on, time to replace or enrich the so-called consensus view of NOS with a philosophically more sophisticated approach and with more authentic views of contemporary scientific practice” (p. 14/XX).

However, before plunging ahead, one might want to step back. Assess the big picture. Why did the consensus view fail? Historically, why did dissensus emerge? Most important, perhaps, what role does nature of science have in science education, and how does that affect what we aim to teach?

One of the chief flaws of the “consensus view” is, ironically again, that it was only ever based on consensus. That is, NOS education was widely adopted without a clear reason or justification. It was just what everyone seemed to agree at the time was important (Osborne et al., 2003). An informal compromise of pragmatic and political considerations. No systematic, well articulated view of science education seemed to inform which particular aspects of NOS were included, which excluded. Lest we replace one flawed set of principles with another, we should review the foundational guiding principles. Hodson (2008) provides a valuable overview (pp. 1-40). Educationally, our first question should be not “*what* NOS?”, but rather “*why* NOS?” The “why” critically informs the “what.” This then leads to other fundamental “*how*” questions about evaluation and teaching methods.

Why NOS?

Curricular visions for science education have become more explicit and detailed over the past two decades. One rationale is certainly to understand “science as a way of knowing” (Hodson, 2008, p. 11) — a “cultural scientific literacy” (Hodson & Wong, 2016, p. 13/XX). Namely, how does science contribute distinctively to human understanding by drawing on empirical investigations and material evidence? Here, one might celebrate how modern medicine — germ theory, genetics, nutrition — has displaced naive perspectives of the supernatural; or how the periodic table has revealed a fruitful order to matter not immediately obvious from experience with common materials like air and water. How does science, or *scientific practice,* achieve these great insights? A humanistic understanding—or, more properly, an aesthetic *appreciation*—of science is undoubtedly enriching.

However, most international science education standards now focus chiefly on functional, or civic, scientific literacy (Allchin, 2013; Hodson, 2008, pp. 11-16, 34-39; Hodson & Wong, 2016, p. 13/XX; Kolstø, 2001; Rudolph, 2000; Ryder, 2001; Toumey et al., 2010). Namely, how do we prepare consumers and citizens for a world that is increasingly shaped by science and by sometimes-controversial scientific claims? In this role, nature of science is found under a variety of different labels: “scientific practices” (U.S.; NGSS, 2013); “ideas about science” (U.K.); “identity and methods” of the discipline (Denmark); or more plainly, “how science works” (E.U.). All promote an understanding of the process of science with respect to the claims that it makes.

Thus, Hodson (2008) has endorsed the view of the U. S. National Research Council:

> A literate citizen should be able to evaluate the quality of scientific information

> on the basis of its source and the methods used to generate it. Scientific literacy also implies the capacity to pose and evaluate arguments based on evidence and to apply conclusions from such arguments appropriately. (p. 35)

In other words:

> *Students should develop a broad understanding of how science works to interpret the reliability of scientific claims in personal and public decision making.* (Allchin, 2013, p. 4)

To make this more concrete and vivid, consider the following examples:

- With the emergence of the zika virus, what factors determine the risk to various individuals? Can sufficient funding provide rapid solutions to avert the apparent urgency of an impending crisis?
- What claims about the environmental and human safety of development projects, such as new dams and mines, can be accepted as reliable?
- Can government policy affecting deforestation in the Amazon foster drought in other regions in Brazil?
- Are informal traditional remedies effective, and how would we know for sure?

No one person can amass all the raw conceptual knowledge to make informative, expert decisions about these and other critical issues. Rather, the diversity invites a solid understanding of how science works to produce the claims, and what factors are important in evaluating their trustworthiness.

Ideally, then, students will learn about a broad spectrum of practices across the experimental, conceptual, and social dimensions of science. Learning will include understanding potential errors due to non-standardized measurement or poorly calibrated instruments; contamination of samples; lack of relevant controls; inappropriate or misused statistical methods; overgeneralization of limited results; confirmation bias; gender bias; and political or economic conflict of interest in communicating science. All have become relevant in contemporary cases (Allchin, 2012d). Especially important is the seamless integration of social perspectives with standard internalist perspectives as part of a complete epistemic view (Allchin, 2001; Allchin, 2004; Kelly, Carlsen & Cunningham, 1993; Zemplén, 2009). Here, then, is a concrete and well contextualized basis for determining just how to broaden and enrich the scope of NOS-oriented curricula. Take as a guide any dimension of NOS relevant in authentic cases of science in society. Elsewhere, I have called this broadened view teaching about *Whole Science* (Allchin, 2011; 2013).

Hodson and Wong (2016), too, advocate "broadening and enriching the scope of NOS-oriented curricula." To move forwards effectively, we need a strategy to link our ultimate educational goals with proximal curricular goals in the classroom. In a Whole Science perspective, the range of contemporary cases — the context of NOS education — determines the scope of the epistemic knowledge required. In notable contrast to the narrow consensus view, the list of NOS elements is expansive, open-ended, and inclusive. Hodson and Wong echo this general approach. Still, it can be fruitful to be specific and concrete. Hence, science educators can benefit from compiling an inventory, or repertoire, of epistemic dimensions (Table 1, Allchin

2013, p. 24). Further, it is helpful for students and teachers alike to have a scheme for organizing, conceptualizing or categorizing, these multiple factors of reliability (Table 1). Following Latour's concept of networks (1987, pp. 177–257), I have rendered them as a rough series of transformations, from the original observations or measurements, through the production of graphs, statistical analyses and formal scientific papers, to the pronouncements that appear in newspapers, blogs, films, legislative testimony, television advertisements, and so forth. Each step in the chain of derivation—from test tubes to YouTube, from the lab bench to the judicial bench—requires justification, and each is a potential source of error to check (Allchin, 2004; 2012b). This is how science works, how we build and enact scientific knowledge. This is what consumers and citizens need to know to assess scientific claims in personal and public decision-making, especially with an eye to detecting misleading or mistaken conclusions.

Some may contend that the scope is too large and an open-ended NOS inventory too overwhelming and unmanageable. Hence, we should retreat to a more focused list of "core" features on which all can agree — namely, a "consensus list." But if we focus only on a small sample of pre-selected NOS features — as the consensus list currently does — we cannot fully prepare our students in the context of functional scientific literacy. Yes, selectivity may well be needed in practice. But there are different ways to be selective. Not all reduce to extracting a common universal list (Allchin, 2012d, pp. 696-698). For example, one may rely on sampling, just as scientists do. Thus, any concrete case, contemporary or historical, that renders the nature of science in its human and cultural, as well as investigative, contexts has the potential to inform students. Indeed, these are the cases and the features of NOS that matter, in contrast to the contrived "black-box" activities widely used in the classroom. These authentic cases exemplify, through analogy and generalization, how NOS analysis will matter in other cases, as well. We need only ensure that students are exposed to a wide spectrum of NOS dimensions—Whole Science—using the inventory and its categories (Table 1) as a guide.

If we teach general engagement in NOS issues, there does not need to be a single, limited list. Still, we need to prepare students to cope with the inevitable incompleteness of their NOS education. They need to learn how to address new NOS issues as they emerge. Hence, we need not only to teach NOS concepts. We need also to teach a posture of *NOS analysis*. Namely, students should ideally develop a habit of asking "how do we know this?" or "based on evidence and expertise, how can we have trust in this particular scientific claim?" Students will learn to delve into an epistemic analysis, using their structured experience with authentic cases. Rather than target declarative knowledge about features of NOS, we foster a population with skills and perspectives that enables them *to continue to learn* about NOS *beyond the classroom* (Allchin, 2013, pp. x-xi, 1-2, 41-44, 73-76, 153-155, 242-244).

A focus on epistemic skills in the context of functional scientific literacy ultimately upends conventional orientations to NOS and science education. There is a shift from an academic preoccupation with "what is science?" or defining science as a "thing," to a scientific *perspective* or *way of thinking*, embodied in a suite of competences, or skills. Hence, the question of demarcation, or of abstractly differentiating science from pseudoscience, largely loses its relevance as an educational aim. The demarcation project plagued philosophers of science for over half a century—with no clear resolution. The concept of falsification—still popular among practicing scientists and science teachers—is equally slippery (Allchin, 2013, pp. 5-12. Losee, 2001). It is time to set them aside, along with the consensus list. The goal is not to characterize science as a discrete enterprise, or even a vague one based on Wittgensteinian "family resemblances," or to describe a handful of diagnostic "features of science." In a Whole Science orientation, what matters for functional scientific literacy (the ultimate “why” of NOS) is not any formal definition of science, but the reliability of the claims. Hence, any “pseudoscientific” or other objectionable conclusion will inevitably exhibit some flaw in epistemic justification, even if framed in scientific terms. Advocates of Intelligent Design thus appeal to empirical evidence in a scientific way, but their reasoning is woefully incomplete. Their use of data is selective and biased—the ordinary scientific error of “cherry-picking” of evidence, which everyone should learn. Critics of climate change typically exhibit the same weakness, borrowing legitimate scientific claims piecemeal in unwarranted ways. Likewise, those who purport a link between the measles vaccine and autism *believe* that they are heeding good science by citing published scientific work. But the evidence for such a link was never very strong, and it is now clear that the original research publication was fraudulent, a result of an undisclosed conflict of interest. Similarly, most of the problematic cases that matter nowadays involve fraud, or deliberate misrepresentation, not naive pseudoscience. Students thus need to learn about science con-artists (Allchin, 2012a) and other forms of “bending” science towards political, ideological and commercial ends (Goldacre, 2010; McGarity & Wagner, 2008; Oreskes & Conway, 2010). This notably expands the dimensions of NOS into the realm of the public communication of science, the nature of scientific expertise and testimony, and trust and the credibility of sources in reporting, or purporting to represent, science. The time is ripe for concerns about pseudoscience to yield to broader lessons about expertise and credibility, con-artistry, fraud and misrepresentation in communicating science—key NOS dimensions in a Whole Science perspective that have also escaped inclusion in the narrow consensus list. Again, clarifying the goal of NOS education as active functional scientific literacy helps underscore the role of “understanding scientific practice” as a practical analytical skill, not an academic undertaking of definitions.

How to Assess NOS Understanding

In reassessing the status of NOS in education (yet again), our second set of questions should focus on teaching practice. Planning *what* to teach should be coupled with a clear and practically realizable sense of *how* to teach it. This includes, in our era of accountability, *how* the target knowledge or competences will be evaluated. If there is going to be yet another reform, let it not be utopian and impractical, and thus susceptible to yet more new calls for reform another decade or two hence. We should take the long view, as exemplified in Project 2061 of the American Association for the Advancement of Science (1995).

Thus, any educational view of NOS nowadays should be simultaneously expressed in concrete terms of assessment. How will teachers or educational researchers know that teaching NOS analytic skills has been effective? Any assessment should meet three basic criteria. Any test should, ideally, be *meaningful, authentic*, and *transparent* (Nightingale et al., 1996). That is:

> To be meaningful, tests should address knowledge relevant to the ordinary citizen and the kinds of personal and public decision-making cases that involve science. To be transparent, they should be explicit, and the standards clear and relatively concrete. To be authentic, they should reflect the kinds of complex, real-life situations where scientific and nature-of-science knowledge is used or applied. (Allchin 2013, p. 152).

In other words, the “why” of NOS education (reviewed above) should carry through into practice and should be explicitly addressed from the outset in terms of prospective forms of evaluation. Indeed, the “test” will implicitly define, *functionally*, what any particular conception of NOS ultimately means. What is the desired outcome, in terms of measurable student behavior? For a conception of NOS to be complete—and thus viable institutionally—the corresponding prospective assessment should be explicit.

This is a challenge yet to be addressed by many recent proposals to replace the consensus list and, with it, the VNOS instrument. For example, how does a teacher (or researcher) determine that a student knows that scientific knowledge is “constructed”? What does this mean in concrete terms of student performance? What competence is to be observed or measured? The same can be asked of the other features of NOS: how does a student demonstrate understanding, in an authentic context, that scientific claims are “tentative”? For example, does “tentative” mean contingent and fallible, uncertain (vague or underdetermined), or simply adopted with qualifications or probabilistic confidence? How does this knowledge uniquely shape student behavior? How is understanding of the difference among disciplines applied? How is this concretely meaningful in contemporary controversies? The same questions apply to variations in predictive and explanatory power, to appreciating various methodologies or the norms and ethos of scientists, or to having a “firm grasp of practice.” All these philosophical concepts, easily introduced in reform rhetoric, need to be operationalized to be taken seriously. Educational pragmatics matter, even in envisioning goals.

The view of Whole Science noted above has already been expressed in terms of prototype assessments (Allchin, 2011, 2012b, 2013, pp. 152-162). The format is a series of case analyses, each focusing on a contemporary case involving contested scientific claims. In keeping with the goals of NOS education, each question asks the student "to interpret the reliability of scientific claims in personal and public decision making." Each presents information available to typical citizens—from the news media, from the Internet, from advertisements, etc. (see also Korpan, Bisanz, & Bisanz, 1997). Each asks the student to provide a *well informed analysis* of the reliability of the claims, based on their "broad understanding of how science works." In other words, students perform a practical epistemic analysis: first, identifying various relevant NOS dimensions and then, describing how each shapes the trustworthiness of the claims at issue. In this way, an educator can assess the degree to which the student has progressed towards the ultimate goal of becoming scientifically literate (directly reflecting, again, the "why" of NOS). This alternative is open to criticism and development, of course. Other assessments may well accommodate our needs. But they need to be explicitly articulated and open to review, not left to a promissory note.

How to Teach NOS

Of course, coupled with a means for assessing NOS understanding is a need for methods to teach it effectively. Nowadays, in the wake of one failed reform after another, a full vision of NOS education must be considered incomplete without clarifying how the desired lessons are actually learned. Here, the challenge involves a dramatic and possibly difficult shift: from teaching declarative knowledge (the conventional—and easy—mode of instruction and multiple-choice exams) to teaching analytical skills.

What will such NOS lessons look like? Educators generally now agree that inquiry is ideal (Deng, Chen, Tsai, & Chai, 2011). By this, they mean that learning is student-centered and active. Students are engaged in their own learning, typically prompted by "discrepant events" or curious anomalies that challenge their former understanding and lead to exploration and cognitive reconstruction.[1] Namely, teachers cannot just list and describe the dimensions of NOS. NOS must be *problematized*. Students must engage in *NOS* questions, *NOS* reflection, and *NOS* problem-solving (such as the benchmark cases in the first section above). They must confront the various challenges of doing science, assess the reliability of claims, and work through their solutions. “How do we know this?” “What justifies our reasoning from the evidence?” “Are there other alternative conclusions possible?” “Do qualifications apply?” “How might we be in error?” In other words, the strategy is to immerse students in the epistemic problems of “science-in-the-making” (Flower, 1995; Latour, 1987). This is how they train to be lifelong NOS-learners.

However, inquiry as a general form of learning does not specify the context or occasion through which such inquiry is undertaken. Educators now generally recognize three such contexts for developing NOS understanding: student-directed investigations, contemporary cases, and historical cases (Allchin, Andersen & Nielsen, 2014; Clough, 2006). Student-directed investigation is often also referred to as “inquiry” as well, so one may easily conflate the *general learning method* (described above) and *activities* for students, where the relevant investigations are *specifically initiated and lead by the students themselves*. The goal here is not just to “do” science, but to think reflexively on and articulate the process. Not “cookbook” labs, but creative cuisine labs. From their own modest experiences “constructing” scientific knowledge, students are to generalize to the professional practice of science (Schwab, 1962). Student “inquiry” activity becomes a model for science, through an inquiry learning process. Such a strategy is

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[1] This may be distinguished from the largely ineffective “discovery” method, where students are left to learn wholly on their own in a largely unstructured environment. Inquiry, by contrast, is always structured and, to some extent, monitored and guided by the instructor.

now widely endorsed and adopted (Deng, Chen, Tsai, & Chai, 2011), as exemplified in the focus on “scientific practices” and inquiry in the new Next Generation Science Standards (2013) in the United States. Again, the focus is not “What is science?”, but “How does science work? What justifies its conclusions?”

Nevertheless, the wave of support for student-led activities and investigations does pose problems for a complete NOS education. The implicit goal in many initiatives is to train students *as scientists*. The imagined outcome is that when students attain “a firm grasp of practice,” they will be fully able to assess the evidence directly and make their own *scientific* judgments—about the zika virus, the safety of mines or dams or fracking, medical treatments, climate change, and so forth. Unfortunately, this grossly overstates the potential of NOS learning and science education. No individual—not even professional scientists themselves—can acquire enough expertise to make such judgments on their own across all fields of science. This requires specialized expertise, along with sufficient background knowledge and familiarity with particular types of errors. Inevitably, we all depend on (other) experts. We must confront the dilemma of *epistemic dependence* (Hardwig, 1991; Goldman, 1999). Understanding the basis for trust in science is essential. Most NOS education now completely overlooks how epistemic dependence affects the goal of scientific literacy (Norris 1995, 1997; Gaon & Norris, 2001). Accordingly, new NOS lessons must include problematizing and guiding reflection on the social nature of knowledge, expertise, testimony and credibility (for example, Zemplén, 2009, 2010). To guard against yet another failed science education reform, we must shape the “how” of our curricular goals to fit realistically with the “why” of NOS.

For a second way to contextualize NOS inquiry, one may turn, as Hodson and Wong (2016, pp. 20–21/XX–XX) aptly note, to contemporary cases (see also Wong et al., 2008; Wong, Wan, & Cheng, 2011). A focus on contemporary cases certainly resonates with the “why-NOS?” goal of informing current science policy and consumer choices. As recognized by Danish teachers, contemporary cases excel at raising motivation and awareness of the relevance of NOS issues. At the same time, there are also significant limits (Allchin, Andersen, & Nielsen, 2014, pp. 465–467, 472–474). Contemporary cases are not yet resolved, and so the appropriate epistemic solutions are unknown. The inquiry is *inherently* incomplete. In addition, students’ political and ideological perspectives can easily obscure intended lessons or, worse, reinforce negative lessons. Moreover, the critical details of scientific practice are often inaccessible in current cases—buried in technical literature, private e-mails or lab notebooks. Instructors must invest an inordinate amount of time in collecting what details are available, only to have those efforts become outdated in a few years. While contemporary cases are an indispensable part of NOS education—reflected in the common teacher habit of discussing cases in the news—one cannot rely on them exclusively.

The third form of contextualizing NOS inquiry is historical cases. At first, their value may seem paradoxical. Surely, accounts of scientific practice in the past can reveal important dimensions of the nature of science. “Authentic” or “real” science is hardly limited to just contemporary science. Yet the historical cases are closed. How can they promote open-ended inquiry style learning? Here, one must attend to transforming science of the past into “science-in-the-making” once again (Allchin, 2013, pp. 41–44). One must revive the historical perspective and reconstruct the once unsolved NOS problems for students today. Teachers simulate history in an open-ended inquiry context. Ironically, perhaps, it is cases form the past—with their long-term resolution—that allow students to appreciate and understand some of the key NOS dimensions today—such as the role of errors and conceptual change, and how cultural biases may shape scientific claims (Allchin, Andersen, & Nielsen, 2014, pp. 469–475). Retrospect matters. So, historical cases (in inquiry mode) seem just as important as contemporary cases and student-directed investigations for complete NOS education (Allchin, 2013; also see Allchin, 2012c, for discussion of some sample cases and the challenges of combining history and inquiry).

Hodson & Wong (2016, p. 21/XX) propose framing a newly revised NOS curriculum as "learning *about* scientists, learning *from* scientists, and learning *with* scientists." It is a catchy slogan, rolling easily off the tongue. Of course, learning *with* scientists is already included in the upper levels of university education. Can such work be meaningfully reoriented and effectively expanded to lower levels? Certainly, some adaptations have already proven effective (e.g., Crawford, 2012). But practicalities matter. Are there enough professional researchers, along with the requisite time and resources, to make this vision realistic for all at K-12 levels? Learning *from* scientists, a second strategy, is already adopted by many K-12 teachers. They are happy to invite student parent-scientists to visit the classroom, or use science television shows and videos—when they are available. That should continue, too. Finally, learning *about* scientists is an excellent way to frame science as a human endeavor in all three inquiry contexts noted above. In particular, a focus on scientists, not just practice, can remind students that in their own classroom investigations they might be scientists, too, just like their contemporary and historical counterparts in other lessons *doing* science (Hagen, Allchin, & Singer, 1996).

Ultimately, then, by attending to the "why" of NOS education—which critically helps shape the "what" of Whole Science understanding—along with the "hows" of NOS assessment and classroom lessons, one might forge a vision of enduring NOS education that not only reaches beyond the consensus view, but is practically realizable, as well.

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Table 1. Partial inventory of dimensions of reliability in science (Allchin, 2013, p. 24)

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Observational	*Observations and measurements*	Accuracy, precision
		Role of systematic study (versus anecdote)
		Completeness of evidence
		Robustness (agreement among different types of data)
	Experiments	Controlled experiment (one variable)
		Blind and double-blind studies
		Statistical analysis of error
		Replication and sample size
	Instruments	New instruments and their validation
		Models and model organisms
		Ethics of experimentation on human subjects
Conceptual	*Patterns of reasoning*	Evidential relevance (empiricism)
		Verifiable information versus values
		Role of probability in inference
		Alternative explanations
		Correlation versus causation
	Historical dimensions	Consilience with established evidence
		Role of analogy, interdisciplinary thinking
		Conceptual change
		Error and uncertainty
		Role of imagination and creative syntheses
	Human dimensions	Spectrum of motivations for doing science
		Spectrum of human personalities
		Confirmation bias/role of prior beliefs
		Emotional versus evidence-based perceptions of risk
Sociocultural	*Institutions*	Collaboration and competition among scientists
		Forms of persuasion
		Credibility
		Peer review and response to criticism
		Resolving disagreement
		Academic freedom
	Biases	Role of cultural beliefs (ideology, religion, nationality, etc.)
		Role of gender bias
		Role of racial or class bias
	Economics/funding	Sources of funding
		Personal conflict of interest
	Communication	Norms for handling scientific data
		Nature of graphs
		Credibility of various scientific journals and news media
		Fraud or other forms of misconduct
		Social responsibility of scientists