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Complementary Approaches to Teaching Nature of Science: Integrating Student Inquiry, Historical Cases, and Contemporary Cases in Classroom Practice

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ABSTRACT: Research has now demonstrated that students can learn nature of science concepts variously through student-led investigations, contemporary cases, and historical cases. Here we articulate more precisely the merits, deficits, and context of each approach and begin to profile how to integrate them as complementary methods. Emphasis now needs to shift to the needs of practicing teachers and the detailed strategies and modes of assessment that make each method effective and manageable in a classroom and institutional context. © 2014 Wiley Periodicals, Inc. *Sci Ed* **98:**461–486, 2014

INTRODUCTION

Many countries include in their science education standards a major role for teaching about the nature of science (NOS). Some refer to "scientific practices" (United States), "science as a way of knowing" (Organization for Economic Cooperation and Development [OECD]), or "identity and methods" of the discipline (Denmark). Generally, they address "ideas about science" (United Kingdom), or more plainly and descriptively, "how science works" (Andersen, 2008; Board on Science Education [BOSE] 2012; Evans & Jennings, 2008;

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OECD, 2009; see fuller discussion below). To meet this call, educational researchers generally recognize three basic approaches to NOS instruction: historical cases, contemporary cases, and student inquiry activities (Bell, 2007; Clough, 2006; Osborne, Collins, Ratcliffe, Millar, & Duschl, 2003). Our concern is the perspective of practicing teachers. More guidance about the contexts and relative efficacy of these approaches is needed (Boston Working Group, 2013). Here, we view the approaches as *complementary* and assess the particular *merits and deficits* of each. Equally important, we draw on teachers' classroom experience in a recent Danish program to interpret the practical challenge of integrating and balancing them, so as to capitalize on the strengths of each, while accommodating their respective weaknesses.

Our comments throughout are informed by the perspectives of roughly three dozen experienced upper secondary science teachers involved in short-term professional development programs in Denmark. The programs included 2 full days of presentations and reflections, each followed by classroom applications (designed by each teacher), and a final session for reflection and integration. While this was not a formal study, the comments based on the situated view of practicing teachers help contextualize the results of education research amid practical teaching decisions and thus indicate the tasks and challenges in moving from current research to the classroom. In addition, Danish teachers have a great deal of autonomy and a close rapport with students, so their judgments seem a good indicator of what can optimally be achieved in a classroom environment.

We present our analysis in four sections: first, we articulate how the context of scientific literacy, or science in the service of citizens and consumers, shapes a particular characterization of NOS for science education; second, as background, we survey the details of research on each of the three main approaches to NOS education and analyze the ways each succeeds and the ways each fails, and thereby establish the particular circumstances in which each may be considered effective; third, we sketch an example of how a pair of classroom teachers fruitfully integrated those approaches; and fourth, we indicate topics for further work.

THE CONTEXT FOR CHARACTERIZING NOS IN THE CLASSROOM

The primary purpose of incorporating NOS in a science curriculum is to help educate scientifically literate citizens to address complex scientific and technological problems in modern life and in a democratic culture (Andersen, 2008, p. 10; BOSE, 2012, p. 1; OECD, 2009, p. 128). The aims of science education, and thus of NOS topics, are firmly situated in the needs of citizens and consumers in addressing contemporary socioscientific issues (SSIs).

Still, there has been sustained debate about what knowledge and skills mark a scientifically literate individual (Hodson, 2009, pp. 1–22). Ryder (2001) addressed this challenge empirically. He examined 31 cases in which nonscientists interacted with scientific knowledge and/or scientists concerning SSIs. A viable concept of scientific literacy, he found, must meet utilitarian, democratic, and (to a lesser extent) social arguments for why people must know something about science. He called this *functional* scientific literacy. He categorized the necessary aspects of understanding science as subject matter knowledge, collecting and evaluating data, interpreting data, modeling, uncertainty in science, and science communication. Among other things he concluded, "some coverage of social and epistemological issues . . . would be appropriate at school age" (p. 39). Likewise, Toumey et al. (2010) focused on what enables citizens to engage in civic discourse on science and to make practical individual decisions: what they called science in the service of citizens and consumers (SSCC). They identified three major types of knowledge: factual scientific knowledge, knowledge about scientific processes and standards, and knowledge of how scientific institutions operate. The latter specifically included "peer review; the adjudication of scientific claims; the funding of scientific research; how science identifies and prioritizes emerging issues; how scientific advice is used; processes of making science policy; and so on" (p. 5). That is, large amounts of knowledge *about* science would be needed. That is, the aim of functional scientific literacy (or SSCC) forms the context for NOS education (see also Allchin, 2011; Gormally, Brickman, & Lutz, 2011; Kolstø, 2001; McClune & Jarman, 2010).

The central context of scientific literacy importantly guides an appropriate characterization of NOS. What features of NOS are most relevant? According to Ryder, individuals should, for example, "recognize that it is necessary to ask questions about the spread in a data set, the distinction between correlation and causation, time horizons, the assumptions within a model, and the funding sources of scientists" (2001, p. 37). Gormally et al. (2011) note also the need to evaluate the validity of sources and the use and misuse of scientific information. Allchin (2012c) comments on understanding a wide spectrum of sources of error, including gender, class, or cultural bias alongside instrumental calibration or absence of appropriate experimental controls. The emphasis on functional scientific literacy means that an effective view of NOS must be inclusive: an open-ended inventory of specific concepts relevant to interpreting contemporary SSIs. In particular, it emphasizes NOS aspects that relate to assessing the trustworthiness and reliability of scientific claims in a public setting.

This broad view contrasts notably with a widely familiar "consensus" view established in the late 1990s. According to this "consensus list," science is empirical, theory-laden, inferential, creative, tentative, socially embedded, and not exclusively experimental (McComas & Olson, 1998; also see Osborne et al., 2003 and recent defense by Abd-el-Khalick, 2012). Yet the notion that the relevant NOS features can be characterized as a brief and declarative list of tenets has been substantively questioned. Duschl and Grandy (2012), referring to a list of 11 "consensus aspects" of NOS taken from Niaz (2009), recently summarized this criticism. Among other things, consensus lists confuse epistemological, ontological, sociological, ethical, and philosophical features of science, and—by being general across many scientific domains—tend to inaccurately render actual scientific practices in specific domains and to distort historical depictions of science (pp. 2123–2124). Also, K. H. Nielsen (2012) has argued that consensus lists ignore the communicative aspects of science and the role played by language in the construction of knowledge. Particularly relevant to this paper are van Dijk's (2011, 2012) concerns that because consensus views ignore the heterogeneity of science and present a simplified and invalid portrayal of science, they may actually work against the aim of enhancing the public's functional scientific literacy.

As part of our professional development project, the consensus tenets were introduced to 20 Danish upper secondary school science teachers with little or no prior knowledge of NOS. After planning and testing activities on NOS in their own classrooms, the teachers indicated almost unanimously that they could not plan or implement NOS instruction structured around the NOS tenets. They did not find the tenets wrong. But in a classroom setting, they wanted a more concrete and detailed approach for teaching NOS. While they perceived the NOS tenets as informative, helping them to sharpen their own understanding of NOS, none regarded the "consensus list" operationally as an entry into NOS teaching. The teachers preferred to teach NOS in context. They wanted their students to acquire a more complex and contextualized understanding of NOS in relation to personal scientific inquiry or contemporary cases. Notably, the teachers in our program—our critical benchmark for the central perspective of practice—felt comfortable drawing from an open-ended inventory of specific NOS concepts, as expressed in their curriculum design work, summarized in Table 2 (see also Allchin, 2011, p. 525).

BACKGROUND: RESEARCH ON APPROACHES TO NOS EDUCATION

Educational researchers have invested considerable effort in assessing the efficacy of different modes of teaching NOS. Recently, Deng, Chen, Tsai, and Chai (2011) effectively reviewed much of this research with regard to different orientations to NOS (also see Hodson, 2009). We build on, but go beyond this valuable survey.

For example, as noted above, we focus on NOS primarily as it proves relevant to the ultimate goal of students' scientific literacy and their ability to tackle contemporary SSIs. Our comments thus bridge the original orientation of each study and our aims.

Research has already established several general principles for NOS education, which form an important foundation. For example, in a constructivist perspective, all learning relies on engaging and transforming preconceptions. Thus, explicit engagement and student reflection are essential (Clough, 2006; Craven, 2002; Klopfer, 1969; Kurdziel & Libarkin, 2002; Peters & Kitsantas, 2010; Russell, 1981; Scharmann, Smith, James, & Jensen, 2005; Seker & Welsh, 2005; Yacoubian & BouJaoude, 2010). One of our Danish teachers expressed it succinctly:

> An explicit approach to NOS is extremely important because there are so many myths about how science works, both among students and fellow teachers—not having participated in any NOS courses.

Such reflection must also be mindfully guided by an instructor. Otherwise, a student's own preconceptions can powerfully reinforce prior beliefs. Personal epistemologies can be extraordinarily resilient, even in the face of apparent anomalies (Kahneman, 2011; Sandoval, 2005). Thus, Tao (2003) noted,

> When studying the science stories, many students selectively attend to certain aspects of the stories that appear to confirm their inadequate views; they are unaware of the overall theme of the stories as intended by the instruction. (p. 168)

Hence teachers need to also actively monitor and help shape students' understandings (p. 169) as articulated in depth by Clough (2006).

Second, some proposed lessons isolate NOS and treat it abstractly, as illustrated in several "black box" activities (e.g., see http://msed.iit.edu/projectican/teachers.html). That is, there is a continuum between decontextualized and contextualized NOS lessons, the latter richly embedded in authentic scientific practice (Clough, 2006). Yet decontextualized scenarios typically need careful scaffolding if students are to transfer their understanding to real-life examples and contemporary SSIs (Ault & Doddick, 2010; Clough, 2006; Irwin, 2000; Johnson & Stewart, 1990; Sandoval & Morrison, 2000). Again, our teachers agreed with Zeidler, Walker, Ackett, & Simmons (2002) that

> Instead of the NOS being taught as a discrete topic in the delivery of a course, this study suggests that it may be successfully integrated into the curriculum being taught when students are actually experiencing those aspects of the NOS while involving in scientific inquiry and addressing anomalous data. (p. 361)

That is, decontextualized NOS lessons seem to have limited value, insufficient alone for the ultimate goal of scientific literacy. It remains an open question whether they are needed at all. Notably, other research indicates that learning may occur primarily, or most vividly, through exemplars, not through instruction on general principles (Gentner & Colhoun, 2008; Gentner, Loewenstein, & Thompson, 2003; Kolodner, Hmelo, & Narayanan, 1996).

Thus, there has been wide advocacy, even outside science education, of case-based learning (Allchin, 2013b; Barnes, Christensen, & Hansen, 1994; Herreid, 2007; Lunberg, Levin, & Harrington, 1999). Such perspectives imply a larger role for cases and authentic examples in NOS education.

All these themes—case-based learning, explicit reflection and teacher-guided reflection, and contextualized NOS—are important in guiding effective NOS teaching, regardless of the setting. Still, the teacher must choose just how to contextualize students' NOS learning. Should one use student-based investigations, contemporary cases, or historical cases? All three may contextualize NOS, and all three may exhibit varying levels of authenticity (or, conversely, of selective abstraction).[1] We recognize the potential advantages of each. We aim here to articulate *when and in what ways* each approach can be effective, and *when and in what ways* each encounters inherent limits (i.e., in ways apart from their "degree of contextualization," as characterized by Clough, 2006). Toward guiding classroom practice, we want to identify what *particular features* of NOS each approach effectively conveys and, where possible, *how* it does so.

Contemporary Cases

Teaching NOS in the context of contemporary cases is an obvious approach when the ultimate aim is students' functional scientific literacy (Khishfe, 2012a; Sadler, Chambers, & Zeidler, 2004; Wong et al., 2011; Zeidler, Applebaum, & Sadler, 2011). And it is directly relevant to the contemporary SSIs that students will address outside the classroom, where contentious scientific claims mingle with discourse on values.[2] In addition, many students find contemporary cases relevant and interesting and are easily motivated by them. Wong and collaborators, for example, found that familiar stories can be both intriguing and effective in relation to students' learning and ability to identify aspects of NOS in the context of contemporary science (Wong, Hodson, Kwan, & Yung, 2008, p. 1420, 1434). They developed a case on the severe acute respiratory syndrome (SARS) outbreak in 2003 in Hong Kong, which was taught to student teachers, all having memories the SARS incident. The case addressed many of the traditional NOS dimensions: the *tentative nature* of scientific knowledge, *theory-laden observation and interpretation*, *multiplicity of approaches* adopted in scientific inquiry, the *interrelationship between science and technology*, and the *nexus of science, politics, and cultural practices*. In addition, some other dimensions of NOS were emphasized: the need to combine and *coordinate expertise* in a number of scientific fields, the intense *competition* between research groups, the significance of affective issues relating to *intellectual honesty*, the courage to challenge *authority*, and the pressure of *funding* (Wong et al., 2008; Wong, Wan, & Cheng, 2011). According to Wong's group, the effectiveness of the SARS story was due to its immediacy,

[1]Clough (2006) places these categories along a continuum, with historical and contemporary cases as authentic, or deeply contextualized, and student inquiry as implicity decontextualized, or inauthentic. By contrast, we contend that when historical or contemporary cases are presented in a minimalized form, they are effectively decontextualized. At the same time, student investigations may vary from simple exercises with little autonomy or decision making to laboratory internships or participation in ongoing research, which thus can (in some cases) be highly authentic. Thus, we regard these three categories as alternative contexts, without privileging any category as inherently more or less "contextualized."

[2]SSIs represent a distinctive subset of contemporary cases. As articulated by Sadler and Ziegler (2005), SSIs are issues of social relevance that involve *both* scientific information *and* value judgments, and thus span the problematic relationship of facts and values. They often involve controversies simultaneously in both realms (epistemic and ethical). The problems are often open-ended, ill-structured, and debatable, involving multiple perspectives and interpretations. SSIs are important for society and for people's personal lives and the conflicts often require personal decision making (Ekborg, Ideland, & Malmberg, 2009).

relevance, and familiarity, each making the case more engaging. The compelling interviews with scientists in the midst of crises probably also contributed to students' understanding of science's human dimension (Wong et al., 2008, p. 1435; 2011, p. 248).

Of course now, more than 10 years after the SARS outbreak, the case is resolved, students' recent memories differ, and it no longer seems a "contemporary" case, but one from recent history. A key feature of contemporary cases is that they are unresolved. Science is still "in-the-making" (Latour, 1987). The drama of uncertainty is one reason why they are compelling vehicles for NOS education in the classroom. In another such contemporary case, Sadler et al. (2004) found that conflicting scientific reports about global warming could stimulate students' understanding of NOS and scientific practices. Students became aware of how researchers interpret conflicting evidence, and how social interactions and personal beliefs sometimes influence their claims. This study showed how one can use a contemporary issue to contextualize teaching *empiricism, tentativeness,* and *social embeddedness* (Sadler et al. 2004). Knowing that researchers' interpretations and evaluation of conflicting evidence is not purely objective is an important aspect of students' functional scientific literacy. Khishfe (2012a) explored student decision making in a case on genetic engineering (an SSI case that also involved values). She likewise found that high school students improved their understanding of science as *tentative, empirical,* and *subjective* (assessed by an open-ended questionnaire). The intervention did not influence students' decisions regarding genetic engineering, but it changed the stated reasons they gave for their decisions. Decision making and argumentation are central competences for functional scientific literacy.

Many researchers have found that reading and analyzing contemporary newspaper articles can promote the development of critical thinking and help students recognize how science is used to argue for certain points of view (Cakmakci & Yalaki, 2012; Elliott, 2006; Jarman & McClune, 2007; Oliveras, Márquez, & Sanmarti, 2011; Shibley, 2003). The news media can be a suitable source of teaching material on NOS in a contemporary context, showing how science and technology interact with other domains in public life and how various agents influence collective decisions in our society (Dimopoulos & Koulaidis, 2003). Ironically, newspaper articles rarely contain much factual information about science and technology and only rarely refer to methodological elements (Dimopoulos & Koulaidis, 2003; Oliveras et al., 2011; Ryder, 2001). So newspaper articles cannot be the sole source of material for teaching NOS. In addition, students must already have a basic understanding of NOS (or "knowledge of science") to critically engage with science in the media (Elliott, 2006; McClune & Jarman, 2010). Still, working with newspaper articles can make students aware of some other aspects of NOS, such as the *uncertainty* of "science-in-the-making" and the *role of experts* in discussing science and technology in society (Kolstø, 2001; McClune & Jarman, 2010).

SSI cases, with their added dimension of values, form a special subcategory of contemporary cases. The introduction of ethics or politics seems to pose both opportunities and challenges for science teachers. On the positive side, the science often becomes more vivid and relevant, as the SSIs involve personal decisions or social choices. On the other hand, when students discuss SSIs, they tend to drift away from the science and focus more exclusively on the values (J. A. Nielsen, 2012). In addition, several researchers have found that students (and others) focus selectively on the scientific evidence and other aspects that support their own views and values. They do not consider all the available evidence in a more complete or balanced way (Kahneman, 2011; Martin, 1991; J. A, Nielsen, 2012, 2013; Sadler et al., 2004; Zeidler et al., 2002). In the classroom, such tendencies tend to subvert efforts to teach how science works or even to show how judgments in science may be unduly biased by prior beliefs. Walker and Zeidler (2007) claimed that a proper understanding of NOS will inform students' decision making (p. 1389), but this claim is far from tested. Indeed, as noted by Thomas (2000), students' emotional engagement in current politics or ideology can easily confound clear NOS analysis. Khishfe (2012b) suggests, as a counterstrategy, that teachers might be able to minimize students' focus on value-based argumentation by forcing them also to consider counterarguments for a claim. But, again, the efficacy of this proposed strategy has not been fully examined. In short, where contemporary issues touch upon values (or ideology), as in SSIs, occasions for *learning* NOS—rather than *applying* NOS—can ironically become more treacherous, even as their relevance becomes more vivid.

In summary, contemporary cases (including SSIs as an important subset) thus seem suitable for introducing some aspects of NOS and can contribute to student appreciation of the *importance of* understanding NOS. The relevance and familiarity of the cases make the abstract more tangible. By working with contemporary cases, students can become aware of critical aspects of "science-in-the making," such as *uncertainty, tentativeness, subjectivity, multiple perspectives, the role of funding, political interests,* and *social embeddedness* of science. In addition, they can apply their NOS knowledge in debates about authentic SSIs and practice the skills of competent citizens in a "rehearsal" environment. But contemporary cases do not in themselves equip students with basic scientific literacy tools to *resolve* the scientific controversies—namely, how to interpret or address the "tentativeness" (or scientific uncertainties) in a particular case; or how to assess the empirical evidence or the role of subjective factors biasing the evidence. Such critical NOS understanding will not be gleaned from contemporary cases.

Student-Based Investigations

Next, one may consider classroom inquiry, or student-based investigation, as a means for contextualizing NOS. The aim of inquiry in a class/lab is to make the teaching and learning resemble or mimic authentic investigative scientific processes (Schwab, 1962). The teacher strives to embody scientific practices and thereby show how knowledge about nature is created, or constructed. Of course, inquiry-style learning can be adapted to many contexts (even to historical and contemporary cases). Here, we are concerned specifically with the investigative efforts directed by (if not also initiated by) students themselves and that introduce epistemic problems.

Inquiry processes, as a model of "scientific practices," include identifying problems, generating research questions, designing and conducting investigations, analyzing and interpreting data, and formulating, communicating, and defending hypotheses, models and/or explanations (Abd El-Khalick et al., 2004; National Research Council [NRC], 2013). More technical aspects may also be involved: designing complex procedures, using techniques to avoid perceptual and other biases, reasoning about experimental error, and resolving conflicting results from multiple studies (Aydeniz, Baksa, & Skinner, 2011). Inquiry work can be done by an individual student or by a group, reflecting the real world of scientific research (K. H. Nielsen, 2012). But the teacher's role is also indispensable. In any learning environment, they inevitably provide some external structure and guidance. As Sandoval (2005) noted, "the largely unstructured approach to discovery learning advocated in the 1960s ... [by, e.g., Jerome K. Bruner] is too difficult for most students" (p. 637).

Inquiry in various forms undoubtedly fosters learning about NOS. Deng et al. (2011) recently examined empirical studies, published between 1992 and 2010, of curriculum interventions intended to change students' views on NOS. Of 35 effective studies, 32 included inquiry activities combined with one or more other learning activities (pp. 989–991). Seven other cases that involved inquiry were ineffective, but in four of these inquiry was the sole learning activity. Other examples documenting NOS learning through inquiry (not cited by Deng et al.) include Ford (2005), Lehrer, Schauble, and Lucas (2008), and Yacoubian and BouJaoude (2010). So, inquiry-based NOS instruction, combined with other approaches, appears be quite effective in changing students' views on NOS. (Deng et al., 2011, p. 979, 983) conclude that

> As found in this review, all the "successful" intervention studies generally involve learning activities such as inquiry, discussion, reflection, and/or argumentation.

Yerrick (2000), in particular, documented achievement even among "low achieving marginalized students" alienated by conventional school structures. Similarly, such activities can be dramatically effective even for sixth graders (ages 11–12), as shown by Smith, Maclin, Houghton, and Hennessey (2000) and Lehrer et al. (2008). The overall virtue of student inquiry is now well established.

There are qualifications, of course. Other factors also matter to whether students who participate in inquiry-based or school lab activities deepen their comprehension of NOS. As noted above (in the general comments), reflection and contextualization seem equally essential for realizing the potential lessons fully (also see Khishfe & Abd-el-Khalick, 2002; Sandoval & Morrison, 2003).

Also, the documented virtues of student inquiry seem limited. For example, inquiry studies seem to have targeted only some items on the NOS consensus list: that science is *tentative*, *empirical*, *inferential*, *creative*, and *communal* (social). Portraying science in its *social and cultural milieu*, for example, does not seem well suited to student inquiry. Nor does *large-scale theory change*, akin to scientific revolutions. Also, NOS lessons are not guaranteed for all students. Even in "successful" interventions of 10–12-week duration, gains on these NOS features were documented for only about one-quarter to one-half the students (Khisfe, 2008; Khisfe & Abd-El-Khalick, 2002; Yacoubian & BouJaoude, 2010).

Most inquiry studies have focused chiefly on foundational epistemological views, or a basic constructivist perspective. That is, the interventions effectively engage students in appreciating how generating knowledge is a human task, with problems to resolve. Problems of authority or uncertainty or alternative interpretations all need to be resolved by appeals to evidence or are subject to collective agreement. When students participate in solving these problems themselves, and reflect on the process, they can make remarkable gains in epistemic understanding, as well as develop skills in simple scientific practices. Inquiry situations allow students to personally experience how claims about nature are actively "constructed" by investigators and do not simply appear as passive consequences of whatever evidence is at hand (Sandoval, 2005). Shifts in student views can be substantial and sometimes nearly universal, as documented in interviews, essays, and other student artifacts (e.g., Ibáñez-Orcajo & Martínez-Aznar, 2007; Ryder, Leach, & Driver, 1999; Smith et al., 2000; Yerrick, 2000).

Another popular theme in student inquiry projects is modeling (Giere, 1999; Johnson & Stewart, 1990). Recent developments in science studies (cognitive, historical, sociological, and anthropological) underline the role of models and deflate the monolithic image of theories. Duschl and Grandy (2012) accentuate "[the] importance that models and modeling, visual representations, knowledge exchange mechanisms and peer interactions have in the refinement of knowledge" and point to the work of Lehrer et al. (2008) as path breaking in the use of models in inquiry teaching.

Still, in the context of a fully developed functional scientific literacy, and the ability to address complex science in contemporary SSIs, the student inquiry approach to NOS, however fruitful, seems critically incomplete. One potential problem with focusing too strongly on just student investigations is the possibility of developing an "epistemology of school science." That is, traditionally much school science is unlike professional science. The artificially simple and diluted problems in school settings may not be the basis of an informed understanding of NOS. Students do not automatically transfer lessons from their own activities to real-life contexts (Clough, 2006; Sandoval & Morrison, 2003). It is immensely challenging to structure student inquiry or research as *authentic* in a way that can appropriately model science in culture (Crawford, 2012).

Another problem is that even if students do engage in authentic inquiry activities, not much is known about how they interpret their own activities. One can argue, as Kelly and Duschl (2002) do, that such reflections on the part of the student are not that important since science is a practice. But that is to miss the point, says Sandoval, because later in life,

> . . . most students will not really engage in science as a practice. Rather as citizens they must be able to reflect on scientific knowledge claims as they relate to personal or policy decisions. It is far from clear that simply engaging in practices of authentic science leads to such reflective ability. (Sandoval, 2005, p. 645)

At the very least, instructors need to actively scaffold the transfer of NOS lessons from student investigations to more socially relevant contexts (Clough, 2006; Wilcox, Smith, & Kruse, 2013). Through successful inquiry activities, students may learn how scientific claims are constructed. This, Ford argues, enhances their ability to question and criticize such claims:

> Scientists have, precisely as a result of their scientific training, "a disposition to critique claims." . . . And because of their training, scientists also know *how* to criticize, what questions to ask. (Ford, 2008, p. 150)

To be scientifically literate, then, citizens need not be able to evaluate and question scientific evidence or arguments directly. Only scientists can do this, and, then, only within their specific discipline or professional subfield. Rather, informed citizens and consumers will be able to analyze testimony, credibility, and expertise. They know that direct questioning and critique is possible, and, with some knowledge about how scientists do it, they can design and formulate such criticism. This illuminates the foundations of scientific arguments, including situations when they are used politically.

In summary, student-based inquiry—when well managed—is exceptionally valuable in developing basic skills in the process of science and a corresponding understanding of their epistemic purposes. When appropriately framed (especially with the relevant student motivation and autonomy), such lessons can become deeply internalized. Such understanding is limited, however, to what a student can achieve in a school setting—far short of the processes relevant in citizen and consumer decision making. In addition, there are larger scale contexts of science—for example, cultural biases, economics and conflicts of interest, historical contingency, or problems of epistemic dependence, credibility, and expertise—that cannot be easily modeled in the classroom. Student investigations form a powerful tool for NOS learning, but also need to be complemented by others methods.

Historical Cases

A third approach to teaching NOS is historical cases (Allchin 2012a). These are not merely anecdotes about historical figures serving as role models (motivation as teaching objective), nor romantic stories of already well-known discoveries (celebratory objective), nor rational reconstructions that idealize science according to some preordained scientific methodology (ideological objective). Rather, they focus on science as a process (as science in the making) and, like the contemporary or student cases, highlight the *epistemic* issues on a human scale. What empirical studies demonstrate their effectiveness for learning NOS?

Deng et al. (2011) cited 12 such studies, of which eight documented positive effects (pp. 989–990). Two unsuccessful interventions, however, were 1 week or less. To these, one may add several other studies that have demonstrated NOS learning through historical perspectives: Clough (2011), Faria, Pereira, and Chagas (2010), Howe and Rudge (2005), Kruse and Wilcox (2011), Lin and Chen (2002), and Rudge, Cassidy, Fulford, and Howe (2013). Properly presented, history *can* be a vehicle for NOS lessons.

Yet our chief concern is about the individual NOS features, such as the cultural context of scientific theories, or the potential for theoretical preconceptions to bias interpretation of data, or the existence of error and historical theory change. Not every historical case will exhibit all features equally. As noted poignantly by Rudge et al. (2013), their students learned just what the historical case in their unit illustrated, no more. Nor is it any wonder that, after reading two stories that involve chance discovery (penicillin and bacterial cause of ulcers), students maintained their view of experiment as "serendipitous empiricism" (Tao, 2003). Similarly, three (of four) stories (in the same study) depicted theories being tested and confirmed, and students—rather predictably, perhaps—tended to view theories (i.e., these conspicuously confirmed theories) as "facts," not merely as explanatory structures.

One may thus diagnose the earlier studies in more detail for precisely which NOS features each highlighted effectively. For example, Solomon, Duveen, Scot, and McCarthy (1992) is frequently cited as evidence for the role of history in improving NOS understanding. Yet their analysis focused on just four student questions, all involving the *interaction of theory and experiment*. This is a substantive NOS feature, and the efficacy was noteworthy. Deeper views were exhibited by ∼20–28 of the 94 students (about one-quarter). But it was also quite narrowly focused.

Many studies have been guided by the "consensus list" of NOS features noted above (Lederman, Abd-El-Khalick, Bell, & Schwartz, 2002). They have shown that history may help students toward more sophisticated views on *empirical foundations*, the *function of theories*, the *nature of experiment* (and, alternatively, of observation), the constructed and *subjective dimensions of scientific interpretations*, and the *sociocultural context* of scientific practice (Clough, Herman, & Smith, 2010; Howe & Rudge, 2005; Kim & Irving, 2010; Lin & Chen, 2002; Rudge et al., 2013). Surprisingly, perhaps, the improvement with the assessment instruments used is for only one of about every six students (or less).

By far the most significant NOS element learned through historical lessons seems to be *theory change, or the tentative or fallible nature of science*. Irwin (2000) specifically targeted his lessons to convey the "changing degrees of doubt" in the history of atomic theory, aiming to inform contemporary cases on "the likely certainty of knowledge and to the extent of the reliance that could be placed on the 'experts'" (p. 23). He reported 45% efficacy for a modest eight-class unit. Likewise, Howe and Rudge (2005) documented an impressive 38% improvement based on an eight-class unit on the changing historical views on sickle cell anemia. Given that "tentativeness" or *fallibility* (variously expressed) has been a central component of NOS goals for over half a century (Lederman, Wade, & Bell, 1998), these findings about the role of historical episodes of theory change are indeed noteworthy.

Research indicates that other features of NOS can be learned from history. Students of Irwin (2000) showed deeper understanding of the *role of prediction*, made vivid by the case of Mendeleev and the periodic table. In another study, after two short stories, sixth graders were able to self-report on learning about: *laboratory vs. nonlaboratory research, methodological pluralism, the effort (work and time both) involved in research,* and *the* *diversity of scientific contributors* (efficacy for 10–37 of 84 students on each; or 1/8–3/8; Kruse & Wilcox, 2011). The first feature was not even targeted through explicit reflection during instruction. This might indicate the potential of historical cases, especially when assessment of NOS learning is more open ended (Lin & Chen, 2002).

Historical cases can certainly illustrate the roles of criticism and debate, theoretical bias, cultural or biographical perspective, general cognitive biases, motivations, contingency (or "chance"), collaboration, interdisciplinary connections, funding, expertise and credibility, conflict of interest, and more (Allchin, 2011, 2012c). All these may affect the emergence of knowledge and shape a citizen's or consumer's assessment of the reliability of public scientific claims. Namely, all contribute to how science works (scientific practices). And, with respect to inquiry mode, all may frame NOS questions for explicit reflection (Allchin, 2013a; Clough, 2007). This is especially important given the aim of addressing NOS relevant to SSIs (Allchin, 2012b).

By contrast, there are certainly instances where instruction using history has not yielded NOS learning. Given the positive evidence from the studies cited above, however, it would seem ill advised to generalize from these particular failures and thereby eclipse a role for history. After all, many science studies scholars turn to history precisely for insights into NOS. Rather, the failures may help us identify ancillary factors that must accompany the history for it to prove effective. Explicit reflection is, of course, a major constructivist learning factor, absent from most of the failed efforts (such as Abd-el-Khalick & Lederman, 2000; Meichtry, 1992; and Tao, 2003). Also, one cannot reasonably expect "quick fixes" across all features of NOS from limited student engagement, anymore than one might expect just a few lessons to convey a major thematic lesson, say, about the relationship of structure and function or energy in its various forms. Nevertheless, some studies, such as Kruse and Wilcox (2011), are beginning to indicate some key factors fostering short NOS lessons: novelty, teacher emphasis, story emphasis, as well as embedded questions that invite explicit reflection.

The curricula that document the most significant gains seem to involve activities that engage students in authentic (even if simplified) problem solving—that is, adapting general inquiry strategies to a concrete case in historical context (Allchin, 2012a; Irwin, 2000; Howe & Rudge, 2005). Simply "observing" or commenting on historical stories seems less effective (Clough et al., 2010). Still, positioning students "too deeply" in history, where they might measure their own modest performance against the achievements of great heroes, may foster a problematic sense of individual inadequacy or failure (Henke & Höttecke, 2013). Similarly, asking students to adopt a counterintuitive historical perspective soon to be abandoned, for the sake of "recapitulating" actual history, can be equally problematic (Eric Howe, personal communication, 2012). Historically based NOS lessons must be crafted and presented mindfully.

Finally, the challenge of assessing the value of historical cases to NOS learning may be limited methodologically, with current diagnostic instruments not well structured to probe the particular NOS features most effectively highlighted in historical cases. History presents NOS in context and through concrete examples, whereas NOS probes tend to decontextualize NOS or express it in abstract terms. Closed-ended forms such as Nature of Scientific Knowledge Scale (NSKS) or Views on Science-Technology-Society (VOSTS) (e.g., used by Meichtry (1992) and Dass (2005)) may be particularly ill equipped to capture the lessons from highly contextualized lessons from history (Lin & Chen, 2002, p. 786).

In summary, history seems valuable for contextualizing NOS lessons, especially on theory change and the cultural (including biographical) contexts of science, and other aspects that embody long timescales and expansive human contexts. Historical cases may also help frame authentically situated inquiry activities, yielding outcomes similar to those noted for student investigations above (more below). As in all lessons, history needs to be framed appropriately to encourage student engagement and guide focus on NOS. As articulated more fully below, practical teaching considerations seem critical in realizing the potential benefits of history fully.

COMPARING APPROACHES TO NOS LEARNING

As described in the foregoing background discussion, research indicates that while different modes of NOS instruction may each be effective, each approach seems most effective *in distinct and characteristic ways*. Here, we resituate this knowledge in the ultimate classroom context based on the experience of practicing teachers, as well as on our own experience in teaching students in various contexts. In parallel to Clough (2006) on the benefits of using *both* decontextualized and contextualized scenarios, we contend that teachers should use *all three* modes of NOS instruction. Teachers may thereby benefit from the topical merits of each, while also accommodating each other's inherent deficits. That is, no method used exclusively can be fully effective. The three modes should be used jointly to complement one another, as indicated in Table 1, presented here as the centerpiece of our paper.[3]

Given that a primary aim of NOS education is competence in addressing contemporary SSI cases, one surely wants to address *contemporary cases* in the classroom, to profile the role of NOS analysis in such contexts. That is, SSIs require knowledge of NOS and skills in NOS analysis: for example, to understand theory change as a basis for a new policy, interpret uncertainty in a public debate, or ascertain whose scientific claims in a controversy should be deemed credible. SSIs are prime occasions for profiling the relevance of NOS and for motivating inquiry (Walker & Zeidler, 2007). Students typically appreciate the "here-now" dimension of such cases, when framed in age-appropriate terms.

One might therefore imagine that one should rely exclusively on such current SSIs or other contemporary cases. However, while such cases are valuable for *rendering* NOS relevance, or *showing how to apply* NOS knowledge, they seem far less effective for *learning* about NOS. Most notably, the cases are unresolved. Uncertainty persists. Without the outcome, one cannot assess which among alternate scientific claims or methods ultimately proves trustworthy (a problem exemplified in Collins and Pinch's *The Golem* [1993]). Newspaper presentations of contemporary cases often lack details about scientific practice and evidence (Dimopoulos & Koulaidis, 2003, p. 248), making it difficult to discuss process and product. Thus, while students may readily see the importance of evaluating evidence, they are not in a position to *learn* how to do so (Kolstø, 2001, pp. 299, 305). This is the challenge of "science-in-the-making" (Latour, 1987). Controversies certainly provoke student interest, but they rarely can inform how one reaches a solution. There is no end to the story. Indeed, without prior NOS knowledge, students will likely not notice or appreciate all the relevant NOS dimensions in an unfamiliar SSI, or know which information is most significant. Indeed, if students tend to interpret such cases using their NOS preconceptions, one may only reinforce misconceptions and foster misleading conclusions (Clough, 2006; Kahneman, 2011; Tao, 2003). In addition, as noted above, students' emotional engagement

[3]This integrative approach echoes Clough (2006), but does not regard the contextualized/ decontextualized continuum as the major axis motivating or organizing integration. Rather, we regard the primary variable as the different features of NOS. The corresponding challenge is to secure complete coverage of NOS: through complementary use of incomplete methods. The important task of keeping students engaged in conceptual change by shuttling between contextualized and decontexutalized scenarios (Clough's focus) is orthogonal to our primary concern.

TABLE 1
Merits and Deficits of Modes of NOS Instruction

Mode	Merits	Deficits
Contemporary case	• helps motivate engagement through authenticity and "here-now" relevance • can support understanding of cultural, political and economic contexts of science • can support understanding of how science and values relate • develops scientific literacy skills in analyzing SSI	• cannot be fully resolved, leaving uncertainty and incomplete NOS lessons • cannot exhibit details of process which are not yet public or are culturally obscured
Inquiry	• helps motivate engagement through personal involvement • fosters personal integration of lessons • supports understanding of constructed interpretations, models, forms of evidence, and model revision • develops experimental competences: framing hypotheses, designing investigations, handling data, evaluating results • relates nature of scientific knowledge to inquiry skills and methods • develops understanding of how scientific claims can be defended or criticized in contemporary SSI cases	• difficult to motivate all students, especially as a group • may be viewed as artificial exercise or school "game," not as genuine science • when investigations "fail," can prompt negative emotions, alienating student from NOS lessons • typically shuttered off from cultural, social, or political contexts • hard to model role of "chance," or contingency • requires substantive amounts of time and resources
Historical case	• helps motivate engagement through cultural and human contexts and through narrative format • can support understanding of long-scale and large-context NOS features: esp. conceptual change, and cultural/biographical/economic contexts of research problems and interpretive biases • can support understanding of investigative NOS: problem-posing, problem-solving, persuasion, debate • can support understanding of complexity of scientific practice, as well as historical contingency • supports analysis of process and product, since ultimate outcomes are known • when framed in inquiry mode, can develop scientific thinking skills—more efficiently than with hands-on inquiry • can foster understanding of error and revision—without risking emotions of personal failure	• may seem "old" and irrelevant • difficult or time-consuming for teachers to learn background or historical perspective • if text-based only, limits development of hands-on experimental competences • if rationally reconstructed only or presented as final-form content, does not support understanding of "science-in-the-making"

in current politics or ideology can easily confound clear NOS analysis. Students often focus exclusively on the values, upstaging the science and NOS issues (J. A. Nielsen, 2012).

Here one may note, by contrast, one of the great benefits of *student investigations*. When students are involved in a well-constructed (authentic, blind, even if scaffolded) process of investigation, they can learn how scientific claims are constructed and tested through a trial and error process, through criticism and response, with conclusions circumscribed by the available evidence and mutual agreement. One might develop a deeper sense of what evidence may be uncertain or absent, in addition to whatever evidence is secured. These are important NOS lessons for assessing SSI, but do not conspicuously announce themselves when one examines a contemporary case naively. Ironically, then, student inquiry may help yield a more intimate or "authentic" understanding (of some NOS features) than a contemporary case. Student investigations present other virtues of NOS instruction, as well. The most notable, perhaps, are personal engagement (provided the student is "invested" in solving the problem) and personal framing, with lessons deeply rooted in individual cognitive structures. As noted above, research has shown how, through inquiry and (as always) explicit reflection, students can develop a deep appreciation of models, the nature of evidence, model revision, and the constructed ("creative") nature of scientific explanations or theories. In addition, inquiry activities foster the practical skills that students might use in their own modest life-investigations or in a future career as a scientist or engineer.

Yet there are also limits to student investigations as a context for NOS instruction. First, while inquiry can motivate many students, not every student may be committed to sustaining an investigative effort, precipitating a tedious (or even odious) task that works against meaningful learning (e.g., many compulsory science fair projects). Depending on the topic of inquiry, students may not perceive their own work as a genuine, even if modest, sample of the scientific enterprise (Clough, 2006). They may construe it as yet another school "game," when contrasted to the high-tech and complex science widely portrayed on television and in film. Students may not always connect their own efforts to real scientists or to SSIs in the news. Yet another challenge arises when experiments "fail," as they often do. They may not yield "favorable" (expected) results, or even results that can be clearly interpreted. The emotions from perceived "failures," again, can diminish or eclipse effective lessons.

What, then, is the role for *historical cases*? For many educators and students, history may seem the last resource to consider for NOS instruction—based on an initial impression that "old" science is inherently "wrong" and thus irrelevant (Clough, 2006; Henke & Höttecke, 2013; Höttecke & Silva, 2012). Ideas and methods of science have changed over time, and delving into history may seem a waste of time, especially where a long list of modern conceptual content looms. Yet history offers many advantages, *not found in student inquiry lessons or contemporary cases*. Most notably, a historical case can collapse time and thus render larger-scale features of NOS, such as incremental theory change, recovery from error, or scientific revolutions. Second, the cultural and temporal "distance" facilitates learning about science in a cultural context (economic, political, gendered, racial), dimensions that are much harder to recognize in one own's culture. Such awareness is foundational for analyzing possible bias in contemporary SSIs. Third, by using history, one can render the role of contingencies, or opportune moments of interdisciplinary connections or biographical idiosyncrasies, sometimes mistakenly attributed to native "genius" or inherent progress (Allchin, 2014; Kolstø, 2008). The basis for scientific insight becomes more concrete, more human, and more accessible. Finally, one can explore the complexity of science, with the advantage of hindsight to guide the sense of overall organization. These are all important NOS lessons that bridge the artificial simplicity of student inquiry, on the one hand, and the complexities and inaccessible details of contemporary cases, on the other.

History offers several other benefits, as well. While historical theories or NOS-relevant events can be addressed abstractly, they are also readily adapted to a narrative format. Stories are important forms of communication and learning that have emerged from human evolution (Hsu, 2008). Historical stories can thus provide an effective framework for presenting NOS lessons in familiar, humanly approachable terms (Herreid, 2007; Metz, Klassen, McMillan. Clough, & Olson, 2007; Solomon et al., 1992). In addition, one may engage students in science with biographical and cultural perspectives—of curiosity or wonder, as well as of compelling social problems. Students need not share the historical motivations personally to appreciate them and find them a context for addressing scientific inquiry. History, when cast in human and cultural terms, rather than as chronology or a series of successive landmark discoveries, becomes an important resource for engaging students and conveying the "human" dimensions of NOS.

Compared to contemporary cases and their inherent incomplete status, historical cases have an outcome that is known. One can compare the "finished" science with how things appeared during a historical period when science was still "in-the-making." One can follow a debate through its resolution. One can thus compare process with product. For example, how were the uncertainties—the conflicting evidence and testimony, alternative lines of reasoning, and/or competing models—ultimately resolved? Was confirmation of novel predictions really important, or does it just seem so in retrospect, once you know already the answer (Brush, 1989; 1994; Losee, 2005)? Not all historical cases will embody NOS lessons. However, *when history is presented specifically in a historical context—as "science-in-the-making"*—and followed through to "science made," it can foster an understanding of how scientific processes lead to reliable conclusions.

Effective use of historical cases can also remedy some of the inherent deficits of inquiry as a mode of NOS instruction. First, the science is patently authentic. The NOS is "real." Second, students are relatively insulated from the emotions of "failure." They can engage in a historically situated inquiry and adopt the position of a past scientist, yet the sense of self is not so vulnerable. Errors can be experienced first-hand, yet can easily be attributed in retrospect to the context and analyzed with more critical distance. Ironically, then, history can accommodate some of the deficits of student inquiry-based NOS instruction.

Still, historical cases provide many practical challenges. Preconceptions of history as "dead" and useless chronology need to be addressed, especially among teachers. Impressions of heroic tales embedded in history, which subvert NOS lessons, also need to be addressed (Allchin, 2003). Teachers also need to be able to adopt or apply a posture of uncertainty, as they do in student inquiry cases—even where the outcome is clearly already known historically. Finally, good historical cases, while easy to teach, require substantial time, effort, and expertise to assemble. While many exemplary case study modules are available, the repertoire is still far below what is needed (Allchin, 2012a).

To summarize, then, student inquiry, contemporary/SSI cases, and historical cases each provide occasions for teaching NOS. Each has merits, as well as deficits (Table 1). In pragmatic terms, we contend, teachers should capitalize on the opportunities of each, while explicitly balancing their shortcomings by also using the other approaches.

INTEGRATING THE APPROACHES IN THE CLASSROOM

What, then, does the complementary nature of NOS approaches mean for teachers and classroom practice (as noted, our ultimate concern)? To ensure a complete and unified understanding of NOS, it seems appropriate for teachers to combine and integrate the different modes of rendering NOS. Therefore, just as Clough (2006) advocated using *both* contextualized and decontextualized approaches to NOS and—equally important—shuttling between them with well formed questions, we indicate the need to use *all three* forms of contextualizing NOS and to mindfully integrate them as an ensemble of complementary lessons. For example, Kolstø (2008) advocated pairing history with contemporary cases:

> . . . the use of narratives from the history of academic science needs to be combined with examinations of contemporary socio-scientific issues that include post-academic science and controversial science in the making. Such a balance between historical and contemporary case studies is crucial for a science curriculum for democratic citizenship. (p. 996)

The primary challenges now lie in integrating the approaches in a classroom setting.

For example, in our program with experienced Danish teachers, one instructor presented two complementary cases on the same theme, "Using Statistics to Persuade Others." He paired the historical case of Florence Nightingale's use of statistical graphics in trying to persuade the British government to change the hospital treatment of wounded soldiers with a contemporary case where a Danish business organization tried to use a misleading statistical presentation to argue for reducing unemployment relief. In another instance, a pair of collaborating teachers integrated a contemporary case with student inquiry in a set of lessons on climate change. Students measured carbon dioxide released from a candle in the lab, and then combined this with Internet research on sources of CO_2. All the teachers found that the combined approached fostered more robust learning about NOS than the cases would individually.

One classroom effort is particularly worth comment, as it used all three approaches while presenting the same scientific topic. The teaching module focused on "vitamins and dietary supplements." It was designed and implemented by two chemistry teachers in Danish upper secondary school as a part of a developmental project on teaching NOS. The module combined learning of NOS and core chemical subject knowledge. Integrating the two aspects seems important to most teachers, because they experience an already crowded curriculum, which leaves little room for teaching NOS as an add-on (Leach, Hind, and Ryder, 2003). The module consisted of smaller units each addressing different aspects of NOS and chemical content. Table 2 shows how the different subunits and approaches complemented each other. First, the teachers presented a historical case on Christiaan Eijkman's research on beriberi (Allchin, 2010). Next the students were introduced to films and articles from the media concerning recommendations and peoples' intake of vitamins (SSI approach). After that, the students themselves investigated some myths/ideas about vitamin C in fruits and vegetables by setting up lab experiments (inquiry approach). Finally, through role-play, they simulated an official roundtable debate on dietary supplements and vitamin enrichment of foods (hybrid SSI-inquiry approach). Table 2 indicates how different NOS aspects were brought into play by the different approaches: Student led investigations initiated considerations about NOS in relation to *methods of investigation* and *observation and reasoning*. The same aspects were addressed by the historical case, but in addition it also addressed aspects like *experimental practice*, *culture* and *economics/funding*, etc. One of the teachers described in her evaluation report, how the combination of the historical case on beriberi and the film "The Truth about Vitamins" made the students discuss the similarities between contemporary research and Eijkman's work on beriberi. The students noticed that in both contexts it was relevant to consider "investigations showing unexpected results" and "difficulties conveying results from experiments done on animals to humans." This comment validates students' ability to transfer knowledge from one context to another and reflects the aim of using history to highlight NOS aspects in contemporary SSIs. Knowledge transfer from history to contemporary case also occurred in the module mentioned above on statistics and persuasion.

TABLE 2
The Module "Vitamins and Dietary Supplements" and NOS Aspects Addressed

Lesson	Approach and Activities	NOS Aspects
1	*Historical case:* Christiaan Eijkman's investigations on the cause of beriberi (lack of vitamin B_1)	• Observations and reasoning: alternative explanations • Methods of investigation: controlled experiment, replication and sample size, correlation vs. causation • Experimental practice: model organisms, ethics of human subject experimentation • Culture: cultural beliefs • Economics: sources of funding
2–3	*Contemporary case (SSI):* Viewing film on "The Truth about Vitamins," with group discussions	• Communication and transmission of knowledge: norms of handling scientific data, credibility of scientific journals and news media
4	*Contemporary case (SSI):* Students present the content and claims of popular science articles on vitamins in groups	• Communication and transmission of knowledge: norms of handling scientific data, nature of graphs, credibility of various scientific journals and news media
5–6	*Student inquiry:* Planning and conducting experiments on different claims about vitamins (in small groups)	• Methods of investigation: controlled experiments, replication, etc.
7	*Student inquiry:* Student groups present their experiments and results, and related aspects of NOS	• Observation and reasoning: completeness of evidence, role of systematic study • Methods of investigation: controlled experiments, replication and sample size
8	*Contemporary case (SSI):* Roundtable debates on "Enrichment of foods with vitamins" and "Vitamins as dietary supplements"	• Communication and transmission of knowledge: norms of handling scientific data, nature of graphs, credibility of various scientific journals and news media

The merits and deficits of each approach in this concrete teaching module are addressed in students' and teachers' evaluations. Most students found the topic interesting and relevant for their everyday life, and they participated eagerly in discussion about of validity of investigations and trustworthiness information from different sources. In these discussions and critical analyses, students applied their knowledge about NOS acquired in other contexts (teachers' report). So, apparently students' knowledge about NOS can be transferred from one context to another in the classroom.

When the students were asked about the most engaging elements in the sequence, half identified the roundtable debate about intake of vitamins. Student enjoyment of role-play activities was echoed by other teachers in the Danish program, who had used role-play in other cases: A historical trial on who invented calculus (Newton vs. Leibniz) and a contemporary SSI case about using genetically modified plants to detect hidden landmines in war-ravaged areas. But the students were also very engaged in the student-led investigations and one student wrote in her evaluation of the module: "The best thing was to do 'Myth-buster-experiments', which was a good way of integrating some practical work in the topic." The teachers were very impressed by how hard the students worked in the laboratory. One wrote in her evaluation:

> During the lab session the students were very active and carried out an enormous amount of titrations [vitamin C] and they were very conscious about working precisely.

None of the students mentioned the historical case on beriberi as a favorite activity. Still, the teachers experienced them as being quite engaged in the case. One teacher noted:

> The students experienced the beriberi case as quite nice. The learning environment was very cosy—the students were sitting in a big circle for listening and making smaller circles for group discussions. They liked the setting and the story.

The teachers experienced all three approaches as valuable, because each approach brought new aspects of NOS and vitamins into the learning process. According to the teachers, the students liked the whole module and they participated actively in all the activities. Students' enthusiasm and engagement is reflected in one student's comments in the evaluation of the sequence:

> The best and most interesting topic we have had in chemistry so far, because of all the different activities and that we have learned a lot.

Table 3 summarizes the merits and deficits of the different subunits and approaches. It is remarkable to see how the different approaches compensated for each other's deficits: "old and irrelevant" (historical approach) versus "authenticity and relevance" (SSI approach), "no hands-on competences" (historical/SSI approach) versus "development of experimental competences" (inquiry approach), and "cannot be fully resolved" (SSI approach) versus "can foster understanding of error and revision" (historical approach).

The teachers used a number of questioning strategies to scaffold students' learning and understanding of NOS (Clough, 2006). During the presentation of the beriberi case, the students were asked to discuss different questions relevant for Eijkman's investigations, and they were asked to take his perspective. These questions supported students' understanding of challenges and dilemmas in the work of a scientist. To link this discussion to a more general understanding of NOS students should conclude the lesson by writing answers to questions such as "In the process of understanding and explaining data; what kind of problems may you encounter?" or "How do you distinguish between correlation and causation?" Teachers' questions are very important for guiding and structuring students' learning of NOS, since they prompt students' thinking and challenge their original ideas about NOS.

PROSPECTS

Our analysis has focused on how educational research on various approaches to NOS learning can inform classroom practice. Significant findings support the use of historical cases, contemporary cases, and student investigations (inquiry). Still, no single method is without deficits. One needs all three approaches to complement one another, as an

TABLE 3
Merits and Deficits of the Different Approaches in the Module "Vitamins and Dietary Supplements": Comments from Teachers and Students

Lesson	Approach and activities	Merits	Deficits
1	*Historical case:* Christiaan Eijkman's investigations on the cause of beriberi (lack of vitamin B_1)	"The students found the Beriberi case quite nice. We had a cosy environment in the classroom—sitting in a circle and having small group discussions. They liked the setting and the story."	"a bit long" "a bit boring in the end" [No student mentioned this case as their favorite.]
2–3	*Contemporary case (SSI):* Viewing film on "The Truth about Vitamins," with group discussions	"The students were very motivated. They could relate to the topic personally and they were quite frustrated because you don't get the real information. Scientists are saying different things . . . "	"incomplete knowledge—focus on only three women and their use/abuse of vitamins"
4	*Contemporary case (SSI):* Students present the content and claims of popular science articles on vitamins in groups	"The students have been very engaged and well-prepared for the group work . . . some e-mailed material to their peers because they couldn't join the lesson." "The students had some very interesting and qualified discussions about claims and trustworthiness of the information presented in the popular science articles in lesson 4."	"boring to read the articles" "the article from women's magazine was silly"
5–6	*Student inquiry:* Planning and conducting experiments on different claims about vitamins (in small groups)	"The students were quite good at designing their own experiments . . . and aspects of NOS were discussed."	
7	*Student inquiry:* Student groups present their experiments and results, and related aspects of NOS	"During the lab session the students were very active and the carried out an enormous amount of titrations (vitamin C) and they were very conscious about working precisely. They demonstrated a lot of ownership." "The best thing was to do the experiment, because I find it exciting to do investigations."	
8	*Contemporary case (SSI):* Roundtable debates on "Enrichment of foods with vitamins" and "Vitamins as dietary supplements"	"The role-play was the best thing because you had to get a really good understanding of the topic to formulate the different opinions." "The best thing was to discuss the role of vitamins for public health, applying your knowledge in a different setting."	

ensemble. Considerable work thus remains for teachers in combining and integrating the three approaches in the classroom. Our recent program experience indicates informally that experienced teachers, given an overall framework for conceptualizing NOS, can recognize the virtues and limits of each pedagogical approach and can combine them creatively.

The practical considerations of the classroom may now, in turn, inform the next phases of research. First, NOS education research should focus more on particular concepts. Most research to date has been oriented to NOS as an undifferentiated concept, even if features within it are distinguished. That is, educational researchers tend to present conclusions about teaching "NOS" generally. We suggest that this is much like focusing instruction on electromagnetism or ecology rather than on individual concepts such as electrical current or food webs. Interventions should be explicitly organized around specific NOS concepts, such as how scientists can make errors, the role of gender bias in interpreting results, or historical theory change. Each concept may need its own form of assessment, styled to profile learning against a specific set of naive preconceptions. The recent Next Generation Science Standards in the United States (NRC, 2013) begin to articulate the meaning of "scientific practices," by specifying seven sets of particular competencies, mostly basic skills in the process of science. However, these targets, like the NOS "consensus list" before it, hardly exhaust the inventory of NOS understandings needed for addressing SSIs. Given that the three different approaches addressed here exhibit different particular strengths, research now needs to focus more on identifying *specific* NOS features from an inclusive inventory and associating each with *specific* educational strategies (as exemplified in the data analysis by Rudge et al., 2013). Similarly, NOS outcomes need to be linked with *specific* aspects of the use of history, contemporary cases, or student investigations. One should not expect simple, uniform solutions for teaching the multiple features of NOS.

Second, new forms of NOS assessment are needed (Allchin, 2011, 2012b; Clough & Olson, 2008; Deng et al., 2011, pp. 981–983; Gormally et al., 2012; Rudge & Howe, 2013). The new instruments will facilitate classroom evaluation of NOS as an accountable educational objective and support research on a more extensive and more finely resolved inventory of NOS features (commensurate with SSI contexts). For example, student characterizations of NOS tend to be context dependent, whereas most current instruments for assessing NOS understanding frame NOS abstractly, as universal statements (Sandoval & Morrison, 2003; Thoermer & Sodian, 2002; van Dijk, 2011). Furthermore, teachers facing institutional contexts of accountability need to operationalize NOS knowledge as concrete performance, or as observable or measurable behaviors (Gormally et al., 2012; Sadler, 2014). Open-ended assessments can valuably profile what students learn or perceive beyond what an instructor targeted or expected (Kruse & Wilcox, 2011), but criteria are needed for "scoring" such responses. Thus, our observations here echo sentiments expressed elsewhere: developing new methods of NOS assessment remains a major goal.

Third, more work is needed on how to integrate the various instructional approaches in fruitful ways. This will draw, first, on the recommended research that articulates in more detail the specific strengths and shortcomings of each approach. That is, we need to profile more sharply how each approach is situated to complement the others (Table 1, as a preliminary sketch). Such research should also take into account numerous practical dimensions, such as institutional contexts, the culture of science teaching, professional development, special pedagogical knowledge, and attitudes (e.g., concerns raised by Höttecke & Silva, 2012). More examples of effective integration from the perspective of the classroom, such as those discussed above (Tables 2 and 3), are needed as models for novice teachers. Clough (2006) has already emphasized the need to draw together relevant lessons and pose the appropriate questions that will foster fruitful reflection and synthesis. Teachers already know that important thematic concepts like structure and function (in biology) or conservation of energy (in physical science) are ideally conveyed through repeated encounters and explicit cross-references. Just so for NOS concepts such as controlled experiments, confirmation bias, or conflict of interest.

Fourth, NOS understanding needs to be further integrated with education about political and ethical thinking toward addressing the aim of scientific literacy, involving SSIs and their added dimension of values. While we recognize the ultimate importance of SSIs, we focused our analysis solely on the epistemic dimension of the scientific claims. Teaching the nature of cultural and personal values and how they intersect with scientific claims is yet another layer of challenge—one that cannot be taken for granted. SSIs, we have noted, form an important subset of contemporary cases, but of course they have also played an important role in history, as well, and enter intro students' personal lives. Thus, one can easily envision a parallel trio of approaches in education for thinking about values. These, too, must be integrated with each other and with the epistemic dimension of science. This is yet another significant horizon for NOS education.

A fifth and final area of prospective research will focus on how to integrate history and inquiry (Höttecke, 2013). There is a fundamental tension. Inquiry essentially depends on open-ended alternatives and student autonomy, whereas the history has already happened, with known answers and actual pathways to discovery completed by the historical scientists. While the historical trajectories can be deeply informative, they have already been established and are "nonnegotiable." Will the history upstage student effort or constrain student creativity (Henke & Höttecke, 2013)? Alternatively, if one diverges significantly from the narrative of the past, why delve into history at all? Deng et al. (2011) cited four studies that showed effective NOS learning using inquiry and history together: Solomon et al. (1992), Tsai (1999), Irwin (2000), and Kim and Irving (2010). Many others have explored this nexus, as well, with documented effectiveness: Becker (2000), Faria et al. (2012), Höttecke, Henke, and Rieß (2012), Johnson and Stewart (1990), Klopfer and Cooley (1963), and Lin and Chen (2002). Numerous others have integrated these strategies, some even using historical apparatus, all with apparently positive results: Allchin (1993; 2013a, pp. 184–201); Allchin et al. (1999), Chang (2011); de Berg (1989), Habben et al. (1994), Hagen, Allchin, and Singer (1996), Heering (1992), Heering and Wittje (2011), Kafai and Gilliland-Swetland (2001), and Reiß (1995). For many teachers already attuned to a role for history, integrating inquiry seems an intuitive next step. Yet the combination also seems to pose inherent challenges. Educational researchers may now be prepared to formally address the problem of open-ended versus closed inquiry in historical contexts.

In summary, the focus of research needs to shift from "how" to teach NOS to how to help teachers make best use of the knowledge about NOS teaching that now exists. That involves articulating more clearly the individual features of NOS relevant to functional scientific literacy, and how different approaches are appropriate to each; developing new NOS assessments for classroom use; crafting ways to integrate the complementary NOS lessons from different approaches, as well as integrate NOS with the values dimension of SSIs; and finding ways to integrate history and inquiry in teaching NOS more effectively.

REFERENCES

Abd-el-Khalick, F. (2012). Examining the sources of our understanding about nature of science. International Journal of Science Education, 34, 353–374.

Abd El-Khalick, F., BouJaoude, S., Duschl, R., Lederman, N. G., Mamlok-Naaman, R., Hofstein, A., et al. (2004). Inquiry in science education: International perspectives. Science Education, 88(3), 397–419.

Abd-El-Khalick, F., & Lederman, N. G. (2000). The influence of history of science courses on students' views of nature of science. Journal of Research in Science Teaching, 37(10), 1057–1095.

Allchin, D. (1993). Of squid hearts and William Harvey. The Science Teacher, 60(7), 26–33.

Allchin, D. (2003). Scientific myth-conceptions. Science Education, 87, 329–351.
Allchin, D. (2010). Christiaan Eijkman & the cause of beriberi. Minneapolis, MN: SHiPS Resource Center. Retrieved March 14, 2014, from http://ships.umn.edu/modules/biol/beriberi.htm.
Allchin, D. (2011). Evaluating knowledge of the nature of (Whole) Science. Science Education, 95, 918–942.
Allchin, D. (2012a). The Minnesota Case Study Collection: New historical inquiry cases for nature of science education. Science & Education, 21, 1263–1282.
Allchin, D. (2012b). Towards clarity on Whole Science and KNOWS. Science Education, 96, 693–700.
Allchin, D. (2012c). Teaching the nature of science through scientific error. Science Education, 96, 904–926. .
Allchin, D. (2013a). Teaching the nature of science: Perspectives & resources. St Paul, MN: SHiPS Education Press.
Allchin, D. (2013b). Problem- and case-based learning in science: An introduction to distinctions, values and outcomes. CBE—Life Sciences Education, 12, 364–372.
Allchin, D. (2014). On genius and happenstance in scientific discovery. American Biology Teacher, 76, 145–148.
Allchin, D., Anthony, E., Bristol, J., Dean, A., Hall, D., & Lieb, C. (1999). History of science—with labs. Science & Education, 8, 619–632.
Andersen, N. O. (2008). Et fælles løft. Rapport fra arbejdsgruppen til forberedelse af en National Strategi for Natur, Teknik og Sundhed. Retrieved March 14, 2014, from http://www.uvm.dk/~/media/UVM/Filer/Aktuelt/PDF08/080215_nts.ashx.
Ault, C. R., Jr., & Dodick, J. (2010). Tracking the footprints puzzle: The problematic persistence of science-as-process in teaching the nature and culture of science. Science Education, 94, 1092–1122.
Aydeniz, M., Baksa, K., & Skinner, J. (2011). Understanding the impact of an apprenticeship-based scientific research program on high school students' understanding of scientific inquiry. Journal for Science Education and Technology, 20, 403–421.
Barnes, L. B., Christensen, C. R., & Hansen, A. (1994). Teaching and the case method (3d. ed.). Boston: Harvard Business School Press.
Becker, B. J. (2000). MindWorks: Making scientific concepts come alive. Science & Education, 9, 269–278.
Bell, R. (2007). Teaching the nature of science through process skills: activities for grades 3–8. Boston: Allyn & Bacon.
Board on Science Education, U. S. National Academies of Sciences. (2012). A framework for K-12 science education. Washington, DC: National Academies Press. Retrieved March 14, 2014, from http://www.nap.edu/catalog.php?record_id=13165.
Boston Working Group. (2013). How can history and philosophy of science contribute to understanding the nature of science for scientific literacy?: Mapping research needs. Report from the Conference on How Can the History and Philosophy of Science Contribute to Contemporary U.S. Science Teaching, Boston University, Boston, MA, Nov. 2012. Retrieved March 20, 2014, from http://www.bu.edu/hps-scied/working-group-reports.
Brush, S. G. (1989). Theory and prediction: The case of light bending. Science, 246, 1124–1129.
Brush, S. G. (1994). Dynamics of theory change: The role of predictions. PSA 1994, 2, 133–145.
Cakmakci, G., & Yalaki, Y. (2012). Promoting student teachers' ideas about nature of science through popular media. Trondheim, Norway: S-TEAM/NTNU. Retrieved March 14, 2014, from http://s-teamproject.eu/s-team/course/view.php?id=24.
Chang, H. (2011). How historical experiments can improve scientific knowledge and science education: The cases of boiling water and electrochemistry. Science & Education, 20, 317–341.
Clough, M. F. (2006). Learners' responses to the demands of conceptual change: Considerations for effective nature of science instruction. Science & Education, 15(5), 463–494.
Clough, M. P. (2007). Teaching the nature of science to secondary and post-secondary students: Questions rather than tenets. The Pantaneto Forum, 25 (January). Retrieved January 3, 2011, from http://www.pantaneto.co.uk/issue25/clough.htm.
Clough, M. (2011). The story behind the science: Bringing science and scientists to life in post-secondary science education. Science & Education, 7, 701–717.
Clough, M. P., Herman, B. C., & Smith, J. A. R. (2010). Seamlessly teaching science content and the nature of science: Impact of historical short stories on post-secondary biology students. Sacramento, CA: Association of Science Teacher Educators Conference.
Clough, M. P., & Olson, J. K. (2008). Teaching and assessing the nature of science: An introduction. Science & Education, 17, 143–145.
Collins, H., & Pinch, T. (1993). The golem. Cambridge, England: Cambridge University Press.
Craven, J. A. (2002). Assessing explicit and tacit conceptions of the nature of science among preservice elementary teachers. International Journal of Science Education, 24, 785–802.
Crawford, B. (2012). Moving the essence of inquiry into the classroom: Engaging teachers and students in authentic research. In K. C. D. Tan & M. Kim (Eds.), Issues and challenges in science education research: Moving forward (pp. 25–42). Dordrecht, The Netherlands: Springer.

Dass, P. M. (2005). Understanding the nature of scientific enterprise (NOSE) through a discourse with its history: The influence of an undergraduate "history of science" course. International Journal of Science and Mathematics Education, 3(1), 87–115.
De Berg, K. C. (1989). The emergence of quantification in the pressure–volume relationship for gases: A textbook analysis. Science Education, 73, 115–134.
Deng, F., Chen, D.-T., Tsai, C.-C., & Tsai, C. S. (2011). Students' views of the nature of science: A critical review of research. Science Education, 95, 961–999.
Dimopoulos, K., & Koulaidis, V. (2003). Science and technology education for citizenship: The potential role of the press. Science Education, 87, 241–256.
Duschl, R. A., & Grandy, R. (2012). Two views about explicitly teaching nature of science. Science & Education, 22(9), 2109–2139.
Ekborg, M., Ideland, M., & Malmberg, C. (2009). Science for life—A conceptual framework for construction and analysis of socio-scientific cases. NorDiNa, 5(1), 35–46.
Elliot, P. (2006). Reviewing newspaper articles as a technique for enhancing the scientific literacy of student-teachers. International Journal of Science Education, 28(11), 1245–1265.
Evans, M., & Jennings, C. (2008). Ideas about science. Stevenage, England: Badger. Also retrieved March 14, 2014, from www.badgerlearning.co.uk/ecommerce/ProductPDFs/IdeasAboutScience.pdf.
Faria, C., Pereira, G., & Chagas, I. (2012). D. Carlos de Bragança, a pioneer of experimental marine oceanography: Filling the gap between formal and informal science education. Science & Education, 21, 813–826.
Ford, M. J. (2005). The game, the pieces, and the players: Generative resources from alternative instructional portrayal of experimentation. Journal of the Learning Sciences, 14(4), 449–487.
Ford, M. J. (2008). "Grasp of practice" as a reasoning resource for inquiry and nature of science understanding. Science & Education, 17, 147–177.
Gentner, D., & Colhoun, J. (2008). Analogical processes in human thinking and learning. In B. Glatzeder, V. Goel, & A. Muller (Eds.), Towards a theory of thinking (pp. 35–48). Berlin, Germany: Springer.
Gentner, D., Loewenstein, J., & Thompson, L. (2003). Learning and transfer: A general role for analogical encoding. Journal of Educational Psychology, 95, 393–408.
Giere, R. (1999). Science without laws. Chicago: University of Chicago Press.
Gormally, C., Brickman, P., & Lutz, M. (2012). Developing a test of scientific literacy skills (TOSLS): Measuring undergraduates' evaluation of scientific information and arguments. CBE—Life Sciences Education, 11, 364–377.
Habben, D., Mehrle, U., Heering, P., Meya, J., Reiß, F., Rohlfs, G., & Sibum, H. O. (1994). Vom Bernstein zur Volta-Säule: Geschichte der Elektrizität im Unterricht [From amber to the Voltaic pile: History of electricity in the classroom]. Marburg, Germany: Redaktions-Gemeinschaft Soznat.
Hagen, J. B., Allchin, D., & Singer, F. (1996). Doing biology. Glenview, IL: Harper Collins. Retrieved January 3, 2011, from http://doingbiology.net.
Heering, P. (1992). On J.P. Joule's determination of the mechanical equivalent of heat. In S. Hills (Ed.), The history and philosophy of science in science education: Proceedings of the Second International Conference on the History of Philosophy of Science and Science Teaching (Vol. 1, pp. 495–505). Kingston, ON, Canada: Queen's University.
Heering, P., & Wittje, R. (2011). Learning by doing: experiments and instruments in the history of science teaching. Stuttgart, Germany: Franz Steiner Verlag.
Henke, A., & Höttecke, D. (2013). Science teachers' perceived demands while teaching science with and about history and nature of science. Paper presented at the 12th IHPST Conference, Pittsburgh, PA. Retrieved June 24, 2013, from http://conference.ihpst.net/Procs-2013/Henke-Hottecke%20symposium.pdf.
Herreid, C. F. (Ed.) (2007). Start with a story: The case study method of teaching college science. Arlington, VA: NSTA Press.
Hodson, D. (2009). Towards scientific literacy: a teachers' guide to the history, philosophy and sociology of science. Rotterdam, The Netherlands: SensePublishers.
Höttecke, D. (2013). A sketch of the problem of authentic inquiry-based learning from a history of science perspective. Paper presented at the 12th IHPST Conference, Pittsburgh, PA. Retrieved from http://archive.ihpst.net/2013/Procs/Hottecke%20symposium.pdf.
Höttecke, D., Henke, A., & Rieß, F. (2012). Implementing history and philosophy in science teaching: Strategies, methods, results and experiences from the European project HIPST. Science & Education, 21(9), 1233–1261.
Höttecke, D., & Silva, C. C. (2012). Why implementing history and philosophy of science in school science education is a challenge: An analysis of obstacles. Science & Education, 20, 293–316.
Howe E. M., & Rudge, D. W. (2005). Recapitulating the history of sickle-cell anemia research: improving students' NOS views explicitly and reflectively. Science & Education, 14, 423–441.

Hsu, J. (2008). The secrets of storytelling: Why we love a good yarn. Scientific American. Retrieved March 13, 2014, from http://pragmasynesi.wordpress.com/2008/09/24/the-secrets-of-storytelling-why-we-love-a-good-yarn/.

Ibáñez-Orcajo, M. T., & Martínez-Aznar, M. M. (2007). Solving problems in genetics, Part III: Change in the view of the nature of science. International Journal of Science Education, 26(6), 747–769.

Irwin, A. R. (2000). Historical case studies: Teaching the nature of science in context. Science Education, 84(1), 5–26.

Jarman, R., & McClune, B. (2007). Developing scientific literacy: Using news media in the classroom. Maidenhead, England: Open University Press.

Johnson, S., & Stewart, J. (1990). Using philosophy of science in curriculum development: An example from high school genetics. International Journal of Science Education, 12, 297–307.

Kafai, Y. B., & Gilliland-Swetland, A. J. (2001). The use of historical materials in elementary science classrooms. Science Education, 85, 349–367.

Kahneman, D. (2011). Thinking, fast and slow. New York: Farrar, Straus and Giroux.

Kelly, G. J., & Duschl, R. A. (2002). Toward a research agenda for epistemological studies in science education, Paper presented at the Annual Meeting of NARST 2002, New Orleans, LA.

Khishfe, R. (2008). The development of seventh graders' views of nature of science. Journal of Research in Science Teaching, 45(4), 470–496.

Khishfe, R. (2012a). Nature of science and decision-making. International Journal of Science Education, 34(1), 67–100.

Khishfe, R. (2012b). Relationship between nature of science understandings and argumentation skills: A role for counterargument and contextual factors. Journal of Research in Science Teaching, 49(4), 489–514.

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(7), 551–578.

Kim, S. Y., & Irving, K. E. (2010). History of science as an instructional context: Student learning in genetics and nature of science. Science & Education, 19(2), 187–215.

Klopfer, L. E. (1969). The teaching of science and the history of science. Journal of Research in Science Teaching, 6, 87–95.

Klopfer, L. E., & Cooley, W. W. (1963). The history of science cases for high schools in the development of student understanding of science and scientists. Journal of Research in Science Teaching, 1, 33–47.

Kolodner, J. L., Hmelo, C. E., & Narayanan, N. H. (1996). Problem-based learning meets case-based reasoning. In D. C. Edelson & E. A. Domeshek (Eds.), Proceedings, 1996 International Conference on Learning Sciences (pp. 188–195). Charlottesville, VA: American Association for Computers in Education.

Kolstø, S. D. (2001). Scientific literacy for citizenship: Tools for dealing with the science dimension of controversial socio-scientific issues. Science Education, 85(3), 291–310.

Kolstø, S. D. (2008). Science education for democratic citizenship through the use of history of science. Science & Education, 17, 977–997.

Kruse, J. W., & Wilcox, J. (2011). Using historical science stories to illuminate nature of science ideas and reduce stereotypical views in a sixth grade classroom. Paper presented at the Association for Science Teacher Educators International Conference, Minneapolis, MN.

Kurdziel, J. P., & Libarkin, J. C. (2002). Research methodologies in science education: students' ideas about the nature of science. Journal of Geoscience Education, 50(3), 322–329.

Latour, B. (1987). Science in action. Cambridge, MA: Harvard University Press.

Leach, J., Hind, A., & Ryder, J. (2003). Designing and evaluating short teaching interventions about the epistemology of science in high school classrooms. Science Education, 87, 831–848.

Lederman, N. G., Abd-El-Khalick, F., Bell, R. L., & Schwartz, R. (2002). Views of nature of science questionnaire: Toward valid and meaningful assessment of learner's conceptions of nature of science. Journal of Research in Science Teaching, 39(6), 497–521.

Lederman, N. G., Wade, P., & Bell, R. L. (1998). Assessing understanding of the nature of science. Science & Education, 7, 595–615.

Lehrer, R., Schauble, L., & Lucas, D. (2008). Supporting development of the epistemology of inquiry. Cognitive Development, 23, 512–529.

Lin, H., & Chen, C. (2002). Promoting preservice chemistry teachers' understanding about the nature of science through history. Journal of Research in Science Teaching, 39(9), 773–792.

Losee, J. (2005). Theories on the scrap heap: Scientists and philosophers on the falsification, rejection, and replacement of theories. Pittsburgh, PA: University of Pittsburgh Press.

Lunberg, M. A., Levin, B. B., & Harrington, H. L. (1999). Who learns what from cases and how? Mahwah, NJ: LEA.

Martin, B. (1991). Scientific knowledge in controversy: The fluoridation debate. Binghamton, NY: SUNY Press.

McClune, B., & Jarman, R. (2010). Critical reading of science-based news reports: Establishing a knowledge, skills and attitudes framework. International Journal of Science Education, 32(6), 727 – 752.

McComas, W. F. (2008). Seeking historical examples to illustrate key aspects of the nature of science. Science & Education, 17, 249 – 263.

McComas, W. F., & Olson, J. K. (1998). The nature of science in international science education standards documents. In W. F. McComas (Ed.), The nature of science in science education: Rationales and strategies (pp. 41 – 52). Dordrecht, The Netherlands: Kluwer.

Meichtry, Y. J. (1992). Influencing student understanding of the nature of science: Data from a case of curriculum development. Journal of Research in Science Teaching, 29(4), 389 – 407.

Metz, D., Klassen, S., McMillan, B., Clough, M., & Olson, J. (2007). Building a foundation for the use of historical narratives. Science & Education, 16, 313 – 334.

National Research Council. (2013). Next generation science standards. Washington, DC: National Academies Press.

Niaz, M. (2009). Critical appraisal of physical science as a human enterprise: Dynamics of scientific progress. Berlin, Germany: Springer Science + Business Media.

Nielsen, J. A. (2012). Gymnasieelevers sociovidenskabelige argumentation. Mona, (3), 21 – 39.

Nielsen, J. A. (2013). Delusions about evidence: On why scientific evidence should not be the main concern in socioscientific decision making. Canadian Journal of Science, Mathematics and Technology Education, 13(4), 373 – 385.

Nielsen, K. H. (2012). Scientific communication and the nature of science. Science & Education, 22(9), 2067 – 2086.

OECD. (2009). PISA 2009 assessment framework. Paris: Author. Retrieved March 14, 2014, from http://www.oecd.org/pisa/pisaproducts/44455820.pdf.

Oliveras, B., Márquez, C., & Sanmarti, N. (2011). The use of newspaper articles as a tool to develop critical thinking in science classes. International Journal of Science Education, 35(6), 885 – 905.

Osborne, J., Collins, S., Ratcliffe, M., Millar, R., & Duschl, R. (2003). What "ideas-about-science" should be taught in school science? A Delphi study of the expert community. Journal of Research in Science Teaching, 40, 692 – 720.

Peters, E. E., & Kitsantas, A. (2010). Self-regulation of student epistemic thinking in science: The role of metacognitive prompts. Educational Psychology, 30(1), 27 – 52.

Reiß, F. (1995). Teaching science and history of science by redoing historical experiments. In F. Finley, D. Allchin, D. Rhees, & S. Fifield (Eds.), Proceedings, Third International History, Philosophy and Science Teaching Conference, Minneapolis, MN (Vol. 2, pp. 958 – 966). Minneapolis: University of Minnesota Office of Continuing Education. Reprinted by SHiPS Education Press, Saint Paul, MN.

Rudge, D. W., Cassidy, D. P., Fulford, J. M., & Howe, E. M. (2013). Changes observed in views of the nature of science during a historically based unit. Science & Education. doi: 10.1007/s11191-012-9572-3.

Rudge, D. W., & Howe, E. M. (2013). Whither the VNOS? In C. C. Silva & M. E. B. Prestes (Eds.), Aprendendo ciência e sobre sua natureza: Abordagens históricas e filosóficas (Proceedings of the First Latin American Conference of the International History, Philosophy, and Science Teaching Group) (pp. 219 – 228). (1st IHPST-LA). São Carlos, Brazil: Tipographia Editora Expressa.

Russell, T. L. (1981).What history of science, how much, and why? Science Education, 65, 51 – 64.

Ryder, J. (2001). Identifying science understanding for functional scientific literacy. Studies in Science Education, 36, 1 – 44.

Ryder, J., Leach, J., & Driver, R. (1999). Undergraduate science students' images of science. Journal of Research in Science Teaching, 36(2), 201 – 219.

Sadler, T. D. (2014). Assessment of socio-scientific reasoning: Linking progressive aims of science education to the realities of modern education. In M. Mueller, D. J. Tippins, & A. J. Steward (Eds.), Assessing schools for generation R (responsibility): A guide to legislation and school policy in science education (pp. 101 – 113). New York: Springer.

Sadler, T. D., Chambers, F. W., & Zeidler, D. L. (2004). Student conceptualizations of the nature of science in response to a socio-scientific issue. International Journal of Science Education, 26(4), 387 – 409.

Sadler, T. D., & Zeidler, D. L. (2005). Patterns of informal reasoning in the context of socio-scientific decision making. Journal of Research in Science Teaching, 42(1), 112 – 138.

Sandoval, W. A. (2003). Conceptual and epistemic aspects of students' scientific explanations. Journal of the Learning Sciences, 12(1), 5 – 51.

Sandoval, W. A. (2005). Understanding students' practical epistemologies and their influence on learning through inquiry. Science Education, 89, 634 – 656.

Sandoval, W. A., & Morrison, K. (2003). High school students' ideas about theories and theory change after a biological inquiry unit. Journal of the Research in Science Teaching, 40(4), 369–392.
Scharmann, L. C., Smith, M. U., James, M. C., & Jensen, M. (2005). Explicit reflective nature of science instruction: Evolution, intelligent design, and umbrellaology. Journal of Science Teacher Education, 16, 27–41.
Schwab, J. (1962). The teaching of science as enquiry. In J. Schwab & P. Brandwein, The teaching of science (pp. 3–102). Cambridge MA: Harvard University Press.
Seker, H., & Welsh, L. C. (2005). The comparison of explicit and implicit ways of using history of science for students understanding of the nature of science. Paper presented at Eighth International History, Philosophy, Sociology & Science Teaching Conference, Leeds, England.
Shibley, I. A. Jr. (2003). Using newspapers to examine the nature of science. Science & Education, 12(7), 691–702.
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(3), 349–422.
Solomon, J., Duveen, J., Scot, L., & McCarthy, S. (1992). Teaching about the nature of science through history: Action research in the classroom. Journal of Research in Science Teaching, 29, 409–421.
Tao, P. K. (2003). Eliciting and developing junior secondary students' understanding of the nature of science through a peer collaboration instruction in science stories. International Journal of Science Education, 25(2), 147–171.
Thoermer, C., & Sodian, B. (2002). Science undergraduates' and graduates' epistemologies of science: The notion of interpretive frameworks. New Ideas in Psychology, 20, 263–283.
Thomas, J. (2000). Using current controversies in the classroom: Opportunities and concerns. Critical Studies in Education, 41(2), 133–144.
Toumey, C., Besley, J., Blanchard, M., Brown, M., Cobb, M., Ecklund, E. H., et al. (2010). Science in the service of citizens & consumers: The NSF Workshop on Public Knowledge of Science, October 2010. Columbia: University of South Carolina Nanocenter.
Tsai, C.-C. (1999). The progression toward constructivist epistemological views of science: A case study of the STS instruction of Taiwanese high school female students. International Journal of Science Education, 21(11), 1201–1222.
van Dijk, E. M. (2011). Portraying real science in science communication. Science Education, 95(6), 1086–1100.
van Dijk, E. M. (2012). Relevant features of science: Values in conservation biology. Science & Education, 22(9), 2141–2156.
Walker, K. A., & Zeidler, D. L. (2007). Promoting discourse about socio-scientific issues through scaffolded inquiry. International Journal of Science Education, 29(11), 1387–1410.
Wilcox, J., Smith, J. A. R., & Kruse, J. W. (2013). Teaching secondary students the nature of science by scaffolding experiences along the decontextualized/highly contextualized nature of science continuum. Paper presented at the 12th International History, Philosophy, and Science Teaching Conference, Pittsburgh, PA.
Wong, S. L., Hodson, D., Kwan, J., & Yung, B. H. W. Y. (2008). Turning crisis into opportunity: Enhancing student–teachers' understanding of nature of science and scientific inquiry through a case study of the scientific research in severe acute respiratory syndrome. International Journal of Science Education, 30(11), 1417–1439.
Wong, S. L., Wan, Z., & Cheng, M. W. (2011). Learning nature of science through socio-scientific issues. In T. D. Sadler (Ed.), Socio-scientific issues in the classroom. Dordrecht, The Netherlands: Springer.
Yacoubian, H. A., & BouJaoude, S. (2010). The effect of reflective discussions following inquiry-based laboratory activities on students' views of nature of science. Journal of Research in Science Teaching, 47(10), 1229–1252.
Yerrick, R. K. (2000). Lower track students' argumentation and open inquiry instruction. Journal of Research in Science Teaching, 37(8), 807–838.
Zeidler, D. L., Applebaum, S. M., & Sadler, T. D. (2011). Enacting a socio-scientific issues classroom: transformative transformation. In T. D. Sadler (Ed.), Socio-scientific issues in the classroom. Dordrecht, The Netherlands: Springer.
Zeidler, D. L., Walker, K. A., Ackett, W. A., & Simmons, M. L. (2002). Tangled up in views: Beliefs in the nature of science and responses to socio-scientific dilemmas. Science Education, 86(3), 343–367.