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From Science Studies to Scientific Literacy: A View from the Classroom

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Abstract The prospective virtues of using history and philosophy of science in science teaching have been pronounced for decades. Recently, a role for nature of science in supporting scientific literacy has become widely institutionalized in curriculum standards internationally. This short review addresses these current needs, highlighting the concrete views of teachers in the classroom, eschewing ideological ideals and abstract theory. A practical perspective highlights further the roles of history and philosophy—and of sociology, too—and even broadens their importance. It also indicates the relevance of a wide range of topics and work in Science Studies now generally absent from science educational discourse. An extensive reference list is provided.

In October 2012, an Italian court ruled that cell phone use was linked to a plaintiff's brain tumor, although even with several large scale studies, no scientific consensus supports such a causal connection, and the measured levels of radiation are theoretically unlikely to have any effect (Alimenti 2012; Alleyne 2012; Owens 2012). Here is a concrete example of the role of scientific literacy: being able to assess the reliability of scientific claims relevant to personal and social decision making. Such cases are common. One might equally invoke the controversy over hydraulic fracturing in oil and natural gas extraction ("fracking"), with questions about environmental impacts and the safety of the chemicals involved. Or new recommendations on ages for regular breast cancer screening. Or human causes of climate change. Such cases underscore the need for understanding the nature of science, or how science works (including the presentation of its claims through news, marketing, and politics). They exemplify what science students need to know as citizens and consumers (see also Kolstø 2001; Ryder 2001). How might history and philosophy of science—as well as allied disciplines—contribute to this central aim of science education?

From the first article in its first issue, this journal has promoted a theoretical role for history and philosophy of science (HPS) in science education. Over two decades later, a

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role for the nature of science, as informed by HPS, has become widespread in curricula standards internationally (American Association for the Advancement of Science 2009; National Research Council 2013; OECD 2009). Accordingly, the challenge for historians and philosophers of science contributing to science education has shifted considerably. Advocacy of prospects and abstract theoretical discussion has now yielded to addressing the concrete realities of the classroom. Accordingly, this paper adopts as its central orientation the perspective of practicing teachers. It focuses less on what historians or philosophers or others might want to "contribute," than on what a teacher will find enriches student understanding about cases such as those noted above. The ultimate aim forms the standard or context for gauging what is valuable to teach.

A further consequence of this orientation is that the relevant fields expand well beyond the history and philosophy of science. Any study of science, from whatever perspective, can provide insight for interpreting science and scientific claims in a cultural context. Thus, the teacher will equally welcome contributions from the sociology of science, as well as from anthropological, cognitive, literary, rhetorical, technical, psychological, cultural, political, economic, feminist, and Marxist perspectives: all the disciplines that now fit along with history and philosophy of science under the banner of Science Studies (Hackett et al. 2007; Hess 1997). In the twenty-first century, an HPS-informed approach to science education conjures a vast net stretching from the breadth of Science Studies to functional scientific literacy on socioscientific issues. In this essay, I survey some of the territory, highlighting in particular relevant contributions from Science Studies still largely absent from the discourse among science educators. For some, the essay may function like an annotated bibliography of major ideas from Science Studies in the last several decades relevant to educating the scientifically literate citizen.

The survey is arranged in two major parts. First, I profile a pair of benchmarks that help frame the appropriate classroom context. Second, I consider the role of three familiar approaches in teaching the nature of science—student-based inquiry, contemporary cases, and historical cases—and explore how different perspectives from Science Studies may prove valuable for each. General conclusions follow in a closing section.

1 Two Benchmarks for Effective NOS Education

As noted above, many international science curriculum standards now explicitly identify nature of science (NOS) as an integral component of scientific literacy. Terminology varies. Some refer to "scientific practices," some to "science as a way of knowing," "ideas about science," "how science works," or the "identity and methods of the discipline." But all indicate how understanding *about* science should help students as citizens and consumers in contemporary society, able to participate responsibly in personal and social decision making. Most allude to history and philosophy of science as a major source of that understanding. This ultimate aim establishes an informative first benchmark for considering just how the history and philosophy of science and allied fields are primarily relevant to science education.

For example, some educators, apparently buoyed by philosophical discussion on the nature of explanation, have focused on teaching about explanations in science (Duschl and Grandy 2008). Indeed, based on this aim, educators have demonstrated that one can indeed effectively engage students in scientific model-building and discussion about the explanatory status of models or of scientific theories. Yet, again using functional scientific literacy as a benchmark, one may question the emphasis on explanation. Contemporary debates on climate change do not hinge on the whether global warming can *explain* climate change. They focus on whether claims about anthropogenic sources of warming are *warranted*, whether the naysayers have the relevant *expertise*, or whether the models that predict future climate change scenarios are robust or *trustworthy*. The same applies to fracking. *Explaining* how it works—especially in an idealized conceptual sense—does not fully address the central issue of whether one can trust the claims about its safety. Reliability seems to be the central principle, not explanation. A shift from philosophers' favored topics to the demands of scientific literacy seems critical for guiding science education effectively towards it goal.

Philosophers have certainly debated how to characterize, or demarcate, science—without any measurable success after many decades of effort (Allchin 2013b, pp. 5–12). Educators, too, have discussed what core features of NOS might be relevant for science education—and in the late 1990s seemed to reach a general consensus (McComas and Olson 1998; Osborne et al. 2003). Yet the benchmark of scientific literacy means that what constitutes relevant knowledge of NOS is largely an empirical question, not a matter of judgment. Several analyses into what knowledge one needs to interpret the scientific claims in socioscientific issues (SSIs) have yielded a concrete inventory of functional NOS knowledge and its major categories.[1] This is far deeper, more specific, and more concrete than the familiar NOS "consensus list" (see recent spirited defense by Abd-el-Khalick 2012) or the narrow claim (defended in this journal especially by A. Lawson) that all science is "essentially" hypothetico-deductive in nature (see earlier critiques by Allchin 2003a, 2006a, b). Others try to use the banner of NOS to mix features of epistemic understanding with ideological beliefs. Matthews (2009), for example, insists that student understanding of the scientific tradition should include not only experimentation and a respect for evidence, but also (in the very same list) appreciation of the values of "hard work," "independence of mind," "a deep suspicion of authoritarianism and dogmatism, and the concern for promotion of an open society" (pp. 955–956). These are political positions and personal values, not the basis for assessing the reliability of scientific claims in SSIs. Concrete cases of contemporary SSIs then, as a point of reference, can discount much philosophical and ideological wrangling about NOS in educational contexts. Indeed, this benchmark helps shift the focus from "pure" philosophy of science (for its own sake) to applied philosophy of science (as reflected, for example, in the focus of the recently established Society for the Philosophy of Science in Practice). Metaphysical concerns about epistemology need to shift to understanding of epistemics, or situated epistemology and its pragmatic dynamics (Callebaut 1993). While many insights from HPS are valuable, only some are directly relevant to the foremost goals of science education. NOS education needs ultimately to inform cases such as those cited above: cell phones and cancer, the safety of fracking, mammogram screening, and climate change.

A second important benchmark for effective NOS education is the teacher's perspective and the practical dimensions of the classroom context. Efforts to integrate history of science into science education are certainly not new. One may note several major projects over the past several decades involving some prominent historians of science as contributors (Table 1). While each had some limited success, all have languished—even where educational research has indicated that the project had some positive impact on views or attitudes about science or on NOS understanding. Their ultimate fates provide cautionary tales for the naive historian-enthusiast. They indicate, for example, that sweeping systematic projects are probably not the answer (as least not currently). The challenges in

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[1] Allchin (2013b, pp. 12–26), Kolstø (2001), Ryder (2001), Toumey et al. (2010).

Table 1 Major initiatives in integrating history into science education

Introduction to Concepts and Theories in Physical Science and Physics, the Human Adventure	Holton and Brush (1952, 1972, 2001)
Harvard Case Histories in Experimental Science	Conant and Nash (1957)
History of Science Cases	Klopfer (1964–66)
The Study of Biology	Baker and Allen (1967, 1971)
Project Physics	Rutherford et al. (1970)
Biology: The Network of Life	Mix et al. (1992, 1996)
Doing Biology	Hagen et al. (1996)
History of Science Classroom Lesson Plans	Hatch (1999)
Mindworks	Becker (2000)

large-scale overhaul for both teachers (professional development and training) and school systems, involving not just a curriculum but also the very culture of teaching, are formidable (Henke and Höttecke 2013; Höttecke and Silva 2011). For a system in transition, smaller scale, incremental changes, will be needed: ones that can accommodate the local needs of the teachers (Friedman 2009). The teacher's perspective, as a second benchmark, is an important "check" on plans to import HPS perspectives wholesale into real classrooms.

Understanding the teacher's perspective is also relevant in conceiving the kind of HPS or Science Studies that is relevant in the classroom. Science teachers are typically burdened with teaching an excessive scope of content. While reforms now underway should ease this problem, one must be aware not to substitute it with another, different kind of content. Science teachers are not history teachers. They are not philosophy teachers. The HPS appropriate to the K-12 science classroom is limited to the perspectives that can enrich a generalist's understanding of how science works. Metaphysical issues about realism versus instrumentalism, for example (the topic of one earlier debate about NOS; Alters 1997; Eflin et al. 1999), or reductionism in biology or chemistry (a classic favorite among philosophers), are rarely relevant to the K-12 classroom. Likewise, a detailed understanding of the historical factors fostering the Scientific Revolution, or of what makes modern science "modern," are beyond the scope of the teacher teaching functional scientific literacy. Historians and philosophers ready to contribute to science education need to acknowledge that the science classroom has its own needs, quite distinct from their "ordinary," but ultimately specialized academic concerns.

The HPS academic who listens attentively to classroom teachers will soon learn that most practicing teachers perceive their primary challenge as motivating students. This is not motivating them merely about science. It is about motivating them in school generally. Thus, approaches merely to make science "interesting" may not be effective. In particular, one should note the difference between capturing a student's attention in the short-term, and engaging them cognitively in a way that fosters meaningful long-term learning. As expressed in part in the goal of functional scientific literacy, the fundamental challenge is to make the science *meaningful*. Of course, historical and philosophical perspectives are ripe for fostering such engagement. History, in particular, can help restore science to its human and cultural contexts. It can help motivate inquiry through reviving the original historical contexts that once fueled science-in-the-making. Epistemic questions, too, are best motivated through authentic cases. The artificial thought-experiments so common to philosophical discourse are best reserved for more advanced study. History and philosophy, as potential motivational factors, need to be properly framed for the classroom, the second benchmark.

Another challenge in shifting from academic to classroom perspectives is in integrating history and philosophy. The relation between history and philosophy has always been viewed as problematic if also fruitful (Brush 2007b; Losee 1987; Nickles 1995). Philosophers typically regard scientific methodology *normatively*, in terms of ideal principles for generating reliable knowledge. They tend to generalize. Historians, by contrast, tend to be *descriptive*. They document—often emphasizing the significance of particular details—what scientists actually did, even if it was unplanned or not ideal. The contrasting perspectives can foster contention about "the" nature of science (Allchin 2013b, pp. 107–120). Currently, the narrowly idealized accounts predominate (for example, the "Understanding Science" website (2013); or the recent defense by Abd-el-Khalick 2012, pp. 366–369). Yet in a classroom trying to develop understanding of real, often incomplete and uncertain science, they foster misleading images. Both views are needed. Educators might thus benefit from exploring more fully just where the fields of philosophy and history (and sociology) intersect. For example, philosopher John Losee (1987, 2001) has long advocated a *descriptive* philosophy of science, treating scientific methods as subject to historical scrutiny, not merely philosophical analysis. David Hull (1988), likewise, has promoted a "science of science." He suggests, for example, that claims about whether age influences a scientist's acceptance of new theories, need rigorous historical evidence. Other philosophers, too, have taken "the naturalistic turn" (Callebaut 1993), studying the achievements (and limitations) of real scientists in authentic contexts, not merely crafting imagined norms. Historian Stephen Brush (1994, 2004, 2007a) has answered the call in part, by a series of analyses on the role of predicting new findings (versus accommodating existing results) in the reception of new theories, and on the limited use of the hypothetico-deductive method (see also Donovan et al. 1992, on "testing" theories of scientific change). Another important orientation has been to profile the work of scientists in terms of "strategies," or context-dependent methods or tools—as exhibited in the hybrid HPS work of Lindley Darden (1991) on the history of Mendelian genetics; Bill Bechtel and Bob Richardson (2010) on reductionism in biology; and William Wimsatt (2007) on numerous topics (also see book reviews in this journal, Vol. 4 [1995], pp. 399–402). The classroom perspective, as a second benchmark, underscores the need to mindfully select, integrate, and adapt material from both the history and philosophy of science.

2 Three Approaches to Contextualizing NOS Education

In the classroom, the teacher faces the concrete challenge of creating specific learning experiences that will help students develop an understanding of how science works, to contribute towards the ultimate goal of functional scientific literacy. One strategy is to focus particular lessons on NOS exclusively, targeting NOS principles in an abstract or decontextualized way (for example, see http://msed.iit.edu/projectican/teachers.html). Yet such lessons lack authenticity. When scenarios are stripped of context, the teacher needs to add further lessons, to carefully guide students in transferring their understanding to real-life examples (Ault and Doddick Ault and Dodick 2010; Clough 2006; Sandoval and Morrison 2003; Zeidler et al. 2002). NOS lessons, even if selective, streamlined or simplified, are ideally contextualized (for example, Irwin 2000; Johnson and Stewart 1990).

Science educators now generally recognize three basic approaches for contextualizing NOS: through students' own inquiry activities, contemporary cases, and historical cases

(Bell 2009; Deng et al. 2011; Osborne et al. 2003). While these might well be viewed as alternative, competing approaches, each exhibits both benefits and deficits. The pragmatic teacher views them instead as complementary, adopting and integrating all three approaches (Allchin et al. forthcoming). Scholarship in Science Studies can potentially inform each approach, although in different ways.

2.1 Student Inquiry

First, consider the most widely acknowledged approach to contextualizing NOS lessons: student inquiry, or student-led investigations (BOSE 2012; Deng et al. 2011; Duschl and Grandy 2008). The objective is for students to engage in authentic research (appropriately scaled and scaffolded to their ability levels) and to explicitly address and reflect on the epistemic problems they encounter, such as the quality of evidence, conflicting interpretations of the same data, anomalies based on new observations, disagreement about alternative models, and so forth (Bell 2007; Crawford 2012). Such exercises can clearly be informed by understanding how historical and contemporary scientists think through similar problems. Notable philosophical work articulating important reasoning patterns, enriched by historical study, has been done by Kevin Dunbar (2001; Dunbar and Fugelsang 2005a, b), Ron Giere (1988, 2006), Nancy Nersessian (1984, 2008), Paul Thagard (1995, 1999), and Ryan Tweney (1991, 1992, 2001) (also see Gorman et al. 2005). Their work has already helped science educators develop an appreciation of model-based reasoning and informed the design of activities for guiding students through similar activities (for example, Lehrer et al. 2008; Smith et al. 2000). The studies support a relatively deflationary view of the nature of science. That is, they can help whittle away at common epistemological preconceptions that scientific theories are absolutely certain and thus permanent, and that scientific evidence is unambiguous and unmediated by human interpretation. Left unaddressed, such black-and-white views tend to polarize public debate on SSIs (Martin 1991). When not met, they may trigger disillusionment about science. Moderating the extreme expectations by drawing on philosophical studies can thus contribute to the benchmark of more scientifically literate citizens and consumers, able to participate in more nuanced (and presumably fruitful) public discourse about scientific claims.

Yet this particular philosophical view of scientific reasoning, like many philosophical views, also tends to idealize the thinking process. Further philosophical work might now add to even deeper understanding relevant to SSIs, and thus the classroom. Namely, scientists often reason pragmatically and indirectly, through analogy and heuristics. That is, with limits to time, resources, and/or funding, or faced with “messy” system complexity, they economize with alternative methods. Such alternatives are productive, although not infallible. Consider the high profile case from the late 1980s and early 1990s of research indicating a possible link between cancer and electromagnetic fields (EMFs) (Park 2000, pp. 140–161). One study found that leukemia was more common among children living close to high voltage power lines. A second study in 1989 confirmed this. With concerns high, a flurry of further investigations ensued. Many years later, in 1996, a National Research Council panel reviewed over 500 available studies, but found no causal link. The original researchers had used distance from power lines as an easy proxy for the degree of EMF exposure (what philosopher Donald Campbell (1960, 1974) has appropriately dubbed a “vicarious selector”). Subsequent researchers actually entered the homes and measured the EMFs directly. There was no correlation. Starting in 1989, however, a notable science reporter had raised public alarm with a prominent article in *The New*

Yorker and two successive books. Many concerned parents lobbied for local changes and filed lawsuits for damages. All because there was not sufficient caution about a surrogate measurement technique as a possible source of error. The world is complex and scientists often adopt such heuristic strategies, usually fruitfully. Here, it is the methods themselves, not the resulting models, that are less than some oft-imagined ideal. The same applies to our cognition. Our brains function pragmatically, not ideally. They exhibit limits and sometimes built-in biases in reasoning. The widespread impression of error-proof methods in science is ill informed. As exemplified in the case of EMFs and cancer, these factors about how science works should inform complete science education, too. For insights, educators may turn to the work of Donald Campbell (1960, 1974), Daniel Kahneman (2011), Peter Taylor (2005), and William Wimsatt (2007), among others (Creager et al. 2007).

Another important dimension of scientific inquiry modeled in the classroom is the social process of cross-checking, or critical discourse (Duschl and Grandy 2008; Finkel 1992; Keiny and Gorodetsky 1995). Such lessons can inform, in particular, an understanding of disagreement among scientists in contemporary debates on SSIs. Consensus matters. Appeal to evidence in resolving disagreement matters. Different perspectives can be a strength, not an inherent weakness, nor a reflection of incompetence or willful error. This dimension of science—*social epistemology*—has been profiled recently by several philosophers of science: for example, Alvin Goldman (1999, 2002); Sandra Harding (1991, 1998), David Hull (1988), Helen Longino (1990, 2001), Steve Shapin (1994), and Miriam Solomon (2001), among others. Their work, too, has informed educational developments and research on inquiry (Duschl and Grandy 2008). However, as in the case of reasoning strategies, educators have tended toward a potentially misleading, somewhat positivistic view. That is, the sources of individual interpretation can be deeply rooted: in gender or racial bias, in cultural or nationalistic values, or in class relations or politics. These can shape SSI perspectives. For example, in the case of mammogram screenings noted above, there was concern that gendered perspectives might have influenced conclusions that reduced costs, while placing undue additional risks on women. Although those attributions proved ill founded in that case, such biases are hardly unprecedented—for example, in historical diagnoses of hysteria (Scull 2009); breast-feeding or the female skeleton as a "natural" basis fo social roles (Schiebinger 1989, pp. 189–213; 1993, pp. 40–74); or craniology as a rationale for social discrimination based on women's presumed lower intelligence (Fee 1979).

Cultural biases can permeate science. And awareness of the potential of these biases is concretely relevant for functional scientific literacy. Indeed, the philosophical attention to social epistemology was largely spurred by awareness of the adverse social or cultural influences in such cases. Social prejudices and blind spots are not easily modeled in the classroom. Exposing them risks violating a professional environment of respect for students, for example, as well as introducing a formidable task of managing strong emotions. Yet a fully informed view of how science works (or, in some cases, does not work) includes understanding the role of cultural perspectives (including race, gender and class). Science educators are well advised to be attuned to these issues, amply profiled by historians, sociologists, and other in the cultural studies of science: including (as a sampling) works by Elazar Barkan (1992); Stephen Jay Gould (1981); Donna Haraway (1989); James Jones (1981); Leon Kamin (1974); Richard Lewontin (1996); Richard Lewontin, Stephen Rose and Leon Kamin (1984); Londa Schiebinger (1989, 1993); Steve Shapin and Simon Shaffer (1985); and Marianne van der Wijngaard (1997).

Many supporters of inquiry instruction tend to treat science as just scientific *thinking* or scientific *reasoning*. Philosophers and sociologists of science, however, have noted the equally significant role of *laboratory skills*, the *materiality* of experiment, and semi-autonomous (non-theory-based) work on *experimental systems*, as articulated in the work of Robert Crease (1993); Allan Franklin (1986); Ian Hacking (1983), Robert Kohler (1994); Andrew Pickering (1995); and Hans-Jorg Rheinberger (1997, 2010). Such elements may indeed be effectively integrated into classroom inquiry activities, and their relevance underscored through student reflection, as demonstrated in the work of a handful of historian-educators (Heering 1992; Reiß 1995). Indeed, educators may further reflect on the politics of privileging intellectual work (versus labor) (Conner 2005; Shapin 1989).

Another frequent element in discovery, highlighted especially in the work of historians, is chance, or contingency. That is, new concepts, awareness of meaningful new phenomena, or recognition of new theoretical patterns often arise through the unexpected and unplanned convergence of events or people. In such cases, “method,” in the sense of systematic search or trial, is secondary. Of course, this is hard to model through inquiry in a classroom. The teacher may certainly hope for occasional opportunities and capitalize on them, but it is hard to count on them in a planned curriculum. Still, contingency can be an important feature in interpreting contemporary science. Citizens cannot reasonably expect science to leverage solutions to problems at will, even with extraordinary inputs of resources. One cannot summon at will a cure to breast cancer or alternative energies to replace fossil fuels, in order to reduce greenhouse gas emissions or the demand for oil that drives the economy of fracking. “Breakthroughs” often enough emerge only from happenstance. Nor does every investigation necessarily yield important “new” findings. The cost of science includes its “failures.” The key role of contingency is one limit to student inquiry as an exclusive means of teaching NOS. Educators may find general discussions of chance, sometimes generously called serendipity, by Horace Freeland Judson (1980, pp. 67–86), Alexander Kohn (1989) and Royston Roberts (1989). Some vivid historical accounts of contingency and the complexity of discovery involve Priestley’s work on airs (Johnson 2008); Marshall and Warren on the bacterial cause of ulcers (Thagard 1999); Meselsen and Stahl’s haphazard route to the “most beautiful experiment in biology” (Holmes 2001); and the discovery of transfer RNA and the mechanisms of protein synthesis in the cell (Rheinberger 1997). These may help educators embrace the importance of using historical stories to complement student inquiry.

While student-led inquiry is frequently touted as the foremost method for NOS lessons, historical and sociological perspectives on cultural bias and chance, among other topics, indicate important limits to what it can achieve. Problems of the distribution of expert knowledge and negotiating one’s way through the social architecture of trust (profiled more fully below) are also beyond the scope of most K-12 classroom settings. Thus, while inquiry is an indispensable tool for NOS education, it is at the same time limited (Allchin et al. forthcoming). Inquiry is appropriately integrated with other acknowledged methods for contextualizing NOS, to which I now turn.

2.2 Contemporary Cases

Consider next the second way to contextualize NOS lessons: contemporary cases. These resemble most closely the ultimate aim of informing engagement with SSIs. They help illustrate vividly the relevance of NOS, or epistemic, topics. They offer opportunities for students to exercise and practice their skills in interpreting such cases.[2] For example, many

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[2] Khishfe (2012); Sadler et al. (2004); Wong et al. (2008); Wong et al. (2011); Zeidler et al. (2011).

researchers have found that analyzing news presentations about SSIs can promote NOS awareness and critical thinking about argumentation.[3]

Such occasions for learning about NOS differ significantly from student inquiry lessons, however, and offer opportunities to extend them in particularly fruitful ways. Most importantly, perhaps, inquiry lessons tend to emphasize scientific thinking skills. They aim to develop students able to assess as well as generate evidence, and to dissect and evaluate arguments. The implicit—and often explicit—goal is to develop independent thinkers, able to assess evidence and arguments in a social context. While basic skills may be useful in some settings, philosophers and sociologists of science now consider such a grand vision of independence utopian. Even for professional scientists themselves. In modern society, with its vast distribution of specialized knowledge, we cannot be fully independent thinkers. We all rely on others for knowledge, and for justifying that knowledge independently of our own judgment. For example, the members of the task force that reviewed appropriate ages for mammogram screenings were experts on statistics, epidemiology, radiology, and clinical medicine. But at the same time, they would be ill-equipped to evaluate arguments about the hydrogeology of fracking or the environmental hazards of transporting its chemicals or storing its wastes. And vice versa. Even a single scientific paper can exhibit the inevitable reliance on others for scientific knowledge. The paper announcing the discovery of the top quark had over 200 authors, the list filling the journal article's opening page and spilling over onto the second. Science and scientific literacy both involve *epistemic dependence*, a principle articulated by John Hardwig (1991) and its implications for science education vividly discussed by Stephen Norris (1995, 1997), Gaon and Norris (2001). Testimony and expertise—whose roles are underscored when one engages contemporary cases—are just as important to the nature of modern science as evidence and argument.

Two dimensions of epistemic dependence are especially important for science educators. First, what is the nature of expertise, and the means for a non-expert to know who to trust? One may recall the case of an earthquake predicted for New Madrid, Missouri, in late 1990. The National Guard was called out and residents invested more than $22 million in additional home insurance, all based on a forecast by someone without proper credentials. Residents (and the governor) behaved as if they knew better than the experts of the U.S. Geological Survey, who had firmly profiled the prediction as ill founded (Spence et al. 1993). A proper understanding of expertise could have of forestalled much needless expense and effort. Climate change critics, too, invite ordinary citizens to draw conclusions from fragments of negative evidence. They rely on popular impressions that each person is competent to judge the evidence for themselves. They cannot. We rely on the consensus of intergovernmental panels of experts to guide us in such complex science. As contemporary cases indicate, then, the nature of expertise is an additional key feature of the nature of science, now generally absent in science curricula. For further insight, educators may delve into the philosophical work of Alvin Goldman (1999, 2001) and Evan Selinger and Robert Crease (2006), among others (also see a sample advanced student inquiry lesson sequence by Gábor Zemplén 2010).

A second dimension of epistemic dependence concerns communication and credibility. Who can be trusted as a credible source of information about science? That is, conflicts of interest or ideological, political, or commercial motives can readily distort scientific results. One can purport scientific expertise or evidence where there is none. As an extreme, in modern society, ordinary consumers and citizens are susceptible to science

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[3] Cakmakci and Yalaki (2012); Elliot (2006); Jarman and McClune (2007); Oliveras et al. (2011); Shibley (2003).

con-artists (Allchin 2012b). For example, one glaring example is the public image campaign from the early 1990s to the present over supposed uncertainty about anthropogenic climate change—the political tactics now documented in detail by historians Naomi Oreskes and Eric Conway (2010; also see Union of Concerned Scientists 2007). Indeed, as they have shown, the public subterfuge was a legacy of earlier efforts to mislead the public on second-hand smoke, acid rain, ozone depletion, and pesticides. One 1969 tobacco industry document referred explicitly to the intent:

> Doubt is our product since it is the best means of competing with the "body of fact" that exists in the minds of the general public. It is also the means of establishing a controversy. (Michaels 2008, pp. x, 11)

Efforts to "bend" science for power and profit permeate modern society (McGarity and Wagner 2008). Given these challenges, functional scientific literacy now involves preparing individuals to analyze the credibility of sources, the context that must be addressed *before* one can even begin to consider the evidence or arguments they present. One may wonder who gave testimony to the Italian court on cell phones and cancer, and how their expertise and credibility were assessed. Science educators may find effective profiles of this important topic in Goldacre (2010); McGarity and Wagner (2008), Michaels (2008); Mooney (2005), Oreskes and Conway (2010); and Rampton and Stauber (2002).

Classroom teachers, in my experience, have long been attuned to the critical analysis of science reports in the news, a challenge now amplified by the flood of information—and misinformation—on the Internet. These informal practices now find strong justification in formal philosophical and sociological terms. Moreover, they fit squarely within the framework of familiar epistemic problems, already construed as the nature of science. The institutions that establish curricula may now find reason to acknowledge and adopt the practices that responsible science teachers have long used. For example, the recently released Next Generation Science Standards in the U.S. explicitly mention science and society issues (NRC 2013). However, they also currently frame such issues as separate from "scientific practices." The shared epistemic themes, as described above, are yet to be fully profiled, a deficit in the Framework document (BOSE 2012) that guided their development.

Ironically, mere engagement with contemporary SSIs does not necessarily lead to *learning* about NOS. For students not already experienced in NOS issues, the NOS features do not necessarily announce themselves. One needs to already have some NOS awareness to be able to probe such cases effectively and *notice* the relevant NOS features as relevant (Elliot 2006; McClune and Jarman 2010). In addition, news reports rarely refer to researchers' methods, details of their practice, or other factors in how science works (Dimopoulos and Koulaidis 2003; Oliveras et al. 2011; Ryder 2001). Even worse, perhaps, in controversial issues, students (like others) tend to focus selectively on the scientific evidence that supports their own views and values. They do not consider all the available evidence in a more complete or balanced way.[4] In the classroom, such tendencies tend to subvert efforts to teach how science works. Even less can they illustrate how prior beliefs may blindly influence scientific interpretations. Indeed, as noted by Thomas (2000), students' emotional engagement in current politics or ideology can easily confound clear NOS analysis. Educators owe more attention, perhaps, to cultural studies on the public understanding of science—such as Kahneman (2011); Martin (1991); and Toumey (1996)—and

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[4] Kahneman (2011), Martin (1991), Nielsen (2012), Sadler et al. (2004), Zeidler et al. (2002).

how they might inform deeper and more meaningful lessons about NOS in structured classroom environments.

Thus, while contemporary cases have a valuable role in *rendering the relevance of* NOS, they seem more problematic in fostering effective NOS *learning*. In addition, contemporary issues are typically open-ended. There is no clear resolution, or outcome, with which to gauge, in retrospect, how the various scientific claims ultimately fared. So the learning is open-ended, too. For closure, one needs history, the third approach to teaching NOS.

2.3 Historical Cases

A third form of contextualizing NOS is through historical cases. Some major initiatives have been noted in Table 1. Successful efforts have also been documented by Clough, Herman and Smith (2010); Faria et al. (2012); Howe and Rudge (2005); Irwin (2000); Kruse and Wilcox (2011); Lin and Chen (2002); Rudge et al. (2013); and Solomon et al. (1992). These lessons have been especially effective at conveying the "tentativeness" of science, historically regarded as the most important dimension of NOS (Lederman et al. 1998). That is, historical cases help render conceptual change, error, and learning from error (sample lessons in Allchin 2012c, Table 3). In particular, history can depict change that is more substantive than the gradual succession of models frequently a part of student inquiry activities. An understanding of revolutionary change seems to require the large scope and imaginative repertoire of history. Perhaps, then, someone concerned about breast cancer need not be alarmed or confused about the dramatic change in recommended ages for screening. With historical perspective, such persons understand how, with additional evidence and meta-studies, scientists might outright reject former conclusions. Sometimes, knowledge progresses by replacing rather than adding to previous findings. The landmark claims of Thomas Kuhn (1970), already widely known among educators, are still vividly relevant. (For an authoritative guide to Kuhn's complex and multi-layered thinking, see Hoyningen-Huene 1993).

History is also an indispensable resource for learning about the cultural context of science, which tends to be invisible within one's own culture. That is, where the culture is remote in time or place, one can more readily perceive the ideas and values as distinctive, and appreciate how they influenced the science: in the research that was funded, the types of questions that were asked, the theories that were developed, the filtering of observations, the possibly biased interpretations of results, and perhaps the casual discounting of cogent criticism. As noted above, these lessons are largely unavailable through student inquiry or contemporary cases, yet are compellingly rendered through history.

Yet for such lessons to be effective, they must also be rendered in human scale and in a perspective that makes the scientists' actions and thinking seem reasonable. Educators need to revive the sense of being present at the moment, making sense of events in historical context. Sociologist Bruno Latour (1987) called this situated perspective "science in the making," as contrasted to the retrospective "ready-made science," familiar from textbooks and popular triumphal accounts of scientific achievement. The science-in-the-making of the past is how today's students find relevance in the history, enabling them to transfer the lessons to contemporary science, also in-the-making (Flower 1995). Recovering historical perspective can be challenging. But this is precisely what historians are trained to do. And why their skilled work is so essential for science teaching.

A few examples may help illustrate the importance of the historian's professional perspective. First, consider what one scientist described as "the most beautiful experiment in biology," Meselsen and Stahl's 1959 demonstration of how DNA replicates. The experiment is sometimes described in college-level introductory textbooks. It is simple to describe and its elegant design easy to understand. Yet the history of the experiment extended over 5 years, and was itself anything but elegant. It started with a chance encounter over afternoon cocktails, and involved false starts, abandoned plans, trial and error, opportune new technology, negotiations for centrifuge time, struggles to find methods to lyse cells, etc. Historian Larry Holmes needed a full 500-page book (2001) to document it fully. Just one experiment. Of course, that is far more than most students need to know. But small tastes of the detailed complexity are telling. Without them, the aesthetic "textbook" appreciation of the published experiment (ready made science) can eclipse an informed understanding of the authentic nature of science (based on science in the making). That is why the historical perspective of science-in-the-making is so critical.

The same applies to images of Galileo's trial, widely viewed as emblematic of a supposedly enduring conflict between science and religion. The intimate historical accounts by Mario Biagioli (1993) and Dava Sobel (2000) offer quite a different image. First, Galileo was himself religious. Indeed, he wrote theologically about Copernicanism—the origin of his troubles with the Church: based not on his science, but his theology. Politically, he implicitly challenged the Vatican's authority in interpreting scripture. Second, Galileo's science was not as conclusive as many imagine. His *Dialog on the Two Chief World Systems* (whose frontispiece has for years adorned the cover of this journal) presented the tides as physical evidence of the movements of the Earth. His explanation of the tides, by modern standards, was plainly *wrong*. At the time, most Church astronomers adopted the Tychonic system. The only evidence that might distinguish between that and a Copernican world, was annular stellar parallax, and none could then be observed. Finally, Galileo was a shrewd courtier, negotiating his patronage through treacherous court politics. But he seems to have stepped on too many toes, contributing to his ultimate demise, quite apart from any of his scientific claims. This is how science happens, embedded in the securing of funds, academic rivalries, and cultural settings. Again, history determined by the perspective of ready made science can eclipse an understanding of science in the making, the window into the forward-looking nature of science, as we experience it today. A judge who does not take the time to consider the politics of science-in-the-making or the epistemic dimension behind testimony presented in a courtroom—whether about cell phones and cancer, or other topics—can easily be led astray. The contributions from historical scholars are essential.

The perspective of restoring history as science-in-the-making resonates strongly with a general inquiry approach to learning. That is, the historical perspective can motivate and contextualize inquiry questions, whether about investigative processes, the interpretation of results, the design of new experiments to address criticism, or the nature of science itself (Allchin 2012a). In addition, narratives are a familiar format, conducive to learning. Histories thus seem excellent vehicles for NOS learning.

At this point, the educator will benefit from further excursions, not into history itself, but into historiography, or the philosophy of history. For many, perhaps, the content of the story and the way the story are told are separate and independent. However, historian Hayden White (1987) has profiled how the story implicitly *is* the message. How the story is told is as important as what the story is about. The form is part of the content. A story about a scientist is thus simultaneously a lesson about the human dimension of science. A story about scientific knowledge in an indigenous culture is, in part, a lesson that science is in some sense universal. In the same way, a storytelling approach that tries to romanticize scientists (Hadzigeorgiou et al. 2012) will inevitably romanticize the nature of science, as well, and thus mislead students. While such heroic story styles may tempt the teacher interested in motivating students or recruiting future scientists, they may come at a cost of promoting distorted public views of the nature of science. An Italian court recently found 6 geologists guilty for failing to predict an earthquake (Hall 2011). Where did such an unrealistic expectation of science come from? Conveying an authentic nature of science depends not only on authentic scientific practices, but also on an authentic and complete history. As White observed, the story form has content. Popular culture is already replete with caricatures and counterproductive scientific myth-conceptions (Allchin 2013b, pp. 46–76). We do not need more in the science classroom. Science teachers are ideally situated, rather, to remedy the cultural stereotypes. In this sense, the philosophy of history is just as important to science educators as the philosophy of science, or the history itself.

The form of the history also includes its characters and settings. Thus, histories of science that focus only on historical achievements by men convey an implicit lesson that science is male. Historical case studies that focus only on Western science convey an implicit lesson that science is exclusively Western. Here, again, historians are resources for the information that will help broaden these images in authentic and enriching ways. For introductory surveys on women in science, see works by Kass-Simon and Farnes (1993), Ogilvie (1993), Rossiter (1982, 1995, 2012), and Schiebinger (1989), among many others. On non-Western science, see for example works by Aikenhead and Michell (2011), Bass (1990), DeKosky and Allchin (2008), Freely (2009), González (2001), McClellan and Dorn (1999), Ronan (1982), Ronan and Needham (1978–1995), Selin (1997), Temple (2007), and Teresi (2002).

Another important historiographic role for professional historians among educators is to help ensure that the history is responsible to the spectrum of available historical evidence and thus not unduly biased by theoretical perspective or ideology. It is very easy to read history selectively and extract just those items that accord with one's own view of science. Historical cases based on *reconstructing* the history according to some predetermined or idealized view of science can grossly mislead students about NOS (Allchin 2003a, 2013a, b, pp. 77–92; for an analysis of some offenses in this journal, see Allchin 2006b, 2013a, b, pp. 94–100). The rhetorical power of history poses an additional danger. That is, historical examples implicitly become normative. By appealing to the past, an author can try to justify current or personal ideas by inscribing them in the "facts" of history. That is, they endeavor to *naturalize* particular values or perspectives into our heritage and thence wedge them into education (Allchin 2003b, 2008, 2013b, pp. 71–73). History acquires a rhetorical and political, not just an informative, role. Accordingly, Herbert Butterfield (1959) alerted historians to what he called the Whig interpretation of history. For example, in this journal Matthews (2009) presented Joseph Priestley as a role model, implying that Preistley's achievements as a scientist justify trying to inculcate his Enlightenment values in modern students today (Allchin 2013b, pp. 59–64). The past alone, however, does not justify values. Historical scholars are a partial antidote to the potential dangers of trying to naturalize personal perspectives or ideologies into history. On how an educator, as non-expert, might begin to distinguish good history from counterproductive ideology, see Allchin (2013b, pp. 77–106).

Historical cases continue to earn focus among science educators. Several recent projects are noted in Table 2. Like those noted above, all involved professional historians. But expert historical perspective, while foundational, does not guarantee classroom success. Several other factors have emerged as important. For example, active reflection by students on NOS issues is generally recognized as essential, helping to ensure that new concepts are integrated into each student's own cognitive repertoire. Second, as noted by Deng et al.

Table 2 Recent major projects integrating history and science education

HIPST	http://hipstwiki.wetpaint.com/page/hipst+developed+cases HIPST (2008); Höttecke et al. (2012)
Stories Behind the Science	http://storybehindthescience.org Clough (2011)
The Minnesota Case Study Collection	http://ships.umn.edu/modules Allchin (2012b)
Storytelling as Teaching Model (S@TM)	http://science-story-telling.eu/en Heering (2013) [in German]

(2011) in their comprehensive review of research on NOS lessons, inquiry experience seems to strongly promote NOS learning (again, as it does in all learning contexts). One project, the "Story Behind the Science," used short stories and interrupted the narratives with explicit NOS comments and prompts for reflection. But full scale inquiry was not possible within the given constraint of a college lecture format. NOS learning gains were solid, but modest compared with the most effective lessons (Clough et al. 2010). Third, there can be attitudinal challenges, both among teachers and students. HIPST, a multinational project in the E.U., had variable successes among different participants, but one team encountered marked cognitive "resistances." For example, teachers felt constrained by the storyline. Students did not always appreciate the historical perspectives and by judging past scientists "wrong," simply dismissed their views as "unscientific" (missing the intended NOS lessons). Some students were alienated by the historical achievements as standards for their own inquiry work (Henke and Höttecke 2013). The S@TM Project, another multi-national effort, is still underway, but aims explicitly to address the motivation problem through inspiring stories (Heering 2013). Here, with an emphasis on narratives and scientific content, the inquiry activities are modest and NOS reflection almost absent. The consequences of "romantic" engagement for NOS understanding are not yet known. The Minnesota Case Study Collection (Allchin 2012a) includes narratives of particular episodes of discovery, built around a set of process of science and NOS as situated *problems*. Some include supplemental lab activities, but the inquiry chiefly involves addressing the scientists' challenges within the context of the case. While no formal research has assessed these case studies, reports from a handful of Danish, German and American teachers indicate active student engagement and the teachers' informal sense of NOS learning gains (fostering continued use). Overall, practical challenges remain for using historical cases to contextualize NOS, even when the history is done well.

3 Toward a More Richly Informed NOS and NOS Education

These three approaches for NOS education—student investigations, contemporary cases, and historical cases—face yet one more formidable problem, reported almost universally by practicing K-12 teachers: the institutional demands of testing (and thus "teaching to the test"), coupled with insufficient time. That is, while the formal curricula may promote NOS as a goal, the tests do not genuinely reflect this. Even the most recent reforms in the U.S. (the Next Generation Science Standards) continue the pattern of piecemeal responses, although the responses now incorporate items from a master list of "scientific practices." They hardly expect students to contextualize NOS understanding in contemporary socio-scientific cases, or to exhibit competence in social discourse about them. The grand rhetoric of the curricular standards remains just rhetoric. That is, teachers recognize the merits of NOS lessons oriented to scientific literacy, but institutional contexts generally eclipse their realization in the classroom. Without systems for concretely valuing and crediting these lessons, they will not take root.

As illustrated in the discussion above, the skills required for functional scientific literacy must be articulated, and the role of NOS made vivid, through concrete and detailed examples. Science teachers need new methods of assessment that will document that students have learned the NOS concepts and skills that we ultimately want them to learn and perform (Allchin 2011, 2012d). Historians and philosophers of science and their colleagues could well help contribute to crafting these new forms of assessment, creatively applying their expertise about how citizens and consumers apply (or should/can apply) their understanding of NOS in contemporary socioscientific cases. Until such assessments appear, the relevance of Science Studies may well remain peripheral in the typical classroom, regardless of its promise for informing scientific literacy.

Important research certainly remains on how HPS (or, more broadly, Science Studies) can contribute to NOS education (Boston Working Group, this volume). In this paper, however, I have endeavored to sketch insights that are already available and how they may inform educators and provide opportunities towards reaching current goals. Indeed, some such insights could greatly transform current teaching practice. Notably, the focus on history and philosophy of science in the past few decades seems to have peripheralized full consideration of the valuable insights from the sociology of science and other fields (Allchin 2013b, pp. 107–120; Cunningham and Helms 1998; Kelly et al. 1993; Zemplén 2009). "Scientific practices" extend well beyond cognitive operations or habits of mind now profiled in education, most vividly involving practical issues of material resources and technical skills, cultural contexts and potential biases, historical contingency, expertise, and credibility. As the role of NOS understanding in functional scientific literacy becomes clearer, the perspectives at the intersection of science and society, and of epistemics and values will become more and more critical.

The breadth of NOS epistemic issues that arise in socioscientific issues points to corresponding pedagogical challenges. A narrow set of NOS features, as exhibited in the earlier "consensus list," is clearly inadequate to the needs of well informed consumers and citizens. In the classroom, science needs to be profiled authentically, in its entirety: namely, as Whole Science, which includes a broader, untruncated inventory of NOS elements and their epistemic dimensions (Allchin 2013b, pp. 23–27, 39–41, 165–183). The emerging view of the complexity of NOS and of teaching Whole Science poses new challenges for teachers. In such cases, the conventional impetus to simplify is inappropriate. Rather, teachers may more effectively adopt a strategy of *sampling*. Students will encounter small cross-sections of Whole Science, rather than a few target NOS principles set in isolated and minimalistic (or perhaps inauthentic) contexts. While focus on NOS remains, the principles will emerge from the contexts that give them relevance and meaning. This strategy of immersion and finding a pathway through a complex environment is already proving effective in teaching about causal complexity in highly integrated systems, such as ecosystems (EcoMUVE 2013; Grotzer 2012). Educators are already familiar with the values of case-based learning in other subjects (Allchin 2013b; Lundberg et al. 1999; Major and Palmer 2001), and their experience should prove valuable for NOS education, as well. Whole Science cases are prime settings for NOS inquiry, and through them, NOS learning (Allchin 2012a).

In inaugurating this journal (Vol. 1, No. 1), the Editor discussed the "rapprochement" between science education and the history and philosophy of science. Horizons have since changed. Now we are ripe for another, quite different but equally important integration:

between NOS education aiming to inform socioscientific issues and the full spectrum of disciplinary studies of science that can inform those issues. The science classroom is set firmly in the middle of that challenge. With due attention, the path from Science Studies to scientific literacy will be able to yield a more deeply informed view of NOS and more effective NOS education.

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