Sci & Educ
DOI 10.1007/s11191-012-9520-2

Teaching *With* and *About* Nature of Science, and Science Teacher Knowledge Domains

Fouad Abd-El-Khalick

Abstract The ubiquitous goals of helping precollege students develop informed conceptions of nature of science (NOS) and experience inquiry learning environments that progressively approximate authentic scientific practice have been long-standing and central aims of science education reforms around the globe. However, the realization of these goals continues to elude the science education community partly because of a persistent, albeit not empirically supported, coupling of the two goals in the form of 'teaching about NOS with inquiry'. In this context, the present paper aims, first, to introduce the notions of, and articulate the distinction between, teaching *with* and *about* NOS, which will allow for the meaningful coupling of the two desired goals. Second, the paper aims to explicate science teachers' knowledge domains requisite for effective teaching with and about NOS. The paper argues that research and development efforts dedicated to helping science teachers develop deep, robust, and integrated NOS understandings would have the dual benefits of not only enabling teachers to convey to students images of science and scientific practice that are commensurate with historical, philosophical, sociological, and psychological scholarship (teaching about NOS), but also to structure robust inquiry learning environments that approximate authentic scientific practice, and implement effective pedagogical approaches that share a lot of the characteristics of best science teaching practices (teaching with NOS).

1 Introduction

Helping precollege students develop informed conceptions of nature of science (NOS)—that is, understandings about science as a knowledge generation and validation enterprise—has been a long-standing, consistent, and central goal for major reform efforts in science education around the globe. An equally ubiquitous and highly desired goal is engaging precollege students with inquiry science learning experiences, which are

F. Abd-El-Khalick (✉)
Department of Curriculum and Instruction, College of Education,
University of Illinois at Urbana-Champaign, 1310 South Sixth Street, Champaign, IL 61820, USA
e-mail: fouad@illinois.edu

Published online: 04 August 2012

commensurate with, or progressively approximate, authentic scientific practice (e.g., American Association for the Advancement of Science [AAAS] 1990; CMEC Pan-Canadian Science Project 1997; Curriculum Council [Western Australia] 1998; Millar and Osborne 1998; Ministry of Education [Venezuela] 1990; Ministry of Education [Taiwan] 1999; Ministry of National Education [Turkey] 2000; National Research Council [NRC] 1996; National Science Teachers Association 1982). However, despite such consistent focus and associated curricular and instructional efforts, research consistently indicates that the overwhelming majority of precollege students continue to ascribe to naïve conceptions of NOS (e.g., Dogan and Abd-El-Khalick 2008; Kang et al. 2005; Rubba and Anderson 1978), and that teachers continue to structure and conduct precollege science instruction in ways that are incommensurate with how scientists undertake their inquiries into natural phenomena (e.g., Anderson 2007; Sweitzer and Anderson 1983). These two central and consistently valued goals, thus, continue to elude the science education community.

The factors underlying this state of affairs, no doubt, are numerous and intertwined. They range from curricular priorities that have historically typified school science education (AAAS 1990), to the culture of school science (e.g., Shanahan and Nieswandt 2011), to the nature of science teacher education and the development of teacher understandings vis-à-vis NOS and scientific inquiry (Abd-El-Khalick 2005; Abd-El-Khalick and Lederman 2000a), to challenges that often hamper systemic change in precollege science education (e.g., Vesilind and Jones 1998). The present paper focuses on a single, but rather crucial factor; namely, science teachers' knowledge domains relevant to achieving the aforementioned two goals. Toward this end, the present paper aims to (a) introduce the notions of, and articulate the distinction between, teaching *with* and *about* NOS, and (b) explicate science teachers' knowledge domains requisite for effective teaching with and about NOS. In this context, given the realities of school science teaching in an era of increased accountability, mostly in the form of increased testing (Donnelly and Sadler 2009; Judson 2010), a foremost consideration framing my present discussion is the need to make NOS instruction an integrated and meaningful component of science teaching, which chiefly is aimed at achieving instructional outcomes related to the development of student science content knowledge and inquiry understandings and skills (Monk and Osborne 1997). Approaches focused on adding modules (e.g., NOS-specific or history of science units) onto already expansive science curricula and the extensive agendas of science teachers are unlikely to receive serious attention, irrespective of their perceived or actual effectiveness. As will become evident below, a framework of teaching with and about NOS is likely to be useful in addressing the well-documented difficulties associated with developing student NOS understandings and enacting science-learning environments that are commensurate with authentic scientific practice. In this paper, the phrase 'scientific inquiry' and the term 'inquiry' are meant as proxies for authentic scientific practice (Chinn and Malhorta 2002a).

2 Teaching With and About NOS

I start with introducing, and clarifying the distinction between, teaching with and about NOS. Such introduction and clarification are best achieved through an interlude that would serve to contextualize and help appreciate the nuances of this distinction. The paper opened with emphasizing the ubiquitous and long-lived emphasis in science education on the dual goals of developing student understandings of NOS and engaging students with inquiry-based learning experiences that approximate authentic scientific practice (in whichever manner these constructs were conceptualized or defined at the times of various reform efforts). It goes without saying that, over the past several decades, researchers and reform documents have coupled the goals of improved NOS understandings and engagement with scientific inquiry. The coupling of these two goals is, by no means, novel (see for e.g., Robinson 1965; Rutherford 1964). Interestingly enough, an early coupling was focused on science teacher understandings of NOS and their ability to enact inquiry teaching. Almost 50 years ago, Rutherford (1964) argued that:

> Science teachers must come to understand just how inquiry is in fact conducted in the sciences. Until science teachers have acquired a rather thorough grounding in the history and philosophy of the sciences they teach, this kind of understanding will elude them, in which event not much progress toward the teaching of science as inquiry an be expected. (p. 84)

In other words, for Rutherford (1964), teachers' understandings of NOS are necessary for their ability to teach science with inquiry (NRC 1996). Rutherford, however, did *not* articulate or conceptualize the ways in which NOS understandings would result in improved ability among teachers to implement inquiry instruction.

Nonetheless, at some point along the way (see for e.g., Riley 1979) there emerged an alternative and persistent form in which the coupling of NOS and inquiry has been approached, which could be best described as 'teaching about NOS with inquiry'. In other words, this coupling assumes that science teachers can help students develop informed NOS understandings by engaging them in inquiry experiences: Inquiry teaching, it was assumed, can serve as an instructional approach for developing NOS understandings. This stance has been advocated as a means to teach about NOS both in the case of precollege students and science teachers. For instance, Barufaldi et al. (1977) "believed that students [student teachers] completing a science methods course should have developed a more tentative view of science because of the nature of the course" (p. 291). The course itself, it should be noted, did not feature any NOS instruction, including activities or discussions that drew on history and/or philosophy of science (HPS) or other forms of direct discussion of one or more aspects of NOS. Instead, Barufaldi et al. (1977) argued that the inquiry-oriented nature of the course and engagement with science in and of themselves should result in improved NOS understandings among their preservice science teachers:

> [Student teachers] were presented with numerous hands-on, activity-centered, inquiry-oriented science experiences… that assisted students in making reasonable responses or choices, supporting or refuting hypotheses. The uniqueness and the variety of the learning experiences in the courses provided the students with many opportunities to understand the tentativeness of scientific findings. (p. 291)

'Teaching about NOS with inquiry' continues to guide some current empirical studies (e.g., Marchlewicz and Wink 2011; Russell and Weaver 2011). Some science educators even went further to suggest that "NOS… cannot be taught directly, rather it is learned, like language, by being part of a culture," namely, the culture of scientific practice (Duschl 2004, as cited in Abd-El-Khalick et al. 2004, p. 412; see also Kelly and Duschl 2002). Empirical evidence, however, does not support this coupling (e.g., Bell et al. 2003; Khishfe and Abd-El-Khalick 2002; Sandoval and Morrison 2003). Studies have shown that learners' "epistemological ideas did not appear to change as a result of their inquiry experiences" (Sandoval and Morrison 2003, p. 384).

It now is well understood and documented that while inquiry might serve as an ideal context for helping students and teachers develop informed NOS views, it does not follow that engagement with inquiry would necessarily result in improved understandings. Carefully planned and structured opportunities for reflection on inquiry experiences are needed to achieve desired NOS understandings (see Abd-El-Khalick and Lederman 2000a;

Bell et al. 2003; Khishfe and Abd-El-Khalick 2002; Peters and Kitsantas 2010; Yacoubian and BouJaoude 2010). In this regard, it should be noted that research also shows that engagement with HPS, *absent* critical and structured reflection, also is not likely to achieve desired NOS understandings for science teachers (e.g., Abd-El-Khalick and Lederman 2000b; Howe and Rudge 2005) and precollege students (e.g., Welch 1973). The most notable example of this lack of impact is derived from the Harvard Project Physics course, later dubbed The Project Physics Course (PPC) (Holton et al. 1967; Rutherford 1964). The PPC was "a national curriculum improvement project, which was funded by the U.S. Office of Education, the National Science Foundation"; the course "includes aspects of the philosophy and history of science that put the development of the major ideas of physics into a humanistic and social context" (Holton et al. 1971, p. 1). Welch (1973) noted that research on the impact of the PPC—which took the form of rigorous large-scale quasi-experimental studies, identified a total of 17 significant differences that reflected positively on the course. However, "no significant differences were found on the… Test on Understanding Science [TOUS]" (p. 374), which was widely used to assess student NOS understandings at the time.

In this regard, it is crucial to emphasize that the above discussion should not be taken to mean that inquiry and/or HPS cannot or should not be used to help learners develop informed NOS conceptions. On the contrary, inquiry experiences and HPS provide ideal contexts for teaching and learning about NOS. The thrust of the above comments is that, both in the case of using inquiry and HPS, an explicit-reflective framework is needed to achieve the goal of improving understandings about NOS among science teachers and students (Abd-El-Khalick et al. 1998; Abd-El-Khalick and Lederman 2000a). Empirical evidence does not support the assumed positive impact on learners' NOS understandings of 'teaching about NOS with inquiry' when such teaching lacks structured and meaningfully integrated explicit and reflective elements. Elsewhere, I argued that this assumed coupling also would not hold under theoretical and conceptual scrutiny (see Abd-El-Khalick 2012).

The notions of teaching with and about NOS can facilitate meaningful discussion, and help advance development and research efforts in the field beyond the seemingly evidence-defiant and persistent stance that engagement with inquiry and HPS per se would necessarily result in improved NOS understandings (e.g., Lin and Chen 2002; Marchlewicz and Wink 2011; Russell and Weaver 2011; Schmuckler 2004). Teaching *about* NOS refers to instruction aimed at enabling students to achieve learning objectives focused on informed epistemological understandings about the generation and validation of scientific knowledge and the nature of the resultant knowledge. In comparison, teaching *with* NOS entails designing and implementing science learning environments that take into consideration these robust epistemological understandings about the generation and validation of scientific knowledge. The latter notion provides a conceptual framework to help articulate and concretize Rutherford's (1964) claim that NOS understandings would result in improved ability among teachers to implement inquiry instruction. To be sure, teaching with and about NOS are interrelated but, as will become evident below, are not one and the same.

2.1 Teaching About NOS

Teaching *about* NOS is instruction aimed at helping learners (both students and science teachers) develop informed epistemological understandings about the generation and validation of scientific knowledge, and the nature of the resultant knowledge. As noted above, evidence shows that engagement with inquiry or HPS per se, while necessary, is not sufficient to achieve such learning. Instead, effective NOS instruction is better achieved through an explicit-reflective framework (Abd-El-Khalick et al. 1998; Abd-El-Khalick and Lederman 2000a; Akindehin 1988). To start with, it is important to address some confusions or misrepresentations with regard to this framework (e.g., Allchin 2011). The label "explicit" should not be taken to refer to any variety of direct or didactic instruction. Indeed, the label has no instructional implications. The label "explicit" has curricular implications and entails the inclusion of specific NOS learning outcomes in any instructional sequence aimed at developing learners' NOS understandings. The label "reflective," on the other hand, has instructional implications in the form of structured opportunities designed to help learners examine their science learning experiences from within an epistemological framework. Specifically, such reflection would center on questions related to the development and validation, as well as the characteristics of, scientific knowledge (for a detailed discussion see Abd-El-Khalick and Akerson 2009).

Another important point to highlight is that "the inclusion of specific NOS learning outcomes in curricular materials does not entail a specific instructional approach," since the selection of a specific approach "depends on a number of factors, including the instructional outcomes themselves; the characteristics, abilities, aptitudes, and skills of the learners; available resources; and the larger educational milieu" (Abd-El-Khalick and Akerson 2009, p. 2163). Strong preference should be accorded to pedagogical approaches that are active, student-centered, collaborative, and inquiry-oriented in nature. Indeed, researchers have reported substantial gains in precollege students' and science teachers' NOS understandings using explicit-reflective NOS interventions that draw on, and/or are embedded within, rich historical case studies (e.g., Abd-El-Khalick 2005; Howe and Rudge 2005; Howe 2007; Kim and Irving 2010), authentic scientific practice (e.g., Bell et al. 2003), inquiry-based contexts (e.g., Khishfe and Abd-El-Khalick 2002; Yacoubian and BouJaoude 2010), teacher professional development (e.g., Morrison et al. 2009), learning-as-conceptual change (e.g., Abd-El-Khalick and Akerson 2004), argumentation (McDonald 2010), and meta-cognitive strategies (Abd-El-Khalick and Akerson 2009; Peters and Kitsantas 2010).

To clarify the nature of the explicit-reflective framework, consider the aforementioned illustrative cases starting with the use of HPS to improve precollege students' understandings of NOS. The reader will recall that the PPC (Holton et al. 1967) included aspects of the philosophy and history of science intended to convey the humanistic and social contexts associated with the development of ideas in physics. The course, however, was not effective in impacting high school students' NOS understandings as measured by the TOUS (Welch 1973). Another major contemporary effort, however, was especially successful where the PPC had failed, namely, the *History of Science Cases* (HOSC) for high schools (Klopfer and Cooley 1963). An explicit-reflective framework would account for the latter success. To start with, Klopfer (1969) emphasized that "the inclusion of history of science in science teaching must be planned as carefully as the use of any other instructional materials" (p. 92). The "Teacher's Guide" to the HOSC advised that students "should be made aware from the beginning that the case is not primarily a vehicle for learning science subject matter… the primary purpose of the HOSC units—to teach *about* science and scientists—should remain permanently in the foreground [emphasis in original]" (Klopfer 1964a, p. 6). In accordance with an explicit curricular emphasis on NOS, each HOSC case included a number of learning objectives related to understanding ideas about science and scientists, in addition to objectives focused on learning scientific facts and understanding scientific concepts and principles. For example, HOSC units aimed to enable students to understand that, "A scientist's observations and interpretations are influenced by his perceptions and background… A theory serves to correlate and explain many phenomena within its scope and should be fruitful in stimulating new scientific research" (Klopfer 1964a, p. 10), and that "A controversy over rival theories is resolved, ideally, by an appeal to experimentation. However, the outcome of a controversy can also be affected by the personalities and personal biases of the scientists involved… Scientists sometimes ignore facts that do not fit into a proposed theory" (Klopfer 1966, p. 9).

The cases and associated units themselves were quite interactive: students were engaged with conducting experiments and interpreting data. However, Klopfer was keenly aware that the inclusion of specific NOS learning outcomes and engaging students with experimentation were not enough to impact their understandings about science and scientists. He acknowledged that the HOSC materials did not provide the single most important factor in the study of historical case studies. This factor, which he considered essential for success, is served by the teacher: "The objectives of HOSC can be effectively achieved only through the kinds of bringing out and bringing together that come in the framework of a well-led, intensive classroom discussion" (Klopfer 1964a, p. 7). These reflective discussions were centered on explicit questions that guided students as they engaged with the HOSC materials, such as, "What is a scientific law?" (1964b, p. 16) and "Are scientific ideas replaced very often?" (1964b, p. 24). Teachers and students also were expected to discuss specific statements of an epistemological nature that were provided along the margins of the text, such as "observations do not speak for themselves; they must be interpreted" (Klopfer 1964b, p. 14). This explicit-reflective approach to using HPS in the service of learning about NOS was found to be effective: In a pretest–posttest experimental study with random assignment of the HOSC treatment to 108 experimental and comparison classrooms, Klopfer and Cooley (1963) reported significant gains in the experimental students' NOS understandings as measured by the TOUS.

Next, consider the aforementioned illustrative case of instruction centered on inquiry. The reader will recall that Barufaldi et al. (1977) used what could best be described as a 'teaching about NOS with inquiry' approach in the context of a science methods course to enhance preservice science teachers' NOS understandings. Abd-El-Khalick and Lederman (2000a), however, noted that Barufaldi and his colleagues' efforts were not very effective: their participants achieved minimal gains in their NOS understandings as measured by the *Views of Science Test* (VOST) (Hillis 1975). In the same context, researchers who draw on an explicit-reflective instructional framework would argue that the goal of improving understandings about NOS among teachers "should be planned for instead of being anticipated as a side effect or secondary product of… science content or science methods classes" (Akindehin 1988, p. 73). In this case, Akindehin used an eight-unit instructional package focused on inquiry to successfully improve prospective secondary science teachers' conceptions of NOS. Prospective teachers were engaged with conducting scientific inquiries. Additionally, Akindehin's instructional package integrated a number of lectures and examination of historical episodes (e.g., Francesco Redi's work on refuting the notion of spontaneous generation), as well as discussions that encouraged participants to reflect on their experiences around issues related to the role of established theory, ethical and regulative mechanisms in science, creativity in scientific investigation, the nature of scientific (vs. supernatural) explanations, and the human aspects of engaging with science.

2.2 Teaching With NOS

Science teachers who have developed deep and integrated understandings about NOS can be enabled to utilize effective approaches (e.g., those that draw on an explicit-reflective framework) to address this domain instructionally (Abd-El-Khalick 2005), that is, teach *about* NOS. Equally important, teachers equipped with such understandings *can be enabled* to enact learning environments commensurate with those that approximate authentic scientific practice, that is, teach *with* NOS. In other words, teaching with NOS turns the aforementioned ‘teaching about NOS with inquiry’ coupling—which, despite its persistence, lacks robust empirical support—on its head in favor of a coupling that revives Rutherford’s (1964) half-a-century-old assertion. Instead of continuing to assert—in the face of evidence to the contrary, that teachers can use inquiry to help precollege students develop informed NOS understandings, teaching with NOS asserts that teachers with informed NOS understandings are better positioned to enact inquiry learning environments in their classrooms.

The assumption that undergirds the teaching with NOS notion is that the ways students develop their understandings of scientific knowledge bear some resemblance (though by no means a one-to-one correspondence—see Abd-El-Khalick 2008) to the ways scientific communities of practice generate and validate such knowledge. Starting with such an assumption, science teachers who have internalized robust understandings of key aspects of NOS, and who seriously entertain the importance of these aspects to scientific practice, are more likely to abandon some ‘old orientations’ (Anderson 2007) or traditional science teaching practices (see for e.g., AAAS 1990) in favor of practices that would bolster authentic science learning environments. The following sections articulate some specific ways in which the suggested coupling works, whereby what I refer to below as ‘syndromes’ of traditional science instruction that continue to persist in many science classrooms, would be abandoned. The aspects addressed below are illustrative and, in no way, meant to be exhaustive. Readers can generate additional examples of their own. The following sections also aim to go beyond asserting the coupling suggested by Rutherford (1964) to fleshing out the specifics of such a coupling.

2.2.1 Theory-Laden NOS and the “Go Observe the Fish” Syndrome

> Scientists’ theoretical and disciplinary commitments, beliefs, prior knowledge, training, and expectations influence their work. These background factors affect scientists’ choice of problems to investigate and methods of investigations, observations… and interpretation of these observations… Contrary to common belief, science never starts with neutral observations. Like investigations, observations are always motivated and guided by, and acquire meaning in light of questions and problems derived from, certain theoretical perspectives. (Abd-El-Khalick et al. 2008, p. 838)

Popper (1963) emphatically noted, “The belief that science proceeds from observation to theory is still so widely and so firmly held that my denial of it is often met with incredulity” (p. 46). Popper’s complaint is still as relevant today as it was in the early 1960s, if not within philosophical circles, then surely in the case of a majority of science teachers as this pertains to their conceptions of the relationship between observation and theory (e.g., McDonald 2010; Wahbeh 2009). To help drive the point home, Popper noted that he often would begin a lecture with instructing his physics students to “‘Take a pencil and paper; carefully observe, and write down what you have observed!’” At that point, Popper continued, the students “asked, of course, *what* I wanted them to observe [emphasis in original]. Clearly the instruction, ‘Observe!’ is absurd” (p. 46). Despite its absurdity, this exercise continues to thrive in one form or another in many school science classrooms and laboratory activities today (Lunetta et al. 2007). I am sure many readers can relate to my experience with observing an elementary classroom where students were instructed to take their pens and pads and ‘go observe the fish’ in the corner aquarium. The students diligently followed instructions: some were laboriously scribbling about the color and size of the fish, others about how filthy the water was, and still others about the little plastic castles, which decorated the bottom of the tank! Such inductive (Baconian) tasks are likely more common in elementary and middle grade science classrooms than science educators would like to see (by the time students reach secondary classroom, the pendulum would have swung to the other end and students mostly are engaged with verification-type science activities). These naïve inductive tasks, which assume that starting with a presupposition-less set of observations, students will somehow reach (the teacher's or textbook's) desired conclusions, most often end with frustration on the side of both students and their teachers.

In comparison, teachers with understandings of the theory-laden (or theory-driven) nature of observation are less likely to send their students on such perilous tasks—from the perspective of actually leading to some meaningful conclusions or claims to 'knowledge'—because those teachers appreciate that "observation is always selective. It needs a chosen object, a definite task, an interest, a point of view, a problem" (Popper 1963, p. 45). From the perspective of teaching with NOS, teachers equipped with an understanding of the theory-laden NOS would come to realize the significance of students' points of view when engaged with inquiries. After all, as Darwin put it in a letter to Henry Fawcett in 1861, "all observation must be for or against a point of view if it is to be of any service!" (Barlow 1993/1958, p. 161). Those teachers are better positioned to carefully structure inquiry experiences around student interests and guiding questions, preferably questions of which students have some genuine ownership. More importantly, those teachers would carefully consider the *specific* points of view, prior knowledge, and/or hypotheses and theories (naïve or otherwise) that students are likely to bring to bear on the observations at hand in the service of addressing the question or problem guiding their inquiries. Equally important, teachers are more likely to make their students aware—preferably through planned reflective prompts—of the ways in which their extant ideas interact with the activities of identifying, gathering, and interpreting data and evidence. It now is well understood that the careful design, deployment, and interplay between guiding questions, prior knowledge, and/or theory on the one hand, and observation and data on the other, are key to designing and enacting effective inquiry learning environments, especially those aimed at helping students develop integrated inquiry skills (AAAS 1990; Crawford 2007; NRC 1996). Science teachers with understandings of the theory-laden NOS would be poised to plan student inquiries along these very principles.

2.2.2 The Underdetermination of Theory by Evidence and the "Blank Slate" Syndrome

The "blank slate" syndrome refers to the assumption that students are passive receivers of knowledge, which underlies more traditional approaches to science teaching, specifically those focused on the transmission of scientific knowledge with little, if any, specific regard to students' prior ideas (Anderson 2007; NRC 1996; BouJaoude et al. 2004). While addressing this assumption and associated instructional practices had received a lot of attention in the science education literature, research shows that the gap between what is known about the impact of student naïve ideas or theories on their learning and the *realities* of classroom instruction continues to be large (Duit et al. 2008; Crawford 2007; Salloum and Abd-El-Khalick 2010). To be sure, teachers with a robust understanding of the theory-laden NOS are highly likely to appreciate the significant role that students' prior ideas play in learning science, and abandon a transmission orientation to teaching in favor of a student-centered inquiry-oriented approach. They would initiate inquiries to address specific student naïve ideas and facilitate conceptual development and change by grounding these inquiries in student ideas, interests, and/or questions, and facilitating student collection and examination of evidence that is "of service" to these guiding questions or problems. Nonetheless, those very teachers would still need to negotiate the fact that, more often than not, many students would continue to hold fast to their ideas even after having collected or been provided with data and evidence that contradict their naïve conceptions and support canonical alternatives (Brewer and Chinn 1994; Chinn and Malhotra 2002b; Duncan et al. 2011; Scott et al. 2007).

Many teachers find such lack of conceptual development and change especially frustrating as it increases their anxiety vis-à-vis dilemmas they often face attempting to justify the time and effort involved in enacting inquiry learning environments versus demands placed on them in terms of content coverage and preparing students for high stakes examinations (Anderson 2007). However, an understanding of the underdetermination of scientific theories by evidence (Duhem 1954; Gillies 1998; Quine 1951) would likely enable teachers to appreciate students' seeming resistance to changing their naïve ideas about natural phenomena, many of which become the object of classroom inquiries. In its weak sense, the underdetermination thesis suggests that "in the practice of science… available evidence may not decide between rival hypotheses or theories" (Newton-Smith 2000, p. 532). In its strong sense, the thesis claims that "theories are underdetermined by all actual and possible observational evidence… [because]… any scientific theory has an incompatible rival theory to which it is empirically equivalent" (Newton-Smith 2000, p. 532). In both senses, proponents of the underdetermination of scientific theories by evidence (Duhem 1954; Quine 1951) have convincingly argued that, from a logical point of view, scientists can hold on to their theories come what may in terms of new, or even contradictory, empirical evidence (see below for an account of Duhem's argument; for a detailed discussion see Abd-El-Khalick 2003). The underdetermination thesis helps to explain why refuting or anomalous evidence often does not play as major a role in compelling students to restructure their naïve ideas as teachers and researchers hope it would (Chinn and Malhotra 2002b; Scott et al. 1992).

Based on examining the HPS and psychological literatures, Chinn and Brewer (1993) identified seven distinct ways in which scientists and science students respond to anomalous data. Only one of the seven responses entails scientist and student acceptance of the anomalous data and changing their ideas. The remaining six responses enable scientists and students to maintain or only slightly modify their core theories and prior conceptions, respectively. These responses include ignoring anomalous data, rejecting the data, excluding the data from the domain of the theory/prior conception, holding the data in abeyance, reinterpreting the data while retaining the theory/prior conception unchanged, or reinterpreting the data and making peripheral changes to the theory/prior conception. These patterns of student responses to anomalous data were evident in several empirical studies (e.g., Brewer and Chinn 1994; Chinn and Malhotra 2002b; Duncan et al. 2011). In this context, it is important to note that, according to Duhem (1954), scientists and students in the six cases identified by Chinn and Brewer are *not* necessarily acting irrationally or illogically when they maintain their core ideas in the face of seemingly refuting evidence.

Duhem (1954) made the convincing case that the logic of theory testing suggests that it is not possible to empirically test an isolated hypothesis or theory. Any such test actually entails testing an entire theoretical system comprising several core ideas, a set of assumptions, and a number of auxiliary hypotheses. Thus, while refuting evidence might indicate that something is amiss with the system, such evidence does not specify for the scientist or student exactly which part of the system is not valid, which enables ad hoc adjustments within the system to accommodate anomalous data. Indeed, Duhem had to introduce a theory of 'good sense' because "logic does not determine with strict precision the time when an inadequate hypothesis should give way" to more fruitful alternatives (p. 218). For Duhem, good sense is constituted of "motives which do not proceed from logic and yet direct our choices… 'reasons which reason does not know' and which speak to the ample 'mind of finesse' but not to the 'geometric mind'" (p. 217).

To help ameliorate the issue, Chinn and Brewer (1993) suggested a number of instructional approaches and strategies, which are consistent with best science teaching practices derived from research into student naïve conceptions and conceptual change (e.g., Hewson et al. 1998; Scott et al. 2007). Several crucial instructional elements identified by Chinn and Brewer also would support the enactment of authentic inquiry learning environments. These include, for example, making discussion of underlying student epistemological commitments an explicit component of classroom discourse; helping students develop domain-specific background knowledge that allows for the meaningful identification, collection, and interpretation of relevant data, and promote reflective theory revision; and allowing the open-ended exploration of ideas and theories without the need to reach pre-determined conclusions. Another crucial element that gains special significance in light of the issues brought about by the underdetermination of theory by evidence is the need to make student inquiries genuinely communal rather than individual endeavors (Chinn and Brewer 1993), which brings us to the next dimension of teaching with NOS.

2.2.3 The Social NOS and the "Go-at-it-Alone" Syndrome

Scientific knowledge is produced by communities of practice, which range from relatively small laboratory teams to rather large groups organized by scientific disciplines and subdisciplines. In this sense, science is done in groups, both small and large. Through extended and iterative cycles of activity, these groups plan, conduct, and troubleshoot investigations; analyze, interpret, and make sense of data; build, scrutinize, and refine arguments; challenge, criticize, defend, and revise claims to scientific knowledge; and collectively vet and admit such claims to the scientific cannon. The social interactions, particularly extensive communication, associated with these activities range from the loosely structured laboratory team discussions, to highly structured and rigorously implemented and monitored blinded reviews involved, for example, in examining findings submitted for publication in peer refereed professional journals or reviewing proposals for federal or state funding. The social NOS, or "science as social knowledge," refers to the epistemic function of these social activities: It refers to the constitutive values associated with those established venues for communication and criticism within the scientific enterprise (e.g., blind review processes), which serve to enhance the objectivity of collectively scrutinized scientific knowledge through decreasing the impact of individual scientists' idiosyncrasies and subjectivities (Longino 1990). In this specific sense, it should be noted, social NOS refers to conceptions of science as advanced by philosophers of science such as Helen Longino (e.g., Longino 1990) and should *not* be confused with relativistic notions of scientific knowledge.

Contrast the above image of science and how scientists work with the way in which many precollege science classrooms are organized: Students often "go-at-it-alone." They work, learn, and produce artifacts (e.g., homework, examinations) alone, which are focused on gauging their mastery of codified scientific knowledge (Crawford 2007; Olitsky 2005; So and Ching 2011; van Garderen et al. 2012). In other cases students work in groups, mostly with the aim of sharing limited resources or simply 'sharing the load'. In the latter cases, students collectively produce artifacts, such as (mostly prescribed) laboratory reports. Still, the goals associated with these activities continue to be directed toward the mastery of content or scientific processes (AAAS 1990; Anderson 2007; NRC 1996). Even in the case of many well-designed and executed inquiries, student groups are allowed 'one shot' to produce artifacts that represent their findings or learning. Additionally, in more cases than not, the teacher remains the final arbiter and judge of the merits of claims, answers, or arguments produced by student groups. Thus, the whole communicative dimension of science, as it pertains to producing and validating claims to scientific knowledge, is sidestepped and ignored in most science classrooms.

Science teachers who have developed deep understandings and appreciation of the epistemic relevance of the social NOS are less likely to enact science learning environments similar to those described above. Teaching with the social NOS, those teachers would organize extended learning experiences that allow students to work through the various dimensions of their investigations together, and present, explain, and defend their findings before their peers. Most importantly, teachers would structure learning environments such that student groups collect and act on feedback, questions, and critiques offered by their peers. Students would be allowed to revisit and revise their analyses, interpretations, and conclusions. They also would be provided the option to collect more data or rework their investigations altogether before coming back for another cycle of sharing their 'learning' with, and defending their conclusions before, their peers. It could be seen that teaching with the social NOS entails the design and enactment of science learning environments that are commensurate with best practices associated with inquiry teaching and learning (Lee et al. 2006).

The reader is reminded that the above examples of teaching with NOS are meant to be illustrative rather than exhaustive. Additionally, the reader should have noticed the many qualifications built into the above discussion. In particular, I was careful *not* to indicate a necessary and straightforward translation of teachers' NOS understandings into their instructional practice. It now is well documented that such translation is rather complex and mediated by a host of situational and contextual factors (Abd-El-Khalick et al. 1998; Aguirre et al. 1990; Brickhouse 1989; Lederman et al. 2001). Instead, my argument is that science teachers who had developed deep and integrated understandings of some crucial dimensions of NOS "could be enabled," "are better positioned," "would be poised," or "are more likely" to enact instructional practices that are commensurate with robust inquiry-oriented learning environments. Nonetheless, even with a mediated translation of teachers' beliefs into their practice, there is no disagreement that understandings of NOS are necessary (albeit not sufficient) to teach about NOS and, as explicated above, with NOS. The central point to take away from this discussion is that research and development efforts dedicated to improving teachers' NOS understandings would have the dual benefits of not only enabling teachers to convey to students images of science and scientific practice that are commensurate with scholarship in history, philosophy, psychology, and sociology of science (HPPSS) (teaching about NOS), but also to structure robust learning environments and implement effective pedagogical approaches that build on our understanding of how knowledge is generated and validated by scientific communities of practice (teaching with NOS). The latter environments and approaches will (a) share important aspects that characterize authentic science without attempting to replicate scientific practice in precollege science classrooms (a replication that is much advocated but hardly achievable; see Abd-El-Khalick 2008; Burbules and Linn 1991); and (b) share a lot of the characteristics of what are considered to be best practices in science teaching (Treagust 2007). The fact that teacher understandings remain cornerstone to instructional enactments brings us to the crucial question: What knowledge domains will enable precollege science teachers to teach *about* and *with* NOS?

3 Teacher Knowledge Domains for Teaching With and About NOS

To contribute to the realization of the dual goals of improving precollege students' NOS understandings and engaging students with authentic inquiry, it is crucial for science teachers to teach *both* with and about NOS. Thus, we should be concerned with those knowledge domains that enable teachers to teach with and about NOS in an integrated and seamless manner. It is crucial, nonetheless, to note that teaching with or about NOS does not necessarily entail the realization of the other dimension. Consider a teacher who had developed robust understandings of NOS. The teacher, for instance, could start a chemistry unit with a well-articulated case study of the "overthrow of the phlogiston theory" (e.g., Conant 1957) and help students develop an understanding, for example, of the theory-laden NOS as it pertains to the differential ways in which Priestly and Lavoisier came to interpret the same set of observations. Indeed, as Kuhn (1996) noted, "Lavoisier saw as a counterinstance [i.e., that metals increase in weight when roasted] what Priestly had seen as a successfully solved puzzle in the articulation of the phlogiston theory [i.e., negative phlogiston]" (p. 79). The teacher then could proceed with teaching the unit in a rather traditional manner, which is devoid of inquiry or instances in which students revisit their newly acquired NOS understandings in the context of science content or processes. The teacher would have taught students something about NOS but failed to organize a learning environment that is commensurate with his/her NOS understandings, an environment which enables students to experience NOS as manifested in scientific inquiry. Thus, teaching about NOS would not have translated into teaching with NOS. The teacher, alternatively, could deploy his/her NOS understandings to design and engage students with extended inquiry experiences that simulate several features of authentic scientific practice. The teacher, however, could fail to build explicit NOS-related instructional outcomes into his/her instructional planning, and structured reflective prompts and other strategies into the learning environment, which would enable students to reflect on their experiences and develop an understanding of the epistemological dimensions that undergird their inquiries (i.e., NOS). In the latter case, teaching with NOS would not have translated into teaching about NOS.

It could be seen that teaching with NOS—that is, enacting learning environments that are commensurate with authentic scientific practice, could create ideal contexts for teaching about NOS through implementing explicit-reflective NOS instruction. However, merely engaging students with authentic inquiry is not sufficient to foster their NOS understandings (Abd-El-Khalick and Lederman 2000a; Khishfe and Abd-El-Khalick 2002; Sandoval and Morrison 2003; Yacoubian and BouJaoude 2010). On the other hand, it is possible to teach about NOS in some content-lean contexts, such as an introductory unit on the scientific enterprise or stand-alone historical vignettes, and help students develop some level of understanding about NOS. Such an approach to teaching about NOS, however, is not likely to help students experience firsthand, and develop an understanding of, the ways in which epistemological issues mediate the interplay between scientific practices and the development and validation of claims to scientific knowledge. These latter understandings are better developed in situations where teaching about NOS is meaningfully embedded and integrated into addressing instructional outcomes related to science content knowledge, integrated inquiry skills, and/or understandings about inquiry. In this sense, the knowledge domains outlined below are intended to be *necessary* and, when certain mediating factors are satisfied (see the "discussion and conclusions" section below), will become *sufficient* to enable teachers to seamlessly teach with and about NOS.

The most obvious and core domain of knowledge relevant to teaching with and about NOS is science teachers' own NOS understandings. However, as noted above, the translation of teachers' NOS understandings into their practice is a mediated affair. For example, Lederman (1999) reported that "teachers' conceptions of the NOS do not necessarily influence their classroom practice… [even in the case of teachers who]… possessed views consistent with those advocated by current reforms in science education" (p. 927). So, while necessary, teachers' understandings of NOS are not sufficient (Abd-El-Khalick and Lederman 2000a) to enable teaching with and about NOS. Among the factors found to mediate such translation were novice teachers' preoccupation with classroom management and other survival issues; teachers' beliefs about the importance of their students learning about NOS; teacher perceptions of student abilities and motivation for learning about NOS; curricular priorities, and pressures to cover science content and prepare students for high stakes standardized examinations; and availability of instructional materials and assessments specific for teaching about NOS (e.g., Abd-El-Khalick et al. 1998; Brickhouse 1989; Lederman 1999). It could be seen that, with the exception of issues associated with making available NOS-specific instructional and assessment materials and resources, almost all of the aforementioned mediating factors are beyond the control of science teachers and/or researchers. Thus, research efforts aimed at explicating the knowledge domains that would enable teaching with and about NOS have been conflated by the effects of these mediating variables, which are very difficult to control for. Nonetheless, the need to disentangle the effect of these conflating variables gained more significance in light of evidence showing that some of these variables interacted with the depth and breadth of teachers' NOS understandings and their science content knowledge (Abd-El-Khalick 2005; Akerson et al. 2010; Lederman et al. 2001; Schwartz and Lederman 2002).

In this regard, Wahbeh (2009) capitalized on a naturalistic setting, which allowed the researcher to substantially ameliorate the potential impact of a number of the aforementioned mediating variables and tease out teacher knowledge domains requisite for effective NOS instruction. Wahbeh conducted the study in the Palestinian context where a mandated national science curriculum explicitly emphasized teaching about NOS. Thus, teachers' awareness of the importance of addressing NOS instructionally was heightened, and their anxiety was increased by the fact that they did not necessarily know how to approach this task. Thus, they were receptive and eager to engage with any effort toward helping them teach about NOS. It follows that the well-documented mediating factors related to curricular priorities, content coverage, and the importance teachers place on teaching about NOS, as well as teacher perceptions of their students' interest in learning about NOS were substantially less prominent in this particular context. Also, by working with a select group of 19 veteran teachers, constraints that derive from novice teachers' struggles with classroom management and daily survival issues were substantially reduced.

To help participants develop the sort of robust NOS understandings necessary to address this domain in their classrooms, Wahbeh (2009) engaged the teachers in a summer-long intensive course dedicated to improving their NOS conceptions. They experienced explicit-reflective NOS instruction embedded within a learning-as-conceptual-change approach (Abd-El-Khalick and Akerson 2004) coupled with the use of metacognitive strategies (Abd-El-Khalick and Akerson 2009), as well as NOS-related readings and historical case studies (Mathews 1994). These instantiations of teaching about NOS were embedded in extended inquiry activities, which were related to topics derived from the teachers' own science curricula. Toward the end of the course, teachers worked in groups to plan science units that integrated teaching about NOS. They were to implement these units in their classrooms at the outset of the new academic year.

Following the conclusion of the course, Wahbeh (2009) used data derived from NOS assessments completed by all 19 participants to select a group of six teachers who had demonstrated substantial growth in their NOS understandings over the course of the summer experience. This selection was used to help account for teachers' understandings as a possible factor in impeding their teaching about NOS (Abd-El-Khalick 2005). Finally, the six teachers were randomly split into two groups of three members each. The two teacher sub-groups were observed as they implemented their planned units, as well as units beyond those planned for during the summer NOS course in order to check for transfer. In the case of the first sub-group classroom implementation, the researcher served as a non-participant observer. The second teacher sub-group, in comparison, were told they had full access to the researcher in whichever manner they thought was helpful to their success in implementing their planned science units and NOS instruction: The researcher served as a participant observer. The latter measure was undertaken to shed light on teachers' needs beyond informed understandings of NOS. Participants in this second group did ask for, and received, several scaffolds ranging from historical case studies that apply to specific science content they were teaching, to having the researcher co-teach with them and model how to address NOS in the context of the regular Palestinian science curriculum.

The instructional implementations of all six participants were meticulously documented in the form of multiple case studies. The case studies drew on several sources of data, including instructional plans, classroom observations, researcher fieldnotes, teacher and researcher reflective diaries, formal and informal interviews, and other classroom artifacts. Comparing and contrasting the instructional implementations of participants within and across the two sub-groups allowed Wahbeh and Abd-El-Khalick (2011) to build an empirically-derived model of the knowledge domains that seemed requisite to teachers' success in addressing NOS instructionally. The model is presented in Fig. 1 and is adapted from Wahbeh and Abd-El-Khalick (2011).

Three intersecting knowledge domains seem to be crucial for teaching with and about NOS (see Fig. 1). Teachers' *science content understandings* represent the first domain: Like participants in the Wahbeh (2009) study, deep and integrated understandings of science content enable teachers to better implement effective NOS instruction (see also Lederman et al. 2001). The second domain could be thought of as a set of *pedagogical understandings and skills* related to (a) enacting student-centered and inquiry teaching, and (b) appreciating, assessing, and monitoring changes in, students' conceptions of NOS. Wahbeh (2009) found that teachers who appreciated the crucial role that students' prior ideas play in their learning were more effective in implementing NOS instruction due to taking an active role in assessing and monitoring growth (or lack thereof) in student understandings of the NOS aspects they taught. Also, teachers who valued and strived to actively engage students in their own learning—be it through various student-centered instructional modalities, guided inquiry, or full-fledged inquiry experiences—were more effective NOS instructors. At the intersection of these two knowledge domains lies the domain of *inquiry as instructional means* (Fig. 1) or teacher understandings and skills related to teaching science content by using inquiry as an instructional method (Anderson 2007; NRC 1996).

The third dimension is related to teachers' *NOS understandings* requisite for teaching with and about NOS. Nonetheless, what emerges under the model depicted in Fig. 1 is a nuanced articulation of understandings within this domain. To start with, there are *heuristic or domain-general NOS understandings,* which would be equivalent to what Lederman (1999) referred to as NOS conceptions that are consistent with those articulated in science education reform documents (e.g., AAAS 1990; NRC 1996). For instance, teachers would

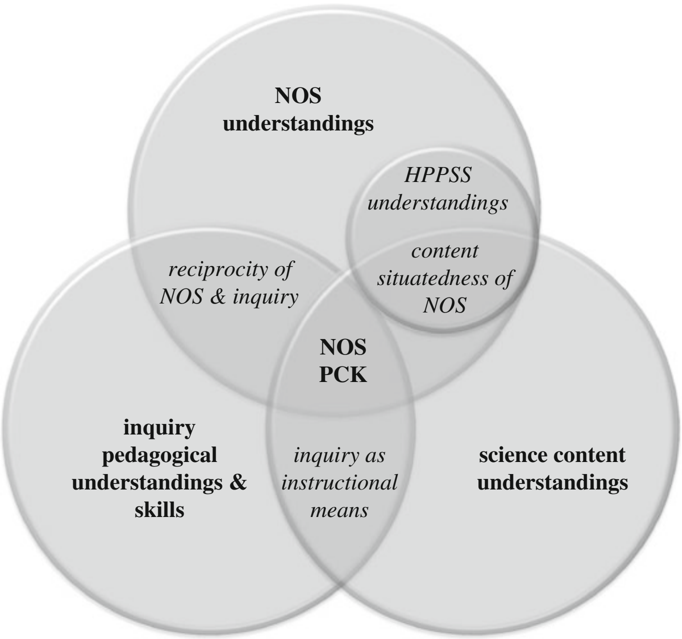

Fig. 1 Teacher knowledge domains for teaching *with* and *about* NOS

have developed an understanding and appreciation of the theory-laden NOS. It should be noted that in some cases, these understandings are acquired within a particular context, such as a specific content domain or historical episode. In other cases, teachers would have developed these understandings in content-lean contexts, such as activities of the black-box variety (e.g., Lederman and Abd-El-Khalick 1998). Heuristic NOS understandings surely are important for teaching with and about NOS; but, nonetheless, are not sufficient. Three nuanced sub-domains of NOS understandings are needed for such teaching. The first lies at the intersection of inquiry as practice and NOS as the underlying epistemological dimension of inquiry (referred to as *reciprocity of NOS and inquiry* in Fig. 1). This dimension refers to understanding that, while interrelated, scientific inquiry practices and NOS are not one and the same. NOS refers to the epistemological elements (e.g., theory-laden NOS) that account for, justify, and/or explain certain scientific practices (e.g., double-blind experiments undertaken in clinical medical trials, or the blind review process implemented by professional peer-refereed journals). This dimension enables teachers to align student inquiry activities with authentic scientific practice *and* identify and act on opportunities to help students reflect on their inquiry experiences in the service of learning about NOS.

The second sub-domain of teacher NOS understandings is *content-situated or domain-specific NOS understandings*. This dimension refers to the specific ways in which heuristic NOS conceptions (e.g., inferential NOS) might apply within a specific content domain (e.g., Mendelian genetics). This situatedness is intimately intertwined with the third sub-domain related to the historicity of NOS understandings. The latter dimension specifically refers to knowledge of narratives that integrate the historical, philosophical, psychological, and/or sociological aspects of the development of scientific knowledge (*HPPSS* in Fig. 1) relevant to the content being taught (e.g., the periodic table). In Wahbeh's (2009) study, the latter two sub-domains played a major role in enabling teachers to *transfer* their heuristic or domain general NOS understandings from within the contexts tackled in the intervention summer NOS course into markedly different contexts dictated by the teachers' science curricula. The latter teachers had more facility with locating, modifying, and/or designing NOS-related instructional resources and, thus, moved beyond the well-documented limitation of teachers finding it necessary to repeatedly ask for additional content and/or context specific NOS instructional materials (Abd-El-Khalick 2005). The intersection of all of the aforementioned knowledge domains and sub-domains would correspond to the illusive teachers' pedagogical content knowledge (PCK) (Shulman 1986, 1987) for teaching with and about NOS, or NOS PCK.

4 Discussion and Conclusions

The domains represented in Fig. 1 and unpacked in the previous section are meant to be necessary *and* sufficient knowledge domains for *enabling* science teachers to successfully engage in teaching with and about NOS. Nonetheless, as noted above, the translation of teachers' knowledge into instructional practice remains a mediated affair (Lederman 1999). Thus, while the outlined knowledge domains are necessary and sufficient to enable teaching with and about NOS, the actual enactment of commensurate instructional practices will hinge on a number of mediating factors. Chief among these factors are curricular mandates and priorities, and the extent to which learning outcomes related to developing student NOS understandings are valued curricular outcomes, or stand a chance to receive serious attention when teachers are overwhelmed with pressures to cover extensive science content related outcomes. Another set of factors stems from the value that teachers place on the importance of their students learning about NOS, and their perceptions of student abilities and motivation for learning about NOS (e.g., Abd-El-Khalick et al. 1998; Aguirre et al. 1990; Brickhouse 1989; Lederman et al. 2001). These aforementioned factors surely are interdependent, but are distinct in substantial ways from the knowledge domains for teaching with and about NOS. While the enactment of teaching with and about NOS might be dependent on these mediating factors, curricular mandates and teacher beliefs in the importance of student learning about NOS would not result in effective NOS instructional enactments.

When considering knowledge domains for teaching with and about NOS, one might be tempted to take on the task of dissecting and identifying those knowledge domains and sub-domains, as well associated mediating factors, that would result in teaching with or about NOS. After all, as explained above at some length, while interrelated, teaching with or about NOS does not necessarily entail the realization of the other dimension. This task, however, is not necessarily fruitful, because the core argument of the present paper is that to be successful in addressing the two longstanding and valued goals of enacting inquiry learning environments in science classrooms and helping students develop robust NOS understandings, we need to enable teachers to teach both with and about NOS. When properly implemented, these two facets of deploying teachers' NOS PCK would allow a seamless and synergistic approach to achieve the two espoused goals without adding to the expansive agendas of science teachers: Addressing NOS-related instructional outcomes would not need to be (or perceived by teachers to be) another standalone unit or component to further weigh down teachers and science instruction. Indeed, the significant investment in terms of time and energy that need to de dedicated toward developing science teachers' knowledge domains for teaching with and about might only be justifiable in terms of contributing to the achievement of these dual goals. The question follows: How can we help teachers develop these knowledge domains? After all, the academy's approach to undergraduate college education in the sciences is almost devoid of education in the history, philosophy, psychology, and/sociology of science, and mostly focused on initiation into specific disciplinary scientific traditions (Kuhn 1996). How best to go about developing teachers' NOS PCK?

As significant as these may be, an expansive answer to the above questions is beyond the scope of the present paper. Only outlines to such an answer are provided here. To start with, it should be noted that helping teachers develop the sorts of understandings suggested in Fig. 1 is a substantial challenge given the nature of science teacher education programs (Abd-El-Khalick and Lederman 2000a, b). While some of the requisite knowledge domains, such as heuristic understandings about NOS or understandings related to inquiry as a means to teach science content, are to some extent generalizable and transferrable across contexts, other knowledge domains are not. By definition, the sorts of content-situated NOS understandings and the historicity of these understandings (see Fig. 1) are domain-specific and can be only cultivated in tandem with developing deep understandings of specific science content knowledge. Thus, in addition to heuristic NOS and inquiry pedagogical understandings (see Fig. 1) science teachers are expected to develop robust understandings of their science content and narratives about the ways through which their disciplinary content was developed and came into its current forms. It follows that, even within a disciplinary subject matter (e.g., chemistry), we might expect science teachers to develop such robust knowledge domains in relation to specific topics (e.g., the periodic table, kinetic molecular theory) but not others (e.g., orbital valence theory). The sets of understandings that teachers do master, nonetheless, could serve as exemplars or roadmaps to guide teachers toward nurturing these understandings in the context of other disciplinary topics.

Helping science teachers develop heuristic NOS understandings could be effectively achieved through robust explicit-reflective NOS instructional interventions (e.g., Abd-El-Khalick and Akerson 2009; McDonald 2010; Wahbeh 2009). In the same token, the development of content-situated NOS understandings can be addressed through carefully tailored historically based explicit-reflective interventions, such as that implemented by Howe (2007). Coursework in HPS specifically geared toward teachers' needs would also be important (Abd-El-Khalick 2005; Abd-El-Khalick and Lederman 2000b). However, above all, teachers will need to experience the sort of teaching with and about NOS we are expecting of them as integrated packages in the context of teacher education programs. These latter experiences, it should be noted, would only serve as a primer because research indicates (e.g., Wahbeh 2009) that the development of robust knowledge domains for teaching with and about NOS is best achieved with extensive support and scaffolding in the context of science teachers' own classrooms. Carefully planned on-site interventions, coupled with long-term communication and support by researchers and teacher educators seem very important. In other words, cycles of classroom implementations, followed by structured reflection and refinement of the sort that Shulman (1986, 1987) suggested for the growth of teachers' PCK would be needed for the development of science teachers' NOS PCK.

References

Abd-El-Khalick, F. (2003). Socioscientific issues in pre-college science classrooms: The primacy of learners' epistemological orientations and views of nature of science. In D. L. Zeidler (Ed.), *The role of moral reasoning in socioscientific issues and discourse in science education* (pp. 41–61). Dordrecht, The Netherlands: Kluwer.

Abd-El-Khalick, F. (2005). Developing deeper understandings of nature of science: The impact of a philosophy of science course on preservice science teachers' views and instructional planning. *International Journal of Science Education, 27*(1), 15–42.

Abd-El-Khalick, F. (2008). Modeling science classrooms after scientific laboratories. In R. A. Duschl & R. E. Grandy (Eds.), *Teaching scientific inquiry: Recommendations for research and application* (pp. 80–85). Rotterdam, The Netherlands: Sense.

Abd-El-Khalick, F. (2012). Nature of science in science education: Toward a coherent framework for synergistic research and development. In B. J. Fraser, K. Tobin, & C. McRobbie (Eds.), *Second international handbook of science education* (Vol. 2, pp. 1041–1060). The Netherlands: Springer.

Abd-El-Khalick, F., & Akerson, V. L. (2004). Learning about nature of science as conceptual change: Factors that mediate the development of preservice elementary teachers' views of nature of science. *Science Education, 88*(5), 785–810.

Abd-El-Khalick, F., & Akerson, V. L. (2009). The influence of metacognitive training on preservice elementary teachers' conceptions of nature of science. *International Journal of Science Education, 31*(16), 2161–2184.

Abd-El-Khalick, F., Bell, R. L., & Lederman, N. G. (1998). The nature of science and instructional practice: Making the unnatural natural. *Science Education, 82*, 417–437.

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

Abd-El-Khalick, F., & Lederman, N. G. (2000a). Improving science teachers' conceptions of nature of science: A critical review of the literature. *International Journal of Science Education, 22*(7), 665–701.

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

Abd-El-Khalick, F., Waters, M., & Le, A. (2008). Representations of nature of science in high school chemistry textbooks over the past four decades. *Journal of Research in Science Teaching, 45*(7), 835–855.

Aguirre, J. M., Haggerty, S. M., & Linder, C. J. (1990). Student-teachers' conceptions of science, teaching and learning: A case study in preservice science education. *International Journal of Science Education, 12*, 381–390.

Akerson, V. L., Buzzelli, C. A., & Donnelly, L. A. (2010). On the nature of teaching nature of science: Preservice early childhood teachers' instruction in preschool and elementary settings. *Journal of Research in Science Teaching, 47*(2), 213–233.

Akindehin, F. (1988). Effect of an instructional package on preservice science teachers' understanding of the nature of science and acquisition of science-related attitudes. *Science Education, 72*(1), 73–82.

Allchin, D. (2011). Teaching whole science. *American Biology Teacher, 73*, 53–55.

American Association for the Advancement of Science. (1990). *Science for all Americans*. New York: Oxford University Press.

Anderson, R. (2007). Inquiry as an organizing theme for science curricula. In S. Abell & N. Lederman (Eds.), *Handbook of research on science education* (pp. 807–830). Mahwah, NJ: Lawrence Erlbaum Associates.

Barlow, N. (Ed.). (1993/1958). *The autobiography of Charles Darwin: 1809–1882*. New York: W. W. Norton.

Barufaldi, J. P., Bethel, L. J., & Lamb, W. G. (1977). The effect of a science methods course on the philosophical view of science among elementary education majors. *Journal of Research in Science Teaching, 14*(4), 289–294.

Bell, R. L., Blair, L. M., Crawford, B. A., & Lederman, N. G. (2003). Just do it? Impact of a science apprenticeship program on high school students' understandings of the nature of science and scientific inquiry. *Journal of Research in Science Teaching, 40*(5), 487–509.

BouJaoude, S., Salloum, S., & Abd-El-Khalick, F. (2004). Relationships between selective cognitive variables and students' ability to solve chemistry problems. *International Journal of Science Education, 26*(1), 63–84.

Brewer, W. F., & Chinn, C. A. (1994). The theory-ladenness of data: An experimental demonstration. In A. Ram & K. Eiselt (Eds.), *Proceedings of the sixteenth annual conference of the cognitive science society* (pp. 61–65). Hillsdale, NJ: Lawrence Erlbaum.

Brickhouse, N. W. (1989). The teaching of the philosophy of science in secondary classrooms: Case studies of teachers' personal theories. *International Journal of Science Education, 11*, 401–415.

Burbules, N., & Linn, M. C. (1991). Science education and philosophy of science: Congruence or contradiction? *International Journal of Science Education, 13*(3), 227–242.

Chinn, C. A., & Brewer, W. F. (1993). The role of anomalous data in knowledge acquisition: A theoretical framework and implications for science instruction. *Review of Educational Research, 63*, 1–49.

Chinn, C. A., & Malhorta, B. A. (2002). Children's responses to anomalous scientific data: How is conceptual change impeded? *Journal of Educational Psychology, 94*(2), 327–343.

Chinn, C. A., & Malhotra, B. A. (2002). Epistemologically authentic inquiry in schools: A theoretical framework for evaluating inquiry tasks. *Science Education, 86*, 175–218.

Conant, J. B. (1957). *Harvard case histories in experimental science* (Vol. 1). Cambridge, MA: Harvard University Press.

Council of Ministers of Education, Canada (CMEC) Pan-Canadian Science Project. (1997). *Common framework of science learning outcomes K to 12* [On-line]. Available: http://www.cmec.ca/science/framework/Pages/english/CMEC%20 Eng.html.

Crawford, B. A. (2007). Learning to teach science as inquiry in the rough and tumble of practice. *Journal of Research in Science Teaching, 44*(4), 613–642.

Curriculum Council. (1998). *Curriculum framework for Kindergarten to Year 12 education in Western Australia*. Osborne Park, WA: Author.

Dogan, N., & Abd-El-Khalick, F. (2008). Turkish grade 10 students' and science teachers' conceptions of nature of science: A national study. *Journal of Research in Science Teaching, 45*(10), 1083–1112.

Donnelly, L. A., & Sadler, T. (2009). High school science teachers' views of standards and accountability. *Science Education, 93*(6), 1050–1075.

Duhem, P. (1954). *The aim and structure of physical theory (with a new introduction by Jules Vuillemin)*. Princeton, NJ: Princeton University Press.

Duit, R., Treagust, D., & Widodo, A. (2008). Teaching science for conceptual change: Theory and practice. In S. Vosiniadou (Ed.), *International handbook of research on conceptual change* (pp. 629–646). Mahwah, NJ: Erlbaum.

Duncan, R. G., Freidenreich, H. B., Chinn, C. A., & Bausch, A. (2011). Promoting middle school students' understandings of molecular genetics. *Research in Science Education, 41*(2), 147–167.

Gillies, D. (1998). *Philosophy of science in the twentieth century: Four central themes*. Cambridge, MA: Blackwell.

Hewson, P. W., Beeth, M. E., & Thorley, N. R. (1998). Teaching for conceptual change. In B. J. Fraser & K. G. Tobin (Eds.), *International handbook of science education* (pp. 199–218). Dordrecht, The Netherlands: Kluwer.

Hillis, S. R. (1975). The development of an instrument to determine student views of the tentativeness of science. In E. J. Montague (Ed.), *Research and curriculum development in science education: Science teacher behavior and student affective and cognitive learning* (Vol. 3, pp. 32–38). Austin, TX: University of Texas Press.

Holton, G., Rutherford, J., & Watson, F. G. (1971). *About the Project Physics Course: An introduction to the teacher resource book*. New York: Holt, Rinehart, and Winston.

Holton, G., Watson, F. G., & Rutherford, F. J. (1967). Harvard project physics: A progress report. *The Physics Teacher, 5*(5).

Howe, E. M. (2007). Addressing nature-of-science core tenets with the history of science: An example with sickle-cell anemia & malaria. *American Biology Teacher, 69*(8), 467–472.

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*(3–5), 423–441.

Judson, E. (2010). Science education as a contributor to adequate yearly progress and accountability. *Science Education, 94*(5), 888–902.

Kang, S., Scharmann, L. C., & Noh, T. (2005). Examining students' views on the nature of science: Results from Korean 6th, 8th, and 10th graders. *Science Education, 89*(2), 314–334.

Kelly, G. J., & Duschl, R. A. (2002, April). *Toward a research agenda for epistemological studies in science education*. In *Paper presented at the annual meeting of the National Association for Research in Science Teaching*, New Orleans, LA.

Khishfe, R., & Abd-El-Khalick, F. (2002). Influence of explicit 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. (1964a). *History of science cases: The cells of life (teacher's guide)*. Chicago, IL: Science Research Associates.

Klopfer, L. E. (1964b). *History of science cases: The cells of life*. Chicago, IL: Science Research Associates.

Klopfer, L. E. (1966). *History of science cases: Frogs and batteries (teacher's guide)*. Chicago, IL: Science Research Associates.

Klopfer, L. E. (1969). The teaching of science and the history of science. *Journal of Research in Science Teaching, 6*(1), 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: A report on the HOSC instruction project. *Journal of Research in Science Teaching, 1*(1), 33–47.

Kuhn, T. S. (1996). *The structure of scientific revolutions* (3rd ed.). Chicago: The University of Chicago Press. (First published 1962).

Lederman, N. G. (1999). Teachers' understanding of the nature of science and classroom practice: Factors that facilitate or impede the relationship. *Journal of Research in Science Teaching, 36*, 916–929.

Lederman, N. G., & Abd-El-Khalick, F. (1998). Avoiding de-natured science: Activities that promote understandings of the nature of science. In W. McComas (Ed.), *The nature of science in science education: Rationales and strategies* (pp. 83–126). Dordrecht, The Netherlands: Kluwer.

Lederman, N. G., Schwartz, R., Abd-El-Khalick, F., & Bell, R. L. (2001). Preservice teachers' understanding and teaching of nature of science: An intervention study. *Canadian Journal of Science, Mathematics and Technology Education, 1*(2), 135–160.

Lee, O., Buxton, C., Lewis, S., & LeRoy, K. (2006). Science inquiry and student diversity: Enhanced abilities and continuing difficulties after an instructional intervention. *Journal of Research in Science Teaching, 43*(7), 607–636.

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

Longino, H. (1990). *Science as social knowledge: Values and objectivity in scientific inquiry*. Princeton, NJ: Princeton University Press.

Lunetta, V. N., Hofstein, A., & Clough, M. P. (2007). Learning and teaching school science laboratory: An analysis of research, theory, and practice. In S. K. Abell & N. G. Lederman (Eds.), *Handbook of research on science education* (pp. 393–441). Mahwah, NJ: Lawrence Erlbaum.

Marchlewicz, S. C., & Wink, D. L. (2011). Using the activity model of inquiry to enhance general chemistry students' understanding of nature of science. *Journal of Chemical Education, 88*(8), 1041–1047.

Mathews, M. R. (1994). *Science teaching: The role of history and philosophy of science*. New York: Routledge.

McDonald, C. V. (2010). The influence of explicit nature of science and argumentation instruction on preservice primary teachers' views of nature of science. *Journal of Research in Science Teaching, 47*(9), 1137–1164.

Millar, R., & Osborne, J. (Eds.). (1998). *Beyond 2000: Science education for the future*. London: King's College.

Ministry of Education. (1990). *Programa de articulación. Caracas.* Programa de Articulación. Venezuela: Author.

Ministry of Education. (1999). *Curriculum outline for "nature science and living technology."* Taipei: Ministry of Education (In Taiwanese).

Ministry of National Education. (2000). *Journal of Announcements of Ministry of National Education.* Ankara, Turkey: Author [In Turkish].

Monk, M., & Osborne, J. (1997). Placing the history and philosophy of science on the curriculum: A model for the development of pedagogy. *Science Education, 81*(4), 405–424.

Morrison, J. A., Raab, F., & Ingram, D. (2009). Factors influencing elementary and secondary teachers' views on the nature of science. *Journal of Research in Science Teaching, 46*(4), 384–403.

National Research Council. (1996). *National science education standards*. Washington, DC: National Academic Press.

National Science Teachers Association. (1982). *Science-Technology-Society: Science education for the 1980 s*. Washington, DC: Author.

Newton-Smith, W. H. (2000). Underdetermination of theory by data. In W. H. Newton-Smith (Ed.), *A companion to the philosophy of science* (pp. 532–536). Malden, MA: Blackwell.

Olitsky, S. (2005). Social and cultural capital in science teaching: Relating practice and reflection. In K. Tobin, R. Elmesky, & G. Seiler (Eds.), *Improving urban science education: New roles for teachers, students and researchers* (pp. 279–297). New York: Rowman & Littlefield.

Peters, E., & Kitsantas, A. (2010). The effect of nature of science metacognitive prompts on science students' content and nature of science knowledge, metacognition, and self-regulatory efficacy. *School Science and Mathematics, 110*(8), 382–396.

Popper, K. R. (1963). *Conjectures and refutations: The growth of scientific knowledge*. London, UK: Routledge & Kagan Paul.

Quine, W. V. (1951). Two dogmas of empiricism. *Philosophical Review, 60*, 20–43.

Riley, J. P., I. I. (1979). The influence of hands-on science process training on preservice teachers' acquisition of process skills and attitude toward science and science teaching. *Journal of Research in Science Teaching, 16*, 373–384.

Robinson, J. T. (1965). Science teaching and the nature of science. *Journal of Research in Science Teaching, 3*, 37–50.

Rubba, P. A., & Anderson, H. (1978). Development of an instrument to assess secondary school students' understanding of the nature of scientific knowledge. *Science Education, 62*(4), 449–458.

Russell, C. B., & Weaver, G. C. (2011). A comparative study of traditional, inquiry-based, and research-based laboratory curricula: Impacts on understanding of the nature of science. *Chemistry Education Research and Practice, 12*(1), 57–67.

Rutherford, F. J. (1964). The role of inquiry in science teaching. *Journal of Research in Science Teaching, 2*, 80–84.

Salloum, S., & Abd-El-Khalick, F. (2010). A study of practical-moral knowledge in science teaching: Case studies in physical science classrooms. *Journal of Research in Science Teaching, 47*(8), 929–951.

Sandoval, W. A., & Morrison, K. (2003). High school students' ideas about theories and theory change after a biological inquiry unit. *Journal of Research in Science Teaching, 40*(4), 369–392.

Schmuckler, J. S. (2004). Using the history of science to strengthen an understanding of the nature of science. *Abstracts of papers of the American Chemical Society, 228*(1), 312.

Schwartz, R. S., & Lederman, N. G. (2002). "It's the nature of the beast": The influence of knowledge and intentions on learning and teaching nature of science. *Journal of Research in Science Teaching, 39*(3), 205–236.

Scott, P. H., Asoko, H. M., & Driver, R. H. (1992). Teaching for conceptual change: A review of strategies. In R. Duit, F. Goldberg, & H. Niedderer (Eds.), *Research in physics learning: Theoretical issues and empirical studies* (pp. 310–329). Kiel, Germany: Institute for Science Education at the University of Kiel.

Scott, P., Asoko, H., & Leach, J. (2007). Student conceptions and conceptual learning in science. In S. Abell & N. Lederman (Eds.), *Handbook of research on science education* (pp. 31–56). Mahwah, NJ: Lawrence Erlbaum Associates.

Shanahan, M.-C., & Nieswandt, M. (2011). Science student role: Evidence of social structural norms specific to school science. *Journal of Research in Science Teaching, 48*(4), 367–395.

Shulman, L. S. (1986). Those who understand: Knowledge growth in teaching. *Educational Researcher, 15*, 4–14.

Shulman, L. S. (1987). Knowledge and teaching: Foundations of the new reform. *Harvard Educational Review, 57*, 1–22.

So, W. M. W., & Ching, N. Y. F. (2011). Creating a collaborative science learning environment for science inquiry at the primary level. *Asia-Pacific Education Researcher, 20*(3), 559–569.

Sweitzer, G. L., & Anderson, R. D. (1983). A meta-analysis of research on science teacher education practices associated with inquiry strategy. *Journal of Research in Science Teaching, 20*(5), 453–466.

Treagust, D. (2007). General instructional methods and strategies. In S. K. Abell & N. G. Lederman (Eds.), *Handbook of research on science education* (pp. 373–392). Mahwah, NJ: Lawrence Erlbaum Associates.

van Garderen, D., Hanuscin, D., Lee, E., & Kohn, P. (2012). A collaborative professional development model to meet the needs of diverse learners in K-6 science. *Psychology in the Schools, 49*(5), 429–443.

Vesilind, E. M., & Jones, M. G. (1998). Gardens or graveyards: Science education reform and school culture. *Journal of Research in Science Teaching, 35*(7), 757–775.

Wahbeh, N. (2009). *The effect of a content-embedded explicit-reflective approach on inservice teachers' views and practices related to nature of science.* Unpublished doctoral dissertation, University of Illinois at Urbana-Champaign, Champaign, IL.

Wahbeh, N., & Abd-El-Khalick, F. (2011, September). *The primacy of content-embedded teacher understandings of nature of science in impacting instruction.* In *Paper presented at the biannual conference of the European Science Education Research Association,* Lyon, France.

Welch, W. W. (1973). Review of the research and evaluation program of the Harvard project physics. *Journal of Research in Science Teaching, 10*(4), 365–378.

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.