Chapter 1
Nature of Science in Science Instruction: Meaning, Advocacy, Rationales, and Recommendations

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1.1 An Introduction to Science and Its Nature as the Foundation for Science Learning

For centuries, formal education has included some aspects of science content and process. The science curriculum has generally had a somewhat utilitarian focus with content related to what was necessary in specific trades, future education, the health and welfare of the individual or society, and general knowledge for citizenship. Some maintain that science is inherently interesting and, because of this, worthy. Regardless of why science has been included and often required in the school curriculum, the focus has traditionally been on covering vast amounts of content sometimes augmented with "hands-on" experiences. This aspect of the science experience has typically highlighted experimentation as a problem-solving tool accompanied by data collection that involves measuring, observing, and other processes of science. These important inquiry skills often are included in school science, and they provide fruitful opportunities for addressing the nature of science. However, NOS content has largely been neglected, and other aspects (such as the objectivity of scientists and the step-by-step scientific method) are frequently incorrectly or misleadingly offered as accurate lessons about how science works.

This general disregard for NOS is puzzling given that science has a pervasive, but often subtle, impact on virtually every aspect of modern life—both from the technology that flows from it and the philosophical and ethical implications arising

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from its ideas. Science is increasingly being ignored by policy-makers and the public, and thus citizens must come to understand how science works and even defend science from those who view well-established scientific consensus as mere opinion. Everyone ought to be well-educated regarding the most fundamental scientific knowledge but also understand science as “a way of knowing,” more comprehensively, the NOS.

Before proceeding, what is meant by “science” and “nature of science” must be addressed. However, the complexity of science and its nature both defy simplistic and universally accepted definitions. While one very important outcome of NOS scholarship is that clearly demarcating science from other disciplines is problematic, an initial characterization of science is possible and needed to move forward.

1.1.1 What Is Science?

While no simple characterization can wholly capture what science is, a reasonable and brief definition is that science is a human endeavor directed at exploring the natural world to produce valid and reliable knowledge (explanations and generalizations) supported by evidence and reasoning that is, in principle, open to review by all. This definition is certainly too basic because existing knowledge and traditions constrain both the focus of the work of scientist and the tools (intellectual and otherwise) that can be brought to bear in the process of scientific work, but it is a good start. However, a more complete description of it can only be achieved through an examination of its nature and its products, our next section’s topic.

Our modern term *science* comes from the Latin word *scientia* or *knowledge*. This was a generic use of the word in much the same way that *philosophy* was the label for a lover of knowledge itself. In this sense, many things could be called a science, and those seeking wisdom in any field were philosophers. However, thoughout much of history those working in ways that resemble our modern conceptualization of science were often known as “natural philosophers,” and the domain was called “natural philosophy.” The key here is that such individuals began slowly to limit their investigations to the natural world, increasingly valuing naturalistic explanations. Gradually, “natural philosophy” became “natural science” and finally just “science” as we call it today. This evolution was also seen with respect to the name for those working in the natural sciences. In 1833, polymath and historian of science William Whewell coined the term “scientist” (and “physicist” too for good measure) as a counterpoint to the common term “artist.” The term grew slowly in popularity and finally emerged in the form that we know it today by the end of the nineteenth century. Scientific knowledge has become so vast that perhaps we have reached the point where calling someone a scientist requires greater clarity; even the description “biologist,” “physicist,” or “chemist” is quite broad, and only a label like biochemist, wildlife biologist, particle physicist, or vertebrate paleontologist or even more specific titles can truly capture the incredible level of specific knowledge and practice of those working in the natural sciences.

1.1.2 What Does the Expression "Nature of Science" Mean?

Nature of science (NOS) is not a description of how the natural world works (that's science itself), but rather a description of how the scientific enterprise works. Just as scientists devote their careers to better understanding the natural world, those interested in the nature of science want to understand how scientists work and engage with each other and society, how science answers questions, and how this thing called science generates knowledge about nature. The NOS addresses issues such as what is science, how science works (including issues of epistemology and ontology), how science impacts and is impacted by society, and what scientists are like in their professional and personal lives. Those interested in the study of science ask questions like "What, if anything, demarcates science from other human endeavors?", "In what sense are science ideas discovered or invented?", and "How is consensus regarding conclusions reached in the scientific community?"

In an earlier work (McComas et al. 1998, p. 4), we wrote and still maintain that:

> The nature of science is a fertile hybrid arena which blends aspects of various social studies of science including the history, sociology, and philosophy of science combined with research from the cognitive sciences such as psychology into a rich description of what science is, how it works, how scientists operate as a social group and how society itself both directs and reacts to scientific endeavors.

As a shorter characterization, "The nature of science involves the basic values and beliefs that make up the scientific world view, how scientists go about their work, and the general culture of the scientific enterprise" (AAAS 2001, p. 15). Although the term "nature of science" is occasionally used by some outside the domain of science education, this label has found a home and strong advocacy among those who care deeply about science teaching and learning. As stated in the preface, we agree that there is no single nature of science as might wrongly be inferred from "the" nature of science. However, as discussed throughout this book, much has been learned about the nature of science that science educators frequently recommend be shared with science learners in efforts to promote science literacy.

1.1.3 Why "NOS"?

For a variety of reasons, names other than "nature of science" have been suggested. These include Nature of Science Studies, Features of Science (Matthews 2012), History and Philosophy of Science, Ideas About Science (Osborne et al. 2003), Nature of Sciences, Nature of Scientific Understanding, Nature of Scientific Knowledge (Lederman 2007), Views of Science, and others. Of course, the specific name does convey a certain orientation, and the nuances represented by each of these suggestions has value. However, in the interest of space rather than because of a lack of interest, we have avoided an analysis of each. Rather, considering the long use of the "NOS" label in science education, we will continue that tradition throughout this book. Disagreements about the label “NOS” and referring to NOS instruction as “teaching NOS,” “teaching about NOS,” “teaching the NOS,” reflect the perspectives and passions of those with interests in this pedagogical arena.

1.1.4 What About NOS Should Be Taught and Learned?

The ultimate set of NOS elements that should be the focus of science instruction and even how those elements are best provided in standards documents remains unsettled to some degree. This important debate will be highlighted and discussed in detail in Chap. 2, but a review here is important. On one side of the debate, we find that with a human endeavor as complex and diverse as science, some (Herron 1969) submit that no sound and precise description could exist concerning the nature and structure of science. Laudan et al. (1986) stated that “…we have no well-confirmed general picture of how science works, no theory of science worthy of general assent” (p.142). Decades ago Welch (1984) and Duschl (1994) also expressed concern about a lack of consensus regarding what image of scientific inquiry and growth of scientific knowledge should be shared with students. More recently, van Dijk (2011) has taken up the cause by suggesting that totally understanding science and therefore precisely demarcating it from other human pursuits is not possible. Even if this were true, this would not prevent us from adequately and accurately sharing a “big picture” view of science useful for school science purposes.

If we keep our focus on describing science for science learners—particularly in introductory instructional settings—there is much known about NOS that can and even must inform science education efforts directed at promoting science literacy. Convergence on a shared view of aspects of NOS worthy for inclusion in science classes has been developing for decades represented by suggestions in *Benchmarks for Science Literacy* (AAAS 1993), Osborne et al. (2003), McComas et al. 1998, McComas 2004), Lederman (2002), and the US Next Generation Science Standards (Achieve 2013). These sources offer similar but not identical sets of NOS content recommendations. Chapter 3 features an extensive discussion of nine key NOS ideas that many in the science education community see as a reasonable foundation for use in classroom conversations, standards, textbooks, and student assessment. This includes issues such as the distinction between law and theory, the place for creativity in science, the ranges of shared methods used by scientists, cultural and social elements that impact science, the role and nature of evidence, and other considerations in understanding the natural world.

These ideas frame NOS instruction in the US *Next Generation Science Standards*, although many in the science education community sought a much more prominent role for NOS in the document. Unfortunately, NOS appears almost as an afterthought in an appendix (Appendix H) with various NOS issues linked, often poorly, to the cross-cutting themes and science and engineering practices that along with science content are collectively called the three dimensions of science teaching. McComas and Nouri (2016) have suggested that NOS be featured as a fourth dimension of science learning. Nevertheless, NOS does appear in the document destined to inform and direct science teaching in US public schools in those states that adopt its recommendations. Furthermore, because NGSS has been so widely circulated generally both within and beyond the United States, its contents, including NOS, will likely impact thinking about science teaching broadly and for many years to come.

In establishing desired NOS learning outcomes, we agree with Matthews (1998) that we develop achievable objectives. He wisely states that, "It is unrealistic to expect students or prospective teachers to become competent historians, sociologists, or philosophers of science. …There is no need to overwhelm students with cutting edge [philosophical] questions." (pp. 168–169). Reflecting this, we strongly recommend striking a balance between a shallow and perhaps even banal description of how science functions and high-level discussions that would be much more appropriate in postsecondary history and philosophy of science coursework. While NOS must not be misrepresented or over simplified, students should be engaged in learning the fundamental and most meaningful ideas regarding the social studies of science with a goal to improve their science literacy for purposes of personal and societal decision-making. We further advocate that, while proposed NOS instructional goals should be debated and periodically reexamined, such discussions must not halt the teaching and learning of NOS in science education. Those who insist on the impossibility of defining NOS or recommend waiting until complete consensus is achieved can unintentionally set back efforts to ensure that all students leave school with NOS understanding sufficient for informed citizenship.

1.2 How We Know What We Know About How Science Works: A Brief Introduction

If you want to know about water, don't ask a fish
Chinese Proverb

Simply asking scientists about how they do their work is insufficient for understanding the scientific enterprise. Einstein (1934/1982) recommended that if you want to know how scientists work, "don't listen to their words, fix your attention on their deeds" (p. 270). Of course, scientists do understand the nature of their work better than most, but they are often so focused on understanding how nature works that they rarely stand back and deeply reflect on how science itself functions. That perspective is taken on by philosophers, historians, and sociologists of science along with psychologists who intently investigate those who do science and how they engage in their pursuits. Through these efforts, we have come to understand much about science and scientists. Science educators draw from this wealth of knowledge

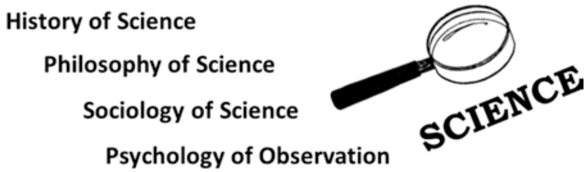

Fig. 1.1 The four major disciplines that provide important evidence in support of an accurate picture of how science functions

to determine NOS content appropriate for inclusion in school science learning experiences and the preparation of those who will become science teachers.

Detailing the contributions of scholars who provide understanding about how science operates is beyond the scope of this book, but a cursory overview is necessary to appreciate the distinction between "science" and the "social studies of science." At a macro level, four major groups of experts have contributed to our knowledge of NOS (Fig. 1.1). Importantly, these scholars often have undergraduate and graduate degrees in science and may even have practiced science. Historians of science look to the past and often extract lessons about how science functions and how social systems and culture have impacted science. Philosophers of science often draw on evidence from history or logical analyses about how science works. Sociologists of science study the interactions of scientists as a social group and consequently develop insights about power structures, expertise, and how ideas come to be accepted within the community of scientists. Psychologists of science are not mentioned as prominently as the others in providing a vital nuance to any view of science. However, such scholarship has contributed significantly to our understanding of how all observation, including that by scientists, is impacted by pre-existing knowledge and presuppositions.

The combined contributions of experts in these areas have provided extensive descriptions about how science functions. Our job in science education is to consult the conclusions of these scholars who describe the enterprise of science and extract a rich, accurate, engaging, reasonably nuanced picture of the science to inform the science curriculum and teaching in ways that learners can understand, teachers can embrace and communicate, and instructional time will allow. The insights found at the intersection of the various social studies of science in Fig. 1.1 represent the content domain (NOS) which offers a rich view of science for those who have limited opportunity (i.e., school and informal science education settings) to take in the scenery.

1.3 A History of Advocacy for NOS in Science Instruction

Most science educators agree that NOS understanding is a crucial component of scientific literacy. Advocacy supporting students' understanding of science and its nature can be traced back to the early years of the twentieth century with antecedents extending back even further (Matthews 2012, 2015). Although the phrase "understanding the nature of science" has not alwasy been in use, some elements and characteristics of science were noted as goals worth pursuing in science teaching. For example, the Central Association of Science and Math Teachers (CASMT 1907) strongly emphasized inclusion of the scientific method and processes of science in science teaching. Hodson (1991) cites Dewey's 1916 argument that understanding scientific method is more important than the acquisition of scientific knowledge.

British educator Frederick Westaway (1929) was quite direct in his influential science teaching methods book with the clever title *Science Teaching: What it Was—What it Is—What it Might Be*. This book includes a full chapter on the role of the history of science and another on the philosophic foundations of science. This chapter is surprisingly contemporary with suggestions that students "must now learn to examine the nature of scientific evidence, hypotheses, induction and laws…" (p. 386). Furthermore, students are warned to work at eliminating bias when forming judgments, that "our senses may deceive us" (p. 388) and that it is difficult to ensure "that the facts from which [we] reason are objective and untainted." Westaway continues by mentioning the importance of the problems of induction and the notion of tentativeness (the provisional aspect of science) in our models and ideas while alluding to the limits of science. At much the same time, Jaffe (1938), in his high school textbook *New World of Chemistry*, included nature of science objectives such as a willingness to swing judgment while experiments are in progress, willingness to abandon a theory when new evidence is available, and knowledge that scientific laws may not be the ultimate truth.

When James Bryan Conant delivered his three influential Terry Lectures at Yale (Conant 1946), he advocated using history in science instruction by suggesting that all students must understand the tactics and strategies of science. One way to share such an understanding is for students to see science in action through its history. However, not until the second half of the twentieth century was the construct "nature of science" stated explicitly by Hurd (1960) as a major aim of science teaching:

> There are two major aims of science-teaching; one is knowledge, and the other is enterprise. From science courses, pupils should acquire a useful command of science concepts and principles. Science is more than a collection of isolated and assorted facts … A student should learn something about the character of scientific knowledge, how it has been developed, and how it is used (Hurd 1960, p. 34).

Several of the 1960s science curriculum projects in the United States attempted to move science instruction away from the typical focus on "what do scientists know?" to an examination of the question "how do scientists know?" Klopfer's (1964–1966) *History of Science Cases* and Schwab's seminal contributions to the *Biological Science Curriculum Studies* in the early 1960s are important efforts illustrating both the process and products of science in formal curricula. Among the most effective example of such a curriculum was *Harvard Project Physics* which began in 1962 and resulted in three editions of the *Project Physics* text (Rutherford et al. 1970), a project chronicled in Holton's (2000) overview.

Robinson (1968) in his book *The Nature of Science and Science Teaching* prompted science educators to see the value of the philosophy of science in science teaching and learning. His book provided an overview of the nature of physical reality; aspects of physical description including probability, certainty, and causality; and view of the nature of science in various science disciplines. He concluded with considerations for the interplay between science instruction and the nature of science. Another pioneer, Martin (1972), in *Concepts of Science Education: A Philosophical Analysis*, reiterated several arguments put forward by Robinson for attending to NOS in science education. He reviewed many of the important concepts from the philosophy of science including the value of inquiry learning, the nature of explanation, and the character of observation both in science and in science teaching and learning. This quest engages us today as we endeavor to extract conclusions from those scholars whose work focuses on describing the scientific enterprise and transforming those descriptions into lessons giving students rich and accurate views of science.

Incorporating aspects of nature of science content in school science has been widely embraced by organizations such as the Association for Science Education (1981) in Britain and organizations in the United States such as the National Science Teachers Association (1995, 2000, 2012), the American Association for the Advancement of Science (1990, 1993), and the National Research Council in the *National Science Education Standards* (1996) and in many international standards documents developed to guide science teaching and learning in classrooms. The American Association for the Advancement of Science publication *Science for all Americans* (AAAS, 1990) prominently featured the history and nature of science in science education efforts, devoting a full chapter to both. The US *Next Generation Science Standards* (Achieve 2013), as previously noted, overtly features NOS (regrettably in an appendix) along with recommendations that science instruction should focus on communicating science content, science, and engineering practices.

In 1987, reflecting the increasing scholarly interest in NOS, a new professional association was established—the International History, Philosophy and Science Teaching Group (IHPST)—which sponsors regional and international conferences and a well-regarded journal, *Science & Education*, that has effectively become the journal of record for work at the intersection of NOS and science teaching. NOS presentations at both practitioner and academic science education conferences are increasingly well-attended indicating that interest in this area continues to grow. Certainly contemporary science educators would agree that encouraging students to understand science, its presuppositions, values, aims, and limitations should be a central goal of science teaching. As Shamos (1995) suggested in *The Myth of Scientific Literacy*, knowledge of science content itself may not be necessary for obtaining science literacy, but understanding the nature of science *is* prerequisite to such literacy.

1.4 Rationales for the Inclusion of NOS in Science Instruction

Many scholars (Allchin 2013; Driver et al. 1996; Duschl 1990, 1994; Hodson 1986, 1988, 2014; Matthews 1989, 1994, 2015) have suggested that learning about NOS will promote a variety of important outcomes that serve as rationales for NOS instruction. Admittedly, not all rationales offered are necessary supported by empirical studies, but each presents a degree of face validity. We have examined this and other literature and have drawn on our experience to suggest the following reasons for the value of accurate NOS understanding. Each rationale offers a distinct significance for understanding NOS but is not necessarily mutually exclusive.

1.4.1 NOS Understanding is Fundamental for Understanding Science

Some content is so central to a field of study that ignoring it in instruction could be considered a matter of educational malpractice. For instance, instruction regarding cells, ecology, and biological evolution must be part of any course that can honestly be said to be an introduction to biology. A course titled introductory chemistry must address atoms, atomic theory, and other ideas that are at the heart of chemistry. Likewise, any science course is simply incomplete if it does not address NOS issues and related ideas. Simply put, NOS is fundamental to any conception of a science *education*. Joseph Schwab, philosopher and science educator, strongly recommended that science instruction place greater emphasis on what scientists do and how science works. He and others have lamented that science is often taught as an "unmitigated rhetoric of conclusions in which the current and temporal constructions of scientific knowledge are conveyed as empirical, literal, and irrevocable truths" (Schwab 1964, p. 24).

In support of this rationale, *Benchmarks for Science Literacy* (AAAS 1993) reminds us that NOS knowledge can provide something of the epistemological foundations of science within the school science experience:

> When people know how scientists go about their work and reach scientific conclusions and what the limitations of such conclusions are, they are more likely to react thoughtfully to scientific claims and less likely to reject them out of hand or accept them uncritically.… They can follow the science adventure story as it plays out during their lifetimes. (p. 3)

McCain and Segal (1982) write that, "Since [science] touches almost every facet of our life, educated people need at least some acquaintance with is structure and operation" (p. v). In summary, understanding how science operates is intrinsically important in any characterization of a well-educated and scientifically literate person.

1.4.2 NOS Understanding Nutures Students' Interest and Encourages Appreciation for Science

This rationale is rooted in the affective domain and is important for nurturing students' latent interest in science and perhaps encouraging them in their study of science and in pursuit of science-related degrees. Tobias (1990) reported that many high-performing university science students—those she calls the second tier—opted out of science, lamenting that science classes ignore the historical, philosophical, and sociological foundations of science, particularly the creative aspects of science. Moreover, interest often promotes better attitude and a higher degree of attention, both which impact learning. Addressing NOS when teaching science content can humanize science and convey the practice of science as a collaborative puzzle-solving adventure to understand nature.

Clough et al. (2010) report that among 85 biology majors who read short historical stories addressing how science ideas were developed and came to be accepted, 79 stated that doing science research appears more interesting that they previously thought. Thirty-six of the 85 stated they were more interested in science as a career, while 48 of the majors reported no change in their interest in a science career. In a similar study at the secondary school level, Reid-Smith (2013) reported that 41% of 500 students who read short historical science stories that accurately portrayed NOS found the science content more interesting, while 44% reported no impact on their interest, and 37% reported that science was more interesting than they previously thought, while 47% reported no change in how interesting science appeared to them. Hong and Lin-Siegler (2012) in a study involving 271 high school students reported that those students who learned about scientists' struggles developing the science ideas being taught to them had greater interest in science, improved their delayed recall of the key science ideas, and improved their ability to solve complex problems that required deeper conceptual understanding.

The next two rationales (utility for practice and citizenship) are related in that NOS may be recommended for its usefulness within science and in life generally; we will discuss each separately because the target of the application of NOS is distinct in each domain.

1.4.3 NOS Knowledge Can Assist Students and Scientists: NOS has Practical Utility

This rationale is founded on the principle that knowing how science works is important to two groups: students learning about science in school settings and scientists applying the "rules" of the game of science as they make in fundamental discoveries. Next we will consider the importance of NOS understanding to those in each of these groups.

We believe that school science should provide opportunities for students to function as much like scientists as possible. However, we recognize that students have not had the life experiences of scientists and therefore will "see" the world in the same way as do scientists. When students apply an accurate understanding of the history and nature of science, they are more likely to see their laboratory and field experiences in a more authentically scientific fashion.

For instance, when students working in the laboratory (also called practical work) are confused that their results do not precisely match those in their textbook, their understanding of idealization will prove useful. Those with a strong background in NOS know that the ideas and principles in science are often stated from the way they operate in ideal settings. Newton's laws of motion are an excellent example. Newton tells us that a rolling object will continue to move, but we recognize that in the real world, friction interferes and brings the object to a stop. Pendulum motion, as described in textbooks, is also idealized so that what students "see" in the laboratory may be somewhat at odds with what they read.

Another vital point is that students must understand that data do not "tell" anyone anything. Observers must personally and collectively make sense of data. Such an understanding will help students more confidently grapple with their own data. These and other NOS ideas can assist us all in making sense of and more productively engage in their school laboratory and field experiences.

Finally, only if students understand the overarching ideas that govern science, will they be able to operate more like scientists do. For instance, there are many shared methods of science including induction, deduction, and inference along with a host of process skills such as observation, measuring, and communicating. In addition, knowledge of the two main purposes of science—forming generalization and proposing explanations—can guide the progress of science. When students are engaged in scientific work in the school laboratory, they must know what acceptable practices are and use them consistently. We recognize that this justification for the inclusion of NOS in the curriculum has a somewhat circular nature because it combines both "learning NOS" and "using NOS," but these do not have to be visualized as separate goals.

Learners will be better "student-scientists" when they have foundation knowledge of many of the recommended elements associated with NOS. At the same time, students will have opportunities to learn more about key NOS elements when they are engaged in hands-on and other practical learning. This is particularly true in classrooms facilitated by teachers who value and understand NOS personally and use the laboratory as a place both to teach about NOS and provide practice in applying NOS principles.

We can now turn our attention to another group who would benefit from a firm understanding of NOS, practicing scientists. Stanley (2016) also puts forward several ways that understanding the history and nature of science can assist the actual practice of science. Among these is acknowledging the diversity of approaches and ideas in the past and how they assisted in pushing forward what was then the frontiers of science. He suggests that the awareness of novel approaches and ways of thinking can, in turn, assist current scientists in reexamining what is known in their efforts to push forward today's frontiers. It is true that even without NOS content included in all formal science learning opportunities, those who become scientists will learn how science functions by trial and error and intuition. If someone who purports to be a scientist is engaging in practices too far outside the realm of science, they will be excluded from the mainstream. A reasonable utilitarian justification for the inclusion of NOS in the science curriculum is that it may produce better scientists faster.

1.4.4 NOS Understanding is Vital for Citizenship

An understanding of how science functions and applying that understanding to both everyday thinking and informed citizenship decisions is what Driver et al. (1996, p. 18) called the "democratic argument" in support of NOS in the science curriculum. On this point, we might apply the delightful compound German term mentioned by Kötter and Hammann (2017), *Bewertungskompetinez*, defined as "the competency to make informed ethical decision in scientific contexts" (p.451). It is difficult to imagine that this label will come into widespread use, but this is precisely the meaning associated with this rationale for including NOS in the curriculum. For instance, NOS understanding plays a role in socio-scientific thinking regarding global climate change (Clough and Herman 2017; Herman 2015) and rejecting efforts of creationists/intelligent design proponents to thwart the teaching of biological evolution. NOS understanding can also assist in combating antiscience, irrationality, and scientism (the notion that science can address all problems) that plagues contemporary society.

As another example, consider the following "democratic" uses that might be made of NOS knowledge. Evidence exists (Ryan and Aikenhead 1992) that science is often confused with engineering and technology leading the public to support science because they wrongly see it as providing society with gadgets, vaccines, and other practical outcomes that improve everyday life. However, basic science research is not directly concerned with practical societal outcomes, but rather an understanding of the natural world for its own sake. The public's failure to see the importance of basic research in technological innovations is evident in citizens' and policy-makers' reluctance to fund basic research (Tyson 2011; Elmer-Dewitt 1994).

Shamos (1995) and Driver et al. (1996) add an interesting element to this rationale for NOS with their suggestion that students must understand who the experts are regarding science content and which experts ought to be trusted. Nonscientists rarely possess the expertise to judge the veracity of scientific conclusions, but NOS knowledge can assist in sorting out well-established consensus in the scientific community from individuals or groups that seek to sew doubt about any scientific conclusions relevant for personal and societal decision-making.

1.4.5 NOS Knowledge Supports the Learning and Teaching of Traditional Science Content

Matthews (1994) provides examples illustrating how NOS understanding places science teachers in a better position to implement conceptual change models of instruction and students in a better position deeply to understand certain science content. In the earlier noted study by Clough et al. (2010), of the 85 students experiencing short stories that accurately portrayed the development and acceptance of fundamental science ideas, 65% of them self-reported that the stories increased their understanding of the science content. Arya and Maul (2012) reported that of 209 middle school students, those experiencing science instruction via narrative accounts of scientists' work achieved higher conceptual understanding and knowledge retention of the relevant science content. Students from socioeconomically disadvantaged backgrounds benefitted even more. The authors speculate that their experimental approach may promote greater attentiveness to the conceptual content. Herman et al. (2019b) reported significant and moderate to moderately large associations existed between the accuracy and contextualization of students' NOS views and the complexity of their trophic cascade explanations. Much evidence (Dagher and BouJaoude 1997; Rudolph and Stewart 1998; Johnson and Peeples 1987; Rutledge and Warden 2000; National Academy of Sciences 1998; National Academy of Science and Institute of Medicine 2008; Smith 2000) supports the contention that NOS understanding assists in teaching and learning about biological evolution.

Having students study the process of historical conceptual development in science may also be useful to students in evaluating their own prior ideas (Wandersee 1986). For example, often students' ideas parallel that of early scientific ideas, as has often been the case in science. The persistence of students' naive ideas in science suggests that teachers could use the historical development of scientific concepts to help illuminate the conceptual journey students must make away from their own naive misconceptions.

1.5 A Brief Overview of the State of Current NOS Education Research

Even a cursory look at articles appearing in science education journals during the past three decades demonstrates extensive and increasing attention to issues regarding NOS teaching and learning. Sessions featuring discussions of NOS learning are common at professional science education conferences and are typically well-attended. Clearly, NOS-related scholarship and implications for practice remain of significant interest to many involved in science teaching and learning. We know much about effective instruction with respect to NOS, but many challenges remain as will be detailed in Chap. 4.

Thus, any satisfactory "review of the literature" would either have to be highly focused or, as it has been said elsewhere, a kilometer wide and a centimeter deep (or a mile wide and inch deep if you prefer). Colleagues writing about NOS have engaged in focused reviews of literature related to a specific issue (e.g., Abd-El-Khalick and Lederman 2000; Deng et al. 2011), while others such as Lederman (2007), Lederman and Lederman (2014) in chapters in the two volumes of the *Handbook of Research in Science Education* and Matthews (2014) in his extensive multivolume, multiauthor *International Handbook of Research in History, Philosophy and Science Teaching* have produced much broader reviews. Both approaches are beyond the scope of this chapter, but we recommend attention to these and other reviews. Instead, here, we provide a broad overview of the kinds of scholarly work in NOS education during the past two decades and end with a summary of what has been well-established regarding NOS teaching and learning.

Using a qualitative approach to determine the kinds of NOS research appearing in the scholarly literature during the past 20 years, Nouri et al. (2017) examined 438 articles appearing in major science education research journals and propose 9 categories in which NOS scholarship may be classified. These include (1) ways to teach NOS to students, (2) teaching NOS to educators, (3) analyses of classroom practices featuring NOS, (4) development of NOS assessment tools, (5) analyses of NOS instructional materials, (6) nonempirical commentaries on NOS such as the debate about NOS content, (7) the relationship of NOS understanding to other science content such as evolution, (8) investigations of scientists' and educators' views of NOS, and (9) analyses of topics and science content that might assist in communicating aspects of NOS. In addition to making apparent the intense scholarly attention to NOS in science education, this study made apparent that the value of NOS is well-established and that researchers now focus primarily on efforts to promote and improve NOS teaching and learning.

Empirical work regarding NOS instruction conducted during the past three decades has largely coalesced in support of the following well-substantiated claims (Lederman 2007):

- Students at all levels do not typically possess "adequate" conceptions of NOS.
- K-12 teachers do not typically possess "adequate" conceptions of NOS.
- Conceptions of NOS are best learned through explicit, reflective instruction as opposed to implicitly through experiences with simply "doing" science.
- Teachers' conceptions of NOS are not automatically and necessarily translated into classroom practice.
- Teachers do not regard NOS as an instructional outcome of equal status with that of "traditional" subject matter outcomes.

In addition, arguments and evidence are increasingly making clear that NOS instruction should occur in a variety of contexts that assist learners in more deeply understanding and flexibly applying the NOS (Bell et al. 2016; Clough 2006; Herman 2018). Further scholarship addressing NOS in science education can presume these well-established claims and direct efforts to promote and improve NOS teaching and learning, as well as other issues that are not yet settled.

1.6 Taking Stock and Considering the Future of NOS in the Science Curriculum

This chapter and chapters to come make clear that a metaphorical glass representing NOS in science education could either be described as half full or half empty. Optimistically, advocacy for NOS teaching and learning remains high among science educators and increasingly with science teachers. Few now argue with the proposition that school science experiences should include significant attention to accurately portraying the NOS. Standards documents speak to the importance of NOS teaching and learning, and much is now well-established about the state of NOS teaching and learning and what effective NOS instruction entails. This and other books offer many ways to engage students in discussions related to specific NOS elements.

NOS pessimists, on the other hand, may find the proverbial glass half empty, a view that is occasionally hard to refute. Despite the presence of well-reasoned rationales, extensive scholarship, and efforts to promote NOS instruction, science teachers and science curricula largely remain rigidly bound to a tradition of communicating the facts or end products of science while generally neglecting or failing to prominently promote accurate NOS understanding. Little of what is known about accurate and effective NOS instruction is widely implemented in science classrooms, and science teacher preparation and professional development efforts targeting NOS instruction are woefully inadequate (Backhus and Thompson 2006). Even current science education standards documents rarely provide and/or emphasize overt NOS learning outcomes (Höttecke and Silva 2011; Olson 2018). Thus, much remains to be done in promoting accurate and effective NOS teaching.

One of the challenges to promoting attention to NOS in school science is that, with rare exceptions, teachers, school administrators, parents, and policy-makers did not experience accurate NOS instruction in their own schooling, and thus, they do not see it as a crucial outcome of science education. This makes science teacher education and professional development efforts directed at NOS teaching and learning all the more important. Beyond promoting a robust understanding of NOS content and pedagogy, science teacher education efforts must first and foremost convince teachers of the crucial role NOS plays in teaching, learning, and citizenship (Herman et al. 2019a). Unless teachers feel compelled to accurately and effectively teach NOS, no amount of effort to improve their NOS content and pedagogy will improve the current state of NOS teaching and learning.

That said, teachers can hardly accurately teach what they do not understand. The importance of teachers' NOS understanding can be summarized by quoting Hollon et al. (1991) who tell us that "…science teachers must develop knowledge that enables them to make two types of decisions—curricular decisions and instructional decisions" (p. 149). Shulman (1986) further reminds us that teachers' knowledge can be divided into three broad categories—pedagogical, curricular, and subject matter—and defines subject matter knowledge as a discipline's facts, principals, *and* structure. NOS, of course, addresses issues related to the structure of science.

For instance, consider this definition of *pedagogical content knowledge* (PCK) (Shulman 1986) in the context of science teaching:

> Teachers must not only be capable of defining for students the accepted truths in a domain. They must also be able to explain why a particular proposition is deemed warranted, why it is worth knowing and how it relates to other propositions, both within the discipline and without, both in theory and in practice. (p. 9)

In science teaching, PCK is a synergistic amalgamation of science and NOS content knowledge, pedagogical skills, knowledge of curricular and instruction tools, use of analogies, and understanding of students' thinking all brought to bear in instructional decision-making to convey subject matter in a way that makes it comprehensible to learners. This means is that PCK applies to the teaching of all content, including NOS. Abd-El-Khalick (1997) first introduced the idea of NOS PCK noting that science teachers must possess an understanding of science and NOS content that is linked to methods for incorporating it into NOS instruction. NOS PCK also includes decision-making regarding how deeply NOS ideas can and should be addressed with students (see also Abd-El-Khalick 2013).

The challenge therefore is for science teacher educators to create learning experiences where science teachers learn about NOS in ways that can be translated into meaningful and effective classroom experiences and appropriate classroom discourse about the nature of science. That this can be accomplished in typical preservice science teacher education programs possessing one or two methods courses is highly improbable. Herman et al. (2013) followed graduates of an extensive and demanding science teacher education program and reported that 11 of the 13 participants were teaching NOS 2–5 years after graduation, and 9 of the 13 were doing so at moderate to high levels. Thus, the burden is on science teacher educators to bolster all science teacher education efforts directed at accurate NOS teaching and learning.

Of course, beyond the realm of teacher education, there are many other considerations that require our attention as we collectively continue to advocate for NOS inclusion in science instruction. Many of these are implied by the topics found in this book (more robust assessment tools, improved NOS learning standards, research-based recommendations linked to NOS learning progressions, and considerations for the role of NOS in higher education science learning environments). However, as readers of this book will see, we have learned much about NOS teaching and learning. For those who see the NOS as a "glass half full," there is reason to be enthusiastic about the future of NOS even as we recognize that much effort remains on a variety of fronts. Those involved in this book look forward to the day when the inclusion of NOS content in science class needs no more justification than does the study of ecology in biology, motion in physics, periodic law in chemistry, and the rock cycle in geology. NOS is the content that ties the sciences together.

Years ago, evolutionary biologist Theodosius Dobzhansky (1973, p. 125) uttered the famous phrase that "nothing in biology makes sense expect in the light of evolution." Today, we could just as earnestly state that nothing in science makes sense except in the light of the nature of science. Let us hope that this statement guides science instruction as effectively as Dobzhansky's has impacted the science of biology and biology instruction.

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