CHAPTER 28

Nature of Science: Past, Present, and Future

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CONCEPTUALIZING THE CONSTRUCT

The construct "nature of science" (NOS) has been advocated as an important goal for students studying science for approximately 100 years (Central Association of Science and Mathematics Teachers, 1907). Most recently, NOS has been advocated as a critical educational outcome by various science education reform documents worldwide (e.g., Australia, Canada, South Africa, United Kingdom, United States). To be blunt, when it comes to NOS, one is hard pressed to find rhetoric arguing against its importance as a prized educational outcome. Still, detractors do exist (Winchester, 1993). The observation that NOS has been a perennial goal of science education, and is now receiving increased emphasis, can be construed to mean that high school graduates, and the general citizenry, do not possess (and never have possessed) adequate views of NOS. The research reviewed later in this chapter provides clear support for such a notion. That said, has anything been lost? Is it really important for students and the general citizenry to understand NOS? What have we not accomplished because our students do not have good understandings of NOS? What can we make of the obsession with NOS?

At a general level, understanding NOS is often defended as being a critical component of scientific literacy (NSTA, 1982). This just begs the question of what it means to be scientifically literate. Perhaps the most concise way of answering the question of why understanding NOS is important is to consider the five arguments provided by Driver, Leach, Millar, and Scott (1996). Their arguments were as follows:

Utilitarian: Understanding NOS is necessary to make sense of science and manage the technological objects and processes in everyday life.

Democratic: Understanding NOS is necessary for informed decision-making on socioscientific issues.

Cultural: Understanding NOS is necessary to appreciate the value of science as part of contemporary culture.

Moral: Understanding NOS helps develop an understanding of the norms of the scientific community that embody moral commitments that are of general value to society.

Science learning: Understanding NOS facilitates the learning of science subject matter.

Certainly, these are all important and noble reasons for why science educators value NOS as an instructional outcome. However, at this point, the arguments are primarily intuitive, with little empirical support. Much like the general goal of scientific literacy, until we reach a critical mass of individuals who possess adequate understandings of NOS, we have no way of knowing whether achievement of the goal has accomplished what has been assumed. If we become generally more successful at teaching NOS to our students, will they become better decision-makers? Will their science achievement improve? My goal is not to contradict or cheapen my life's work. Rather, my goal is to emphasize that the jury is still out. Most important questions are still left to be answered, and there are most assuredly many questions that have yet to arise. Students' and teachers' understandings of NOS remain a high priority for science education and science education research. As mentioned before, it has been an objective in science education (American Association for the Advancement of Science [AAAS], 1990, 1993; Klopfer, 1969; National Research Council [NRC], 1996; National Science Teachers Association [NSTA], 1982) for almost 100 years (Central Association of Science and Mathematics Teachers, 1907; Kimball, 1967–68; Lederman, 1992). Indeed, "the longevity of this educational objective has been surpassed only by the longevity of students' inability to articulate the meaning of the phrase 'nature of science,' and to delineate the associated characteristics of science" (Lederman & Niess, 1997, p. 1).

WHAT IS AND WHAT IS NOT NATURE OF SCIENCE

With all the support NOS has in the science education and scientific community, one would assume that all stakeholders possess adequate understandings of the construct. Even though explicit statements about the meaning of NOS are provided in well-known reform documents (e.g., NRC, 1996), the pages of refereed journals and the conference rooms at professional meetings are filled with definitions that run contrary to the consensus reached by the *National Science Education Standards* (1996) and other reform documents. Some would argue that the situation is direct support for the idea that there is *no* agreement on the meaning of NOS (Alters, 1997). More recently, Hipkins, Barker, and Bolstad (2005) have expressed concerns about the lack of consensus about NOS in New Zealand curricula. However, counterarguments by others (Smith, Lederman, Bell, McComas, & Clough, 1997; Smith & Scharmann, 1999) point out that more consensus exists than disagreement. Others (Lederman, 1998) are quick to note that the disagreements about the definition or meaning of NOS that continue to exist among philosophers, historians, and science educators are irrelevant to K–12 instruction. The issue of the existence of an objective reality as compared with phenomenal realities is a case in point. There is an acceptable level of generality regarding NOS that is accessible to K–12 students and relevant to their daily lives that can be found in the writings of the aforementioned authors as well as the more recent comments of Elby and Hammer (2001) and Rudolph (2003). Moreover, at this level, little disagreement exists among philosophers, historians, and science educators. Among the characteristics of scientific knowledge corresponding to this level of generality are that scientific knowledge is tentative (subject to change), empirically based (based on and/or derived from observations of the natural world), and subjective (involves personal background, biases, and/or is theory-laden); necessarily involves human inference, imagination, and creativity (involves the invention of explanations); and is socially and culturally embedded. Two additional important aspects are the distinction between observations and inferences, and the functions of and relationships between scientific theories and laws.

Before attempting to review the research on NOS it is important to provide some general parameters for the meaning of the construct. What is NOS? It might help to back up to the proverbial question, What is science? The most common answer to this question in the literature is: 1) body of knowledge, 2) method, and 3) way of knowing. NOS typically refers to the epistemology of science, science as a way of knowing, or the values and beliefs inherent to scientific knowledge and its development (Lederman, 1992). What follows is a brief consideration of these characteristics of science and scientific knowledge related to what students should know. It is important to note that the aspects of NOS described below are not meant as a comprehensive listing. There are other aspects that some researchers include or delete (Osborne, Collins, Ratcliffe, Millar, & Duschl, 2003; Scharmann & Smith, 1999). And any of these lists that consider what students can learn, in addition to a consideration of the characteristics of scientific knowledge, are of equal validity. The primary purpose here is not to emphasize one listing versus another, but to provide a frame of reference that helps delineate NOS from scientific inquiry (and processes of science) and the resulting body of knowledge.

First students should understand the crucial distinction between observation and inference. Observations are descriptive statements about natural phenomena that are "directly" accessible to the senses (or extensions of the senses) and about which several observers can reach consensus with relative ease (e.g., descriptions of the morphology of the remnants of a once living organism). Inferences, on the other hand, go beyond the senses. For example, one may develop explanations about the observed morphology in terms of its possible contributions to function. At a higher level, a scientist can infer models or mechanisms that explain observations of complex phenomena (e.g., models of weather, evolution).

Second, closely related to the distinction between observations and inferences is the distinction between scientific laws and theories. Individuals often hold a simplistic, hierarchical view of the relationship between theories and laws whereby theories become laws, depending on the availability of supporting evidence. It follows from this notion that scientific laws have a higher status than scientific theories. Both notions, however, are inappropriate because, among other things, theories and laws are different kinds of knowledge, and one does not develop or become transformed into the other. Laws are *statements or descriptions of the relationships* among observable phenomena. Boyle's law, which relates the pressure of a gas to its volume at a constant temperature, is a case in point. Theories, by contrast, *are inferred explanations* for observable phenomena (e.g., kinetic molecular theory provides an explanation for what is observed and described by Boyle's law). Scientific models are common examples of theory and inference in science. Moreover, theories are as legitimate a product of science as laws. Scientists do not usually formulate theories in the hope that one day they will acquire the status of "law."

Third, even though scientific knowledge is, at least partially, based on and/or derived from observations of the natural world (i.e., empirical), it nevertheless involves human imagination and creativity. Science, contrary to common belief, is not a totally lifeless, rational, and orderly activity. Science involves the *invention* of explanations, and this requires a great deal of creativity by scientists. This aspect of science, coupled with its inferential nature, entails that scientific concepts, such as atoms, black holes, and species, are functional theoretical models rather than faithful copies of reality.

Fourth, scientific knowledge is subjective and/or theory-laden. Scientists' theoretical commitments, beliefs, previous knowledge, training, experiences, and expectations actually influence their work. All these background factors form a *mind-set* that *affects* the problems scientists investigate and how they conduct their investigations, what they observe (and do not observe), and how they make sense of, or interpret their observations. It is this (sometimes collective) individuality or mindset that accounts for the role of subjectivity in the production of scientific knowledge. It is noteworthy that, contrary to common belief, science rarely starts with neutral observations (Chalmers, 1982). Observations (and investigations) are motivated and guided by, and acquire meaning in reference to, questions or problems. These questions or problems, in turn, are derived from within certain theoretical perspectives. Often, hypothesis or model testing serves as a guide to scientific investigations.

Fifth, science as a human enterprise is practiced in the context of a larger culture, and its practitioners (scientists) are the product of that culture. Science, it follows, affects and is affected by the various elements and intellectual spheres of the culture in which it is embedded. These elements include, but are not limited to, social fabric, power structures, politics, socioeconomic factors, philosophy, and religion. The practice of acupuncture, for example, was not accepted by western science until western science explanations for the success of acupuncture could be provided.

Sixth, it follows from the previous discussions that scientific knowledge is never absolute or certain. This knowledge, including "facts," theories, and laws, is tentative and subject to change. Scientific claims change as new evidence, made possible through advances in *theory* and technology, is brought to bear on existing theories or laws, or as old evidence is reinterpreted in the light of new theoretical advances or shifts in the directions of established research programs. The construct of punctuated equilibrium was developed through an interpretation of the fossil record from a different perspective. Rather than taking a Darwinian view of gradual change, the lack of transitional species, among other observations, led to a reinterpretation of classic evolutionary theory. It should be emphasized that tentativeness in science not only arises from the fact that scientific knowledge is inferential, creative, and socially and culturally embedded. There are also compelling logical arguments that lend credence to the notion of tentativeness in science. Some have taken issue with the use of the word "tentative" to describe scientific knowledge. Descriptors such as "revisionary" or "subject to change" are preferred by those who feel "tentative" implies that the knowledge is flimsy and not well founded. Whatever word is used, the intended meaning is that the knowledge of science, no matter how much supported evidence exists, may change in the future for the reasons just discussed.

Finally, it is important to note that individuals often conflate NOS with science processes or scientific inquiry. Although these aspects of science overlap and interact in important ways, it is nonetheless important to distinguish between the two. Scientific processes are activities related to collecting and analyzing data, and drawing conclusions (AAAS, 1990, 1993; NRC, 1996). For example, observing and inferring are scientific processes. More complex than individual processes, scientific inquiry involves various science processes used in a cyclical manner. On the other hand, NOS refers to the epistemological underpinnings of the activities of science and the characteristics of the resulting knowledge. As such, realizing that observations are necessarily theory-laden and are constrained by our perceptual apparatus belongs within the realm of NOS. Distinguishing NOS from scientific inquiry for the purpose of providing focus to this chapter should in no way be construed to mean that NOS is considered more important for students to learn about. Certainly, both constructs are important and inquiry and NOS, although different, are intimately related. For this reason, a separate chapter in this Handbook is devoted to scientific inquiry (Chapter 28). Making a distinction between NOS and scientific inquiry was in no way meant to imply that the two constructs are distinct. Clearly, they are intimately related. Furthermore, there is much evidence that NOS is best taught within a context of scientific inquiry or activities that are reasonable facsimiles of inquiry. That is, inquiry experiences provide students with foundational experiences upon which to reflect about aspects of NOS. [AQ1]

The conflation of NOS and scientific inquiry has plagued research on NOS from the beginning. Hence, the reader will note that many of the earlier studies (and even continuing to the present) are actually more focused on inquiry than NOS. These studies are nevertheless reviewed, rather than excluded, since they have become an accepted part of the history of research on NOS. The definition used by these studies for NOS is just not consistent with current usage of the construct. Again, the aspects of NOS presented here are not meant to be exhaustive. Other listings certainly exist. However, what has been presented is directly consistent with what current reform documents state students should know about NOS and is consistent with the perspective taken by an overwhelming majority of the research literature.

THE CHANGING FACE OF NATURE OF SCIENCE

One of the most vexing issues for those who do research on the teaching and learning of NOS is that NOS can be a moving target. If one considers the differences among the works of Popper (1959), Kuhn (1962), Lakatos (1970), Feyerabend (1975), Laudan (1977), and Giere (1988), it becomes quite clear that perceptions of NOS are as tentative, if not more so, than scientific knowledge itself. In short, NOS is analogous to scientific knowledge. As a consequence, some individuals have dwelled too heavily on such differing perceptions (e.g., Alters, 1997). The recognition that our views of NOS have changed and will continue to change is not a justification for ceasing our research until total agreement is reached, or for avoiding recommendations or identifying what we think students should know. We have no difficulty including certain theories and laws within our science curricula, even though we recognize that these may change in the near or distant future. What is important is that students understand the evidence for current beliefs about natural phenomena, and the same is true with NOS. Students should know the evidence that has led to our current beliefs about NOS, and, just as with "traditional" subject matter, they should realize that perceptions may change as additional evidence is collected or the same evidence is viewed in a different way.

Regardless of the various "problems" associated with reaching consensus on the various aspects of nature of science, and issues created by the tentativeness of the construct itself, the nature of science has been the object of systematic educational research for approximately 50 years. Prior to this review, there were three reviews of research related to the teaching, learning, and assessment of the nature of science (Abd-El-Khalick & Lederman, 2000a; Lederman, 1992; Meichtry, 1992). In addition to revisiting the contents of previous reviews, this review builds on these prior works and, it is hoped, provides some guidance for future research in the field. For practical reasons, the research reviewed is restricted to published reports and to those studies with a primary focus on NOS. These studies have been divided into obvious thematic sections and are presented in a general chronological sequence within each section.

RESEARCH ON STUDENTS' CONCEPTIONS

Considering the longevity of objectives related to students' conceptions of the nature of science, it is more than intriguing that the first formal instrument to assess students' conceptions was developed about 50 years ago (Wilson, 1954). The development of instruments to assess NOS has a long history and is extensive enough to constitute separate treatment in this review. Although it can be argued that placing the discussion of assessment first would provide an important context for the review of the research, it can be equally argued that a discussion of the varied assessments would be too abstract without the context of the specific research investigations. Consequently, the review of NOS assessment has been placed at the end of the review. However, this should not impede those who wish to read the section on assessment first. In Wilson's (1954) investigation, which was primarily an attempt to validate an instrument known as the Science Attitude Questionnaire, a sample of 43 Georgia high school students was found to believe that scientific knowledge is absolute and that scientists' primary objective is to uncover natural laws and truths. The most extensive early attempt to assess students' conceptions of the nature of science (Mead & Metraux, 1957) involved a nationwide sample of 35,000 student essays on the topic "What Do You Think About Science and Scientists?" Mead and Metraux drew a randomized sample that was representative with respect to age, gender, geographic distribution, and socioeconomic status. Their qualitative analysis of the data yielded findings that were consistent with Wilson's (1954) findings on both attitude toward science and students' understandings of the nature of science. It is interesting to note that the earliest studies related to the nature of science often included assessments of attitudes or conflated the nature of science with attitude toward science.

In 1961, Klopfer and Cooley developed the Test on Understanding Science (TOUS), which was to become the most widely used paper-and-pencil assessment of students' conceptions. Using the TOUS and a comprehensive review of several nationwide surveys, Klopfer and Cooley concluded that high school students' understandings of the scientific enterprise and of scientists was inadequate. Miller (1963), also using the TOUS, found student conceptions that were considered totally inadequate. As research began to document that students possessed less than adequate views of nature of science, research in the field began to proliferate (National Science Teachers Association [NSTA], 1962). Early assessments of students' understandings were not limited to the United States. Mackay (1971) pre- and posttested 1,203 Australian secondary students spanning grades 7–10, using the TOUS instrument. He concluded that students lacked sufficient knowledge of (a) the role of creativity in science; (b) the function of scientific models; (c) the roles of theories and their relation to research; (d) the distinctions among hypotheses, laws, and theories; (e) the relationship between experimentation, models and theories, and absolute truth; (f) the fact that science is not solely concerned with the collection and classification of facts; (g) what constitutes a scientific explanation; and (h) the interrelationships among and the interdependence of the different branches of science. Similar findings resulted from the investigations of Korth (1969), Broadhurst (1970), and Aikenhead (1972, 1973).

Bady's (1979) work differed from early efforts in that he focused on a particular aspect of students' understanding of nature of science. Specifically, he investigated students' understandings of the logic of hypothesis testing. His sample included 20 9th-grade students and 20 11th-grade students from a large urban school, as well as 33 9th-grade and 41 12th-grade students from a small private boys' school. Using the Johnson-Laird and Wason (1972) task to assess subjects' understandings of hypothesis testing, he found that most students, regardless of school or grade level, believed that hypotheses can be adequately tested and proved by verification. He concluded that such students are likely to have a simplistic and naively absolutist view of the nature of scientific hypotheses and theories. Similarly, during the development of the Nature of Scientific Knowledge Scale, Rubba (Rubba, 1977; Rubba & Andersen, 1978) found that 30 percent of the high school students surveyed believed that scientific research reveals incontrovertible and necessary absolute truth. Additionally, most of Rubba's sample believed that scientific theories, with constant testing and confirmation, eventually mature into laws. With a sample of 102 high-ability 7th- and 8th-grade students, Rubba, Horner, and Smith (1981) attempted to assess students' adherence to the ideas that laws are mature theories and that laws represent absolute truth. The results indicated that the students, on the whole, tended to be "neutral" with respect to both of these ideas. The authors were particularly concerned about the results, because the sample consisted of students who were considered to be the most capable and interested in science.

During the past two decades a decreasing number of studies have limited themselves to the assessment of students' conceptions. (Lederman, 1986a, 1986b; Lederman & O'Malley, 1990) at the secondary level and at the university level (Cotham & Smith, 1981; Gilbert, 1991), with no attempt to identify or test causal factors. However, a few notable studies are described here to illustrate the consistency of findings across the decades of research on students' understandings. Most recently, Kang, Scharmann, and Noh (2004) examined the views of 6th-, 8th-, and 10th-grade students in South Korea. With the use of a multiple-choice test, the views of 1702 students were assessed. Consistent with prior research, the South Korean students were found to have an empiricist/absolutist view of science. Zeidler, Walker, Ackett, and Simmons (2002) investigated the relationships between students' conceptions of NOS and their reactions to evidence that challenged their beliefs about socioscientific issues. A total of 82 students from 9th- and 10th-grade general-science classes, 11th- and 12th-grade honors biology, physics classes and college-level preservice teachers comprised the sample. Although the authors did not clarify how many of the students in the sample adhered to the array of beliefs presented, it was clear that a significant number of students did not understand scientific knowledge to be tentative and partially subjective, and involve creativity. Although their primary purpose was to investigate relationships between NOS and students' handling of socioscientific issues, the understandings of NOS found are consistent with prior research. Overall, there were no clear differences in the understandings of students with respect to grade level.

In an interesting departure from the usual focus of assessments of students' views, Sutherland and Dennick (2002) investigated conceptions of NOS in students with clearly different worldviews. Historically, research on NOS has failed to consider the influence that world views may have on students' conceptions. The sample consisted of 72 7th-grade Cree students and 36 7th-grade Euro-Canadian students. Although all assessments were done in English, a significant portion of the Cree students spoke English as well as Cree at home. Data were collected with both quantitative (Nature of Scientific Knowledge Scale) and qualitative (interviews) techniques. Although the two groups differed on various aspects of NOS, both groups held views that are considered less than adequate with respect to the following aspects of NOS: tentativeness, creativity, parsimony, unified nature of knowledge, importance of empirical testing, and amoral nature of scientific knowledge. They also found that both language and culture affected students' views, in addition to those factors that affect western students' views. Certainly, the potential influence of worldviews, culture, and language may have on understandings of NOS is important in and of itself and is an area of much-needed research. However, the critical point here is that the findings in this study corroborate what has been found throughout the history of studies that simply aim to assess students' conceptions.

Obviously all studies cannot be reviewed here, but doing so would simply confirm what the cited assessments of students' conceptions have indicated. As will be seen later, studies that have attempted to change students' views also document students' "starting points" as consistent with what has just been described.

Research on students' conceptions of science was a natural extension of the agreement among educators and scientists that promoting accurate students' understandings of NOS should be a primary objective of science education. The overwhelming conclusion that students did not possess adequate conceptions of the nature of science or scientific reasoning is considered particularly significant when one realizes that a wide variety of assessment instruments were used throughout the aforementioned research. Although evidence does exist that casts some doubt on the validity and reliability of some of the instruments used (Hukins, 1963), it is significant that all investigations yielded the same findings. A detailed analysis of these assessment instruments is included in a subsequent section of this review.

RESEARCH ON TEACHERS' CONCEPTIONS

In general, researchers turned their attention to teaching the nature of science (which will be discussed in a later section) and teachers' conceptions as data emerged, indicating that students did not possess what were considered adequate conceptions of NOS. The logic was simple: a teacher must possess an adequate knowledge of what he/she is attempting to communicate to students. Interestingly, however, the first assessment of teachers' conceptions (Anderson, 1950) was conducted prior to any assessment of students' conceptions. Fifty-six Minnesota high school teachers, including 58 biology teachers and 55 chemistry teachers, constituted the sample to be surveyed. Teachers were asked to answer a total of eight questions on scientific method, and it was revealed that both groups of teachers possessed serious misconceptions.

Behnke (1961) used a 50-statement questionnaire to assess the understandings of scientists and science teachers. Using a three-option response format (i.e., favoring, opposing, and neutral), the questionnaire attempted to assess four categories of information: (a) the nature of science, (b) science and society, (c) the scientist and society, and (d) the teaching of science. The teacher sample consisted of 400 biology teachers and 600 physical science teachers. The scientist sample comprised 300, but there was no differentiation based upon specific discipline. Although a number of differences were found between scientists and science teachers, only the data concerning the nature of science are relevant here. Over 50 percent of the science teachers felt that scientific findings were not tentative. Even more surprising was that 20 percent of the scientists felt the same way.

Miller's (1963) comparison of TOUS scores of secondary biology teachers and secondary students is one of the most often cited studies of teachers' conceptions of NOS. Five student groups consisted of prospective biology students, as well as those who had just completed a course in general biology. The student groups spanned grades 7–12. The 87 11th- and 12th-grade students were of high ability. Sixty-three 10th-grade biology students, 52 9th-grade, 328 8th-grade, and 205 7th-grade students constituted the remaining portion of the student sample. The sample of teachers consisted of 51 biology teachers from 20 Iowa high schools. Overall, a surprising percentage (ranging from 11 percent to 68 percent) of students in grades 9–12 scored higher on the TOUS than 25 percent of the science teachers. Of particular concern was the finding that 68 percent of the high-ability grade 11–12 students scored higher than 25 percent of the teachers. Although the students were considered as a group (and not specifically compared with their own teachers), Miller concluded that many teachers do not understand science as well as their students, much less understand science well enough to teach it effectively.

Replication studies are not common in science education, but Schmidt (1967) attempted to replicate Miller's findings several years later. A disconcerting proportion of students in grades 9 and 11–12 were found to score higher (14 percent and 47 percent, respectively) than 25 percent of the teacher sample. Schmidt concluded that the problem identified by Miller four years earlier still existed. A year later, Carey and Stauss (1968) attempted to determine whether 17 prospective secondary science teachers being prepared at the University of Georgia possessed a philosophy of science that exhibited an understanding of NOS. The Wisconsin Inventory of Science Processes (WISP) was used to assess NOS. In addition to attempting an initial assessment of the conceptions possessed by the preservice teachers, an attempt was made to investigate the effectiveness of a science methods course in improving such conceptions. Pretest scores on the WISP indicated that the science teachers, as a group, did not possess adequate conceptions of the nature of science. Correlations of WISP scores with academic variables such as high school science credits, college science credits, specific science courses taken, grade-point average, and mathematics grades did not yield any significant relationships. Based on WISP posttest scores, it was concluded that a methods course "specifically oriented toward NOS" could significantly improve teachers' viewpoints.

Carey and Stauss (1970a) continued their line of research by now assessing experienced teachers' conceptions of NOS. Once again, they used the WISP exam. The results were consistent with their previous study: (a) teachers of science, in general, did not possess adequate conceptions of NOS; (b) science methods courses produce a significant pre- to posttest improvement of WISP scores; and (c) academic variables such as grade-point average, math credits, specific courses, and years of teaching experience are not significantly related to teachers' conceptions of science. They recommended that courses in the history and philosophy of science be included in teacher preparation programs.

Kimball (1968), using his own Nature of Science Scale (NOSS), compared understandings of NOS of scientists and science teachers. In no case were significant differences found between the groups. Kimball concluded that there is no difference in understandings of NOS held by scientists and by qualified science teachers when their academic backgrounds are similar. At the time, the results of Kimball's research were used to discredit public criticisms of teacher education programs as the cause of science teachers' poor understandings. Although research focused on teachers' conceptions of NOS (with no attempts to change such conceptions) proliferated during the period from 1950 to 1970, there have been several notable more recent assessments.

Beginning teachers' and preservice science teachers' views about scientific knowledge were described and compared by Koulaidis and Ogborn (1989). A 16-item, multiple-choice questionnaire was administered to 12 beginning science teachers and 11 preservice science teachers. The questionnaire items focused on scientific method, criteria for demarcation of science and nonscience, change in scientific knowledge, and the status of scientific knowledge. Based on their responses, the subjects were categorized into four predetermined categories of philosophical belief. The high frequency of individuals possessing eclectic views is consistent with previous research, which has indicated that teachers do not generally possess views that are consistently associated with a particular philosophical position. Overall, the authors concluded that although science teachers place value on scientific method, they see the procedures involved as contextually situated. King (1991) investigated beginning teachers' knowledge of the history and philosophy of science. Thirteen beginning students in Stanford's teacher-education program completed a questionnaire on the first day of their introductory course in curriculum and instruction in science. Eleven of the 13 were interviewed at the end of the course and after they had been student teaching for at least one week. Background information from the questionnaires indicated that only 3 of the 13 preservice teachers had taken formal courses in the history or philosophy of science. Additionally, evaluations of the introductory curriculum course (where the nature of science was discussed) indicated that most of the students felt it was more important to learn the nuts and bolts (e.g., lesson planning, evaluation, etc.) of teaching as opposed to the history and philosophy of science. Data from the interviews indicated that although most of the teachers felt that the history and philosophy of science were important, their lack of education in these areas left them lacking with respect to how such topics could be integrated within instruction. The author concluded that the lack of science teachers' background in the history and philosophy of science clearly influences the teaching of science.

Using a case-study approach, Aguirre, Haggerty, and Linder (1990) assessed 74 preservice secondary science teachers' conceptions of NOS, teaching, and learning. Subjects were asked to respond to 11 open-ended questions about science, teaching of science, and learning of science. Qualitative analysis of the responses yielded the following general conclusions. Most individuals believed that science was either a body of knowledge consisting of a collection of observations and explanations or of propositions that have been proved to be correct. Subjects were evenly divided among the "dispenser of knowledge" and "guide/mediator of understanding" conceptions of science teaching. The authors concluded that these preservice teachers (even though they all possessed undergraduate science degrees) did not possess adequate conceptions of the nature of science. The authors further concluded that there could be some connection between teachers' views of NOS and their conceptions of learning and teaching (although observations of actual instruction were not attempted).

Research on teachers' conceptions of NOS is not limited in focus to secondary teachers. Bloom (1989) assessed preservice elementary teachers' understanding of science and how certain contextual variables contribute to this understanding. Using a sample of 80 preservice elementary teachers (86 percent female), enrolled in three methods courses, Bloom administered a questionnaire that contained six questions related to knowledge of science, theories, and evolution. Additionally, a 21-item rating scale pertaining to prior experiences with science, the nature of science, science teaching, and evolution/creationism was administered. A qualitative analysis of questionnaire responses revealed that the preservice teachers believed science is people centered, with its primary purpose being for the benefit of humankind. Much confusion concerning the meaning and role of scientific theories (e.g., theories are related to belief in one's own thoughts apart from empirical observation) was also noted. Of most significance was the finding that beliefs significantly affect preservice teachers' understandings of science. In this particular case, the anthropocentric nature of the subjects' beliefs significantly influenced their conceptualizations of science, the theory of evolution, and how one would teach evolution.

Finally, there have been some attempts to compare understandings of U.S. preservice teachers with those of other nations. Cobem (1989) used Kimball's Nature of Science Scale (NOSS) to compare the understandings of 21 U.S. preservice science teachers with 32 preservice Nigerian teachers. Two significant differences were noted between the groups. Nigerian preservice teachers were more inclined to view science as a way to produce useful technology. This result is consistent with the findings of Ogunniyi (1982) in his study of 53 preservice Nigerian science teachers. This viewpoint is different from that typically desired in the Western hemisphere, which distinguishes theoretical from applied science. However, an applied view regarding science should not be unexpected in a developing nation. (The author expressed an appropriate concern about the future rejection of science in such societies when it eventually fails to deliver solutions to emerging societal problems.) A second difference between the two samples was the Nigerians' view that scientists were nationalistic and secretive about their work.

At its beginning, research on NOS was fairly descriptive and served to establish that neither teachers nor students possessed what were considered adequate understandings of NOS. Although such research makes no attempt to solve the problem, it did establish that a problem existed. Perhaps it is for this reason that virtually all of the research completed in recent years has made at least some attempt to either explain the impact of teachers' conceptions or effect change in students' and teachers' conceptions.

TEACHING AND LEARNING OF NATURE OF SCIENCE (THE EARLY YEARS)

Research on Students

Klopfer (Klopfer & Cooley, 1963) developed the first curriculum designed to improve students' conceptions of NOS. The curriculum was called "History of Science Cases for High Schools" (HOSC). The rationale for the curriculum was that the use of materials derived from the history of science would help to convey important ideas about science and scientists. A sample of 108 geographically representative science classes, including biology, chemistry, and physics (2,808 students), was used to assess the effectiveness of the HOSC curriculum as measured by the TOUS instrument. After a five-month treatment period, students receiving the HOSC curriculum exhibited significantly greater gains on the TOUS than the control groups. This result was consistent across disciplines. In addition, HOSC students showed significant gains on the TOUS subscales (i.e., the scientific enterprise, the scientist, and the methods and aims of science) as well as on the overall test. It was concluded that the HOSC instructional approach was an effective way to improve students' conceptions of NOS. The large sample size used in this investigation gave it much credibility, and it was followed by widespread curriculum development. Jones (1965) successfully "replicated" Klopfer and Cooley's results with a curriculum similar to HOSC and with a traditional physical science course at the college level. Crumb (1965) compared the Physical Science Study Curriculum (PSSC) with traditional high school physics with respect to gains on the TOUS exam. The PSSC program is a laboratory-centered, experimental approach to physics that is designed to emphasize process as opposed to simply science content. Using a sample of 1,275 students from 29 high schools, Crumb found that PSSC students showed greater gains on the TOUS than students exposed to the traditional physics curriculum.

In addition to the aforementioned research, several studies investigated the effectiveness of the 1960s curriculum projects. These curricula were supposedly designed, regardless of specific science discipline, to promote inquiry and process skills. The curricula were laboratory centered, as opposed to the long-lived tradition of lecture/demonstration (Ramsey & Howe, 1969). Yager and Wick (1966) investigated the effects of various curriculum emphases on students' understandings of NOS as measured by the TOUS. Three approaches were used, all of which revolved around the Biological Sciences Curriculum Study (BSCS) Blue Version. The textbook-laboratory approach (TL) utilized only the textbook and accompanying laboratory materials. The multi-referenced laboratory approach (MRL) utilized materials from the TL group as well as additional paperbacks, texts, references, and excerpts from original scientific works. The multi-referenced laboratory and ideas approach (MRLI) resembled the MRL group, but with the added dimension of attention given to the historical development of the major concepts and principles in science. Experiments and their results were always viewed with respect to how they would have been viewed in various historical contexts. For all three groups an attempt was made to control the effect of teacher variation. The results indicated that the MRLI group exhibited the largest gains on the TOUS, with the MRL group placing second, and the TL group showing the smallest gains. Yager and Wick concluded that the MRL was superior to the more common TL approach. Increased emphasis on ideas and their development (MRLI group) was viewed as maximizing the effects of the MRL approach. The similarity of the MRLI approach, with its emphasis on historical development of ideas, to Klopfer and Cooley's (1963) HOSC program is obvious. Gennaro (1964) and Sorensen (1966) also found success with the MRL and MRLI approaches. Thus, it was accepted that a multi-referenced, laboratory-focused approach to the teaching of biology would produce increased student growth in understanding the nature of the scientific enterprise (Ramsey & Howe, 1969).

Aikenhead (1979) developed and field tested a curriculum titled "Science: A Way of Knowing." The primary goals of the curriculum were to have students develop (a) a realistic, nonmythical understanding of the nature, processes, and social aspects of science; (b) a variety of inquiry skills and a realistic feeling of personal competence in the areas of interpreting, responding to, and evaluating their scientific and technological society; and (c) insight into the interaction of science and technology and, in turn, into the interaction of these with other aspects of society. Using the Science Process Inventory (Welch, 1967) and the Test on the Social Aspects of Science (Korth, 1969), grade 11 and grade 12 students were found to make significant pre- to posttest gains on both instruments.

The findings related to the effectiveness of curriculum specifically designed to teach NOS effects were not all positive. Trent (1965) investigated the relative value of the PSSC course and traditional physics (as did Crumb, 1965). A sample consisting of 52 California high schools was used, and the TOUS exam was used to assess students' conceptions of science. Half of the students in the PSSC classes and half of those in traditional courses were not pretested on the TOUS, and the remaining students were. This methodological approach helped to ascertain the influence of any testing effect. No such effort was made in Crumb's (1965) study. At the end of the school year all students were given a posttest. When prior science understanding and student ability were statistically controlled, no differences were found between the students in the traditional and PSSC courses, as measured by the TOUS. Troxel (1968) compared "traditional" chemistry instruction with both CHEM Study and the Chemical Bond Approach (CBA). In theory, CHEM Study and CBA stress inquiry and are laboratory centered, which theoretically should promote better understandings NOS. However, when teacher background in terms of teaching within the discipline, experience in teaching the course, general philosophy, and student background relative to school size were held constant, no significant differences were found in students' conceptions of NOS.

Two other studies using the 1960s curricula were conducted with Israeli high school students. Jungwirth (1970) attempted to investigate the effectiveness of the BSCS Yellow Version, which was first introduced in Israel in 1964. A total of 693 10th-grade students (from 25 schools) comprised the sample. Scores on both the TOUS and the Processes of Science Test (Biological Sciences Curriculum Study [BSCS], 1962) were used to assess students' understandings of scientific knowledge.

Students were given pre- and posttests over the course of one academic year. No significant differences were found between those students studying BSCS biology and those in the comparison group. Thus, Jungwirth concluded, the curriculum was not any more effective with respect to the enhancement of students' conceptions of science. He concluded that pupil achievement in this area could best be enhanced through "redirected teacher effort and emphases." Tamir (1972) compared the relative levels of effectiveness of three curriculum projects with each other as well as with "traditional" instruction. Using the BSCS Yellow Version, CHEM Study, PSSC, and traditional instructional approaches, Tamir assessed changes in students' conceptions of the nature of science on the Science Process Inventory (Welch, 1967). A total of 3,500 students in grades 9–12 were randomly selected from the four types of Israeli high schools (i.e., city academic, cooperation settlement, agricultural, and occupational) so as to allow comparisons among the different school types. The results indicated no significant differences among students studying any of the curriculum projects and those following traditional courses of study. Comparisons among the four school types did not show any differences either. However, comparisons of the relative levels of effectiveness of curriculum projects showed that of the three, BSCS biology had significantly greater effects upon student conceptions of science than either CHEM Study or PSSC.

Durkee (1974) assessed the effectiveness of a special secondary science program, a six-week institute with content similar to that of PSSC. In short, this six-week summer institute was directly aimed at increasing students' scores on the TOUS exam. The sample consisted of 29 high-ability high school students. The students were given pre- and posttests on the TOUS, and the results did not indicate that the specially designed program significantly changed students' conceptions. More recently, Carey, Evans, Honda, Jay, and Unger (1989) assessed the effectiveness of a unit specifically designed to introduce the constructivist view of science on 7th-graders' epistemological views. Their instructional unit was designed to emphasize theory building and reflection on the theory-building process. All classes, in the three-week unit, were taught by the regular teacher, and each lesson was observed by one or two research assistants. Twenty-seven of the students were randomly selected to be interviewed prior to and after being exposed to the instructional unit. Interviews were selected, as opposed to existing instruments, so that assessments of students' understandings would not be limited by the inherent nature of the instrument format/design. The transcripts of the half-hour clinical interviews were qualitatively analyzed blindly with respect to whether the interview was conducted before or after instruction. In general, the pre-instruction interview indicated that most students thought scientists seek to discover facts about nature by making observations and trying things out. However, post-instruction interviews showed many students understood that inquiry is guided by particular ideas and questions and that experiments are tests of ideas. In short, the instructional unit appeared to have been at least partially successful in enabling students to differentiate ideas and experiments.

There was an implicit assumption that clearly guided research that focused solely on the development of curricula and/or instructional materials. It was assumed that student conceptions could be improved if a concerted effort was made in that direction. Certainly, few would deny the logic of this approach. Unfortunately, for the most part, the teacher's interpretation and enactment of the curriculum were ignored. The following statement from two of the earliest investigators of the curriculum development movement (Klopfer & Cooley, 1963, p. 45) did little to establish the importance of the teacher: "The relative effectiveness of the History of Science Cases Instruction Method, in teaching TOUS-type understandings does *not* depend upon whether the teacher rates 'high' or 'low' in his initial understanding." The implication of this statement is clear. That is, a teacher could promote understandings of certain concepts without having an adequate understanding of the same concepts. Fortunately, others, such as Trent (1965), felt that the equivocal findings with respect to the effectiveness of NOS-oriented curricula could only mean that the instructional approach, style, rapport, and personality of the teacher are important variables in effective science teaching. After all, he reasoned, if the same curriculum is effective for one teacher and ineffective for another, and the variable of student ability is controlled, a significant factor must be the teacher.

Research on Teachers

The rather equivocal results concerning the effectiveness of curricula designed to improve students' conceptions of NOS perhaps motivated other researchers to focus their attentions on the teacher as a significant variable, as opposed to the curriculum being used by the teacher. In the 1960s, the distinction between implementation and enactment of a curriculum had not taken hold in the science education community. Yager (1966) selected eight experienced teachers to use the same inquiry-oriented curriculum (BSCS Blue Version). All teachers utilized the same number of days of discussion, laboratories, examinations, and instructional materials. All extraneous variables were held constant, as nearly as possible, with the exception of teacher-student rapport. Students were pre- and posttested on the TOUS exam. An analysis of covariance indicated that differences in students' TOUS scores could not be completely explained by initial differences in mean TOUS scores for each class. It was concluded that there are significant differences in students' abilities to understand NOS when taught by different teachers. Further direct confirmation of the important influence of teachers upon students' conceptions came from Kleinman's (1965) study of teachers' questioning. When one considers the influence of the individual teacher on student learning, there are at least two directions that can be pursued. One would be to study what a teacher does that affects students' understandings of NOS. The other can be a focus on teachers' knowledge. Few would argue against the notion that a teacher must have an understanding of what he/she is expected to teach. Unfortunately, initially the latter was pursued in the research to the exclusion of attention to the former.

Carey and Stauss (1970b) had 35 prospective secondary science teachers and 221 prospective elementary teachers complete the WISP. Scores were correlated with background variables such as high school science courses, college science courses, college grade-point average, and science grade-point average. No relationship was found between either secondary or elementary teachers' conceptions of science, as measured by WISP, and any of the academic background variables. Thus, it was concluded that none of the academic variables investigated could be used to improve science teachers' conceptions of the nature of science. Gruber (1963) surveyed 314 participants of an NSF summer institute designed to improve teachers' understandings of NOS and found little success. During the validation of the NOSS, Kimball (1968) noted that philosophy majors actually scored higher than either science teachers or professional scientists. He intuitively concluded that inclusion of a philosophy of science course as part of the undergraduate science major curriculum might improve the situation. Carey and Stauss (1968) had previously made such a recommendation. Welch and Walberg (1968) did find success in a summer institute designed for 162 physics teachers at four institute sites. The teachers at all four sites showed significant gains on both the TOUS and Science Process Inventory. No documentation of the specific activities at each of the various institutes was available. Thus, it was not possible to establish what goals and activities led to the differential gains in the understanding of the nature of science.

Lavach (1969) attempted to expand on the success that Klopfer and Cooley (1963) had documented with a historical approach. Twenty-six science teachers participated; 11 constituted the experimental group and 15 served as the control group. The experimental group received instruction in selected historical aspects of astronomy, mechanics, chemistry, heat, and electricity. Each three-hour class was divided into two hours of lecture/demonstration, followed by a one-hour laboratory in which an attempt was made to replicate or perform an experiment conducted by the scientist under discussion. The teachers in the control group did not receive lectures or laboratories presented from a historical perspective. All teachers were pre- and posttested on the TOUS. The teachers in the experimental group exhibited statistically significant gains in their understanding of NOS. Further analysis indicated that these gains were not related to overall teaching experience, subjects taught, undergraduate major, previous in-service participation, or length of teaching experience in the same subject.

Six years later Billeh and Hasan (1975) attempted to identify those factors that affect any increase in the understanding of nature of science by science teachers. Their sample consisted of 186 secondary science teachers in Jordan. The teachers were divided into four groups: biology, chemistry, physical science, and physics. A four-week course for the chemistry, physical science, and physics teachers consisted of lectures and demonstrations in methods of teaching science, laboratory investigations emphasizing a guided-discovery approach, enrichment activities to enhance understanding of specific science concepts, and 12 lectures specifically related to the nature of science. The biology group did not receive any formal instruction on the nature of science, thus establishing a reference group with which the other groups could be compared. The Nature of Science Test (NOST) was used to assess understanding of the nature of science. Those lectures that stressed the nature of science were not oriented toward the specific content of the NOST. Each group of teachers were administered pre- and posttests on the NOST, and an analysis of covariance showed significant increases in the mean scores of the chemistry, physical science, and physics groups. The biology group did not show a significant gain, a finding consistent with that of Carey and Stauss (1968). A second result was that there was no significant relationship between teachers' gain scores on NOST and their educational qualifications, a finding in agreement with previous research (Carey & Stauss, 1970a; Lavach, 1969). Additionally, teachers' gain scores were not significantly related to the subjects they taught. Finally, science teaching experience was not significantly related to NOST gain scores. The conclusion that teaching experience does not contribute to a teacher's understanding of NOS was also consistent with previous research (Carey & Stauss, 1970b; Kimball, 1968; Lavach, 1969).

Trembath (1972) assessed the influence of a "small" curriculum project on prospective elementary teachers' views of NOS. The curriculum project focused on participants' understandings of the ways in which hypotheses are developed and tested, the logical structure of theories and laws, and the ways in which theories and laws can be used to make different types of explanations. The program presented prospective teachers with a set of narratives. Each narrative put forth a certain situation and was divided into a set of "frames." Each frame required students to read several paragraphs and provide a short answer in the form of a hypothesis, prediction, or inference. Trembath (1972) seemed to have assumed that participants would develop adequate understandings of the targeted NOS aspects by simply "going through" the program activities. Trembath reported a statistically significant difference between the mean pretest and posttest score for the experimental group, but noted that this score only increased from 7.0 to 10.7 points out of 18 possible points.

Barufaldi, Bethel, and Lamb (1977) argued that "a major affective goal of science teacher education should be the enhancement of the philosophical viewpoint that science is a tentative enterprise and that scientific knowledge is not absolute" (p. 289). The study assessed the influence of elementary science methods courses on junior and senior elementary education majors' understandings of the tentativeness of science. The courses had no components that were specifically geared toward enhancing participants' views of the tentative NOS. Rather, consistent with the authors' view of NOS as an "affective" outcome, an implicit approach was used. Thus, Barufaldi et al. (1977) noted, in these courses: "Students were presented with numerous hands-on, activity-centered, inquiry-oriented science experiences . . . [and] . . . many problem-centered science activities . . . 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).

Barufaldi et al. (1977) thus concluded that a methods course that "stresses inquiry methods and procedures, emphasizing a hands-on approach integrated with individual problem solving, develops, alters, and enhances . . . preservice teachers' . . . philosophical view . . . toward the tentative nature of scientific knowledge" (p. 293). The authors, however, did not present enough evidence to support this rather sweeping generalization. Barufaldi et al. (1977) did not report the pretest mean VOST scores or the mean gain scores for the various groups. However, if we assume that the groups did not differ appreciably on their pretest VOST scores and that the control group mean score did not change appreciably from the pretest to the posttest, then the gains achieved can be assessed. The mean posttest VOST score for the control group was 141. The corresponding scores for the three treatment groups were 153, 149, and 148. As such, the approximate gains achieved were very small and ranged between 3.5 and 6 percentage points. It is difficult to conclude that the reported gains reflect a meaningful improvement in participants' understanding of the tentative nature of scientific knowledge.

Spears and Zollman (1977) assessed the influence of engagement in scientific inquiry on students' understandings of the process of science. Participants were randomly assigned to the four lecture sections and associated laboratory sections of a physics course. Data from only about 50 percent of the original sample were used in the final analysis. The authors, however, did not provide any data to indicate that the remaining participants were representative of the original population. Two types of laboratory instructional strategies served as the treatments. The "structured" approach emphasized verification, whereas the "unstructured" approach stressed inquiry or discovery. Both approaches asked students to investigate problems related to physical principles discussed in the lectures and informed them about the available equipment. Beyond this point the two approaches differed in a major way. In the "structured" laboratory, students were provided with explicit procedures with which they attempted to verify the physical principles concerned. Students in the "unstructured" laboratory, however, were free to investigate the problem in whatever way they deemed appropriate. They made their own decisions regarding what data to collect, how to collect these data, how to treat the data, and how to interpret and present their results.

Data analyses controlled for participants' major, years in college, and course lecture and laboratory grades, as well as the type of lecture presentation in each of the four sections. These analyses indicated that there were no statistically significant differences between the adjusted scores of the two groups on the Assumptions, Nature of Outcomes, and Ethics and Goals components of the SPI Form D (Welch & Pella, 1967–68).

Riley (1979) argued that teachers' understandings of and attitudes toward science would improve as a result of first-hand, manipulative experiences and enhanced proficiency in the processes of science. Riley, like Barufaldi et al. (1977), explicitly labeled an understanding of NOS as an "affective" outcome and attempted to teach about NOS by involving teachers in "doing science." The study investigated the influence of hands-on versus non-manipulative training in science process skills on, among other things, preservice elementary teachers' understandings of NOS. The study had a 3×3 factorial design, with the treatment and science grade point average as independent variables. The treatment had three levels: active-inquiry (hands-on), vicarious-inquiry (non-manipulative), and control. Participants were divided into three groups according to their grade-point average (high, medium, or low), and 30 students from each group were randomly selected and assigned to one of the three treatment levels. The four 1.5-hour-session treatment involved activities that focused on various science process skills, such as observing, classifying, inferring, predicting, communicating, measuring and the metric system, and using space/time relationships. The only difference between the aforementioned levels of treatment was student involvement. In the active-inquiry treatment, participants were trained in science process skills by a hands-on, manipulative approach. Participants in the vicarious-inquiry treatment group did not manipulate any materials. They were trained in science process skills by a demonstration approach where the instructor exclusively manipulated all materials. The control-group participants viewed science-related films for approximately the same amount of time. Data analyses indicated that there were no significant differences between the groups mean TOUS (Cooley & Klopfer, 1961) scores related to the treatments. As such, participants in the active-inquiry, vicarious inquiry, and control groups did not differ in their understandings of NOS.

Haukoos and Penick (1983) investigated the effects of classroom climate on community college students' learning of science process skills and content achievement. The authors replicated their study two years later (Haukoos & Penick, 1985). They argued that gains in the development of students' inquiry skills and science process skills might be related to aspects of the classroom environment, such as the extent to which instruction is directive or non-directive. Implicit in this argument is the assumption that students learn about NOS implicitly through certain aspects related to the classroom environment. The studies featured two treatments: A Discovery Classroom Climate (DCC) treatment and a Non-discovery Classroom Climate (NDCC) treatment. In both studies, participants were enrolled in intact sections of an introductory biology course. Throughout the duration of the course, students in both groups received instruction on the same content. The only difference between the two treatments was the classroom climate that was determined by the extent to which the instructor used direct or indirect verbal behaviors. In the lecture/discussion sessions, students in the NDCC were presented with the content in a manner "that conveyed the impression that science was complete and final, and seldom did the students question it" (Haukoos & Penick, 1983, p. 631). With the DCC group, the instructor assumed a low profile, elicited student questions, and encouraged discussion of the lecture material. All student responses and interpretations were accepted and were not judged as right or wrong. In the laboratory portion of the course, students carried out the same experiments with the same materials. However, during laboratory sessions, students in the NDCC group were told exactly how to manipulate materials. Their results were either accepted or rejected by the instructor. Students in the DCC laboratory were alternatively encouraged to select and explore their own questions and to manipulate the available materials in whatever ways they deemed fit for answering their questions. The instructor kept explicit directions and judgments to a minimum. In this regard, the two laboratory environments were similar to the "structured" and "unstructured" or traditional and inquiry-based treatments that were employed by Spears and Zollman (1977). Data analyses in the first study (Haukoos & Penick, 1983) indicated that the DCC group had a significantly higher mean SPI score than the NDCC group. The reported difference was about eight percentage points. The authors concluded that the classroom climate influenced students' learning of science processes. However, Haukoos and Penick (1985) were not able to replicate these results. Analyses in the second study revealed no statistically significant differences, at any acceptable level, between the DCC and NDCC groups.

Akindehin (1988) argued that attempts to help science teachers develop adequate conceptions of NOS need to be *explicit*. The author assessed the influence of an instructional package, the *Introductory Science Teacher Education* (ISTE) package, on prospective secondary science teachers' conceptions of NOS. The package comprised nine units that included lectures, discussions, and laboratory sessions.

A statistically significant result was obtained for the experimental group. Out of 58 possible points on the NOSS, the grand mean score was 51.84. This mean score, it should be noted, was the highest reported NOSS score among the studies reviewed here. It should be noted, however, that the author did not report the mean pretest and posttest scores. As such, it was difficult to assess the practical significance of the gains achieved by the student teachers.

Scharmann (1990) aimed to assess the effects of a diversified instructional strategy (versus a traditional lecture approach) on freshmen college students' understandings of the nature of scientific theories, among other things. Participants were first given 30 minutes to individually respond in writing to four questions that asked about their feelings and beliefs concerning the evolution/creation controversy. Next, students were randomly assigned to discussion groups of three to five students. They were asked to share their responses to the above questions and then respond to four new questions. These latter questions asked each group to provide reasons that would support teaching only evolution, teaching creation origins in addition to evolution, and teaching neither evolution nor creation origins in science classes. Students were also asked to decide whether, and explain why, one set of reasons was more compelling than another set. Ninety minutes was allocated for this phase of the treatment, during which the author did not interfere in the course of the discussions. For the next 30 minutes, spokespersons shared their groups' concerns, differences, and points of agreement with the whole class. Following a break, the author led a 90-minute interactive lecture/discussion that was intended to resolve any misconceptions that arose as a result of the group discussions and were evident in their presentations. Finally, during the last 30 minutes participants were given the opportunity to reflect on the discussion activity. Scharmann (1990) reported a significant difference between the pretest and posttest scores for both the experimental and control groups. Students in both groups achieved statistically significant gains in their understandings of NOS. Scharmann concluded that both classes provided students with opportunities to grow in their understandings of NOS, but that the diversified instructional strategy was superior in this respect. The author, however, did not provide any evidence to support this claim.

Scharmann and Harris (1992) assessed the influence of a three-week NSF-sponsored summer institute on, among other things, participants' understandings of NOS. The authors noted that "changes in an understanding of the nature of science can be . . . enhanced through a more indirect and applied context . . . and through a variety of readings and activities" that help participants to discuss their NOS views (p. 379). The NOSS (Kimball, 1967–68) was used to assess participants' understandings of the "philosophical" NOS, and an instrument developed by Johnson and Peeples (1987) was used to assess participants' "applied" understandings of NOS. The authors did not elucidate the distinction between "philosophical" and "applied" understandings of NOS. During the first two weeks of the institute, participants were presented with biological and geological content relevant to evolutionary theory. In addition, various instructional methods and teaching approaches, including lectures, small-group and peer discussions, field trips, and other inquiry-based approaches, were taught and modeled by the authors. The authors noted that the "theme" of promoting participants' conceptions of NOS pervaded all the aforementioned activities. However, no direct or explicit NOS instruction was used. Data analyses did not reveal significant differences between pretest and posttest mean NOSS scores. However, statistically significant differences were obtained in the case of the Johnson and Peeples (1987) instrument. The authors thus concluded that even though participants' conceptions of the "philosophical" NOS were not changed, their understandings of the "applied" NOS were significantly improved. Scharmann and Harris (1992), however, did not comment on the practical significance of the gain achieved by the participants. Out of 100 possible points for the latter instrument, the pretest and posttest mean scores were 61.74 and 63.26, respectively.

Shapiro (1996) reported on the changes in one prospective elementary teacher's thinking about the nature of investigation in science during her involvement in designing a study to answer a simple research question. This case study emerged from a larger research project that investigated the ways in which elementary student teachers' thinking and feelings about the nature of investigation in science could be studied. The project was also intended to assess the changes in elementary student teachers' thinking and feelings about the nature of scientific investigation as a result of their involvement in independent investigations.

More than 210 elementary student teachers in four cohorts were involved in the study. During their science methods class, each cohort of student teachers worked on an assignment intended to help them develop an in-depth understanding of science and scientific procedures of investigation. Over the course of about seven weeks devoted to the assignment, student teachers were asked to pose a simple genuine problem, generate a research question, and then design a systematic procedure to answer their question. Throughout the assignment, student teachers kept journals of the various stages of their investigations. Twenty-one (out of the 38) fourth-cohort participants completed a repertory grid at the beginning of the science methods class and again after the conclusion of the investigation. Participants were interviewed following the second administration of the grid. The interviews focused on the changes that students made in their grids.

The repertory grid had two dimensions. The first comprised personal constructs and the second elements related to conducting scientific investigations. Ratings were given along a five-point scale between the opposite poles of each construct. Changes in student teachers' thinking about the nature of scientific investigations were assessed by comparing the grids completed prior to and after the independent investigations were conducted.

Shapiro (1996) only reported in detail on three "themes of change" that were evident in the case of one prospective elementary teacher. The first change theme was related to ideas about the nature of the steps and procedures of investigation in science. The teacher indicated that she often thought of doing science as being synonymous with following rules and checklists. After participating in the investigation, she came to appreciate the role of original thinking and imagination in devising ways to come up with answers to a research question. The second change theme was in the teacher's thinking about what science is. At the beginning of the methods class, Jan indicated that science is a body of information that has been tested and retested so that it now achieved the status of facts. After the completion of the investigation, the teacher came to view science more as a process of inquiry and less as a mere collection of facts. She also indicated that her experience helped her to appreciate the complexity of inquiring into everyday occurrences and the difficulty of drawing conclusions from the generated data. Finally, in the third identified change theme, there was a shift from an objectivist view of science to one that emphasized the role of researchers in creating new knowledge. Perhaps the most important features of the present study were its emphasis on reflection and its explicitness. Shapiro noted that students were often encouraged to reflect on their experiences. Moreover, the author emphasized the reflective nature of the interviews that allowed student teachers to have insights into changes in their thinking about science.

Looking at research investigations that attempted to change teachers' conceptions from an alternative perspective can be enlightening. Overall, these studies took one of two approaches. The first approach was advocated by science educators such as Gabel, Rubba, and Franz (1977), Haukoos and Penick (1983, 1985), Lawson (1982), and Rowe (1974). This approach is labeled the "implicit approach" for this review, as it suggests that an understanding of NOS is a learning outcome that can be facilitated through process skill instruction, science content coursework, and "doing science." Researchers who adopted this implicit approach utilized science process skills instruction and/or scientific inquiry activities (Barufaldi et al., 1977; Riley, 1979; Trembath, 1972) or manipulated certain aspects of the learning environment (Haukoos & Penick, 1983, 1985; Scharmann, 1990; Scharmann & Harris, 1992; Spears & Zollman, 1977) in their attempts to enhance teachers' NOS conceptions. Researchers who adopted the second approach to enhancing teachers' understandings of NOS (Akindehin, 1988; Billeh & Hasan, 1975; Carey & Stauss, 1968, 1970; Jones, 1969; Lavach, 1969; Ogunniyi, 1983) utilized elements from history and philosophy of science and/or instruction focused on various aspects of NOS to improve science teachers' conceptions. This second approach is labeled the "explicit approach" for this review and was advanced by educators such as Billeh and Hasan (1975), Hodson (1985), Kimball (1967–68), Klopfer (1964), Lavach (1969), Robinson (1965), and Rutherford (1964).

TEACHING AND LEARNING OF NATURE OF SCIENCE (CONTEMPORARY YEARS—A SHIFT IN PERSPECTIVE)

During the past 15 years, research on the teaching and learning of NOS has experienced a gradual but drastic change in perspective. This change in perspective has influenced how we attempt to change the conceptions of both teachers and students.

Research on Teachers

The results of the initial research on NOS (which are supported by more recent investigations) may be summarized as follows: (a) science teachers do not possess adequate conceptions of NOS, irrespective of the instrument used to assess understandings; (b) techniques to improve teachers' conceptions have met with some success when they have included either historical aspects of scientific knowledge or direct, explicit attention to nature of science; and (c) academic background variables are not significantly related to teachers' conceptions of nature of science. Two underlying assumptions appear to have permeated the research reviewed thus far. The first assumption has been that a teacher's understanding of NOS affects his/her students' conceptions. This assumption is clear in all the research that focused on improvement of teachers' conceptions with no expressed need or attempt to do anything further. This rather intuitive assumption remained virtually untested, with the exception of two studies that only referred to the assumption in an ancillary manner. Unfortunately, both of these research efforts (Klopfer & Cooley, 1963; Rothman, 1969) contained significant methodological flaws. Klopfer and Cooley (1963) failed to properly monitor teachers' conceptions of NOS throughout the investigation, whereas Rothman (1969) created a ceiling effect by sampling only high-ability students.

The second assumption underlying the research reviewed thus far is closely related to the first. If it is assumed that teachers' conceptions of science affect students' conceptions, some method of influence must exist; naturally the influence must be mediated by teacher behaviors and classroom ecology. In short, initial research concerned with teachers' and students' conceptions of NOS assumed that a teacher's behavior and the classroom environment are necessarily and directly influenced by the teacher's conception of NOS. Although this assumption was explicitly stated by many, including Hurd (1969) and Robinson (1969), it remained an untested assumption into the early 1980s.

As can be seen from the research reviewed thus far, several decades of research on NOS focused on student and teacher characteristics or curriculum development to the exclusion of any direct focus on actual classroom practice and/or teacher behaviors. Although research designed to assess students' and teachers' conceptions continues to the present day, there is clearly less willingness to accept the assumptions that guided earlier research, and the focus is moving toward the realities of daily classroom practice.

The presumed relationships between teachers' conceptions of science and those of their students as well as that between teachers' conceptions and instructional behaviors were finally directly tested and demonstrated to be too simplistic, relative to the realities of the classroom, as a result of a series of investigations (Brickhouse, 1989, 1990; Duschl & Wright, 1989; Lederman, 1986a; Lederman & Druger, 1985; Lederman & Zeidler, 1987; Zeidler & Lederman, 1989). Using a case-study approach, Brickhouse investigated three secondary science teachers' views on the relationship between science and technology, the influence of such views on classroom practice (1989), and the relationship between the same teachers' conceptions of NOS and classroom practice (1990). Two of the three teachers (who were also the experienced teachers) exhibited classroom practices that were consistent with their personal views and philosophy, whereas the beginning teacher's classroom practices were not congruent with his beliefs. Duschl and Wright (1989) observed and interviewed 13 science teachers in a large urban high school. Their results convincingly indicated that the nature and role of scientific theories are not integral components in the constellation of influences affecting teachers' educational decisions. NOS was not being considered or taught to students as a consequence of perceived students' needs, curriculum guide objectives, and accountability.

Lederman and Zeidler's investigation (1987) involved a sample of 18 high school biology teachers from nine schools. The data clearly indicated that there was no significant relationship between teachers' understandings of NOS and classroom practice. Several variables have been shown to mediate and constrain the translation of teachers' NOS conceptions into practice. These variables include pressure to cover content (Abd-El-Khalick, Bell, & Lederman, 1998; Duschl & Wright, 1989; Hodson, 1993), classroom management and organizational principles (Hodson, 1993; Lantz & Kass, 1987; Lederman, 1995), concerns for student abilities and motivation (Abd-El-Khalick et al., 1998; Brickhouse & Bodner, 1992; Duschl & Wright, 1989; Lederman, 1995), institutional constraints (Brickhouse & Bodner, 1992), teaching experience (Brickhouse & Bodner, 1992; Lederman, 1995), discomfort with understandings of NOS, and the lack of resources and experiences for assessing understandings of NOS (Abd-El-Khalick et al., 1998).

Recently, Lederman (1999) attempted to finally put to rest (old habits die hard) the assumption that teachers' conceptions of NOS directly influenced classroom practice. In a multiple case study involving five high school biology teachers with varying experience, Lederman collected data on teachers' conceptions of NOS and classroom practice. All teachers were former students of the author and all possessed informed understandings of NOS. Over the course of a full academic year, data were collected from questionnaires, structured and unstructured interviews, classroom observations, and instructional materials. Data were also collected on students' conceptions of NOS through questionnaires and interviews. The author was unable to find any clear relationship between teachers' conceptions and classroom practice. The two most experienced teachers (14 and 15 years of experience) did exhibit behaviors that seemed consistent with their views of NOS, but interview and lesson plan data revealed that these teachers were not attempting to teach NOS. Data from students in all teachers' classes indicated that none of the students had developed informed understandings of NOS. The results of the investigation indicated that, although the teachers possessed good understandings of NOS, classroom practice was not directly affected. Furthermore, the importance of teachers' intentions relative to students' understandings was highlighted. Even in the classrooms that exhibited some similarity with teachers' understandings, students did not learn NOS, because the teachers did not explicitly intend to teach NOS. Overall, the research was consistent with emerging findings about the relationship between teachers' understandings and classroom practice, as well as the research indicating the importance of explicit instructional attention to NOS. Although it is now clear that teachers' conceptions do not generally translate into classroom practice, concern about teachers' conceptions persists. As was previously mentioned, the past 15 years have been marked by a slow but definite shift in perspective related to how we go about changing teachers' conceptions of NOS. In short, there has been a shift to more explicit instructional approaches in research related to teachers' conceptions of NOS.

Hammrich (1997) used a conceptual change approach to influencing teacher candidates' conceptions of NOS. Students were asked to confront their own beliefs and the beliefs of classmates in cooperative group discussions. The rationale for the approach was that differences of opinions about NOS are inevitable among preservice teachers, and these individuals need opportunities to reflect on what they actually believe and/or know. Although the author claimed her approach to be successful, no documentation of specific understandings was provided, nor was the number of individuals involved mentioned. In addition, Hammrich was more interested in promoting change in students' views rather than having them change toward any particular views. Consequently, it is possible (although no data were provided) that some changes were in directions different from what reform documents have advocated.

In another study of preservice teachers' conceptions of NOS, Bell, Lederman, and Abd-El-Khalick (2000) looked at teachers' translation of knowledge into instructional planning and classroom practice. The subjects were 13 preservice teachers. The teachers' views of NOS were assessed with an open-ended questionnaire before and after student teaching. Throughout the student teaching experience, daily lesson plans, classroom videotapes, portfolios, and supervisors' clinical observation notes were analyzed for explicit instances of NOS in either planning or instruction. Following student teaching, all subjects were interviewed about their questionnaire responses and factors that influenced their teaching of NOS. Although all of the preservice teachers exhibited adequate understandings of NOS, they did not consistently integrate NOS into instruction in an explicit manner. NOS was not evident in these teachers' objectives, nor was any attempt made to assess students' understandings of NOS. The authors concluded that possessing an understanding of NOS is not automatically translated into a teacher's classroom practice. They further concluded that NOS must be planned for and included in instructional objectives, likeany other subject matter content.

Akerson, Abd-El-Khalick, and Lederman (2000) were concerned solely with developing elementary teachers' understandings of NOS and not with the translation of this knowledge into classroom practice. The subjects were 25 undergraduate and 25 graduate preservice elementary teachers enrolled in two separate methods courses. Before and after the courses teachers' views about the empirical, tentative, subjective, creative, and social/cultural embeddedness of scientific knowledge were assessed. In addition, the preservice teachers' views on the distinction between observation/inference and between theories and laws were assessed. The courses explicitly addressed these aspects of NOS with a reflective, activity-based approach. The results indicated that explicit attention to NOS was an effective way to improve teachers' understandings of NOS. However, taken in the context of studies such as the previous one (Bell, Lederman, & Abd-El-Khalick, 2000), the authors were quick to point out that mere possession of adequate understandings will not automatically change classroom practice.

Abell, Martini, and George (2001) monitored the views of 11 elementary education majors during a science methods course. The particular context was a Moon investigation in which the authors targeted the following aspects of NOS: empirically based, involves invention and explanations, and is socially embedded. Students were asked to observe the Moon each night during the course and record their observations. An attempt was made by the instructors to be explicit as possible with respect to NOS. After the investigation, students realized that scientists make observations and generate patterns, but they did not realize that observations could precede or follow the development of a theory. Students were able to distinguish the processes of observing from creating explanations, but they could not discuss the role of invention in science. In various other instances, students were capable of articulating aspects of NOS, but were unable to see the connection between what they learned in the activity and the scientific community. The authors recognized the importance of being explicit in the teaching of NOS. They also recognized that their students' failure to apply what they learned beyond the learning activities themselves, to the scientific community in general, was a consequence of not making an explicit connection between what scientists do and the activities completed in class.

Abd-El-Khalick (2001) used an explicit, reflective approach to teach about NOS in a physics course designed for prospective elementary teachers at the American University of Beirut. Data were collected through pre- and posttests on open-ended surveys about NOS. The author reported significant improvement in the aspects of NOS providing focus for the investigation: tentative, empirically based, theory-laden, inferential, imaginative, and creative characteristics of scientific knowledge. In addition, the relationship between theory and law, and the distinction between observation and inference were investigated. The author definitely concluded that the explicit, reflective approach to instruction was successful. However, the conclusions were tempered by the author's concern that understandings of NOS are more easily applied to familiar contexts than to unfamiliar contexts within science.

The use of the history of science has long been advocated as a means to improve students' conceptions of science. Lin and Chen (2002) extended this logic to a program designed to improve preservice teachers' understanding of NOS. Sixty-three prospective chemistry teachers in Taiwan were divided into experimental and control groups. The teachers in the experimental group were exposed to a series of historical cases followed by debates and discussions that highlighted how scientists developed knowledge. The historical cases were promoted as a way for these prospective teachers to teach science. Different from previous attempts to use the history of science to achieve outcomes related to NOS, the historical materials explicitly addressed NOS. The results clearly showed significant improvement in understandings of NOS by the experimental group relative to the control group. In particular, teachers in the experimental group showed significant improvement of their knowledge of creativity in science, the theory-bound nature of observations, and the functions of scientific theories. The authors claimed that helping teachers learn how to use the history of science in science instruction positively influenced the teachers' understandings of NOS.

Schwartz and Lederman (2002) looked at the improvement of two beginning teachers' understandings of the nature of science as well as their integration of such understandings into classroom practice. Two teachers were studied during their student teaching experience and throughout their first year of full-time teaching. These two teachers were part of a larger cohort, but the authors chose to focus more closely on these two teachers because of the differences in their subject matter knowledge. The results showed that the depth of NOS understanding, subject matter knowledge, and the perceived relationship between NOS and science subject matter affected the teachers' learning and teaching of NOS. The teacher with more extensive subject matter background, who also held a more well-developed understanding of NOS, was better able to address NOS throughout his teaching. This teacher's extensive subject matter background enabled him to address NOS throughout his teaching regardless of science topic. The teacher with less extensive subject matter knowledge was limited with respect to where she could integrate NOS. In addition, this teacher seemed more wedded to the examples of NOS integration provided in her preservice education program. This investigation illustrated for the first time that knowledge of subject matter was a mediating factor in the successful teaching of NOS. Prior to this study correlational studies on the relationship between NOS and subject matter knowledge showed little relationship. Of course, the relationship investigated here was with respect to the teaching of NOS.

Abd-El-Khalick and Akerson (2004) studied 28 preservice elementary teachers in a science methods course. In particular, they investigated the effectiveness of an explicit, reflective instructional approach related to NOS on these prospective teachers' views of various aspects of NOS. Data were collected from a combination of questionnaires, interviews, and reflection papers. As expected, participants initially held naïve views of NOS; however, over the course of the investigation substantial and favorable changes in the preservice teachers' views were evident.

Using a combination of authentic research experiences, seminars, and reflective journals, Schwartz, Lederman, and Crawford (2004) studied changes in secondary preservice teachers' conceptions of NOS. Prior research had indicated that providing teachers with authentic research experiences did not affect understandings of NOS. Consequently, the researchers supported such research experiences with explicit attention to NOS through seminars and a series of reflective journal assignments. The participants were 13 master of arts in teaching (MAT) students. Data were collected via questionnaires and interviews. Most of the interns showed substantial changes in their views of NOS. Participants identified the reflective journal writing and seminars as having the greatest impact on their views, with the actual research internship just providing a context for reflection.

Abd-El-Khalick (2005) considered the perennial recommendation that teachers' should take courses in philosophy of science if we want to affect that knowledge of NOS. The sample was 56 undergraduate and graduate preservice secondary science teachers enrolled in a two-course sequence of science methods. Participants received explicit, reflective NOS instruction. Ten of the participants were also enrolled in a graduate philosophy of science course. The Views of Nature of Science—Form C (VNOS-C) was used to assess understandings of NOS at the beginning and end of the investigation. Participants were also interviewed about their written responses. Other data sources included lesson plans and NOS-specific reflection papers. Results indicated that the students who were enrolled in the philosophy of science course developed more in-depth understandings of NOS than those just enrolled in the science methods course. The author did not take the position that the philosophy of science course was more effective than the methods course for teaching NOS. Rather, the methods course, with explicit instruction about NOS, was seen as providing a framework that the 10 students enrolled in the philosophy of science course could use to significantly benefit from the philosophy course. In short, the methods course provided a lens with which learning of NOS could be maximized. Most recently, Scharmann, Smith, James, and Jensen (2005) used an explicit, reflective approach to teaching NOS within the context of a secondary teaching methods course. Nineteen preservice teachers were the subjects. Overall, the authors decided that the instructional approach was successful and supported the emerging literature on the value of an explicit approach to teaching NOS.

In addition to the typical studies investigating ways to change and improve teachers' conceptions of NOS, there is a slowly emerging attention to the rationales that have been used to justify the importance of teaching NOS to K–12 students. One justification for teaching NOS has been that an understanding of NOS will contribute to informed decisions on scientifically based societal and personal issues. Bell and Lederman (2003) tested this assumption, using a group of 21 highly educated individuals. These individuals were faculty members from various universities. Some were scientists and some were from areas outside of science. Individuals completed an open-ended questionnaire, followed by an interview, designed to assess decision-making on science and technology-related issues. A second questionnaire was used to assess participants' understandings of NOS, and an interview followed the completion of the questionnaire. Participants were separated into two groups based on the adequacy of their understanding of NOS. The two groups' decisions, decision-influencing factors, and decision-making strategies were compared. No differences were found between the two groups. Both groups used personal values, morals/ethics, and social concerns when making decisions, but NOS was not used. The authors concluded that decision-making is complex, and the data did not support the assumption that an understanding of NOS would contribute prominently to one's decisions. The authors also speculated that NOS may not have been considered because individuals need to have instruction on how NOS understandings could be used in aiding the decision-making process.

Research on Students

It is safe to assume that teachers cannot possibly teach what they do not understand (Ball & McDiarmid, 1990; Shulman, 1987). Research on the translation of teachers' conceptions into classroom practice, however, indicates that even though teachers' conceptions of NOS can be thought of as a *necessary* condition, these conceptions, nevertheless, should not be considered *sufficient* (Lederman, 1992). At least one implication for research related to NOS is apparent. Research efforts, it is argued, should "extend well beyond teachers' understandings of nature of science, as the translation of these understandings into classroom practice is mediated by a complex set of situational variables" (Lederman, 1992, p. 351). Clearly, complex issues surround the possible influence of teachers' understandings of NOS on classroom practice and have yet to be resolved. It is safe to say, however, that there is general agreement among researchers concerning the strong influence of curriculum constraints, administrative policies, and teaching context on the translation of teachers' conceptions into classroom practice. Although there is a clear pattern in the research that compares teachers' conceptions with classroom practice, it is not uncommon to find a small minority of studies that continue to claim a direct relationship between teachers' conceptions and classroom practice (e.g., Kang & Wallace, 2005). In addition to investigations that assessed the relationship between teachers' conceptions and classroom practice, efforts to identify those factors that do influence students' conceptions have also been pursued.

In a comprehensive study of 18 high school biology teachers (Lederman, 1986a; Lederman & Druger, 1985), a set of 44 teacher behaviors and/or classroom climate variables was identified as being related to specific changes in students' understandings of NOS, as measured by the Nature of Scientific Knowledge Scale (Rubba & Andersen, 1978). In general, the classes of the most effective teachers were typified by frequent inquiry-oriented questioning, active participation by students in problem-solving activities, frequent teacher-student interactions, infrequent use of independent seat work, and little emphasis on rote memory/recall. With respect to classroom climate, classes of the more effective teachers were more supportive, pleasant, and "risk free," with students expected to think analytically about the subject matter presented. Although this investigation was correlational, the findings were supported by an experimental study conducted in junior college biology classes (Haukoos & Penick, 1983). A quasi-experimental design was used with two different instructional approaches (discovery-oriented and non-discovery-oriented) in general biology classes. Students in the discovery-oriented classes were found to make significant gains in the understanding of NOS as measured by the Science Process Inventory. The important point here is that the description of the discovery-oriented classes is consistent with the teaching approaches and classroom climate documented as "effective" in Lederman's correlational studies (Lederman, 1986a; Lederman & Druger, 1985). The significance of teacher-student interactions to conceptual changes in students' views of science motivated a follow-up study with 18 high school biology teachers and 409 students (Zeidler & Lederman, 1989). In this investigation, specific attention was focused on the nature of teacher-student interactions and the specific language used. In general, when teachers used "ordinary language" without qualification (e.g., discussing the structure of an atom without stressing that it is a model), students tended to adopt a realist conception of science.

Alternatively, when teachers were careful to use precise language with appropriate qualifications, students tended to adopt an instrumentalist conception. At the time, this investigation provided clear empirical support for Munby's thesis (1976) that implicit messages embedded in teachers' language provide for varied conceptions of NOS. Indeed, although the recent literature (past 10 years) predominantly indicates otherwise, some investigators (Craven, Hand, & Prain, 2002) still cling to the value of using implicit instruction for the teaching of NOS.

Inclusion of the history of science has often been touted as being a way to improve students' understandings of NOS. The value of history of science, however, has been held mostly as an intuitive assumption as opposed to being an idea having empirical support. Abd-El-Khalick and Lederman (2000b) assessed the influence of three history of science courses on college students' and preservice teachers' conceptions of NOS. The subjects were 166 undergraduate and graduate students and 15 preservice secondary science teachers at Oregon State University. All subjects were pre- and posttested with an open-ended questionnaire. A representative sample of students was also interviewed in an effort to establish face validity for the questionnaires. The results showed that most individuals entered the history of science courses with inadequate views of NOS, and there was little change after they completed the course. When change was noted, it was typically with respect to some explicit attention to NOS in one of the courses. In addition, there was some evidence that the preservice teachers learned more about NOS from the history of science courses than the other students. This was attributed to the possible benefits of having entered the course with a perceptual framework for NOS provided in their science methods course.

The use of "hands-on" activities has often been recommended as a way to improve students' understandings of NOS. Moss (2001) studied five volunteers from a class of 20 students. The volunteers were 11th- and 12th-grade students in a projects-based Conservation Biology class. Using a participant-observation approach, the author observed students, interviewed them six times during the academic year, and collected various artifacts of work. Over the course of the year, students' views did not change. They entered the course with adequate views on at least half of the eight tenet model of NOS used by the researcher, but little change was noted in any of the tenets. Although the author intuitively felt that students' views would change simply by exposure to a problem-based course, he did recognize that making NOS explicit was necessary. Several students made slight changes in response to implicit messages, which led to the conclusion that there is still a valuable place for implicit learning.

Liu and Lederman (2002) studied 29 gifted Taiwanese middle school students during a one-week summer science camp. The focus of the science instruction was scientific inquiry and NOS. A Chinese version of the Views of Nature of Science (VNOS) scale was developed to assess students in their native language. One question was added that was concerned with western medicine and eastern medicine to see if the students' cultural background influenced their views in any way. Instruction was provided in English, unless students clearly needed additional explanation. Liu presented all of the lessons. On the pretest, the students possessed good understandings of the tentative, subjective, empirical, and social/cultural embeddedness of science. Although all instruction was explicit, no changes were noted in students' understandings on the posttest. The authors explained the lack of change in students' views as a possible consequence of a very short instructional period and a ceiling effect. After all, the authors argued, the students did fairly well on the pretest. No evidence was found to support the notion that cultural background may interact with students' understandings of NOS.

Few studies have studied the effectiveness of explicit, reflective approaches to teaching NOS relative to implicit approaches with K–12 students. One such study was completed by Khishfe and Abd-El-Khalick (2002) in Lebanon. A total of 62 6th-grade students in two intact groups (n = 29 and 32) experienced inquiry-oriented instruction related to energy transformation and sedimentary rocks. One group was taught with an approach that explicitly addressed the tentative, empirical, inferential, imaginative, and creative aspects of scientific knowledge, whereas in the other class only implicit attention to NOS was included. The same teacher taught both classes. Students' knowledge of NOS was assessed through a combination of an open-ended questionnaire and semistructured interviews. The two groups entered the investigation with naïve, and equivalent, views on the various aspects of NOS. After instruction, the implicit group showed no changes in views of NOS, whereas students in the explicit group all exhibited improvement in their understandings of one or more aspects of NOS. Again, this particular study is important in that it demonstrated the relative effectiveness of explicit instructional approaches with a sample of K–12 students as opposed to preservice and inservice teachers.

Tao (2003) initially was interested in eliciting secondary students' understandings of NOS through a combination of peer collaboration and the use of science stories designed to illustrate aspects of NOS. The investigation showed that many students held empiricist views about scientific investigations and believed scientific theories to be absolute truths about reality. The author noticed that students' views were affected by group discussion about the stories. Instead of developing more informed understandings about NOS, however, the author noted that students moved from one indequate view to another. In short, Tao felt that students simply looked for aspects of NOS that confirmed their views in the stories and ignored those aspects that ran contrary to their views.

Dhingra (2003) recognized that students learn about NOS through many sources, not just classroom instruction. The sample consisted of 63 female students from two single-sex high schools in New York City. Data were collected in response to a variety of television shows. The primary finding relative to NOS was that students reacted differently to shows that presented science as a collection of facts and those that presented science as more uncertain. Students had virtually no questions or comments about the science in shows that presented final-form science, but had numerous comments and questions in response to shows that presented science otherwise. A critical point here is that the television shows' depictions of science were explicit, and this explicitness appears to have had an impact on student learning.

Science apprenticeship programs have been a popular approach to engaging high-ability students in science, with an eye to promoting their interest in future careers in science. A commonly stated goal of such apprenticeship programs is that students will develop improved conceptions of NOS. Bell, Blair, Crawford, and Lederman (2003) systematically tested this assumed benefit of an apprenticeship program. The apprenticeship program was eight weeks long during the summer. Ten high-ability high school students (juniors and seniors) were pre- and posttested on their understandings of NOS and scientific inquiry before and after the apprenticeship. Both students and their mentor scientists were interviewed after the program. Although the scientists were of the opinion that their students had learned a lot about inquiry and NOS, student data (from interviews and questionnaires) indicated that changes occurred only in students' abilities to do inquiry. Of importance here is that students' conceptions of NOS on the pretest were not consistent with current reform efforts and, after the apprenticeship, with only one exception, remained the same. The authors ultimately concluded that students' conceptions of NOS (and knowledge about inquiry) remained unchanged because there was no explicit instruction about either associated with the apprenticeship. At least in practice, it appears to have been assumed that students would learn about NOS and inquiry simply by doing inquiry. As can be expected, not all studies involving explicit instruction related to NOS have met with success (Leach, Hind, & Ryder, 2003). In this particular investigation, the explicit instructional approach was not effective in promoting improved student views.

Among the volumes of research that focus on effecting change in conceptions of NOS, a small minority of studies focus on the impact that one's conceptions of NOS has on other variables of interest. Sadler, Chambers, and Zeidler (2004) focused on how students' conceptions of NOS affected how they interpreted and evaluated conflicting evidence on a socioscientific issue. Eighty-four high school students were asked to read contradictory reports related to global warming. A subsample of 30 students was interviewed in order to corroborate their written responses. The participants displayed a range of views on three aspects of NOS: empiricism, tentativeness, and social embeddedness. The authors claimed that how the students reacted to conflicting evidence was at least partially related to their views on NOS. This finding would appear to support the claim that an understanding of NOS is important because it contributes to an individual's decision-making.

ASSESSING CONCEPTIONS OF NATURE OF SCIENCE

The development and assessment of students' and teachers' conceptions of nature of science have been concerns of science educators for over 40 years and arguably constitute a line of research in their own right. Although there have been numerous criticisms of the validity of various assessment instruments over the years, students' and teachers' understandings have consistently been found lacking. This consistent finding, regardless of assessment approach, supports the notion that student and teacher understandings are not at the desired levels. It is important to note, however, that during the early development of assessment instruments there was more of a focus on what we would currently describe as scientific inquiry as opposed to nature of science.

The history of the assessment of nature of science mirrors the changes that have occurred in both psychometrics and educational research design over the past few decades. The first formal assessments, beginning in the early 1960s, emphasized quantitative approaches, as was characteristic of the overwhelming majority of science education research investigations. Prior to the mid-1980s, with few exceptions, researchers were content to develop instruments that allowed for easily "graded" and quantified measures of individuals' understandings. In some cases, standardized scores were derived. Within the context of the development of various instruments, some open-ended questioning was involved in the construction and validation of items. More recently, emphasis has been placed on providing an expanded view of an individual's beliefs regarding the nature of science. In short, in an attempt to gain more in-depth understandings of students' and teachers' thinking, educational researchers have resorted to the use of more open-ended probes and interviews. The same has been true with the more contemporary approaches to assessment related to the nature of science.

A critical evaluation of assessment instruments has recently been provided elsewhere (Lederman, Wade, & Bell, 1998). Therefore, the purpose here is to summarize the various instruments and identify trends in the assessment of NOS. Table 28.1 presents a comprehensive list of the more formal instruments constructed and validated to assess various aspects of NOS. Most of the instruments address only cer-

TABLE 28.1
Nature of Science Instruments

Date	*Instrument*	*Author(s)*
1954	Science Attitude Questionnaire	Wilson
1958	Facts About Science Test (FAST)	Stice
1959	Science Attitude Scale	Allen
1961	Test on Understanding Science (TOUS)	Cooley & Klopfer
1962	Processes of Science Test	BSCS
1966	Inventory of Science Attitudes, Interests, and Appreciations	Swan
1967	Science Process Inventory (SPI)	Welch
1967	Wisconsin Inventory of Science Processess (WISP)	Scientific Literacy Research Center
1968	Science Support Scale	Schwirian
1968	Nature of Science Scale (NOSS)	Kimball
1969	Test on the Social Aspects of Science (TSAS)	Korth
1970	Science Attitude Inventory (SAI)	Moore & Sutman
1974	Science Inventory (SI)	Hungerford &Walding
1975	Nature of Science Test (NOST)	Billeh & Hasan
1975	Views of Science Test (VOST)	Hillis
1976	Nature of Scientific Knowledge Scale (NSKS)	Rubba
1978	Test of Science-Related Attitudes (TOSRA)	Fraser
1980	Test of Enquiry Skills (TOES)	Fraser
1981	Conception of Scientific Theories Test (COST)	Cotham & Smith
1982	Language of Science (LOS)	Ogunniyi
1987	Views on Science-Technology-Society (VOSTS)	Aikenhead, Fleming, & Ryan
1990	Views of Nature of Science A (VNOS-A)	Lederman & O'Malley
1992	Modified Nature of Scientific Knowledge Scale (MNSKS)	Meichtry
1995	Critical Incidents	Nott & Wellington
1998	Views of Nature of Science B (VNOS-B)	Abd-El-Khalick, Bell, & Lederman
2000	Views of Nature of Science C (VNOS-C)	Abd-El-Khalick & Lederman
2002	Views of Nature of Science D (VNOS-D)	Lederman & Khishfe
2004	Views of Nature of Science E (VNOS-E)	Lederman & Ko

tain aspects of NOS and often inappropriately confuse the issue by addressing areas other than NOS, including science process skills and attitudes toward science. Instruments considered to have poor validity have the following characteristics:

1. Most items concentrate on a student's ability and skill to engage in the process of science (e.g., to make a judgment and/or interpretation concerning data).
2. Emphasis is on the affective domain (the realm of values and feelings) rather than knowledge (i.e., over 50 percent of items deal with attitude toward or appreciation of science and scientists).
3. Primary emphasis is placed upon science as an institution, with little or no emphasis placed upon the epistemological characteristics of the development of scientific knowledge.

As mentioned before, the validity of many of these instruments is questionable because their primary focus is on areas beyond the scope of the nature of science. Those instruments with questionable validity (as measures of NOS) include the Science Attitude Questionnaire (Wilson, 1954), Facts About Science Test (Stice, 1958), Science Attitude Scale (Allen, 1959), Processes of Science Test (BSCS, 1962), Inventory of Science Attitudes, Interests, and Appreciations (Swan, 1966), Science Support Scale (Schwirian, 1968), Test on the Social Aspects of Science (Korth, 1969), Science Attitude Inventory (Moore & Sutman, 1970), Science Inventory (Hungerford & Walding, 1974), Test of Science-Related Attitudes (Fraser, 1978), the Test of Enquiry Skills (Fraser, 1980), and the Language of Science (Ogunniyi, 1982).

The remaining instruments have generally been considered to be valid and reliable measures of NOS by virtue of their focus on one or more ideas that have been traditionally considered under the label of "nature of science," as well as their reported validity and reliability data. These instruments have been used in numerous studies, and even the more traditional instruments (e.g., TOUS) continue to be used, even though there is a significant movement away from such types of paper-and-pencil assessments. The validity of some of the assessment instruments listed and briefly described below has been severely criticized (and justifiably so) in the past few years. However, they are presented here as being the most valid (in terms of assessment focus) attempts to assess understandings of NOS using a written response format. Following is a brief discussion of each instrument.

Test on Understanding Science (TOUS) (Cooley & Klopfer, 1961). This instrument has been, by far, the most widely used assessment tool in NOS research. It is a four-alternative, 60-item multiple-choice test. In addition to an "overall" or "general" score, three subscale scores can be calculated: (I) understanding about the scientific enterprise; (II) the scientist; (III) the methods and aims of science. During the past few decades, the content of the *TOUS* has been criticized and has fallen into disfavor (Aikenhead, 1973; Hukins, 1963; Welch, 1969; Wheeler, 1968).

Wisconsin Inventory of Science Processes (WISP) (Scientific Literacy Research Center, 1967). The WISP consists of 93 statements that the respondent evaluates as "accurate," "inaccurate," or "not understood." However, in scoring the exam, "inaccurate" and "not understood" responses are combined to represent the opposite of "accurate." With the exception of the TOUS exam, this instrument has been used more than any other assessment instrument. The WISP was developed and validated for high school students. Although this instrument has excellent validity and reliability data, a few concerns should be considered prior to its use. Of primary concern is its length. The 93-item test takes over an hour to administer, which precludes it from use in a single class period. In addition, this instrument does not possess discrete subscales, which means, unfortunately, that only unitary scores can be calculated.

Science Process Inventory (SPI) (Welch, 1967). This instrument is a 135-item forced-choice inventory (agree/disagree) purporting to assess an understanding of the methods and processes by which scientific knowledge evolves. The content of the SPI is almost identical to that of WISP and TOUS subscale III. The validation of SPI was achieved in the usual manner for such instruments: literature review, devising a model, employing the judgment of "experts," getting feedback from pilot studies, and testing the instrument's ability to distinguish among different groups of respondents. The length (135 items) is a concern, as is its forced choice format. Students are unable to express "neutral" or uncertain answers. Finally, like the WISP, the SPI does not possess subscales.

Nature of Science Scale (NOSS) (Kimball, 1968). This instrument was developed to determine whether science teachers have the same view of science as scientists. It consists of 29 items, which the respondent may answer with "agree" or "disagree" or register a "neutral" response. Kimball's model of NOS is based upon the literature of the nature and philosophy of science and is consistent with the views of Bronowski (1956) and Conant (1951). The specific content of NOSS was validated by nine science educators, who judged whether the items were related to the model. The development, validation, and reliability measures were carried out with college graduates. Thus, it lacks reliability and validity data with respect to high school populations. Another concern is that the instrument lacks subscales and is, therefore, subject to the same criticism as WISP or any other unitary measure of the nature of science.

Nature of Science Test (NOST) (Billeh & Hasan, 1975). This instrument consists of 60 multiple-choice items addressing the following components of NOS: Assumptions of science (8 items), Products of science (22 items), Processes of science (25 items), and Ethics of science (5 items). The test consists of two types of items. The first type measures the individual's knowledge of the assumptions and processes of science, and the characteristics of scientific knowledge. The second type of question presents situations that require the individual to make judgments in view of his/her understanding of the nature of science. The major shortcoming of this instrument is not its content, but rather, that no subscales exist. Thus, only a global or unitary score can be calculated.

Views of Science Test (VOST) (Hillis, 1975). This instrument was developed specifically to measure understanding of the tentativeness of science. It consists of 40 statements that are judged to imply that scientific knowledge is tentative or absolute. Respondents express their agreement with either view, using a five-option Likert scale response format. The instrument is considered too focused by some because it is restricted to a single attribute of scientific knowledge.

Nature of Scientific Knowledge Scale (NSKS) (Rubba, 1976). This instrument is a 48-item Likert scale response format consisting of five choices (*strongly agree, agree, neutral, disagree, strongly disagree*). The test is purported to be an objective measure of secondary students' understanding of NOS. The NSKS and its subscales are based upon the nine factors of NOS specified by Showalter (1974). Rubba (1977) listed these nine factors as tentative, public, replicable, probabilistic, humanistic, historic, unique, holistic, and empirical. He noted a certain amount of shared overlap between the factors and proceeded to collapse them into a six-factor or six-subscale model of the nature of science. These six factors are: amoral, creative, developmental (tentative), parsimonious, testable, and unified. The instrument was developed, validated, and found to be reliable for high school-level students. The five-option Likert scale response format affords maximum freedom of expression to the respondent. The NSKS has generally been viewed positively by the research community; however, there is reason for some concern about its face validity. Many pairs of items within specific subscales are identical, except that one item is worded negatively. This redundancy could encourage respondents to refer back to their answers on previous, similarly worded items. This cross-checking would result in inflated reliability estimates, which could cause erroneous acceptance of the instrument's validity.

Conceptions of Scientific Theories Test (COST) (Cotham & Smith, 1981). The structure of this instrument was dictated by the developers' concern that previously existing instruments were based on single (supposedly enlightened) interpretations of NOS. Thus, the COST supposedly provides for nonjudgmental acceptance of alternative conceptions of science. The instrument is an attitude inventory consisting of 40 Likert scale items (with four options) and four subscales, each corresponding to a particular aspect of scientific theories. These include (I) ontological implications of theories; (II) testing of theories; (III) generation of theories; and (IV) choice among competing theories. The COST provides a theoretical context for four item-sets by prefacing each set with a brief description of a scientific theory and some episodes drawn from its history. The items following each theory description refer to that description. The four theoretical contexts are 1) Bohr's theory of the atom, 2) Darwin's theory of evolution, 3) Oparin's theory of abiogenesis, and 4) the theory of plate tectonics. A fifth context contains items that refer to general characteristics of scientific theories and is, therefore, not prefaced by a description. Two concerns must be addressed prior to the use of COST as an instrument to assess high school students' understandings of the nature of science. The first of these is the cognitive level of the instrument. It was designed for teachers and validated with undergraduate college students. The four theory descriptions used to provide context for the items are presented at a level that may be above the capabilities of many high school students.

A second concern with the COST instrument rests with the authors' claim that it, as opposed to all extant instruments, is sensitive to alternative conceptions of science. Cotham and Smith feel that it is extremely important for education to promote the view that scientific knowledge is tentative and revisionary. In their commitment to this concern, however, they actually specify which subscale viewpoints are consistent with the tentative and revisionary conception. Thus, although they claim to place no value judgments upon the various conceptions of science, Cotham and Smith actually do just that by linking certain viewpoints to the "highly prized" tentative and revisionary conception of scientific knowledge.

Views on Science-Technology-Society (VOSTS) (Aikenhead, Fleming, & Ryan 1989). The VOSTS was developed to assess students' understanding of the nature of science, technology, and their interactions with society. It consists of a "pool" of 114 multiple-choice items that address a number of science-technology-society (STS) issues. These issues include Science and Technology, Influence of Society on Science/Technology, Influence of Science/Technology on Society, Influence of School Science on Society, Characteristics of Scientists, Social Construction of Scientific Knowledge, Social Construction of Technology, and Nature of Scientific Knowledge. The VOSTS was developed and validated for grade 11 and 12 students. A fundamental assumption underlying the development of this instrument was that students and researchers do not necessarily perceive the meanings of a particular concept in the same way. Aikenhead and Ryan (1992) recognized the importance of providing students with alternative viewpoints based upon student "self-generated" responses to avoid the "constructed" responses offered by most of the previous nature of science assessment instruments. Unlike most other instruments, the VOSTS does not provide numerical scores; instead it provides a series of alternative "student position" statements. These statements were obtained from extensive open-ended student "argumentative" paragraphs in which students defended their stated position on a STS issue or topic. The extensive work developing and validating the VOSTS instrument took approximately six years to complete and is reported in a series of research articles published in a special edition of the journal *Science Education* (Volume 71, 1987).

Views of Nature of Science, Form A (VNOS-A) (Lederman & O'Malley, 1990). In an attempt to ameliorate some of the problems noted by Aikenhead et al. (1987) during the development of the VOSTS and those noted in the use of the NSKS (Rubba, 1976) relative to the use of paper-and-pencil assessments, Lederman and O'Malley developed an open-ended survey consisting of seven items. This instrument was designed to be used in conjunction with follow-up interviews, and each of the seven items focuses on different aspects of tentativeness in science. Several problems were noted in the wording of some of the questions resulting in responses that did not necessarily provide information on students' views of "tentativeness." While these difficulties were alleviated by subsequent interviews, they served to reinforce the problems associated with attempting to interpret students' understandings solely from their written responses to researcher-generated questions.

Modified Nature of Scientific Knowledge Scale (M-NSKS) (Meichtry, 1992). This instrument is a modified NSKS instrument with 32 statements from four of the NSKS subscales. These subscales are: (I) creative, (II) developmental, (III) testable, and (IV) unified. M-NSKS was developed, with reliability and validity reported, for use with 6th-, 7th-, and 8th-graders.

Critical Incidents (Nott & Wellington, 1995). The use of "critical incidents" to assess teachers' conceptions of NOS was a significant departure from the usual paper-and-pencil assessment. In particular, Nott and Wellington are of the opinion that teachers do not effectively convey what they know about the nature of science in "direct response to abstract, context-free questions of the sort, 'What is science?'" (Nott & Wellington, 1995). Instead, they created a series of "critical incidents" that are descriptions/scenarios of actual classroom events. Teachers are expected to respond to the incidents by answering the following three questions: 1) What would you do? 2) What could you do? and 3) What should you do? So, for example, the teacher may be confronted with a situation in which a demonstration or laboratory activity does not yield the desired data. How the teacher responds to the aforementioned questions is believed to communicate what the teacher believes about NOS.

Although the use of critical incidents appears to be an excellent instructional tool to generate meaningful discussions in preservice and inservice courses, whether the teachers' responses are related to their views about NOS is still questionable. In short, the approach is based on the assumption that teachers' views of the nature of science automatically and necessarily influence classroom practice, an assumption that is simply not supported by the existing literature.

Views of Nature of Science B,C,D (VNOS B,C,D,E). This series or buffet of instruments has stemmed from the same research group and was meant to offer variations and improvements upon the original VNOS-A (Lederman & O'Malley, 1990). In particular, each instrument contains open-ended questions that focus on various aspects of NOS, with the differences being either the additional context-specific questions in forms B and C, or the developmental appropriateness and language of VNOS-D. From a practical standpoint, VNOS-B and VNOS-C are too lengthy to be administered easily during a regular class period. Teachers often take as long as 1.5 hours to complete VNOS-C. Consequently, VNOS-D and VNOS-E were created with the aid of focus groups of secondary ($n = 10$) and elementary ($n = 10$) teachers and their students. The resulting instruments are easily administered in less than one hour and yield the same results as the longer VNOS-B and VNOS-C. VNOS-E is the most recently developed instrument, and it has been designed for very young students (grades K–3). The items can also be used with students who cannot read or write (using a focus group format), and it represents the first measure of NOS designed for such a young audience. The particular authors credited for the development of each instrument are noted in the table of NOS instruments. A thorough description of the development of the VNOS A, B, and C instruments can be found in Lederman, Abd-El-Khalick, Bell, and Schwartz (2002).

SOME THOUGHTS ABOUT ASSESSING NOS

The validity of instruments purporting to assess NOS has long been criticized on the grounds that each instrument assumes its interpretation of science to be the correct view (Cotham & Smith, 1981). This criticism is derived from the often discussed lack of consensus concerning NOS among scholars from various fields. As previously discussed, however, when one considers the developmental level of the target target audience (K–12 students), the aspects of NOS stressed are at a level of generality that is not at all contentious. Nevertheless, if one is not willing to let go of the idea that the various aspects of NOS lack consensus and assessment of NOS is, therefore, problematic, the "problem" is easily handled. The issue lies not within the test, but rather in the interpretations of those scoring the test. If one interprets test scores simply as a measure of an individual's adherence to a particular conception of science, then no implicit value judgments are made. In short, the inherent bias in the scoring system of any assessment can be avoided if researchers simply use the scores to construct profiles of beliefs and knowledge.

Overall, there are two critical issues that have surrounded the "traditional" paper-and-pencil assessments of NOS: 1) assessment instruments are interpreted in a biased manner, and 2) some assessment instruments appear to be poorly constructed. These criticisms notwithstanding, it is interesting to note that research conclusions based on these instruments have been unusually uniform. That is, teachers and students generally score at levels considered to be less than adequate.

Thus, although the various instruments suffer from specific weaknesses, if these were significant, it would seem improbable that the research conclusions would be so consistent.

There is a more critical concern, however, about the "traditional" paper-and-pencil approach to the assessment of an individual's understanding of NOS. Although not a new insight, Lederman and O'Malley's (1990) investigation clearly highlighted the problem of paper-and-pencil assessments. They documented discrepancies between their own interpretations of students' written responses and the interpretations that surfaced from actual interviews of the same students. This unexpected finding (i.e., the purpose of the interviews was to help validate the paper-and-pencil survey that was used) was quite timely, as it occurred when educational researchers were making a serious shift toward more qualitative, open-ended approaches to assess individuals' understanding of any concept. Although the VNOS-A was created to avoid some of the concerns about "traditional" assessments (as were the subsequent series of VNOS forms), the problem of researchers interpreting responses differently than intended by the respondent remains to this day. The problem exists at all age levels (K–adult), with increasing levels of uncertainty as the age of the respondent decreases. It is for this reason that researchers should not abandon the interviewing of individuals about their written responses. Throughout the history of NOS assessment there has been a clear movement from traditional convergent assessments to more open-ended assessments. Most researchers realize how difficult it is to assess a construct as complex as NOS with multiple-choice and Likert scale items. Within all of us, however, is this "inherent" need to make our lives easier. Interviews and open-ended assessments are time-consuming to conduct and score. However, a quick perusal of the program from the Annual Meeting of the National Association for Research in Science Teaching in 2003–2005 indicates that attempts to create a "better" traditional assessment are alive and well. The desire to create an instrument that can be mass administered and scored in a short period of time continues. It is hoped that the need to collect valid data as opposed to large data sets will prevail.

Finally, there remains a small minority of individuals (e.g., Sandoval, 2005) who insist that students' and teachers' understandings of NOS are best assessed through observations of behavior during inquiry activities (i.e., knowledge in practice). Such a view is a remnant of the previously discussed assumption that a teacher's understanding of NOS is necessarily reflected in his/her behavior. It is déjà vu all over again. The literature clearly documents the discrepancies that often exist between one's beliefs/knowledge and behavior. More concretely, if an individual believes that scientific knowledge is tentative (subject to change) and another individual believes the knowledge to be absolute/static, how would this be evident in their behavior during a laboratory activity? If a student recognizes that scientific knowledge is partly subjective, how would this student behave differently during a laboratory investigation than a student with differing beliefs? Certainly, many similar questions could be asked in relation to other aspects of NOS. In short, this methodology of assessment adds an unnecessary layer of inference to one's research design. Those supporting the "observation" approach also think that asking students to answer questions such as What is an experiment? is too abstract and unrelated to the student's practical world. This view ignores the fact that the nature of an experiment is included in most curricula, and it is related to the work that students do.

The idea is far from being too much of an abstraction. However, if one insists that direct observations of student or teacher behaviors be pursued, then assessments of the subject's views of NOS should be made after observations and document analysis have been completed by the researcher, or the results of the assessments should be hidden until observations are completed. This is analogous to the "blind" studies often used in medical studies to reduce the impact of the researcher's and subject's bias on the results.

FUTURE DIRECTIONS

After approximately 50 years of research related to students' and teachers' conceptions of NOS, a few generalizations can be justified:

- K–12 students 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.

At this point in the history of research on the nature of science, the research has been relatively superficial in the sense of an "input-output" model with little known about the in-depth mechanisms that contribute to change in teachers' and students' views. Even the more recent efforts that have documented the efficacy of explicit, reflective approaches (Abd-El-Khalick & Lederman, 2000) to instruction are superficial in the sense that students and/or teachers are pretested and posttested relative to an instructional activity or set of activities. The specific mechanisms of change and/or the dynamics of change have yet to be explored in depth. We have simply discovered the situations under which change has occurred in the desired direction. Clearly, much more work is needed before we, as a research community, can feel confident in making large-scale recommendations to teachers and professional developers.

Regardless of the "holes" that one can find in the existing research literature, the past 50 or so years of research on NOS does provide us with some clear direction in terms of future research and teaching. What follows is just a few of the critical lines of research that need to be pursued.

How do teachers' conceptions of NOS develop over time? What factors are important, and are certain factors more related to certain aspects of nature of science than others?

We need more in-depth knowledge of how views on NOS change over time. Certainly, change in such views must be similar to the change that one sees with other science concepts. Shifts in viewpoints are most likely gradual, and certain aspects of NOS may be more easily altered than others. It is just as likely that those factors of importance have a differential influence on the various aspects of NOS. To date, the available research simply identifies whether an individual's views have changed from "naïve" to "adequate."

What is the influence of one's worldview on conceptions of nature of science?

Although much research on individuals' worldviews has been pursued, such research has rarely been directly and systematically related to views on NOS. One notable exception has been Cobern's work (2000). It seems that NOS may be a subset of one's worldview or is at least affected by one's worldview. Of primary importance is the relevance of this line of research for the teaching of NOS across cultures. What happens when there is a clash between one's cultural views and the views expressed in western-influenced depictions of science and NOS?

What is the relative effectiveness of the various interventions designed to improve teachers' and students' conceptions? Is one better than another, or is a combination needed?

Although there is strong emerging evidence that an explicit approach to the teaching of NOS is more effective than implicit approaches, there has been virtually no research that compares the relative effectiveness of the various explicit approaches. Are the various approaches equally effective? For example, is explicit instruction in the context of a laboratory investigation more or less effective than explicit reflection within the context of an historical case study? Is a combination of the two approaches more effective than either approach alone?

Is the nature of science learned better by students and teachers if it is embedded within traditional subject matter or as a separate "pull-out" topic? Should the nature of science be addressed as both a separate "pull-out" as well as embedded?

Similar to the issue of the relative effectiveness of various instructional approaches, is the issue of the curriculum context of NOS instruction. There is an existing assumption that when NOS is embedded within the context of lessons on other aspects of subject matter, student learning is enhanced. There is little published research specifically related to this issue. Even the most superficial perusal of the recent research on explicit instruction, however, shows that explicit teaching of NOS has supporters for embedded and non-embedded approaches. Systematic research that compares the relative effectiveness of these instructional approaches alone and in combination is needed.

How do teachers develop PCK for the nature of science? Is it related to their knowledge structures for traditional science content?

The relationship between one's views of NOS, subject matter, and pedagogy remains uncertain. If we are to assume that NOS is analogous to other aspects of subject matter that teachers teach and, it is hoped, students learn, it also stands to reason that teachers can and should develop PCK for NOS. Virtually no research has used the PCK perspective, which was so heavily researched during the 1990s, as a lens for research on the teaching of NOS. Such research would provide critical information for the planning and quality of professional development activities that focus on NOS. After all, it is one thing to teach teachers about NOS; it is a totally different endeavor to teach them how to teach NOS to their students.

How are teachers' conceptions of the nature of science affected during translation into classroom practice? How much of an independent variable is the act of teaching?

Anyone who has ever attempted to enhance teachers' understandings of NOS is aware that the "newly developed" views resulting from a methods course or professional development workshop are fragile at best. Given what is known about how science is typically presented in various curriculum materials, there is the possibility that the curriculum may influence a teacher's views of NOS. Within the literature on PCK, there is some recognition that how one uses his/her subject matter (e.g., teaching) can influence the individual's subject matter structure (Hauslein, Good, & Cummins, 1992). Consequently, it is quite possible that the teaching of science may have an impact on how a teacher views the epistemology of science.

Does the difficulty of the subject matter within which the nature of science is embedded influence student learning?

Unless NOS is taught independently of other science subject matter, it represents an additional outcome that students are expected to learn during science instruction. That is, for example, students would be expected to learn that scientific knowledge is tentative while at the same time learning the details of the model of the atom. It is quite possible that the difficulty level of the subject matter may interfere with the learning of NOS. Should NOS be withheld for situations in which relatively concrete science topics are being addressed?

Does knowledge of the nature of science improve students' learning of other science subject matter?

One of the original rationales for teaching NOS has been the belief that an understanding of NOS will enhance students' subsequent learning of science subject matter. This assumption, as is true with other assumptions related to the purported value of NOS as an instructional outcome, has yet to be systematically tested. Should students learn to view the subject matter they are being asked to learn through a lens of NOS? This line of research would inform the placement and role of NOS within the science curriculum

Does understanding of the nature of science significantly influence the nature and quality of decisions students make regarding scientifically based personal and social issues?

A second rationale for the teaching of NOS has been that such understandings would enhance decision-making on scientifically based personal and social issues. Other than Bell and Lederman's (2003) investigation of university faculty members (scientists and non-scientists), this assumption has remained untested. The results of that investigation did not support the long-held assumption about the value of NOS as an instructional outcome. In general, the assumptions that have been used as advocacies for the teaching of NOS need to be systematically tested. It may very well be that the only value in teaching NOS is that it gives students a better understanding of science as a discipline.

Are the nature of science and scientific inquiry universal, or are conceptions influenced by the particular scientific discipline?

Although NOS has been treated in the research literature as "generic" across all scientific disciplines, there appears to be a growing belief in the view that different disciplines may have different "definitions" of NOS. For example, is NOS in biology the same as it is in physics? Intuitively, it seems that there would be differences. Indeed, the phrase "natures of science" is starting to be heard in the halls of professional meetings. The published research literature, however, does not contain a test of this assumption. At this point, all that exists is the unpublished work of Schwartz (2005), and the results, as usual, do not support our intuitive assumptions. The implications this line of research has for teaching NOS in schools are clearly significant. Should NOS be characterized differently in the different science classes? Clearly, we need much more research that compares the views of nature of science (and scientific inquiry) of individuals viewed to have strong understandings of each. It cannot be overemphasized that researchers should carefully consider the developmental appropriateness of conceptions of inquiry and NOS they consider for use with K–12 students.

How do teachers come to value NOS as having status equal to or greater than that of "traditional" subject matter?

The last bulleted item at the beginning of this section noted that teachers do not value NOS at a level equal to that of "traditional" subject matter. The existing research clearly indicates that teachers can be taught NOS, and it clearly shows that teachers can be taught how to teach NOS to students. However, the research is lacking when it comes to providing guidance for how to develop teachers' valuing of NOS as an important instructional outcome. Few would argue with the notion that teachers spend less time teaching what they don't value or value less than other material. Even teachers who understand NOS and how to teach it may not actually attempt to teach NOS to students. This was illustrated in Lederman's (1999) case study of five biology teachers quite knowledgeable about NOS. One reason teachers may not teach NOS, even though they are capable, is that NOS is typically not assessed on local, national, or international tests. However, if we hope to improve teachers' instructional attention to NOS in a more creative way than just putting it on the test, a concerted effort must be made to unearth what it takes to get teachers to value NOS relative to other instructional outcomes.

At the beginning of this review, some attention was given to the question, Why teach NOS? A pessimistic answer might focus on the observation that each time one of the perennial reasons for teaching NOS is systematically studied, empirical support for our intuitive claims is nowhere to be found. Hence, all of the reasons we have always used for advocating NOS as an instructional outcome may be false. On a more positive note, it can always be argued that an understanding of NOS provides students with an understanding of science as a discipline, and it provides a meaningful context for the subject matter we expect students to learn. In this sense, NOS is advocated because of its inherent educational value in understanding science as a discipline, as opposed to its being anything of concrete instrumental value. Whether one ultimately decides to be an optimist or pessimist can only be derived from our continued research on teaching and learning of NOS. Although systematic research on NOS has existed for approximately 50 years, we are far from any definitive answers. And, of course, none of the answers we will eventually arrive at will be absolute, and they will always be subject to change!

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