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Perhaps Triangulation Isn't Enough: a Call for Crystallization as a Methodological Referent in NOS Research

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Perhaps triangulation isn't enough:
A call for crystallization as a methodological referent in NOS research

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Abstract

This research compares the methodological tools employed in NOS research, with analysis of what the comparison implies about the structure of nature of science knowledge. Descriptions of practicing teachers' nature of science conceptions were compared based on data collected from forced choice responses, responses to a qualitative survey, and course writing samples. Participants' understandings were scored differently on the Views of Nature of Science Questionnaire (VNOS) than the forced-choice measure, Scientific Thinking and Internet Learning Technologies (STILT). In addition, analysis of the writing samples and observations combined with interviews portrayed more sophisticated, but more variable, understandings of the nature of science than was evidenced by either the survey or the forced-choice measure. The differences between data collection measures included the degree to which they drew upon context bound or context general reasoning, the degree to which they required students to move beyond the simple intelligibility of their responses and allowed students to explore the fruitfulness of the constructs, as well as the degree to which they revealed the interconnection of participants NOS conceptions. In light of the different portrayals of a participants NOS conceptions yielded by these different measures, we call for the use of crystallization as a methodological referent in research.

Introduction

Current calls for reform in science education argue that for students to truly understand science they must understand not only scientific concepts (e.g., photosynthesis, conservation of matter) but also recognize the unique characteristics of the nature of scientific knowledge and how that knowledge is shaped by the processes of scientific inquiry (Lederman, 1998). It has been argued that for one to make informed personal and societal judgments as a citizen, one must understand how science works and how those processes shape the nature of the knowledge science generated (AAAS, 1989, 1993; NSES, 1996).

Given our current understanding of the prominent role that the nature of science (NOS) plays within the structure of the scientific disciplines, there has been a flurry of philosophical discussions about the most appropriate characterization of the nature of science as well as how to best to support the learning of the nature of science. Despite the seeming controversy in descriptions of the nature of science in the philosophical and science education literature (Siegel, 1997; Southerland, 2000; Stanely & Brickhouse, 1994), there is some consensus in the science education community on a number of important aspects of the NOS deemed critical for students to understand, including that scientific knowledge is empirical, tentative, creative, subjective, and socially and culturally constructed (AAAS, 1993; Lederman, 1992; McComas, 1998; McComas, Clough, & Almazroa, 1998; McComas & Olson, 1998; NRC, 1996). There is also a growing consensus in descriptions of how this knowledge should be taught, with a wealth of literature describing that instruction should be embedded within a specific science content (Abd-El-Khalick, 2001), explicitly address NOS concepts (Abd-El-Khalick et al., 1998; Gess-Newsome, 2002; Lederman, Schwartz, Abd-El-Khalick, & Bell, 1999), encourage learners to be aware of and reflect upon their own conceptions (Akerson, Abd-El-Khalick, & Lederman, 2000), and/or cause dissatisfaction with their previous conceptions (Akerson & Abd-El-Khalick, 2000).

However, the prominence of the nature of science and scientific inquiry in international descriptions of science education reform, as well as the profusion of research devoted to the teaching of these constructs, are in stark contrast to our state of knowledge on how to best assess this knowledge. Although the nature of science and scientific inquiry has enjoyed some attention by educators since before Dewey, we continue to struggle with assessment of this knowledge. The NOS assessment efforts of the 1970's and 80's were characterized by the use of Likert style, forced-choice questions (Aikenhead, Ryan, & Fleming, 1989; Rubba, 1976; Rubba & Anderson, 1978). However, over a decade ago, Lederman and O'Malley (1990) described how paper and pencil assessments of learners' NOS conceptions often serve to mask underlying meanings, as written means of expression often are insufficient for effective communication. Lederman, Wade, and Bell (1998) explain that the problem is magnified when forced-choice multiple choice tests are used, as these measures act to impose various portrayals of NOS onto participants. These authors argue that the most appropriate descriptions of learners' NOS conceptions are to be arrived at through the use of qualitative measures, including a combination of open-ended questions and subsequent interviews (Lederman, Wade, & Bell, 1998; Lederman et al., 2002). Using the VNOS protocol (*Views of Nature of Science Questionnaire*), participants respond in writing to a small number of open-ended questions about the nature of science, followed by in-depth interviews in which they are asked to reflect on their answers through additional clarifying questions. The result is a measure that draws out learners' conceptions allowing for the development of "profiles" of NOS understandings that the authors argue are better reflections of participants' meanings than can be arrived at with a forced choice measure.

Many in the science education community understand that among the descriptive NOS assessments currently available, the VNOS provides the most insight, arguing that the depth of understanding it generates allows for the clarity and resolution needed to study individual classroom interventions. However, the work of Elby and Hammer (2001) and Nagasawa (2004) call this assertion into question. Elby and Hammer (2001) eloquently describe that students' scientific epistemologies are far more flexible than the fixed descriptions of NOS described within current reforms. Indeed, they argue that movement toward wholesale acceptance of a particular facet of the description of the nature of science embraced by the research community may not signify that the student is becoming more epistemologically sophisticated. Indeed, such a wholesale acceptance of a fixed nature of science description may be undertaken based on an inappropriate rationale (authority of the teacher or text) and in fact be unproductive for some students as they work in the science classroom and laboratory. Indeed, one aspect of nature of science knowledge that may make a fixed understanding of it unproductive is the content specificity of such knowledge. Elby and Hammer (2001) argue that because some aspects of scientific knowledge are more tentative than others, a strict adoption of particular wholesale descriptors of NOS, even those arrived at through some consensus of the science education community, is actually naïve and unproductive. For instance, recognizing that scientific knowledge to be equally tentative may stymie the actions of a student in a laboratory, hobbling her actions and preventing her from collecting the data necessary to decide on a knowledge claim. Thus, these authors call for a much more focused attention on the influence of specific science content on a learner's scientific epistemology, requiring a naturalistic approach to such research. Echoing this, Nagasawa's (2004) work also calls into question the notion that any single measure can adequately describe a learner's scientific epistemology. Her work, in which students' science writings were analyzed to discern epistemological features, determined that the purpose/structure of the writing task (lab report versus essays) revealed different aspects of learners' science epistemologies, with students employing an epistemology that could be considered much more naïve absolutist as they constructed a laboratory report than that employed in an essay.

Thus it appears that some nature of science knowledge may be more contextually situated than the consensually accepted descriptions of nature of science found in the current reforms. This recognition of the more complex understanding of learners' nature of science knowledge again requires that we examine the manner in which we as researchers study this construct. This research is a comparison of the various methodological research tools currently employed in NOS research, with an analysis of the findings in terms of what they may mean for the actual structure of nature of science knowledge.

Research Objectives

- How do the findings of a variety of research tools (forced-choice surveys, surveys supported through interviews, writing tasks) compare for describing learners' nature of science knowledge?

- If the findings do indeed vary, what could account for the differences?

Methods

The context of this study was a graduate level course in education entitled *The Nature of Science and Science Education*, offered to both doctoral and masters level students at a university in the intermountain west. The 8 students in the class were all practicing teachers. These students were, as a group, experienced with a wide range of grade levels (K-12) and classes (e.g., general elementary classes, bilingual classrooms, middle school science, and high school biology). Instruction in the course utilized a series of readings, reflections, written responses, and discussions to enhance learners' awareness of NOS concepts. In addition, class sessions generally included short science lessons with explicit debriefing and discussion sessions to describe the NOS inherent in actually doing science both in the classroom and in the laboratory.

We gathered data that allowed us to compare descriptions of students' nature of science conceptions based on data collected from:

•forced choice responses (STILT, *Scientific Thinking and Internet Learning Technologies*, Southerland et al., 2003). The STILT instrument provides a scored categorization of "understand," "unsure" or "naïve" for each NOS concept measured.

•responses to selected questions from a qualitative survey (VNOS-C, Lederman et al., 2002).

•writing samples (example writing prompts include, What is the difference between a scientific "fact," "law," and "theory"? How do these interact with one another? What does it mean for science to be "tentative" or "changeable"?, Is scientific knowledge created or is it discovered? What is the difference? How does/should this aspect of science be represented in a science classroom?)

See table 1 for a copy of the data collection tools.

Table 1. Writing Assignments for Course; Data collection Tools for Research

Session	Writing Assignment, Data Collection Tools
1	Course introductions: Description of each student's educational background and teaching assignment.
2	VNOS (Lederman et al., 2002) STILT (Southerland et al., 2003)
3	**Response paper 1** What is the difference between a scientific "fact," "law," and "theory"? How do these interact with one another? Why is it important to understand this, and how does/should this be represented in the classroom? Email response: Is umbrellaology a science?
5	**Response paper 2** What does it mean for science to be "tentative" or "changeable"? What examples can you describe for this? Why is this important for students to know; and how can this be portrayed in the classroom?
6	**Response paper 3** Students were to pursue an alleged pseudoscience of their choosing, and then research the pseudoscience in order to evaluate the degree to which it was scientific.
7	**Response paper 4** What kinds of understandings of the nature of science should you expect your students to have? What are you going to do about it? Why?
9	**Response Paper 5: Science & Religion** Compare science and religion. Specifically, how does science come to understand the world, and how does religion come to understand the world -- are these views compatible? Why is this important for science education? How should this be portrayed in the classroom?
	Revisiting VNOS and STILT
	"Prelude to the final" Assignment: Sometime before the next class, send an email to [the course instructor] that answers the following questions. These are meant to be things to think about as you begin to draft your final. It will also be used as things for the friendly yet critical instructor to think about as he reads and grades your final. 1. Briefly describe your own science background. Have you been encouraged or alienated by science? What science coursework has contributed to this (consider all grades, elementary through graduate school)? 2. What/who do you teach? What are your own objectives as a teacher of science? (Yes, you are teaching science, whether it's explicit or not.) Explain who your students are, what you believe they can learn, and what you believe they need to learn.

3. Imagine that you are enrolled in a science course that you've never taken before and has material that is completely new to you; perhaps it's "Astrobiology, ZOOL 3620" or something like this. How would you feel about taking such a course? How confident are you yourself in your ability to learn the material in such a course? What would you want to learn from such a course?
4. In general, what does it really mean to "learn" or "understand" something? In other words, what do you expect a student (or yourself) to be able to do/write/express in order to show that something has been learned/understood?

Spend some time reflecting on this, and save a copy for yourself. This is meant to be a first step in developing your ideas and arguments in the final paper. In fact, it would be completely fair game to copy and paste anything out of this assignment right into your final paper. (In case you haven't noticed yet, this is a particularly useful strategy in graduate school.)

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Final Paper

The final paper was meant to "be a synthesis of the entire class, what you've learned from it, and how you propose to incorporate nature of science learning in your classroom. This should be a formally written paper, but it will rely upon your own reflection. You should cite readings from the course, class discussions, and your own response papers and other activities from the class." Specifically, this final synthesizing assignment asked students to address the following questions:

1. What, in your view, is the nature of science? How has your conception changed?
2. What aspects of the nature of science should a "scientifically literate" citizen know? Why?
3. What aspects of the nature of science should be emphasized in your classroom? Why? (This answer should be tied to your answer to #2.)
4. How can the nature of science be most effectively taught in your classroom? Justify your ideas. (This answer should be tied to your answer to #3.)

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Exit Interview

Each student was required to have an individual "class session" with the course instructor at the student's convenience. This exit interview consisted of a debriefing of the student's final paper and his/her work in the course. Pedagogically speaking, the intentions were pure: The instructor wished to actually interact with students after the "final" paper had been turned in, in order to ask final questions and have the paper actually mean something in the long run. This particular strategy was additionally useful for research purposes, as it gave a final opportunity to really engage the students in "what did you mean by that?" clarifications (Southerland, Smith, & Cummins, 2000).

The questions asked of each interviewee were catered to the student's paper, its points, and questions it raised. In this way, each interview was different, but the goal of each interview was to clarify each student's thinking (both to the instructor and to the student herself). Additionally, this served as a tool to try to further elicit the student's own goals in the classroom, how the NOS fit into these, and how the course enabled and/or influenced such goals. In this manner, the interviews provided an in-depth course evaluation.

Findings

Looking across all three data collection tools, the forced-choice STILT scale targeted the fewest NOS concepts specifically. (See figure 1 for a comparison of the conceptions address through each approach.) Thus, while both the VNOS and course writings asked students to discuss a wider range of the NOS cannon, in this report we limited our analysis to the two broad facets of NOS that were measured by STILT and also shared with the VNOS and course writings: the idea that scientific knowledge is a) tentative yet durable and b) subjective and theory-laden. For a detailed account of how each instrument probes for these different NOS components, see the appendix material.

Insert Figure 1 about here.

The tentative nature of scientific knowledge

The first subcomponent of the STILT scale focuses on the fact that scientific knowledge changes over time, yet is durable and reliable because of the specific practices engaged in by scientists (e.g., debate, peer review, repeated testing, continual reevaluation). Within the VNOS, participants are asked to comment on whether or not scientific theories change over time. It also solicits an explanation of the differences between theories and laws, the response to which often reflects an individual's understandings concerning tentativeness. Finally, describing the tentative nature of scientific knowledge was explicitly prompted by the various course writings. Thus, this particular NOS tenet was assessed by each of the data collection tools and we use one of the participants, Donna, to highlight our assertions.

Looking at the STILT scores for this concept, each of the participants scored well concerning the fact that scientific knowledge changes over time, receiving a categorization of "understand" (as opposed to "naïve" or "unsure"). However, their STILT scores were lower when addressing the role of evaluation, testing, and debate, and other specific internal cultural practices of science that work toward immediately toward the tentative nature of science but that eventually result in its reliability and durability. For example, Donna responds correctly to STILT's notion that "scientific knowledge changes over time to be consistent with evidenced (from data) and/or new reasoning. Knowledge can change through growth and revision." However, she reflects an *unsure* position concerning "the debate of scientific explanations leads to the tentative yet durable nature of science" as she seems not to understand the role of debate in the construction of scientific knowledge. Thus, from the forced-choice instrument, we can begin to see that the she understands that scientific knowledge does in fact change over time, but we also recognize that she has less of an acknowledgment of the processes that provide for that tentative nature.

For this same participant, during to the VNOS, we see that it also supports our assertion that each of the participants understands that scientific knowledge does in deed change over time. This is explicitly addressed through the question: "After scientists have developed a scientific theory (e.g., atomic theory, evolution theory), does the theory ever change?" However, when participants are then asked to distinguish between theories and laws, they often contradict this stated explanation. Donna, like several others, holds the misconception that there exists a hierarchy of truth, with theories being less certain and true than laws. Donna, like others in this study, also often state that while theories are tentative, laws are more like fixed truths that remain unchallenged. Donna writes:

> A scientific theory is subject to change…. A scientific theory will never remain universally unquestioned. …. A scientific law is a fact that is not generally debated and stands the test of time. For example, Newton's laws of motion. These scientific laws have not been disproven or subject to debate because they cannot be disputed.

Her belief that scientific laws do not change is a limitation of her ideas about tentativeness, something that was not reflected in her STILT responses. When asked whether theories can change, she writes:

> Theories change or evolve based on new information gathered by scientists. New information may result from new and better technology that enhances scientists' ability to observe phenomenon in question. Theories may change due to implementation of new methodologies during experimentation. A theory in one field may change according to discoveries made in another field. For example, new discoveries or observations in cell biology may change theories biologists or physiologists have clung to for decades.

Donna conveys an understanding that scientific theories play a generative role in creating explanations and can change over time as new advances and different theoretical perspectives emerge. Thus, there is an awareness that change can occur because of more advanced technology and novel evidence, as well as new theoretical perspectives taking on existing data. What is missing from these responses is an indication that Donna understands how the internal practices of science work toward tentativeness and the eventual durability of scientific knowledge, or the recognition that the goal of science is not to arrive as some absolute truth.

In exploring her course writings in response to the second probe (see table 1), we found that Donna's weakest areas of sophistication of her NOS framework again revolved around the notion that theories and laws each serve unique functions within science as well as her discussions about tentativeness. Although she values the role of extrarational influences on scientific work, her indecisiveness about the whether or not scientific knowledge is *created* or *discovered* reflects a belief that science often works to uncover the workings of "God's natural phenomena." This understanding can be seen as infringing on her understanding of the tentative nature of science. In other words, if the goal of science is to unearth a pre-existing body of truths, then there is a limit to the tentativeness of what knowledge emerges.

Overall, it is within the course writings that we find the most nuanced and detailed understandings of tentativeness. This occurs as the students not only discuss the concept of change over time, but also as they elaborate on its connections to other aspects of the central NOS tenets. As in the example above concerning theory/law distinctions, the participants' writings often reflected contradictory and less sophisticated notions of tentativeness. On the other hand, some participants used the writings to convey very high levels of sophistication about tentativeness. This was especially true for individuals who made connections among the NOS tenets, created science-specific examples of change over time, or were able to discuss the role of the specific scientific practices that are used to ensure reliability and durability in light of subjectivity.

Course writings also provided the participants with the opportunity to engage in discussing the fruitfulness of the NOS concepts within their own classrooms. In particular, through the course writings, we can see that Donna actively resists the incorporation of NOS into her classroom context. In terms of tentativeness, she writes in one of her response papers,

> I refuse to expand on something [nature of science]…that can't be agreed upon.

> It is not a good idea for me to teach students of the tentative nature of science. It is much too confusing. Teaching students that science is tentative is confusing when there is nothing in their scientific world that fits into the "tentative" category. It is a concept that they cannot relate to.

The course writings allow her to wrestle with the nuances of tentativeness and gauge its level of fruitfulness within her own classroom teaching. These nuances in her understanding of tentativeness are not unearthed in her STILT and VNOS responses where intelligibility, and reflecting knowledge of the particular pieces of the cannon for a grade, is the main concern. Understanding learning through a conceptual change framework asks us to not only look at students' levels of intelligibility of the constructs, but also the degree to which they are plausible and fruitful in relation to novel contexts, in this case their own daily science teaching. This task was predominately achieved through the course writings. The forced-choice STILT responses, as well as the VNOS responses, did not facilitate the participants' wrestling with the issues of fruitfulness. Thus, while both the STILT and the VNOS responses could gauge degrees of intelligibility, the course writings proved to be more useful in providing more robust and nuanced overall portraits of participants' NOS understandings.

This notion of tentativeness is a complex concept within the NOS cannon. It asks an individual to not only acknowledge the progressive nature of scientific knowledge, but also the fact that the very process of change is a regulated one, rich with cultural practices that make science a unique way of knowing. In addition to appreciating this productive tension between tentativeness and durability, an individual cannot be expected to achieve absolute truths, such truths cannot be an obtainable goal of science. These markers of intelligibility concerning tentativeness are somewhat discernable through the forced-choice STILT instrument. However with the VNOS, and in particular the course writings surrounding intelligibility, we are able to develop a more robust portrait of the a student's NOS understanding as we see the student grappling with more contextualized and situated applications of the concept of change.

We feel that it is worth mentioning that John, another participant in the study, is someone we see as possessing a constellation of affect and learning dispositions that allow for him to enthusiastically grapple with the nature of science, and in his case to a very profound level. He entered the course with a broad and rather robust knowledge of NOS and, unlike the other learners in our study, John is engaged in another activity aside from honing teaching skills, namely his apprenticeship as a scholar. He is attempting to enter the academic conversation regarding NOS and its intersections with science teaching, and this engagement allowed him to struggle with the material on an insightful plane. His engagement with the NOS components as a means to position himself within academia, pushing him toward engaging with NOS in ways that are not limited to describing NOS for the purposes of the course requirements or for debating its usefulness within his immediate classroom context. Indeed, he successfully demonstrates a knowledge of how the NOS tenets function together to create a more sophisticated approach understanding the characteristics of scientific knowledge.

Therefore, it was a surprise to see "naïve" responses on the STILT scale concerning his understanding of the roles that testing and evaluation play in the durability of scientific knowledge. However, both his VNOS and course writings reflected a very different portrait. In fact, out of all of the participants, John's writing demonstrates the most robust and sophisticated overall understanding of the NOS cannon, both in terms of intelligibility, plausibility, and fruitfulness. He also demonstrates a balanced understanding of both tentativeness and durability, explicating how those two concepts are driven both by the practices of scientists as well as by theoretical presuppositions that scientists hold concerning the goals of science. He also relates how a student's misconception about viewing scientific knowledge as a discovery, instead of a creation, would be in conflict with a robust understanding of tentativeness.

It is our assertion that the forced-choice nature of the STILT scale asked John to ascribe universal and wholesale attributes to the NOS concepts, something with which he was not comfortable (see appendix). His VNOS and course writings persistently described NOS concepts within the context of physics, his chosen field of specialization and experience. Thus, it may be the case that his appreciation of nuance and context-dependency concerning this aspect of tentativeness resulted in a lower score on the STILT, but a high level of understanding on the more qualitative measures.

<u>The subjective and theory-laden nature of science</u>

As with tentativeness, we see the three NOS measurements providing us with different portraits of the students' understandings of how science is very much a subjective, theory-laden process that is socioculturally embedded. We look across the different ways in which we assess another participant, Sarah, in terms of her knowledge of this concept.

As with the STILT scores on tentativeness, the limitations of the forced-choice instrument becomes apparent in that all participants scored a level of "understand" when it came to this construct in general. Sarah is no exception. She successfully responds to the items that center around the fact that "Scientific investigations, and so scientific knowledge, are based upon an understanding of existing ideas. Because of this, what we know determines what we find out in an investigation" and "Because scientists are influenced by what they already know, multiple explanations can be produced from the same set of data" (STILT).

Sarah's responses to the VNOS are unique in that they contradict how she responded to the STILT instrument. When replying to the VNOS prompt about how conflicting explanations concerning dinosaur extinction could arise from two groups of scientists looking at the same body of evidence, she replies, "The groups with the two different hypotheses have come to different conclusions as some scientists use additional data along with the set of agreed upon." Although the VNOS prompt explicitly indicates that the "scientists in both groups have access to and use the same set of data to derive their conclusions," Sarah ignores this fact and thus fails to demonstrate an understanding of the subjectivity involved in the transition from evidence to explanation.

This trend is continued to a degree within Sarah's course writings. Sociocultural and theory-laden aspects of NOS are also places where Sara shows a weaker level of sophistication. In terms of sociocultural influences, her writings emphasize mainly the external influences on scientists, (e.g., funding, religious climate, politics), but do not focus on the wide variety of sometimes conflicting theories that different scientists can bring to bear on a given body of evidence. Thus Sarah is aware of some aspects of the sociocultural influences on scientific knowledge, but has a very limited understanding of how these influences can work through the particular subjectivity of scientists.

Through her writings about classroom application of NOS, we see that Sarah considers science to be a rather formidable discipline, both for herself and her students. Thus, see views her job as centering on increasing her students' affinity and access into science by making it more of a fluid human endeavor rather than a fixed body of rigid scientific facts. She felt compelled to delve quite enthusiastically into certain pieces of NOS, in particular its tentative and creative aspects. Given her drive to concentrate on the immediate classroom applications of these certain NOS pieces, she spent little time fleshing out her own understandings of other tenets. Her resulting discussions concerning her learning in the course were thus top-heavy with fruitfulness with little substance in terms of deep intelligibility. Therefore, chances to wrestle with the nuances of subjectivity within scientific work were short-changed in light of her strong desire to apply those aspects of NOS (i.e., tentativeness and creativity) that she deemed more useful in her classroom. She sees her understanding of the rest of the NOS cannon as not holding the power to provide student access to science in the same way that the creative and tentative nature of science do; thus, her grappling with pedagogical fruitfulness of the latter is somewhat limiting her efforts at intelligibility of the former.

Discussion and Implications

Different faces of an NOS profile

Overall, we find each of the three instruments providing us with different aspects of students' NOS understandings. While the STILT instrument allows us to gain insight into the students' fundamental views concerning various aspects of the NOS cannon (particularly in terms of initial intelligibility), the qualitative approaches of the VNOS and course writings present the students with opportunities to support or contradict basic assumptions in more context-specific ways. Also, the course writings allow us to see the degree to which the students make (mis)connections across the NOS cannon. For example, having only the STILT measurement data, Donna's nuances and persistent misconceptions concerning tentativeness of theories and laws would have never surfaced to our attention. A similar situation occurs within Sarah's writings, where her contradictions concerning subjectivity only emerge from her written responses.

The significance of context-specific NOS responses

Given the nature of the questions asked, the forced choice tool (in this study Stilt) is a somewhat context general NOS measure. It asks for students to think about the specific NOS cannon in ways that are universal. The work of Elby and Hammer (2001) allows us to call this into question and see what benefits lie in other, more conceptualized writings. In contrast, although the VNOS tool on the surface appears to be context general as well (with the exception of a pair of questions), the students' responses to these questions are often situated within familiar science content knowledge. Thus, the STILT tool may be measuring more context-free NOS knowledge, denying students the ability to reason through these responses through more familiar pathways. A similar trend is observed in the written course prompts, with students typically "making a case" for an epistemological stance that is embedded in a familiar, contextually bound domain. However, in these writing prompts a more variable portrait of nature of science knowledge emerges. We find value in unearthing these points of variability and contradiction since they allow us to better understand the students' efforts at wrestling with epistemological issues concerning NOS.

Such contrasts would certainly be a concern if each of these measures were focused on a single construct. But Elby and Hammer's (2001) work as well as that of Nagasawa (2004) become particularly salient as we strive to make sense of these different descriptions. Their work suggests that students' science epistemologies, as well as their nature of science knowledge, are contextually bound and will therefore vary according to the particular scientific construct being considered. Too, the activity in which this knowledge is applied may also change which aspect of their scientific epistemology is applied. Thus, we begin to see nature of science knowledge, not as some sort of fixed knowledge of along 7 or 8 discrete, contextually free, constructs. Instead, this knowledge is variable, depending on the science content and activity in which the knowledge is applied and described. The disparity between John's responses concerning the tentative yet durable nature of scientific knowledge may reflect this assertion, with the forced-choice scale not allowing him to express his more nuanced understandings. The course writings are where students often engaged in finding interconnections among the specific NOS concepts, enhancing an overall understanding of scientific inquiry by seeing NOS as a functioning body of specific language and cultural practices and not simply a tight, fixed body of information to apply universally across all contexts and situations.

<u>Exploring fruitfulness of NOS concepts within a classroom setting</u>

The use of classroom specific examples in particular shed light on how applicable the teachers' considered the NOS cannon within their own science teaching practices. As we engaged in data analysis mindful of conceptual change theory, what became glaring to us was that there existed significant differences in terms of the participants' recognition of the fruitfulness of NOS. In other words, while they each came to understand the central tenets of NOS (finding them intelligible) and came to recognize that these notions were viable descriptions of the characteristics of scientific knowledge (finding them plausible), one important way the candidates differed was in terms of their recognition of the fruitfulness of these conceptions outside of the boundaries of the context in which they were learned. Because these participants were each classroom teachers, an important measure of their conceptualization of fruitfulness of NOS was the degree to which they saw the NOS as applicable in their own classroom teaching. Indeed, this work suggest the need to push beyond the more straightforward issues of intelligibly and plausibility of NOS constructs as we are mindful that concept change also takes into account the fruitfulness of the concept for a new domain. Unlike the STILT or VNOS, the course writings not only provided students with the opportunity to situate facets of the NOS cannon within a familiar science context, it also allowed them to wrestle with its application in their own classrooms.

From this work we understand that research methods in the nature of science must go beyond the simple goal of triangulation, as triangulation implies that a fixed goal is the object of our study. Instead, the work Janesick (2000) and Richardson (1994) is of use here. They describe crystallization as a more suitable goal of research. Using this metaphor, the objects of our study, like crystals, "grow, change, and alter", but are "not amorphous" (Richardson, 1994, p. 522). The use of crystallization as a methodological referent in research, we would understand that a) the manner in we investigate a learner's nature of science knowledge will influence what we find and that b) this knowledge will vary according to the content that the learner is considering, and c) the purpose or goals of her consideration. This methodological referent would require that NOS research be mindful that learners' nature of science knowledge will be variable, but will have a core, albeit a complex one. Our goal as researchers should be to use methods that account for this variation and complexity.

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Appendix

The Tentative Nature of Science

STILT

A1: Scientific knowledge changes over time to be consistent with evidenced (from data) and/or new reasoning. Knowledge can change through growth and revision.

1. When scientists develop a very solid explanation for data and observations, then the explanation becomes a fact that can never be changed.
2. Scientific explanations are never discarded.

A2: Scientific knowledge is reliable because it is continually tested and evaluated.

3. The reliability of scientific knowledge comes from, in part, from the manner in which this knowledge is tested.
4. It is not necessary to test scientific knowledge.
5. In order to be considered scientific, at some point an explanation must be tested though observations or experimentation.

6. The knowledge produced by doing science would be just as strong if observations and experiments were not used.

A3: The debate of scientific explanations leads to the tentative yet durable nature of science.

7. Debates about scientific knowledge will lead to stronger and better explanations.
8. Scientists try to avoid debating scientific knowledge because disagreements make the knowledge weaker and less useful.
9. An important part of science is the debate of ideas and methods.
10. Adjusting our explanations of the natural world in response to new data or different ways of thinking is considered a weakness of science.
11. Although a single scientist can create a scientific explanation, it requires a group of scientists reviewing the work to accept this explanation as scientific knowledge.

VNOS

2. After scientists have developed a scientific theory (e.g., atomic theory, evolution theory), does the theory ever change? If you believe that scientific theories do not change, explain why. Defend your answer with examples. If you believe that scientific theories do change: (a) Explain why theories change, and (b) Explain why we bother to learn scientific theories. Defend your answer with examples.

3. Is there a difference between a scientific theory and a scientific law? Illustrate your answer with an example.

Course Writings

What is the difference between a scientific "fact," "law," and "theory"? How do these interact with one another? Why is it important to understand this, and how does/should this be represented in the classroom?

What does it mean for science to be "tentative" or "changeable"? What examples can you describe for this? Why is this important for students to know; and how can this be portrayed in the classroom?

Final overview paper.

The Subjective and Theory-Laden Nature of Science

STILT

B4: Scientific investigations, and so scientific knowledge, are based upon an understanding of existing ideas. Because of this, what we know determines what we find out in an investigation.

24. The reason the explanations are different even for the same set of data could be because the experiences of the two groups of scientists influence their interpretations.
25. Scientists may be unable to recognize a different way of explaining data because their traditional, standard views interfere with their ability to understand an alternative perspective.
26. A scientist’s background never affects the manner in which she/he reviews data.
27. What a scientist knows does not affect the kinds of scientific questions she asks.

B5: Because scientists are influenced by what they already know, multiple explanations can be produced from the same set of data.

28. If both explanations completely account for all the data then it is difficult to decide which explanation is stronger.
29. The reason the explanations are different even for the same set of data could be because the experiences of the two groups of scientists influence their interpretations.
30. One of the two groups must be doing “bad science” by being biased in their interpretations or doing a bad job of collecting the data.

VNOS

4. It is believed that about 65 million years ago the dinosaurs became extinct. Of the hypotheses formulated by scientists to explain the extinction, two enjoy wide support. The first, formulated by one group of scientists, suggests that a huge meteorite hit the earth about 65 million years ago and led to a series of events that caused the extinction. The second hypothesis, formulated by another group of scientists, suggests that massive and violent volcanic eruptions were responsible for the extinction. How are these different conclusions possible if scientists in both groups have access to and use the same set of data to derive their conclusions?

5. Some claim that science is infused with social and cultural values. That is, science reflects the social and political values, philosophical assumptions, and intellectual norms of the culture in which it is practiced. Others claim that science is universal. That is, science transcends national and cultural boundaries and is not affected by social, political, and philosophical values, and intellectual norms of the culture in which it is practiced. If you believe that science reflects social and cultural values, explain why. Defend your answer with examples. If you believe that science is universal, explain why. Defend your answer with examples.

Class Writings

Compare science and religion. Specifically, how does science come to understand the world, and how does religion come to understand the world -- are these views compatible? Why is this important for science education? How should this be portrayed in the classroom?

What kinds of understandings of the nature of science should you expect your students to have? What are you going to do about it? Why?

What does it mean for science to be "tentative" or "changeable"? What examples can you describe for this? Why is this important for students to know; and how can this be portrayed in the classroom?

Final Review paper.

Figure 1. Comparison of the NOS concepts addressed in three research tools.