

Research Methodologies in Science Education: Students' Ideas About the Nature of Science

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In today's world, individuals must confront complex issues of broad social relevance – ranging from threats from biological weapons, to impacts of global warming, to the implications of new reproductive technologies—yet many individuals lack the necessary skills to evaluate information and make informed decisions (AAAS, 1989). In light of this situation, current reform efforts in science education at all levels, including undergraduate science education, stress that instructors need to help students achieve a deep understanding of important science concepts, as well as an understanding of how scientific knowledge is constructed, including the strengths and limitations of science (NSF, 1996; NRC, 1996, 1997). The latter goal, which pertains to the epistemology of science, is often referred to as the “nature of science” in the science education literature (Lederman, 1992).

Although the goal of improving students' conceptions of the nature of science is laudable, many college science faculty are left wondering what classroom strategies and materials are required to achieve this goal. As administrators at universities and colleges attempt to implement reform efforts, science faculty are faced with the huge task of transforming the rhetoric of reform into classroom practice. In this column we explore how three assistant professors in geology departments attempted to assess college students' understanding of the nature of science. We discuss the usefulness of both qualitative and quantitative data in this assessment, and the ways in which assessment can impact teaching reforms. The faculty and institutions portrayed in this column are all fictional, but the ideas that non-majors hold about the nature of science are based on our collective research experience with college freshman enrolled in introductory courses for non-science majors at many undergraduate institutions.

AN EXPLORATORY STUDY

Laura, Dean, and Nancy had completed their doctorates in geosciences at the same research university in the Northeast. After defending their dissertations in 1998 and completing two-year postdoctoral research positions, they each landed faculty jobs. Laura, a geomorphologist, accepted a position at a large private research university in the Northeast. Dean, a seismologist, took a position at a large state research university in

California. Nancy, a geochemist, who had always loved teaching, took a position at a small liberal arts college in the Midwest. All three had enjoyed their experiences as graduate teaching assistants and although their emphasis on teaching and research varied, all three recognized the importance of teaching in fulfilling their academic roles. As graduate students, they had participated in several workshops on teaching methods both at the university and at professional meetings.

In their first year, all three were asked to teach an introductory geology course for non-science majors. Each course was designed to introduce freshman to important concepts in geology as well as the ways that scientists developed this knowledge. Given that they had never taught a course for non-science majors before, they corresponded regularly about ideas for the course and struggled with how best to teach students about the nature of science in just one semester. Nancy asked a friend in the College of Education for advice. Although this colleague's research area focused on teacher professional development, she was active in several science education professional societies and had just attended a symposium on the nature of science at the past National Association of Research in Science Teaching conference. She gave Nancy the papers from that symposium as well as several other prominent publications in the field. Nancy read through this literature and chose two instruments, one quantitative and one qualitative, that could be used as a first attempt to assess students' ideas about the nature of science. She emailed Laura and Dean the following three questions as well as the two instruments.

- What ideas about the nature of science do college students bring to the classroom?
- Do these three introductory courses have any influence on students' ideas about the nature of science? If so, in what ways?
- Does a quantitative instrument capture students' ideas of various aspects of the nature of science adequately? Although the use of a qualitative instrument gives an instructor a much richer view of students' understanding, is the additional time required to process qualitative data feasible or warranted in large introductory science courses?

Aspect	Description
Empirically based	<ul style="list-style-type: none"> • Scientific knowledge is based on or derived from observations and inferences of the natural world • There are multiple approaches to science in addition to experimentation
Tentative	<ul style="list-style-type: none"> • Scientific knowledge is subject to change as new observations are made and existing data are reinterpreted
Creative	<ul style="list-style-type: none"> • Scientific knowledge is created from logical reasoning and human imagination using observations and inferences of the natural world

Table 1. Nature of science aspects and the descriptions that serve as a basis for evaluation of students' responses. Descriptions are based on national science education reform documents such as the National Science Education Standards published by the National Research Council (1996).

They all agreed that this would be a good start to determining how their approaches to teaching about the nature of science worked in practice. Although they did not plan on publishing any of this research, they thought it might be useful as preliminary data for future in-house grant proposals to improve their respective courses. So they each found out about the guidelines in place for human subjects research at their institutions and all three submitted the required paperwork before collecting any data.

INSTRUMENTS AND METHODS

Although Laura, Dean, and Nancy taught at different institutions, the demographics of their student populations were surprisingly similar. At the time of the study, 56% of all the participants were freshman, 22% were sophomores, 19% were juniors, and 3% were seniors. Approximately 54% of the participants designated their ethnicity as Caucasian, 17% Latino, 5% Asian, 5% African American, and 4% Native American; about 15% of the participants did not choose to provide information on ethnicity. None of the participants planned to major in the natural sciences; the majority planned to major in business, many were undecided, and a small percentage planned to go into elementary education.

The three courses were implemented in the fall semester 2000 for the first time. Laura's course was a large-enrollment university course utilizing a traditional lecture approach coupled with a lab section. The lab focused on activities that were designed to promote conceptual understanding of geology concepts. Additionally, this course had an interdisciplinary focus on global issues. Laura believed that students would learn about the nature of science by reading and hearing about scientific investigations and discussing them in lecture and during labs. Dean's large-enrollment university course had no lab component, but Dean used a Socratic questioning approach and planned class

discussions of several aspects of the nature of science. Both of the university courses had enrollments of 100 students and met in a lecture hall; Laura's course had 4 lab sections of 25 students each. Nancy's course was offered at the liberal-arts college with an enrollment of 24 students. Nancy designed the course to be inquiry-based. Students experienced the processes of scientific inquiry by planning and designing several original research studies and actually carrying out one complete investigation. This investigation unfolded as any scientific study would, from initial conceptualization of a research question, through actual scientific investigation, to presentation in an end-of-semester symposium. Nancy firmly believed this inquiry-based approach would improve students' understanding of the nature of science. However, after reading many research articles in this area, she added three class discussions of the nature of science to discuss specific characteristics that she thought students might not acquire simply through involvement in a scientific investigation.

Two instruments were used to capture students' views of the nature of science using a pre-instruction and post-instruction design (e.g., Libarkin and Kurdziel, 2001) – the qualitative VNOS C instrument developed by Abd-El-Khalick and Lederman (1998) (Figure 1) and the quantitative PASE 8.0 instrument developed by McComas (2001) (Figure 2). The VNOS questionnaire and PASE survey assess students' views of seven aspects of the nature of science. Nancy, Dean and Laura decided collectively to focus on only four of these aspects (Table 1). These four aspects are that science is *empirically based*, scientific conclusions are usually *tentative*, scientists must be *creative*, and science is always based on *subjective* interpretation (Table 1). Dean decided not to use the quantitative instrument and only administered the VNOS instrument in his course; Nancy and Laura administered both instruments during the first week and the last week of classes, respectively. All three instruc-

Views of the Nature of Science (VNOS, version C)

Empirically based

1. What, in your view, is science? What makes science (or a scientific discipline such as physics, biology, etc.) different from other disciplines of inquiry (e.g., religion, philosophy)?

Tentative

2. After scientist have developed a scientific theory (e.g., atomic theory, theory of evolution), 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?

(B) Explain why be bother to learn scientific theories.

Defend your answer with examples.

Creative

3. Scientists preform experiments/investigations when trying to find answers to the questions they put forth. Do scientists use their creativity and imagination during their investigations?

If yes, then at which stages of the investigations do you believe that scientists use their imagination and creativity: planning and design; data collection; after data collection?

Please explain why scientists use imagination and creativity. Provide examples if appropriate.

Subjective

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 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 extinctions. 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?

Figure 1. (Above) Qualitative instrument for assessing students' ideas about the nature of science (4 items taken from VNOS, Abd-El-Khalick et al, 1998).

Figure 2. (Right) Quantitative instruments for assessing students' ideas about the nature of science. (4 aspects taken from McComas et al., 2001)

Pase 8.0

The items in this survey address your thoughts about how science really works (not how you think it should work). There are no right or wrong answers, just agree or disagree with each statement.

SD means Strongly Disagree

D means Disagree

NO means No Opinion, only to be used if you find it impossible to give a definite answer

A means Agree

SA means Strongly Agree

Empirically based

1. Evidence is necessary to support conclusions in science. (+)

2. The results of a scientific investigation must be repeatable by others before they are considered valid. (+)

3. The results of a scientific experiment will be accepted by other scientists even if the experiment does not yield the same results to other scientists. (-)

4. In part, scientific ideas are accepted by the scientific community only if the facts support those ideas. (+)

Tentative

1. Suppose chemists agree that a particular reaction occurs because electrons move from one molecule to another. This problem is now solved forever. (-)

2. Well established scientific conclusions will generally remain unchanged through time. (+)

3. Even when scientific investigations are done correctly, the conclusions that scientists reach may change in the future. (+)

4. With evidence, a scientific idea will be proved conclusively with no likelihood of change in the future. (-)

Creative

1. Scientists commonly use creatively and imagination when conducting scientific investigations. (+)

2. Ideas and conclusions in science come, in part, from imagination and intuition. (+)

3. Scientific ideas are based only on evidence, not on inferences or hunches. (-)

4. Observational or experimental evidence alone is all that is necessary to form scientific ideas. (-)

Subjective

1. When a scientist sees evidence that might show one of her/his ideas to be false, it is likely that the scientist will quickly give up her/his original idea. (-)

2. Scientific conclusions are based on evidence and subjective issues such as personal preferences and opinions of the scientist doing the work. (+)

3. Scientists naturally sometimes de-emphasize or overlook evidence that does not support their favored ideas. (+)

4. Scientists focus only on the evidence. Personal bias, preferences, and opinions play no role. (-)

	pre	post
Empirically Based		
Question 1	3.46	4.56
Question 2	2.57 0.82	4.00
Question 3	2.60	3.40
Question 4	3.41	3.92
Mean Score	2.93	4.10
Tentative		
Question 1	1.08	4.01
Question 2	3.62	3.68
Question 3	3.34	3.39
Question 4	3.29 0.97	3.24
Mean Score	3.47	3.58
Creative		
Question 1	4.02	4.02
Question 2	2.65	2.55
Question 3	4.20	4.16
Question 4		3.94
Mean Score	3.66	3.67
Subjective		
Question 1	3.98	4.01
Question 2	1.01	2.89
Question 3	3.11 1.03	3.29
Question 4	3.31	3.68
Mean Score	3.31	3.47

Table 2. Students' views about the nature of science. Results from quantitative instrument - PASE 8.0, n = 73* students from Laura's large lecture class. (*Although 100 students completed the pre-test, only 73 completed the post-test. Only those students who completed both tests are included in the analysis.)

	pre	post
Empirically Based		
Question 1	3.46	4.56
Question 2	2.57 0.82	4.00
Question 3	3.10	4.40
Question 4	3.41	4.92
Mean Score	3.39	4.47
Tentative		
Question 1	0.98	3.51
Question 2	3.25	3.68
Question 3	3.34	3.39
Question 4	3.29 0.97	3.24
Mean Score	3.26	3.46
Creative		
Question 1	4.02	4.32
Question 2	3.65	3.55
Question 3	3.20	4.16
Question 4		3.51
Mean Score	3.67	3.89
Subjective		
Question 1	3.98	4.01
Question 2	0.98	4.39
Question 3	3.11 1.23	3.19
Question 4	3.14	4.18
Mean Score	3.51	3.94

Table 3. Students' views about the nature of science. Results from quantitative instrument - PASE 8.0, n = 24 students from Nancy's inquiry class.

tors gave their students the option of completing the instruments and assured them that their responses would not affect their grades.

Following the pre-test administration of the VNOS, Laura and Dean interviewed 10% of their students to establish the validity of the instrument following the protocol provided by Abd-El-Khalick et al. (1998); interviewing 25-50% of each population would have been preferable, but given the large number of students in each course, this was the maximum number of interviews that Laura and Dean could complete given the other demands on their time. Nancy interviewed 50 % of her students after administering the VNOS at the beginning of the term. During interviews, Laura, Dean or Nancy read the questions to the students and asked probing questions if a student's response was ambiguous. After the interviews were completed, Laura, Dean and Nancy pooled student responses and developed categories in which to place student answers, a process known as "coding" for thematic analysis (discussed in Libarkin and Kurdziel, 2002). For each student, responses were coded and compared to the contemporary conceptions of the nature of science outlined in table 1. The PASE data was analyzed according the protocol established by McComas et al., 2001. Each item was scored on a 5-point scale (1 = strongly agree, 2 = agree, 3 = no opinion, 4 = disagree, 5 = strongly disagree). Each item in the PASE instrument was purposefully written to provoke either a positive or negative response (see figure 2 for the "correct response") to check for consistency of opinions within each subscale. Items designed to provoke a negative response were reverse scored (1 = strongly disagree to 5 = strongly agree) such that a "perfect" score in each subscale would be a score of "5". The reliability of the PASE instrument and its subscales were also evaluated using Chronbach alpha reliability analyses.

STUDENTS' PRE-INSTRUCTION IDEAS ABOUT THE NATURE OF SCIENCE

Analysis of students' responses on the VNOS and PASE questionnaires (Tables 2, 3 and 4 and Figure 3) revealed that the majority of students held naive conceptions of many aspects of the nature of science when they enrolled in each course. The majority of students viewed science as a static body of facts that described the natural world. Many did not appreciate the role that evidence plays in science or the roles of creativity and subjectivity in scientific inquiry. Students did not view science as a creative endeavor and failed to appreciate the role of theories in guiding scientific research as well as influencing scientists' observations and their interpretations of the data. All three instructors were surprised at the widely held misconceptions about the nature of science. Additionally, they each expected to see a change in their students' thinking after participation in their courses.

Empirically Based (question 1)
Science is facts about the world
Science produces technology that helps people
Science is used to solve problems
Science is used to discover the truth
Science uses the scientific method
Science uses evidence to back up its claims (c)
Science provides explanations for natural phenomena (c)
Tentative (question 2)
Scientific theories never change
Theories change when new equipment allows scientists to make better measurements
Theories change because the scientist changes his mind
Theories change when a scientist finds new evidence (c)
Data can be reinterpreted from a different perspective leading to changes in the theory (c)
Creative (question 3)
Scientists don't use creativity and imagination when they conduct investigations
Strict procedures must be followed - no place for imagination
Scientists are only creative when they design the investigation
Scientists are only creative when they come up with the research question
Scientists use creativity in most aspects, except data analysis
Scientists use creativity in all aspects of the investigation including analysis of data and interpretation (c)
Subjective (question 4)
Event happened too long ago - we can't tell either way
Event happened in the past - we can't do experiments so we can have many interpretations
We need more evidence
The data are ambiguous and support both theories
Scientists are influenced by the way they were trained and the results of previous experiments (c)
Scientists are creative with explanations (c)

Figure 3. Students' ideas about the nature of science. Results from the qualitative instrument VNOS C and interviews, n=55 from Laura's large lecture class, n=47 from Dean's large lecture class and n=24 students from Nancy's class. Only those students who completed both tests are included in the analyses. Responses marked with a (c) coincide with contemporary views as articulated in national reform documents.

CHANGES IN STUDENTS IDEAS ABOUT THE NATURE OF SCIENCE

Interpreting changes to student's understanding of the nature of science using multiple instruments is sometimes difficult, especially when different instruments suggest different effects. In the case of our three example courses, the results from the qualitative VNOS and the quantitative PASE implied different student outcomes. In Laura and Dean's larger, more traditional courses, the VNOS results showed no significant changes in students' views of the nature of science (Table 4 and Figure 3). However, the PASE results from Laura's class (Table 2) suggested that students experienced an improvement in one aspect, an understanding of the empirical basis of science. This ambiguity in the test results may be explained by the reliability analysis of the PASE test. A Cronbach alpha analysis revealed an overall reliability of $\alpha=0.60$, but the reliabilities of the four subscales of the PASE instrument were much lower, all $\alpha<0.45$. This low reliability highlights the need to ensure that a test is reliable before administration. The PASE test was originally designed for adult subjects who served as volunteers on various "Earthwatch" research projects with scientists across the world – a group considerably older than the college students in the three geology courses. Although the PASE survey has been shown to be reliable for this original subject population (McComas et al., 2001), reliability always needs to be reconfirmed when instruments are used with dramatically different test subjects. Ultimately, Laura relied on the VNOS results to determine that her course was not effective at changing students' ideas about the nature of science.

Dean had utilized only the qualitative instrument in his course and his conclusions were similar to Laura's – there were no substantive changes in students' understanding of the nature of science after completion of his geology course (Figure 3, Table 4). In Nancy's more inquiry-oriented course, there appeared to be some improvements in students' views of some aspects of the nature of science after instruction: understanding of the empirical basis of science and the roles of creativity and subjectivity in science seemed to improve as documented by the qualitative VNOS instrument (Table 4 and Figure 3) as well as the PASE instrument (Table 3). Because of the low reliability of the PASE subscales, Laura and Nancy decided to only discuss the PASE results in aggregate. However, they were able to use the qualitative VNOS results to form conclusions about changes in student performance on each of the four targeted aspects of the nature of science. Their experience reinforces the idea that a test must be both valid and reliable to be a useful indicator of student change.

This example illustrates the power and pitfalls of using established instruments for evaluating student

Aspect	Pre-test	Post-test
Empirically based		
Laura's Class	10%	13%
Dean's Class	8%	11%
Nancy's Class	15%	30%
Tentative		
Laura's Class	5%	10%
Dean's Class	9%	12%
Nancy's Class	9%	13%
Creative		
Laura's Class	20%	33%
Dean's Class	26%	35%
Nancy's Class	25%	52%
Subjective		
Laura's Class	10%	14%
Dean's Class	15%	21%
Nancy's Class	16%	49%

Table 4. Students' ideas about the nature of science. Results from the qualitative instrument VNOS C and interviews. The percentages represent the number of students holding contemporary views (as outlined in table 1 and figure 3) about each of the four targeted aspects of science at the beginning of the course and at the end of each course.

learning. Nancy, Dean, and Laura were able to use the PASE and VNOS tests as diagnostic tools at the start of the semester. As a result, they knew before they began teaching that the majority of their students had naive conceptions about the nature of science. This type of information can be a powerful tool for curriculum development, allowing faculty to modify course materials to address weaknesses in student understanding. Additionally, in our example, both the PASE and VNOS tests were used as assessment instruments. Nancy, Dean, and Laura were able to make conclusions about the effectiveness of their courses at modifying student ideas about the nature of science. This type of information allows faculty to make informed decisions about major curriculum overhauls, and is especially important when choosing between different pedagogical approaches. In this example, Nancy was able to conclude that her inquiry-oriented teaching approach was more effective

than her friends' more traditional approaches. Dean and Laura may decide to adopt some of Nancy's ideas, although continued monitoring of course effects is probably warranted. First, the dramatically different class sizes (24 vs. 100 students) may limit Dean's and Laura's ability to implement inquiry. Second, personal style can affect student learning even when pedagogical approaches are identical; it is important to control for the influence of individuals when implementing new curriculum.

Nancy, Dean, and Laura also experienced one of the most difficult aspects of science education research: the issue of validity. Although the PASE test has been validated and is well received by the education community, administration of the instrument in a new area must always be done carefully. If our faculty had not performed a reliability test, they may have drawn dramatically different conclusions about the effect of their courses on student learning, especially with respect to the PASE subscales. Luckily, a Chronbach alpha reliability test was performed. This analysis revealed that PASE has validity to the college student population but its sub-scales do not, and our three faculty were able to interpret the test results accordingly. It is less time-consuming and probably most valid to use established tests when evaluating courses, but concern must always be taken when applying these tests to new populations.

WHAT DOES THE LEADING SCIENCE EDUCATION RESEARCH SAY ON THIS TOPIC?

In his 1992 review of the research literature, Lederman documents that the objective of improving students' understanding of the nature of science has been a goal of science education for at least 85 years; yet in reality, most students do not understand much about how science works. Most of the research effort has focused on K-12 students, pre-service teachers, and in-service teachers. Early on, research focused on improving pre-service teachers' understanding of the nature of science with the hope that this would translate into improved teaching of the nature of science and hence improved student understanding (Duschl, 1990; Abd-El-Khalick et al., 1998). However, improved teacher understanding of the nature of science did not *inevitably* lead to improved classroom instruction of the nature of science, especially with respect to novice teachers (Brickhouse & Bodner, 1992; Abd-El-Khalick et al., 1998).

Recent research has focused on new attempts to improve the translation of teachers' understanding of the nature of science into classroom practice (Lederman and Abd-El-Khalick, 1998; Lederman, 1999; Abd-El-Khalick & Lederman, 2000). One approach that has been advocated in previous research is the addition of history and philosophy of science coursework to teacher prepara-

tion programs or the inclusion of this perspective into science content courses. A recent study by Abd-El-Khalick and Lederman (2000) concludes that this approach does not improve college students' views of the nature of science. The authors advocate an *explicit* approach whereby instruction on specific aspects of the nature of science is incorporated into either science content courses, history of science courses, or teacher preparation courses, such that students have ample time to discuss these aspects and reflect on them. An alternative approach is to give students experience with the processes of science using inquiry-based teaching strategies, which *should* lead to improved conceptions of the nature of science. However, some research at the college level suggests that such an *implicit* approach does not work (e.g., Haukoos and Penick, 1985). Abd-El-Khalick and Lederman (2000) advocates the incorporation of explicit instruction on the nature of science, whether this is coupled with inquiry-based teaching methods or the addition of history and philosophy perspectives in coursework. Several other approaches to improving the teaching of the nature of science can be found in McComas (2000). This research base could be extremely useful in helping college science faculty modify their introductory courses; however, we have a long way to go in communicating the implications of this research to science faculty. Additionally, the college community is still a fertile ground for research, both in determining how best to communicate the nature of science to undergraduates and in developing research methodologies for exploring student understanding.

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