MICHAEL P. CLOUGH

3. HISTORY AND NATURE OF SCIENCE IN SCIENCE EDUCATION

INTRODUCTION

The history and nature of science (HNOS) is a phrase used in science education that encompasses issues such as what science is, how science works, characteristics of scientists, and how scientific knowledge is developed and comes to be accepted by the scientific community. Answers to these questions often seem fairly obvious to most people, particularly teachers and students of science. But an abundance of studies report that the general public, science teachers and their students have significant misconceptions about the HNOS. This chapter addresses why accurately portraying the HNOS is important for both science teachers and students, prevalent HNOS misconceptions, and how to incorporate HNOS instruction in a manner that effectively bolsters understanding of both HNOS and science content.

HNOS IN SCIENCE EDUCATION

Accurately understanding important features of the HNOS is an important aspect of scientific literacy, and a longstanding goal of science education. This is reflected in its being part of most contemporary science education reform documents. But the value of HNOS extends beyond understanding the characteristics of science, scientists and scientific knowledge. When thoughtfully and seriously considered, understanding the HNOS:

- *Helps teachers understand students' difficulties learning science ideas and the tenacity of misconceptions.* The HNOS makes clear that very intelligent scientists struggled to understand the natural world, and how many tenaciously held to ideas that the scientific community has now abandoned. Those scientists had reasons, often good reasons, for committing to those ideas, and even for disagreeing with colleagues who proposed new ways of understanding and explaining phenomena. Teachers are in a better position to understand and assist struggling students if they understand the many historical examples illustrating scientists' struggles to understand phenomena, and how intelligent individuals rejected new ideas or only slowly and with difficulty came to understand the superiority of those new ideas.
- *Assists teachers in understanding why telling and showing do not compel students to change their thinking.* The struggles of scientists noted in the previous bullet occurred despite other scientists explaining the idea they advocated and providing

K. S. Taber & B. Akpan (Eds.), Science Education, 39–51.

evidence they maintained supported their thinking. The HNOS makes clear that the difficulties of understanding and accepting colleagues' ideas occurred in spite of their carefully considering the arguments and evidence of those colleagues. But disagreements continued because data and arguments may be interpreted in a variety of ways. Of course, providing explanations with evidence is important both in science and science teaching, but doing so is often insufficient for bringing about a change in thinking.

- *Assists students in understanding the complexity of learning science and identify with past scientists' struggles, thus increasing students perseverance* (Arya & Maul, 2012; Hong & Lin-Siegler, 2012). Understanding the HNOS can help students better understand their own struggles learning science. As a result, rather than thinking they are incapable of understanding science, they are more likely to persist in their effort to learn.
- *Improve students' attitude toward and interest in science and science education.* Those who have a more accurate view of the HNOS see that science is done by people of all cultures, see science as a creative endeavor that involves interacting with people, and possess improved attitudes toward science, scientists, and science-related careers.
- *Plays a role in socio-scientific decision-making* (Mitchell, 2009; Herman, 2015). For instance, many people deny global climate change, biological evolution, and other important science ideas, in part, because they wrongly think that good science demands control-treatment experiments. However, the HNOS illustrates that for many scientific questions, that approach is either not possible or not appropriate. For much of astronomy, ecology, geology and other fields of study, a control-treatment experimental approach is not possible or appropriate, yet much of the knowledge those disciplines have produced is as well-established as that resulting from control-treatment experiments.
- *Understanding science content.* Many science ideas are counter-intuitive, and are only understood by abandoning our everyday approach to making sense of phenomena. For instance, deeply understanding the law of pendulum motion requires an understanding of the idealized (and impossible) conditions that law is based upon and the value of having such a scientific idea. Understanding biological evolution is, in part, dependent upon understanding methodological naturalism and how well-supported scientific ideas need not always be based on experiments or make specific predictions.

MISCONCEPTIONS REGARDING THE HNOS

HNOS misconceptions like those appearing in Table 1 are widespread, but hardly surprising given the way that science and scientists are portrayed on television, in movies, and in other popular media. However, school science is also to blame. Science textbooks typically ignore information about the work of scientists, how questions and ideas regarding the natural world arise, the disagreements about the meaning of data, and how the scientific community came to eventually reject and accept particular ideas (Leite, 2002). As Postman (1995) noted:

> …textbooks are concerned with presenting the facts of the case (whatever the case may be) as if there can be no disputing them, as if they are fixed and immutable. And still worse, there is usually no clue given as to who claimed these are the facts of the case, or how "it" discovered these facts (there being no he or she, or I or we). There is no sense of the frailty or ambiguity of human judgment, no hint of the possibilities of error. Knowledge is presented as a commodity to be acquired, never as a human struggle to understand, to overcome falsity, to stumble toward the truth. (p. 116)

Table 1. Common misconceptions regarding the HNOS

- Disagreements regarding competing scientific explanations for natural phenomena are resolved through polling scientists on their view of the best explanation.
- Science and those who do science can and should be free from emotions and bias.
- Scientific ideas arise directly from data.
- Data supporting a contentious scientific idea demands that doubting scientists drop their objections to the idea.
- Data that is at odds with a prevailing science idea should result in the rejection of that idea.
- Science, when well done, produces ideas that are proven to be "true". Scientific knowledge falling short of that status is unreliable.
- While creativity and inventiveness assist scientists in setting up their research, the resulting science ideas are discovered, much like finding something.
- Scientific models are exact copies of reality.
- Science is equated with technology, and all science research is thought or expected to be in some way directed at solving societal problems.
- Science research follows a step-by-step scientific method and carefully adhering to this systematic method accounts for the success of science.
- The status of, and relationship between, scientific laws and theories is misunderstood.
- Methodological naturalism is equated with philosophical materialism.

When textbooks do make an effort to convey characteristics of science and scientists, it is often done in superficial ways that wrongly sanitize the actual workings of science and scientists, thus bolstering many of the misconceptions appearing in Table 1. Moreover, highly directive cookbook activities so ubiquitous in science classes reinforce many of the same misconceptions. Lab reports, while written for the sole purpose of communicating results of investigations and justification for conclusions reached, misportray how science is really done (Medawar, 1963) and promote many of the same misconceptions, including wrongly portraying scientific research as following a step-by-step scientific method. Finally, teachers' language when teaching science often distorts the HNOS (Munby, 1976). For instance, asking students "What does the data tell you?" and inappropriately using words such as "theory", "law", "prove" often distort the HNOS.

Several of these HNOS misconceptions coalesce, forming an overarching image of science and scientists that, while incorrect, makes sense and thus requires considerable effort to change. That said, much is known about teaching the HNOS in a manner that promotes among students more accurate understandings that are held long after a course ends (Clough, 1995; Herman & Clough, 2016).

EFFECTIVELY TEACHING THE HNOS

While promoting an understanding of the HNOS has been a persistent goal of science education, science teachers at all levels have struggled to accurately and effectively promote this goal for a variety of reasons including, but not limited to, their own misconceptions regarding the HNOS, uncertainty regarding how to effectively teach the HNOS, and the paucity of curriculum materials to support HNOS teaching. However, science teachers committed to HNOS instruction have successfully integrated it extensively in their classrooms (Herman, Clough, & Olson, 2013a).

Important HNOS Issues Worth Addressing in Science Education

Many issues regarding the HNOS are complex and contextual, but for the purposes of science teaching and learning, general agreement exists regarding ideas that ought to be addressed. However, even these generally agreed upon ideas have nuances that depend on contextual factors. Eflin, Glennan and Reisch (1999, p. 112) caution that "Just as science educators stress that science is more than a collection of facts, we emphasize that a philosophical position about the nature of science is more than a list of tenets." Rather than listing HNOS ideas that both teachers and students may wrongly interpret as facts to be taught and learned verbatim, HNOS issues should be addressed as questions like those found in Table 2. Addressing HNOS matters as questions rather than tenets encourages both teachers and students to think about the HNOS issue and consider how different contexts may call for more nuanced answers to the questions.

HNOS Instruction should be Deliberately Planned

Effectively promoting a deep and robust understanding of the HNOS first demands that science teachers intentionally plan how they will teach HNOS ideas, just as they overtly plan how to promote understanding of science content objectives. Such effort requires that they genuinely value HNOS learning, not merely in a general sense, but for reasons like those noted earlier in this chapter (Herman, Clough, & Olson, In press). HNOS instruction should be planned to challenge prevalent HNOS misconceptions and encourage student actions like those in Table 3. Effectively

Table 2. Example HNOS questions worth exploring in science education (From Clough, 2011)

- In what sense is scientific knowledge tentative? In what sense is it durable?
- To what extent is scientific knowledge based on and/or derived from observations of the natural world? In what ways is it justified on grounds other than observational evidence?
- To what extent are scientists and scientific knowledge subjective? To what extent can they be made less subjective?
- To what extent is scientific knowledge socially and culturally embedded? In what sense does scientific knowledge transcend particular cultures?
- In what sense is scientific knowledge invented? In what sense is it discovered?
- How does the notion of a scientific method distort how scientists actually work? In what sense are particular aspects of scientists' work guided by protocols?
- In what sense are scientific laws and theories different types of knowledge? How are they related to one another?
- How are observations and inferences different? In what sense is an observation an inference?
- How is the private work of scientists similar to and different from what is publicly shared in scientific papers?

Table 3. Example student actions that convey HNOS understanding (From Clough, 2011)

- Accurately describe the differences and interactions between basic science, applied science and technology.
- Articulate why contemporary science explains natural phenomena in naturalistic terms with no recourse to the supernatural.
- Provide arguments against a universal scientific method.
- Explain how imagination and creativity are crucial in doing science.
- Explain and provide examples illustrating how scientists develop ideas to account for data, and how data does not tell scientists what to think.
- Justify why well-supported science ideas, while durable, may be re-examined, modified, and replaced. Explain why this possibility of change is a strength of science.
- Accurately explain how scientific laws and theories are different types of knowledge, yet how they relate to one another?
- Provide examples illustrating that science has both a collaborative and competitive character.
- Identify inaccurate stereotypes of scientists.
- Provide examples of how science and society impact one another.

planning for HNOS instruction entails several important features that include making overt to students the HNOS issues being addressed, creating successful contexts for addressing HNOS ideas, and asking questions that assist students in developing more accurate HNOS conceptions.

Making HNOS Instruction Overt to Students

Lessons that merely have students take part in activities, complete readings, or watch multimedia that accurately portray the HNOS are not effective at altering their mistaken notions regarding what scientists are like and how science works. This is because learners use what they already know—in this case their existing HNOS misconceptions—to make sense of what they encounter. Consequently, they will miss or unknowingly interpret and modify aspects of accurate HNOS experiences so that they appear to fit what they already think (Abd-El-Khalick & Lederman, 2000;

Table 4. Teacher questions that draw students' attention to the HNOS (From Clough, 2011)

- How does your work in this laboratory activity illustrate that you did not follow a step-by-step scientific method? How is your work similar to the work of scientists?
- How does the work of [insert scientist or scientists] illustrate that data does not tell scientists what to think, but instead that creativity is part of making sense of data?
- The word "theory" in science is often wrongly interpreted by people as meaning "guess", "opinion", or a not well substantiated claim. How does that meaning not capture the confidence we have in kinetic molecular theory? [This question is most effective when asked after students have studied and are coming to understand the power of the theory. The question can be asked in the context of any well-established theory such as atomic theory, the theory of plate tectonics, the theory of evolution, etc.]
- How does the DNA work of James Watson, Francis Crick, Maurice Wilkins, Rosalind Franklin and Linus Pauling illustrate that doing science involves both collaboration and competition?
- Consider the model of the atom and the evidence that supports it. How does this work illustrate that science ideas are developed to account for data (i.e. data do not tell scientists what to think)?
- In what ways does this portion of your textbook distort what real science is like? [This question must wait until students have first developed more accurate views of the HNOS, but then may be asked most anywhere with typical science textbooks.]
- How does the process by which science came to understand the link between asteroids and dinosaurs illustrate that science requires creativity and does not follow a linear process (see http://undsci.berkeley.edu/article/0_0_0/alvarez_01)?
- What prior knowledge did you use in developing your laboratory procedure and analyzing your data? How does this illustrate that scientific theories guide researchers in determining what questions to ask, how to investigate those questions, and how to make sense of data?

Tao, 2003). Teachers must therefore include in HNOS lesson planning how students' attention will be drawn to targeted NOS issues in a manner that encourages students to mentally engage in what they are experiencing and more accurately compare it with the ideas regarding the HNOS that they already hold. This demands that teachers think about the kinds of questions they will ask and have students respond to during discussions, assigned readings, laboratory activities and other activities. Table 4 presents examples of questions that overtly draw students' attention to HNOS ideas in a manner that requires them to think deeply about those ideas in light of commonly held HNOS misconceptions.

Important Contexts for HNOS Instruction

Promoting a deep and robust HNOS understanding also requires that it be addressed throughout the school year in a variety of contexts. Table 5 situates instruction regarding the nature of science (NOS) in three broad categories on a continuum.

Decontextualized NOS instruction. The first category is decontextualized in the sense that NOS instruction experiences (e.g., black box and other types of puzzle-solving activities) draw similarities to how science works, but the context is devoid of science content and the workings and words of actual scientists. Decontextualized NOS instruction is useful for introducing and addressing NOS issues without complicating matters with science content. However, disconnected from science content and the work and words of scientists, students will unlikely alter their misconceptions regarding how authentic science really works and what scientists are actually like.

Moderately contextualized NOS instruction. Moderately contextualized NOS instruction is associated with science content, but links to the authentic words or work of scientists are absent or superficial. Using students' experiences in inquiry activities to illustrate how their varied approaches illustrates that scientists do not follow a step-by-step method or how their struggles to make sense of data reflects that data do not tell scientists what to think is an example of moderately contextualized NOS instruction. Teaching science through inquiry is instrumental in effective HNOS instruction because it raises opportunities – planned and unplanned – for HNOS instruction (Herman, Clough, & Olson, 2013b). However, unless these experiences and important NOS ideas are overtly connected to the genuine work of scientists (e.g., scientists using varied investigative methods and their difficulties and disagreements interpreting data), students can easily maintain that they and their situation are not the same as scientists who are more intelligent and have access to better equipment. Thus, moderately decontextualized NOS instruction, like decontextualized NOS instruction, is important, but insufficient, for promoting a genuine and long-lasting accurate view of the NOS.

Table 5. Contexts for teaching about the nature of science (After Clough, 2006)

	Decontextualized NOS Instruction	*Moderately Contextualized NOS Instruction*		*Highly Contextualized NOS Instruction*
Connection to science content	None	Decontextualized NOS activities associated with, but still separate from, content	Inquiry science content activities overtly linked to NOS ideas	Seamless
Connection to actual work of scientists	Absent	Superficial	Superficial	Extensive
Example activities	Black box activities Gestalt images Puzzle solving	A black box activity included with, but not meaningfully connected to, instruction regarding atomic structure	Raising NOS issues in a student inquiry activity determining the mass % of water in a hydrate	Authentic historical and contemporary science examples

Highly contextualized NOS instruction. Highly contextualized NOS instruction incorporates historical and contemporary stories of authentic scientists and science research to overtly draw students' attention, using questions like several appearing in Table 4, to important HNOS ideas. These stories provide needed evidence for many students that the NOS ideas addressed in decontextualized and moderately contextualized NOS instruction accurately reflect authentic science. Such accounts need not be lengthy, but they should engage and intrigue students and over time compel them to alter their previous HNOS misconceptions. Highly contextualized NOS instruction alone may appear sufficient for effective NOS instruction, but as noted earlier, the HNOS misconceptions that students bring to science classes interfere in accurately interpreting historical and contemporary science stories.

Scaffolding between contexts. Decontextualized, moderately contextualized, and highly contextualized NOS instruction all play important roles for promoting deep and robust HNOS understanding. To summarize, decontextualized instruction is important for introducing HNOS ideas, moderately contextualized instruction is important for embedding HNOS instruction in everyday science content instruction (crucial so that HNOS will be addressed consistently throughout the school year), and highly contextualized instruction is important for convincing students that what they are learning about the HNOS accurately reflects what scientists and doing science are like. But students often need assistance in making connections between contexts as they wrestle with the HNOS. The role of teachers is always crucial as illustrated by the following questions, modified from Clough (2015), that exemplify how to assist students in making desired meaning while ensuring they are mentally engaged in making sense of their HNOS experiences.

- *Example question scaffolding between a moderately contextualized and decontextualized NOS experience*. How were your efforts to develop a procedure during your inquiry activity similar to your experience with the black box activity you experienced earlier this school year? In what sense did your work in both instances deviate from what is often called "the scientific method"?
- *Example question scaffolding between a highly contextualized and decontextualized NOS experience*. How were scientists' difficulties making sense of the DNA X-ray crystallography data similar to your struggles earlier this year to make sense of the black box activity data? Some people think data tells people what to think. What would you say to a person who thought that?
- *Example questions scaffolding between moderately and highly contextualized NOS experiences*. How was your effort to make sense of data in our conservation of matter inquiry activity similar to and different scientists' work regarding the same question about nature? How do they illustrate the important HNOS idea that data do not tell researchers what to think?
- *Example question scaffolding back and forth between all three broad NOS instruction contexts*. What do both your and scientists' efforts noted in the prior

bullet have in common with your effort to make sense of the data you collected in the black box activity we conducted earlier this school year? How does this illustrate that researchers create ideas that account for/make sense of data?

The wording of these questions also makes apparent important HNOS ideas. As the school year progresses, questions asked should be more open-ended so that students identify relevant HNOS issues. For example, "What about the HNOS did [insert black box activity and classroom inquiry activity] have in common with scientists' efforts to determine the structure of DNA?

HNOS Learning Must be Assessed

Science teachers who plan for and effectively teach the HNOS as described above can be assured that their efforts will improve students' HNOS understanding. Nevertheless accurately identifying how well individual students understand and can apply particular HNOS ideas, and what struggles and misconceptions remain, demands incorporating HNOS assessments throughout the school year. Moreover, students often place more effort on what appears to be of consequence in a course and "assessment gives clear messages to students about what is important in the subject" (Dall' Alba et al., 1993, p. 633). As with HNOS instruction, HNOS assessment should occur throughout the school year in a variety of contexts including but not limited to exams, quizzes, laboratory activities, and readings. Many of the questions appearing in Table 4 could make fine HNOS assessment questions. Table 6 includes examples of assessment questions I incorporated throughout the school year as a high school teacher to assess my students' HNOS understanding.

SUMMARY

Bullet Point List of Main Chapter Ideas

- A deep and robust HNOS understanding has considerable value for science teachers and students, for science literacy, and socio-scientific decision-making.
- Several HNOS ideas are worth teaching, but they should be explored as questions rather than tenets.
- HNOS instruction should be deliberately planned and implemented, taking into account common and tightly held HNOS misconceptions.
- Because HNOS misconceptions are often tied together and make sense, truly changing those mistaken notions requires that HNOS instruction be incorporated throughout the school year.
- Effective HNOS instruction overtly draws students' attention to targeted HNOS ideas in a manner that requires students to mentally engage and wrestle with those ideas.

Table 6. Example HNOS Assessment questions (From Clough, 2011)

- How is an understanding of the nature of science important when looking at the biological evolution/creation/intelligent design public education controversy? [Question on an exam addressing biological evolution]
- How does the “Plant and Animal Cells” lab demonstrate that theory must precede observation? [Question to be answered in a cell biology laboratory report]
- In our genetics unit, you learned that at one time scientists, looking at the same data, disagreed whether DNA or protein was the genetic material. What does this and similar kinds of disagreements about the meaning of data illustrate about how science works? [Question on a biology exam addressing genetics]
- Science textbooks often claim that scientific laws are discovered. Using the conservation of mass law as an example, critique this claim. [Question on a chemistry exam addressing conservation of mass and balancing chemical equations.]
- People often wrongly think that scientific laws are superior to scientific theories. Use what you have learned about gas laws and kinetic molecular theory to correct this misconception. [Question on a chemistry exam addressing gases]
- List and defend at least three ways that your laboratory work to determine the products of the following chemical reaction

  $$NaHCO_{3\ (aq)} + CaCl_{2\ (aq)} \rightarrow \text{? products}$$

  accurately portrayed the NOS. List three ways it did not accurately portray the NOS. [Question on an exam addressing stoichiometry]
- Reflect on all the thinking you did in this inquiry laboratory activity. What scientific theories were guiding your thinking and explain how they guided your thinking. [Question that can be asked in most any science content inquiry laboratory activity where students have to make decisions such as how to set up their investigation, assess what data are relevant and irrelevant, how to account for their data, and what conclusion(s) are possible and probable]
- Compare and contrast how your science textbook presented the structure of the atom with the historical account presented in class. List at least five ways how your textbook’s presentation of this content misportrayed the HNOS.

- Promoting a deep and robust HNOS understanding demands that the HNOS be taught in a variety of contexts along the decontextualized to highly contextualized continuum, with extensive scaffolding that assists students in drawing appropriate meaning from instruction.
- As with all cognitive objectives, students’ understanding of HNOS should be assessed, but in a way that requires justification for positions rather than mere recall of NOS ideas.
- When HNOS is effectively taught, students learn how science is done along with the evidence and reasoning in support of science ideas, thus developing a deeper understanding of both HNOS and science content.

RECOMMENDED RESOURCES

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Understanding Science: How Science *Really* Works. http://undsci.berkeley.edu/index.php

Story Behind the Science: Bring Science and Scientists to Life. http://www.storybehindthescience.org/

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