TEACHING WHOLE SCIENCE

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Climategate. Erroneous links between the measles vaccine and autism. Revised mammogram recommendations. Suspect communication with coma patients. Ideally, science education prepares students to interpret such cases in the news. These cases, in particular, underscore the role of understanding nature of science (NOS), in contrast to just content. And they reflect a need for broad skills in analyzing the diverse features of reliability in scientific claims. One needs to teach Whole Science, not a pre-processed School Science, lacking in essential conceptual nutrients (*Sacred Bovines*, last issue).

But how? One could, of course, assemble a textbook on nature of science. Describe the various features and illustrate them with examples (McComas, 2008). Then test students on their ability to identify and explain the various principles (Lederman et al., 2002). It is a familiar pattern. Conventional and comfortable. But join me in questioning this sacred bovine: that one teaches most effectively – and respects students most – by simply feeding students the answers. Or voluminous class notes and review sheets. The most valuable NOS lessons may be a series of well-posed problems.

○ Problematizing NOS

Recent research has identified several key strategies for teaching nature of science, often reflecting general principles of effective learning. First, be explicit. For example, truly investigative activities – not cookbook labs – may introduce important concepts about the process of science: say, about sample size, sources of experimental error, or controls. But students generally miss the latent lessons. So, too, for hearing stories about famous biologists or episodes of discovery or science in the news. One needs to highlight the NOS themes. Without clearly articulating the ideas, students do not integrate them into their existing mental frameworks.

Second, guide student reflection (Scharmann et al., 2005). Common constructivist approaches encourage first bringing prior conceptions to mind and then engaging them with discrepant events, anomalies, or other new information. Again, this helps each student situate new ideas into his or her own way of thinking. Accordingly, the ideal teacher regularly poses questions – not just about content, but about how science works. *How* does it generate reliable claims? (Does it always?!) This reflective approach applies equally to student labs, news reports, or historical discoveries:

- "Why should anyone believe this?"
- "Are there alternative explanations or interpretations? How would you investigate those?"
- "Can you see any potential for bias or error? How would you remedy it?"

Discussion activates the mind. Through a problem-posing posture, the teacher can learn more, too. No one starts off as an expert on NOS. But knowledge quickly deepens with more examples and reflection on each. A habit of reflecting helps both student and teacher grow.

Cognitively, humans learn more effectively when they actively participate in the process. Motivation is generally higher. Later memory retrieval is enhanced. Optimally, then, students solve problems on their own. Problem-based learning (PBL) has proved effective in many contexts (Duch et al., 2001; Hmelo-Silver, 2004; Major & Palmer, 2005). Here, the aim is to pose problems specifically *about the nature of science*.

NOS-PBL may introduce a whole new set of question types – although the core theme of reliability will surely be familiar:

- "How did the rivalry between Pasteur and Koch influence their research?"
- "In what ways did Victorian culture relate to Darwin's idea of natural selection?"
- "How did new microscopes and staining techniques alter knowledge of the cell?"

Once familiar with their students' native NOS views, teachers can find appropriate problems that will stretch or deepen their awareness. There is a subtle art to framing fruitful questions at the edge of students' knowledge.

Working on problems – genuine problems – also helps develop analytical skills. The goal is not just remote understanding. Students eventually need to decipher cases on their own. Thus, the teacher may also initially *model* effective analysis – for example, showing how to tease apart empirical questions from ideological values. Or how to find and assess assumptions in an argument. Maybe an occasional sample of cautious, mature judgment.

Effective problems are open-ended. They do not hide targeted "right" answers. An effective characterization of NOS thus profiles dimensions of reliability in science, rather than specific principles (last month's *Sacred Bovine*; http://ships.umn.edu/knows/nos-table.pdf). NOS instruction should foster well-informed analysis, not particular conclusions or positions. Just as scientists must reason from the evidence at hand, consumers of science must learn to reach their own conclusions based on the information available.

As in all constructivist learning, the teacher's role is to facilitate and guide, not serve as ultimate authority. For instance, the teacher monitors solutions to ensure that they are responsible to the evidence. One does not forsake right and wrong – yet there may be many right answers (as well as many wrong answers!). Far more important is how deeply informative they are. A teacher ensures that answers address potential criticism and are sufficiently complete. Unschooled opinion is not learning. And is only made worse by selective evidence and rationalization. Teachers help by pointing to details or examples that require students to delve deeper. And, finally, they celebrate success.

Paradoxically perhaps, motivating and framing questions may be far more important than providing ready-made answers. The aim is for

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the learner to learn, not for the teacher to teach. PBL may thus involve a profound, often unrecognized gestalt switch in professional ethics. In the lecture model, one respects students by being a font of knowledge and sharing expertise. In a PBL approach, respect is based on supporting student autonomy and scaffolding self-directed skill development. For some teachers, the shift in self-image may be quite challenging – even if ultimately rewarding.

○ Rediscovering History

The third and last basic strategy for teaching NOS is: use authentic examples. Namely, draw on real science. Activities based on puzzle boxes or mock forensics games – while plentifully available on the Internet – are not as effective as the real thing (Schwartz et al., 2004; Clough, 2006). Especially if the goal is to render scientific practice fully. One needs samples, or cross-sectional slices, of Whole Science. One needs, at least on occasions, complex case studies (Osborne et al., 2003; Allchin, 2010a).

Case-based learning has its own distinguished heritage (Conant, 1957; Barnes et al., 1994; Lundberg et al., 1999). A few biology textbooks have pioneered a case-based approach for teaching content (Leonard et al., 1998/2008; Postlethwait & Hopson, 2003). NOS-PBL cases may differ dramatically. Cases are not mere stories. Nor are they occasions for a teacher to pontificate on NOS. Cases function to contextualize NOS problems, while providing the resources to resolve them.

A ready source for cases, of course, is the news. Most teachers seem to appreciate the value of such cases, although often only in terms of motivating interest. If the goal is to inform interpretation of science in personal and social decision-making, one might imagine that extended contemporary cases would be the most relevant (Wong et al., 2008). However, that assumption may be yet another sacred bovine, to be critically reassessed.

Indeed, some NOS lessons may be learned well only through historical cases. For example, consider 'tentativeness,' or the provisional nature of scientific knowledge (for decades, the most prominent NOS learning goal). Errors are only really recognized in retrospect. One wants to compare a reasonable "before" with an unanticipated "after." The episode must be past. Cases of historical error are good opportunities for showing honest mistakes, as well as inferring the methods for avoiding further such missteps.

NOS lessons, like all lessons, are more vivid when students experience them first hand. That may seem odd, at first, for history. Imagine how a student learns about conceptual change personally by unexpectedly reorienting their own ideas. They might adopt the position of a famous biologist in a historical scenario – before a revolutionary discovery is made – and address the same problem. They struggle with the new observations or data and the apparent contradictions with earlier theories. Ultimately, reasoning from the available evidence, they reject old concepts and accept a new one. Note that knowing the "right" answer in advance makes this lesson impossible, just as a spoiler ruins a mystery or suspense thriller. Thus a key irony is making the history "present": restoring a sense of "science-in-the-making" through historical perspective.

Recapturing historical uncertainty (or "science-in-the-making") is integral to applying NOS lessons today. Most contemporary decision-making cases involve scientific claims that are "young" and uncertain. The science has not yet benefited from the proverbial "test of time." Debate is often still active. Unlike the voice of absolutism that students encounter in textbooks! The evidence for evolution, genetics, or germ theory is already well established. Of course one can recite the evidence. But rationalizing an answer already known differs markedly from reasoning blindly towards a yet unknown solution. Problems in today's culture rely on the second, more demanding skill.

Historical cases prove useful in another way. Students need the freedom to fail while they practice applying their NOS skills. They also need to evaluate and adjust their emerging sense of judgment. History provides clear solutions for assessing one's growing analytical skills. Contemporary cases, still in process, cannot. By understanding the ultimate historical outcome, one can calibrate one's developing NOS thinking.

Analysis of past cases can also help resolve a major ambiguity in the phrase 'nature of science.' Namely, is it normative or descriptive? Does one learn how science works ideally, or how it actually works in practice? Of course, both are important, as well as the tension between them. Yet students likely need to discuss cases to appreciate the difference. Historical cases open exploration of the inherent limits of science, as well as its norms.

In a similar way, appreciating how social or cultural perspectives influence science requires a relatively remote vantage point. One must be able to see the culture as culture. For example, we no longer share Victorian England's views of competitive society and racial hierarchy. One can thus see how they influenced Darwin's conceptions of natural selection and the evolution of morality (*Sacred Bovines*, February 2009). We can also see how 19th-century views of women (not held today) once shaped theories about the female skeleton, mammals, and even flowers (Schiebinger, 1989, 1993). Cultural beliefs enter science without conscious awareness. Only by studying such historical cases might one be able to see today's cultural perspective of, say, biological determinism and how it shapes concepts of genetic identity, cloning, and genetically modified organisms (*Sacred Bovines*, April 2005).

Historical perspective is an indispensable resource for complete NOS lessons. That is why history and nature of science are typically coupled together in curriculum standards: as HNOS.

○ Finding Cases

The strategy for teaching nature of science, then, is quite simple: engage in samples of authentic scientific practice, or Whole Science. Adopt an analytical perspective, pose problems, and reflect explicitly on the solutions, especially the processes that affect reliability. As natural as that may seem, it contrasts starkly with the endless cascade of facts so typical today. Most notably, it helps restore context and meaning to science for students.

Contrary to intuitions, historical cases may be more valuable than contemporary ones. Consider the recent case of revised mammogram recommendations. Amidst ongoing debate, how can one secure enough scope of perspective? Here, interpreting today's case would be greatly informed by similar historical examples of conceptual change: how more data dramatically altered theories about the causes of pellagra or beriberi (Allchin, 1996; Kraut, 2003), or assessments of the risks of thalidomide or genetic engineering (Fredrickson, 2001; Stephens & Brynner, 2003; Hindmarsh & Gottweis, 2005). Likewise, interpreting the case of Climategate could be informed by knowing about Mendel's suspicious data or the "tricks" Thomas Hunt Morgan's lab used to map chromosomes (Wimsatt, 2007: pp. 94–132). Facilitated communication brings to mind the earlier cases of Clever Hans and Uri Geller, or the recurring pitfalls of research on spiritualism and the "paranormal" (Gardner, 1990; Lyons, 2009: chapters 4–5).

Practically speaking, where does one find good historical cases? Resourceful teachers already keep an eye out for relevant books and television programs. Histories of Darwin and evolution, genetics, and molecular biology are perennial favorites. Of course, such sources may be ill-informed or biased. For example, they frequently romanticize science or its heroes, distorting the nature of science (*Sacred Bovines*, January 2005). Simplistic ideals replace complex realities. The aim is to unpack how science works, not just to celebrate it. With just a few critical tools, however, one can easily sort credible history from ideological junk (Allchin, 2002, 2003a, b, 2004).

Other classroom-ready cases have been developed through collaboration among historians, philosophers, and teachers – and are available online (Hagen et al., 1996; Allchin 2010a). For example, one may wish to follow Lady Mary Whortley as she encounters the practice of smallpox variolation among the Turks in the 1700s and then tries to persuade England's elite about the "heathen" practice (lessons on evidence, credibility, culture, and gender) (Remillard, 2007). Or 17th-century anatomist Richard Lower as he explores the color of the blood and begins to question his mentor's beliefs that the body's heat and vital spirit originates in the heart (on conceptual change and collaboration) (Moran, 2009). Or King Carlos I of Portugal on his voyages to document the diversity of his nation's marine life (on patronage and scientific illustration) (Faria et al., 2010).

Even with all these resources, of course, one challenge in teaching NOS remains: assessing what students have learned – addressed in a *Sacred Bovine* to follow.

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