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The Minnesota Case Study Collection: New Historical Inquiry Case Studies for Nature of Science Education

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Abstract The new Minnesota Case Study Collection is profiled, along with other examples. They complement the work of the HIPST Project in illustrating the aims of: (1) historically informed inquiry learning that fosters explicit NOS reflection, and (2) engagement with faithfully rendered samples of Whole Science.

Education is what survives when what has been learnt has been forgotten.
B. F. Skinner.

1 Introduction

Substantial consensus now exists among science educators about the value of nature of science (NOS) education, the content aims of such education (Osborne et al. 2003; AAAS 2001–2004; Hodson 2008; OECD 2009), and even many facets that foster effective NOS learning, as consolidated and summarized nicely in HIPST's (2008a) recent statement of principles. Yet 'despite this cheery consensus regarding the importance of accurately teaching NOS,' Clough and Olson cautioned in opening a recent thematic issue of this journal, 'much remains to be done in moving the vision to a reality in elementary through post-secondary science education' (2008, 143). An Earth Science teacher echoed the concern (also in this journal) from the perspective of practice (Dolphin 2009):

> From my research, there are few contextualized experiences which have been created for incorporation within the science classroom. . . . To read and assimilate the information available and then create interesting mechanisms to transfer the information to students, i.e. narratives, dramatizations, activities, and models is a huge effort. . . . "Teachers and researchers often describe a gap between research and practice" [Abell and Lederman 2007, p. xiii]. The history and philosophy of science scholars are encouraged to help bridge that gap by creating and publishing these types of contextualized experiences for the classroom teacher. We would all benefit greatly. (p. 439)

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As exmplified in the recent HIPST Project (2010), the challenge has shifted from advocacy to assembling concrete classroom resources that embody standards that are now (despite patchy dissent) relatively well understood.

2 The Minnesota Case Studies

Many science educators are familiar with the *Harvard Case Histories in Experimental Science*, edited and championed by political titan James B. Conant (1957). Yet Conant emphasized mainly the 'strategies and tactics of science' (1947, 16–20, 98–106), recognizing but largely peripheralizing 'the interaction of science and society' (AAAS 2009). By today's standards in Science Studies, the NOS in his 2-volume collection of cases as far too narrow and thus potentially misleading. It tends to exclude social and cultural factors (such as funding, institutional structures, or cultural values shaping scientific ideas), as well as biographical factors (such as personal philosophical beliefs), the material culture of the laboratory, and dimensions of gender and class. For example, while there is substantial discussion of Joseph Priestley's work on plants and the 'goodness of air', there is little discussion of the patronage that afforded Priestley the leisure time to pursue his activities; the social and communication networks that allowed Priestley to recognize the significance of his work and helped expose some of his errors; Priestley's more technical work on apparatus (the pneumatic trough) that enabled effective experimental manipulation of gases; Priestley's philosophical materialism, which helped shape his views on phlogiston; or Priestley's involvement with religion and politics, which ultimately competed with and affected his ability to do science (Nash 1957; Brock 1992; Johnson 2008). Also, while Conant's team introduced students to fragments of original texts, their narratives did not usher students into their own NOS reflection, a benchmark now regarded as essential (see below). Indeed, "it is time," Stinner et al. observed in this journal, "that the ideas of James Conant's case studies be updated and revised to serve the needs of 21st century students and societies" (2003, 639).

Stinner's implicit challenge has now been addressed. Using the Harvard case studies as an inspiring but outdated model, in the last half-dozen or so years a new collection of historical problem-based case studies has been developed at the University of Minnesota, home to the Minnesota Center for the Philosophy of Science and a large program in the History of Science, Technology and Medicine. The cases are now freely accessible online. The cases are hosted by the SHiPS Resource Center, the internet home of the network of teachers that originated at the First International History, Philosophy and Science Teaching Conference in Tallahasee in 1989. Each case highlights a small set of NOS features, typically based on a significant discovery, as summarized below. Each case offers an opportunity to illustrate and highlight certain dimensions of the nature of science (Allchin 2011) prominent in the history of that case. These are discussed as a guide for educators searching for particular lessons.

2.1 'Alfred Russel Wallace & the Origin of New Species' by Ami Friedman (2010)

Most people are familiar with Darwin's theory of evolution by natural selection. Textbooks (even those without an explicit historical focus) often discuss Darwin's travels on the *H.M.S. Beagle* and his great work, *On the Origin of Species*. Many even discuss the influence of Lyell and Malthus on his thinking. However, historians also credit Alfred Russel Wallace with developing a theory on the origin of species independently. This case study focuses on Wallace's story, highlighting his middle class background, his career as a collector, and the observations and experience that led to his own insights. It is ideal for introducing evolution in a controversial setting, where mere mention of Darwin can preempt engagement in learning. Major NOS themes include:

- diversity in scientific thinking
- the role of personal motives of scientists
- the importance of personal experiences and relationships of scientists
- funding
- communication in developing and presenting a theory
- priority and credit

This one case may serve as an exemplar. The basic format is an interrupted narrative, punctuated with questions (see Sect. 3.1 below). The questions aim to engage students in explicit reflection about both the scientific concepts and the nature of science (see Sect. 3.1 below), almost always particular and in the context of a real, historically embedded analysis or decision (see Sect. 3.2 below).

First, the case opens with a brief sketch of the cultural context in Britain in 1847. This helps to situate science in an accessible concrete human and cultural setting. It also introduces some cultural themes that will be echoed later: here, the role of increased leisure time (that led to Wallace's love of reading—about botany, insects, and evolution); and the role of the expanding railroad (which provided a job for Wallace as a surveyor, where he learned drafting skills and deepened his appreciation of geology and the outdoors).

Next, the central scientific problem is introduced, along with the main character: Alfred Russel Wallace and historical uncertainties about how new species originate. The problem is also presented biographically: Wallace was trying to couple a personal study of natural history with collecting exotic animal specimens as a way to earn a living. The concrete human context helps to "motivate" the scientific inquiry, inviting the student to participate along with the historical figure. The life story context also helps frame the conceptual resources available for active thinking by students.

The remainder of the narrative follows Wallace through the unfolding of his thoughts about evolution over the next decade. Students are thereby able to stepwise develop (or "construct") a concept of the origin of new species through natural selection along with Wallace. There are historical images and occasional quotes from Wallace's letters and autobiographical writings, giving first hand testimony and vivid human dimension to the episode.

Questions punctuate the narrative, engaging the students at several levels. Some questions highlight themes in nature of science. For example, students are asked to imagine how they will finance a natural history collecting expedition, highlighting the role of funding in science. Later, after Wallace's ship burns and he loses his valuable collection from the Amazon, students ponder whether to try again, collect elsewhere, or find other forms of employment, thereby highlighting the role of personal motives in science.

Other questions integrate students into the process of scientific thinking. For example, assuming that Wallace wanted to explain similar species, their varieties, and any laws of nature that might explain them, what types of data would one collect on a voyage through the Amazon? Or, given some examples from South America and the Malay Archipelago, how might Wallace account for two similar types of organisms inhabiting neighboring areas at the same time, rather than in succession to one another? Later, when Walalce notices a series of forms with a large gap, how might he explain the lack of intermediates? These questions involve designing an investigation as well as interpreting evidence. All are situated with just enough background and information to allow students to reach plausible conclusions on their own, without prior knowledge of the scientific concepts. They also prime cognitive orientation for understanding Wallace's own reasoning.

The questions are primarily situated historically. Thus they are open-ended. Multiple answers are possible. This encourages students to think broadly. With less vulnerability of being held accountable to just one "correct" answer, students may also more readily contribute to class discussion. In addition, the uncertainty underscores that science is about searching for and reasoning towards justifiable answers from the resources at hand ('science-in-the-making'), not justifying some "right" answer already known ('science-made'). One retrospective question (based on understanding the sequence of events, as well as the similiarities and differences between Wallace and Darwin) asks students who they would credit with the discovery of evolution by natural selection. This nature of science feature—about priority and credit—involves a more synoptic perspective, but again is open to several justifiable views.

In short, the case study presents a fragment, or cross-section, of 'Whole Science', integrating scientific concepts, process of science, and nature of science in biographical and cultural contexts (Allchin 2011). The relevant nature of science features arise from the case itself, not from a limited target list.

The case here also integrates supplemental (optional) activities already developed by the Natural History Museum of London, based on reading and reacting to Wallace's original letters. These can contribute further to underscoring the human dimension of science.

As a conclusion, the nature of science elements are reprised explicitly. Students are asked to reflect on and articulate the influence of early encounters and life experiences on the practice of science, the role of personal motivation and opportunities, the challenge of funding, the role of scientific communication, etc. This helps consolidate learning in the case and prepare application to other cases.

Finally, the case was developed in tandem with a historian of science, helping to ensure the quality of the history—and thus the authenticity of the nature of science. Towards this end, the case was further reviewed by a renowned Wallace scholar and another historian of science, and endorsed by another Wallace scholar.

2.2 'Carleton Gadjusek & Kuru' by Pierre Paul Gros (2011)

In the 1950s, a mysterious neurodegenerative disease called kuru appeared among the primitive Fore people of Papua New Guinea. Natives attributed it to sorcery. American D. Carleton Gajdusek conducted epidemiological studies among the remote tribe and later transmission studies in lab animals. He found that kuru was propagated by a 'slow virus', a new disease transmission type, a discovery for which he received a Nobel Prize. Decades later, Gajdusek's "slow virus" was identified as a prion. Gajdusek's interactions with the Fore people and, later in his life, sexual relations with Fore boys raise many questions at the intersection of science, culture and ethics.

Several NOS features are highlighted by this episode and are the basis of inquiry questions and reflections posed to the student. These include: (1) posing problems. How does one articulate a research question about something one does not yet understand? How does one research the cause of a disease when one must, in a sense, assume a cause to collect the relevant information about it? This case is striking because Gajdusek had encountered a new disease transmission type: a 'slow virus', or prion. (2) research ethics. Gajdusek must conduct autopsies and secure tissue samples, not endorsed by the local culture. Should he trade matches and knives with the indigenous people in exchange for scientific evidence? (3) science journalism. Gajdusek was livid over sensationalistic portrayals (such as one in *Time* magazine) of kuru as ‘the laughing disease’. What are the appropriate standards for reporting on science and who is responsible for “enforcing” them? (4) interdisciplinary relationships & collective nature of discovery. Ultimately, a solution in this case relied on epidemiologists, anthropologists, a nutritionist, medical clinicians and even a critical clue from a veterinarian. Students must articulate the various roles and imagine how information is shared and collaborations established. (5) public image of scientists. Gajdusek developed a close relationship with the Fore people suffering from kuru. That included several ‘adoptions’ and, later (as noted above), allegations of sexual abuse. Scientists are inevitably human: How should we integrate the personal and professional dimensions of their identity? In parallel, what principles should guide how the scientists themselves integrate these coupled identities?

2.3 ‘Lady Mary Wortley Montagu & Smallpox Variolation in 18th-Century England’ by Erika Remillard-Hagen (2010)

Lady Mary Wortley Montagu, author and ambassador’s wife, encountered the practice of variolation during her husband’s stay in Turkey. She came to accept that this treatment effectively prevented the dreaded devastation of smallpox. (Were her beliefs well justified?) Later, back in England, Lady Mary tried to introduce the unconventional “pagan” approach and met much skepticsm. What was needed to establish a persuasive account? Only after many decades, and human experimentation that would raise ethical concerns today, was the practice widely deemed acceptable.

Major NOS themes include: (1) credibility in science (evidence versus personal testimony). Lady Mary was impressed by observational evidence that Turkish women rarely suffered from the smallpox that had disfigured her own face. Should she believe the Turks about why? Later, should others in the Royal family believe Lady Mary, based merely on her reports, without formal studies? (2) the cultural context of scientific thought and reasoning. How should the British interpret practices in Turkey, where the system of medicine is different and the culture perhaps “less advanced”? (3) controlled clinical study. How important is controlled study when there is substantial evidence from experience? Can one use volunteer prisoners to test new treatments? (4) science and gender. Lady Mary was a woman in a culture where authority was given almost exclusively to men. How did her gender influence her reasoning and how her claims were received by men?

2.4 ‘Richard Lower & the ‘Life Force’ of the Body’ by Erin Moran (2009)

What makes the heart beat and the blood flow, features so closely associated with life? Even in modern times, vitalist assumptions linger among students. This case study follows the work of remarkable 17th-century physician Richard Lower as he investigates why the color of the blood differs in veins and arteries. Students adopt the role of the scientific community at Oxford in the mid-1600s and address Lower’s problems, successive observations and claims. Ultimately, students discover that fresh air in the lungs, not heat or the motion of the heart, provide blood with the ‘life force’ and its bright red hue.

Major NOS themes include: (1) science in personal, cultural and historical contexts. Lower’s relationship with his mentor, as well as others, proved important to both motivating his work and shaping his assumptions. His thinking was significantly influenced by a small, close-knit community of researchers. (2) different interpretations of the same evidence. Lower and his colleagues differed in why the blood changed color when it sat. How can such different concepts arise and how are they resolved? (3) conceptual change. Lower's concept that the air from the lungs provided the 'life force' of the blood replaced Harvey's earlier and authoritative view that it was the heat of the heart that was important. How did Lower manage to escape the former view? (4) collaboration, both direct and indirect. Lower's insight relied significantly on Fracassati's finding about blood being exposed to air. This was reported to him by Robert Boyle. He also relied on vivisection techniques developed by Robert Hooke for inflating and insufflating the lungs. What is required for such transfer of information to occur in the promotion of science?

2.5 *Debating Glacial Theory, 1800–1870* by Keith Montgomery (2010)

In the early 1800s, geologists traveled widely, documenting the landscape, asking various questions about geologic forms and history. By 1840, they were addressing the startling proposal that glaciers occured not just in the Alps, but at one time all across Europe. This case study situates students in the period, *allowing them to tour the various sites virtually* through GoogleEarth, while accessing original documents, maps and drawings. They then address Agassiz's glacial theory, either as individuals or, through a simulated debate, as members of the Geological Society of London.

Major NOS elements include: (1) conceptual change. Originally, what we now know as glacial erratics and scouring were originally interpreted as evidence of a Noachian flood (Allchin 1996). How did the alternative idea emerge? How did various geologists respond to the evidence as it gradually emerged? (2) nature of field work. What is it like to 'do' geology, which involves traversing the countryside and examining rock formations in situ? (3) historical reasoning. How does one reason about the past, if no one was there to observe events? Here, the prospect of a former Ice Age required one to be persuaded that the Earth was once substantially different than it is now. (4) role of personality/politics of science. Debates at the Geological Society in London involved some strong personalities, and the social esteem of some individuals seemed to bias beliefs of others. In addition, new ideas came from abroad, and a fair amount of nationalism shaped debate. In what ways do such perspectives foster effective debate, in what ways do they undermine it? How might the social dimension of science be shaped to accommodate such human emotions and politics?

2.6 'Robert Hooke, Hooke's Law & the Watch Spring' by Shusaku Horibe (2010)

Hooke's law is a standard feature of introductory physics classes, yet how often do students learn about Robert Hooke himself? This case follows Hooke from a skilled laboratory assistant and instrument maker in 1658 to his rise as a major innovator and theoretician in late 17th-century London. His work on springs led to the familiar relationship on elasticity now named after him, as well as to a heated priority dispute over the invention of a functioning watch spring. Ironically, Hooke never directly related the two, although so vividly linked in our minds today.

Major NOS themes include: (1) scientific careers (and social class). Hooke rose from the ranks of a technical assistant and instrument maker to the heights of the Royal Society. Yet he experienced a social distinction between 'doers' and 'thinkers'. How does this relate to the reputations we assign today to science versus technology, and to scientists versus engineers? How do these reflect our values? In what ways might these values be justified, in what ways not? (2) credit and priority (and social class). Hooke's class origins also seemed to pursue him and influence judgments about his claims to priority on the invention of the watch spring. On what basis should we give credit for scientific discoveries? How does this further express values about "doing" and "thinking"? In what ways, if any, should priority matter? (3) nature of discovery. How, indeed, did Hooke develop his understanding of the law that now bears his name? How does scientific discovery happen? Here, there are personal, economic and social factors that influenced the development of a new clock.

2.7 'Determining Atomic Weights: Amodeo Avogadro & His Weight-Volume Hypothesis' by Lindsey Novak (2008)

Amodeo Avogadro is memorialized in the number that now bears his name. That constant reflected in part Avogadro's hypothesis about the number of particles in equivalent volumes of gas. In the early 1800s chemists were determining atomic weights, but found some gases—oxygen, nitrogen, hydrogen—problematic. Avogadro's hypothesis resolved those problems by postulating that two atoms paired. But that concept conflicted with other theories, and chemists deferred to the views of the revered Jacob Berzelius. Nor did Avogadro's erroneous proposals about heat contribute to his credibility. Almost a half-century later, his ideas were revived by Stanislao Cannizzaro, in a different theoretical environment, who connected his proposal to interpreting other phenomena. Avogadro's hypothesis was finally accepted, with the startling conclusion that atoms and molecules are different, and that some gases as *diatomic*.

Major NOS themes include: (1) politics in science. The reputation of Berzelius greatly diminished early engagement with the ideas of Avogadro. Yet sometimes credibility matters. How does one balance the tension between relying on the evidence and relying on someone's past record? (2) conceptual change (entertaining vs. accepting ideas; long-unsolved puzzles; factors in theory acceptance). Why did it take 50 years for Avogadro's Hypothesis to be accepted? How did science change over that half a century? Should Avogadro's method have been accepted right away? Why or why not?

2.8 'Interpreting Native American Herbal Remedies' by Toni Leland (2007)

This case study begins with the compelling drama of Jacques Cartier and his crew suffering from an unknown illness as winter traps the expedition unexpectedly in remote territory in 1534. The local Iroquois tribe recommends drinking a juniper tea—but could one trust them, or their remedy? In subsequent episodes, students follow James Lind investigating the same ailment two centuries later (but wth different strategies); the recommended use in Colonial times of bloodroot for digestive problems; and several patent medicines in the 1800s advertised as based on Native American cures—some real, some fraudulent.

Major NOS elements include: (1) science in different cultural contexts. Here, students repeatedly decide whether to accept testimony and evidence for claims across cultures. The knowledge of different cultures and cultural prejudices become evident through the historical events. (2) credibility. Evidence may be central to science, but understanding that evidence also relies on the reports of other scientists. How does one balance these two processes in reaching reliable claims? (3) role of experiment and controlled investigation. How did James Lind's approach differ from that of Cartier or the Iroquois? Was it appropriate to try the diets on his crew members without their consent? Were Lind's results more trustworthy than the Iroquois'? On what does one base such a judgment?

2.9 'Picture Perfect? Making Sense of the Vast Diversity of Life on Earth' by Katie Carter (2007)

Prince Frederico Cesi in the late 1500s used his wealth in a then novel enterprise: documenting the whole of nature and establishing its order. He founded the Accademia Lincei (now regarded as the first scientific society), which included Galileo as one of its esteemed members. Central to Cesi's mission was an effort to record permanently the essential 'reality' of impermanent living specimens through renderings on paper. In this case study, students form mini-scientific societies with the same challenge of documenting and classifying the vast diversity of living things—leading to student discussion and discovery about the role (and limits) of visualization, the significance of a classification system, and the problematic status of anomalous (versus 'normal') samples.

Major NOS themes highlighted here include: (1) funding. Science is not free. Here, we see how the time for research was provided by someone of wealth with a particular interest. But it poses the question of how scientific study occurs without such individual patrons. (2) institutions for social interaction. The Accademia Lincei provided a structure for collaboration and for constructive mutual criticism. Students get to experience that in their own groups. (3) visualization and documentation. Prince Cesi (and others at the time, like Ulisses Aldrovandi) imagined that an accurate illustration provided an adequate record of natural specimens. But as students experience, they encountered problems about perspectives, variation among samples, hidden details and more. Observations may be important, but here one must confront the problems of capturing those observations in a more permanent form that allows study and further discourse. (4) the limits to 'lawlike' ordering of nature. Not all natural specimens fit into exhaustive and mutually exclusive groups. How does one deal with overlapping categories and instances that seem to fit into none? Is a goose barnacle a plant, a strange bird, or a mollusk?

2.10 'Splendor of the Spectrum: Bunsen, Kirchoff & the Origin of Spectroscopy' by Sam Jayakumar (2006)

Robert Bunsen and Gustav Kirchoff met in 1851 and, even with their strikingly different body types, became life long friends. Bunsen, a chemist, was expert at instruments, including the burner that now bears his name. Kirchoff, a physicist, was more mathematically oriented and analyzed electrical circuits. Together, they collaborated on the problem of analyzing the color of light emitted by burning different elements. Their invention of the *spectroscope* led them to discover two new elements and establish an important form of chemical analysis.

Major NOS features highlighted in this episode include: (1) collaboration. In what ways did the development of the spectroscope and the subsequent discoveries of cesium and rubidium depend on the skills of both Bunsen and Kirchoff? How did they come to join their expertise? (In this case, friendship preceded collaboration!) (2) instrumentation. While spectra lines are a standard part of modern analysis, noticing them requires a very specific arrangement of lens and direction of light. Here, the history of the apparatus is critical to the discovery of concepts. (3) long-unsolved puzzles. Students originally think about Wollaston's and Frauenhofer's observations of spectra lines in 1802 and 1814. It was nearly a half-century later that Kirchoff brought new approaches that allowed him to explain them, a challenge presented to the students.

2.11 'Freedom from Decision: The Psychology of B.F. Skinner' by Adam Gallagher (2005)

Psychologist B.F. Skinner observed pigeons roosting outside his window at the University of Minnesota one day, and this led to him using them in what would later become his most famous series of experiments. The significant but unplanned event epitomizes the unexpected unfolding of his research. This case study follows Skinner from his initial explorations of perceived shortcomings in Pavlov's conditional-response theory. Students follow his emerging thoughts on 'superstition' and ultimately reach his provocative views on human's lack of freedom in decision making.

Here the NOS elements that come to the foreground include: (1) nature of scientific discovery and creativity. This case exhibits many occasions where 'chance' or historical contingency intervenes. This type of lesson about the nature of science cannot be learned in a student's own classroom investigation and illustrates the important role of historical cases. (2) growth of knowledge and conceptual change. Students are exposed to the status-quo of psychology in the 1920s, then introduced to B.F. Skinner who took those ideas and changed them to cover some perceived shortcomings. (3) scientific ideas and cultural values. Students reflect on Skinner's views about determinism and their implications for cultural concepts of free will.

2.12 'The King of Colors: The Chemistry of Indigo and Other Dyes' by Deborah Gangnon (2006)

The dyeing of fabrics goes back over 4,000 years. In this module students explore the history and chemistry of indigo, including dye recipes from an Egyptian papyrus from the 4th century and a Liberian legend about how the properties of indigo were discovered. They also investigate how the dye is extracted and produced, including fermentation, reduction and oxidation reactions. Students reflect on the nature of discovery, investigation and the various ways knowledge of chemistry may develop.

Major NOS themes include: (1) science in different cultures. The origin of indigo as a dye in many non-Western cultures offers an opportunity to reflect on the modern view of 'science'. (2) nature of discovery. Plants that yield the blue indigo dye do not appear blue. So how did someone discover their use? How did they make it work? Did they get the results they wanted right away? (3) science and commerce. Students explore the economic impact of indigo on dye-producing countries and the Old and New Worlds.

2.13 'The Earliest Microscopes' by Kristin Gabel (2005)

This case study situates students in the 1600s when the first microscopes appeared. Images by Robert Hooke provide inspiration for the student's own observations and explorations of the technical aspects of this new instrument (lighting, magnification). They also encounter the challenges of recording information visually—and how that once helped pay for science.

Major NOS themes include: (1) role of instruments. Students see how certain discoveries were made possible by the microscope. (2) role of visual rendering (scientific communication). Science is not just about measurement and numbers. The role of accurate drawings is profiled here. (3) role of funding/patronage. Students follow in the footsteps of Galileo, who helped secure financial support by creating a new coat of arms for a wealthy patron—based on a microscopic image of bees.

2.14 'Maize: Indigenous Agriculture & Modern Genetics' by Shawn Kuykendall (2005)

Maize, or corn, serves an occasion for a series of lessons about the basis for agricultural knowledge in two different cultures: subsistence maize farming in Mexico and large scale monoculture farming in the U.S. In particular, it shows how practices once considered primitive by Western culture reflect sustainable methods in their native environments and cultures—methods now being taken more seriously by modern societies. Topics also include nutrition, genetic history of modern corn, origins of cultivation, nitrogen cycle and fertilizers, and pesticides.

A second module focuses on genetics, using maize as a model organism. Students learn about selective breeding of plants, hybrid plants, basic genetic elements within maize and modern genetic technologies. Includes standard concepts of inheritance, epistasis and transposable genetic elements, illustrated through examples in maize; economics of hybrid corn; ethics of genetically modified (GM) foods.

Major NOS elements include: (1) science in different cultural contexts. Students reflect on the surprising effectiveness of indigenous agriculture techniques in southern Mexico when compared with industrial farming. (2) ethical dimensions of scientific knowledge. Students discuss whether humans should genetically modify food crops. (3) model organisms. Here, maize is an exemplar for many scientific concepts, introducing the role of studying certain organisms in depth and generalizing from them.

2.15 'Contested Currents: The Race to Electrify America' by Steven Walvig (2010)

At the end of the 19th century, the two titans of the new electrical age, Thomas Edison and George Westinghouse, vied in establishing widescale electrical systems. In this case study, students become members of the 1893 Exposition Planning Committee to decide who should power the World's Columbian Exposition in Chicago—and possibly all of America. Information at different levels, from elementary through high school, adds increasing depth of understanding to interpreting the nature and consequences of AC and DC current.

Major NOS elements highlighted in this treatment of the case include: (1) the role of personality in science. Through narrative, students learn about the character and ambitions of the two lead scientists and how this propelled their work. This, too, is a nature of science lesson that is hard for students to appreciate from reflecting on their own classroom work, thus underscoring again the role for history. (2) competition in science. Sometimes there are alternative theories to consider and sometimes, as in this case, there is quite literally a contest. Here, the competition was a public policy decision based on scientific knowledge about AC and DC currents. (3) science and commerce. Knowledge about how to transmit electricity over long distances (based on resistance in the lines) had great ecnomic implications.

2.16 'The Soul Made Flesh: An Introduction to the Nervous System' by Michelle Stanley (2007)

Where do emotions reside? (Where is the 'soul' embodied?) For many years, the heart was considered the source of all emotions. In this case study, student follow Thomas Willis, who built on William Harvey's work on circulation and shifted focus to the brain in the late 1600s.

Major NOS themes include: (1) conceptual change. A prominent case of someone with migraine headaches led to questions about the source of pain and feeling, which eventually challenged existing ideas that the heart was the seat of emotions (as is still expressed in common metaphors today). (2) science, class and gender. The person with the migraines was Lady Anne Conway, who was quite intelligent but as a woman excluded from academic study, even of her own malady. Her class status, however, allowed her access to physicians with whom she could share her ideas. (3) role of social interactions in science. Conway's physician, Thomas Willis, was part of a circle of friends who shared ideas in investigating the brain. Could he have made all his discoveries alone? (4) ethics of experimentation. Thomas Willis was able to persuade many upper class patients with illnesses to allow post-mortem dissection. But following William Harvey, he also conducting vivisections—for example, injecting ink into a dog's blood and thereby revealing for the first time the massive network of blood vessels supplying the brain. Students are asked to consider (and compare) the effectiveness of such experiments with their moral status. What does 'good' science mean?

2.17 Works in Progress

Over a dozen more cases, from 'Marie Tharp & Mapping the Ocean Floor' and 'Charles Keeling & Measuring Atmospheric CO_2' to 'Inventing Temperature' and 'Archibold Garrod & Inborn Errors in Metabolism', have been developed and are awaiting editorial revision and preparation for online publication. Of course, none of the cases, individually, can convey all that students need to know about the nature of science. They complement one another in ensembles of cases, with prominent themes reappearing and reinforcing central lessons.

3 Commentary

These cases are examples of much needed resources. They were assembled based on features that recent research and experience have indicated such resources should ideally exhibit (see Minstrell and Kraus 2005; Klassen 2006). The recent HIPST Project articulated many of these in their Quality Standards document (2008b), derived from their statement of the theoretical basis for the project (2008a). Here, standards 5–9 are particularly important. They address:

- portraying nature of science
- portraying the tentative (or provisional) nature of science
- portraying the human and cultural context of science
- portraying history in its original context
- using inquiry learning

While the Minnesota cases exhibit a variety of styles (reflecting in part the diverse personalities and styles of individual authors and teachers), all endeavor (with varying levels of effectiveness, perhaps) to address these central aims.

Most important, research has indicated that effective NOS lessons tend to be both explicit and reflective (Craven 2002; Schwartz et al.2004; Scharmann et al. 2005; Seker and Welsh 2005). Essentially, this combines the standards for portraying NOS (#5) and using inquiry learning (or any standard constructivist pedagogy; #9). That is, students do not learn merely by watching videos, hearing stories, or even doing experiments. Nor can one expect lecturing about NOS tenets to be fully effective, even if illustrated with vivid historical examples (McComas 2008). Activities and discussions should *actively engage students in thinking about NOS problems* and in *articulating their developing perspectives*. The effectiveness of active learning has already been widely acknowledged throughout all types of education (Bonwell and Eison 1991; National Research Council (NRC) 1997; Mayer 2004; Michael 2006): NOS education is no exception. The Minnesota cases incorporate occasions to engage students through open-ended problems and questions interspersed throughout the text.

As noted in a review of the many HIPST cases by the project's Advisory Board (2010), one particular standard has seemed especially challenging: presenting science as 'developmental, changeable, tentative and contingent' (#6). This theme, often labeled 'tentativeness' of science, has been central to visions of NOS education for over four decades (Lederman et al. 1998). Five of the Minnesota cases address conceptual change explicitly. For example, one case addresses how Berzelius's electrical concept of atoms excluded the possibility of diatomic molecules, but was later qualified, opening the way for Avogadro's hypothesis on the volumes of gases. Another conveys how William Harvey's landmark work on circulation promoted erroneous views of the role of the heart in vivifying the blood, and how that was ultimately remedied decades later by Richard Lower. Other cases approach the theme of development by underscoring the limitations of scientific thought. For example, the cases on smallpox variolation from Turkey and on Native American herbal remedies highlight the role of credibility and cultural contexts, along with the potential bias they introduce.

Second, in aiming to 'portray science as rooted in culture, history and society as a whole' (HIPST Quality Standard #7), one should 'avoid Whiggish views on history of science' (#8). That is, as noted elsewhere, examples should be authentic (Cunningham and Helms 1998; Schwartz and Crawford 2004; Wong and Hodson 2009a, b). Resources should draw on real science and scientific practice, whether from historical case studies (Conant 1947; Solomon et al. 1992; Irwin 2000), contemporary case studies (Wellington 1991; Dimopoulos and Koulaidis 2003; Wong et al. 2008), a student's own investigative experience, or all combined (Osborne et al. 2003). Decontextualized "black box" activities, like mock forensics, while not wholly unhelpful, have limited effectiveness (Clough 2006). Indeed, given that an ultimate aim is typically 'scientific literacy', the classroom will contextualize science in social, political, economic and cultural, as well as experimental and theoretical, settings.

3.1 Problematizing NOS

One may articulate these two primary standards—explicit NOS reflection and authentic cases—in further detail. First, how does one guide students towards reflecting fruitfully on NOS? One may, of course, ask students plainly to comment on features of particular scientific episodes or narratives of research (Clough 2010). Yet such analysis is likely remote, given the student's role as a spectator, not fully immersed in the scenario. As observed in other fields of education (including science), students learn most effectively when addressing and solving problems. That is, one may consider NOS education in the context of case-based and problem-based learning, already well established and researched in other contexts. While such teaching formats are often framed in narrowly prescriptive and programmatic ways, the extensive literature on these modes of teaching may well inform NOS education (Lundberg et al. 1999; Major and Palmer 2001). The level of student autonomy, or the amount of guidance needed by students, will depend, of course, on the individual classroom, the level of student skills, and a teacher's own skills in facilitating discussion. The Minnesota cases aim to contextualize and frame NOS reflection through concrete problems in historical and biographical contexts.

Most notably, in the model of inquiry learning, instruction ideally becomes student-centered. A primary challenge is to motivate student engagement. Adopting this orientation, one might shift the characterization of NOS: from tenets (to be learned) to questions (to be answered by students through informed reflection) (Clough 2007). That is, declarative NOS knowledge needs to be *problematized*. One needs to reframe familiar NOS tenets (Lederman et al. 2002; Osborne et al. 2003) as *unsolved NOS problems*. The problems must also be accessible: on a scale of human decisions and choices. A corresponding challenge for developing resources, then, includes contextualizing NOS issues in authentic cases and framing them for students at an appropriate developmental level. Historical context can be especially valuable for "motivating" the NOS problems. For example, in one Minnesota case study, the student assumes the role of Robert Hooke and considers the problem of someone else claiming to have invented the watch spring, which he believes is his own discovery (NOS: priority and credit). In another, students must imagine themselves as members of a new academic society in the early 1600s (akin to Prince Cesi's Accademia Lincei) and decide whether to document a set of new organisms through drawings, descriptions, or some other means (NOS: role of visualization). Another poses an ethical question about Thomas Willis's surgical experiments with dogs in the 1600s (NOS: research ethics).

The role of problems and active reflection is especially important where the goal is developing analytical skills. 'Scientific literacy' implies not merely recognizing that 'science is tentative' or 'observations are theory laden', but being able to assess particular claims encountered in everyday life (Rudge 2010; Allchin 2011). Skill development needs modeling and practice (Minstrell and Kraus 2005), not just stories.

The Minnesota cases generally adopt the format of an 'interrupted case study' (Hagen et al. 1996; Herreid 2005). That is, a narrative is interspersed with scientific and meta-scientific problems. Further, to foster fruitful reflection and skill development, the problems are open-ended (vs. close-ended) (Cliff and Nesbitt 2005).

The aim of problematizing NOS raises the question: how does one identify significant or meaningful NOS problems? Just as one might turn to past episodes of 'science-in-the-making' to profitably profile the process of science (Latour 1987), historical perspective can illuminate NOS development. Science methodology, like science itself, has historical roots. Even the notion of controlled experiment has a history (Boring 1954). The effect of gender or ethnic bias in science, too, was not self-evident, with substantive awareness not emerging largely until the 1970s. That is, NOS questions emerge by engaging science *in practice*. Case studies, when not unduly truncated or abridged, allow one to identify and contextualize NOS problems, and thus stimulate effective NOS reflection, discussion and/or problem-solving.

Another method for framing NOS problems is to profile *NOS-anomalies*, or '*discrepant NOS events*' that address popular or naive NOS conceptions. Such occasions of 'cognitive dissonance' may, with appropriate guidance, help motivate and orient inquiry specifically on NOS themes and deepen understanding. Accordingly, resources will benefit from sensitivity to student *NOS* misconceptions as well—and to their historical counterparts. NOS problems may thus frequently focus on errors or missteps in science, because they highlight methodological questions and lead to discussion about how to remedy the mistakes and/or avoid them in other cases (Allchin 2001b). For example, the Minnesota case on B.F. Skinner underscores the gradual nature of his discovery of operant conditioning—

at odds with the popular notion of ‘eureka’-like moments of scientific insight. In another, discussion of the competition between Westinghouse’s alternating current (AC) and Edison’s direct current (DC) challenges the student to consider whether science is always ‘pure’ and how research may intersect with commercial interests.

3.2 Fidelity to Authentic Science

The second fundamental NOS teaching standard—fidelity to authentic science—adds yet further challenges to effective resource development. Foremost, case studies must be historically *and* philosophically *and* sociologically well informed. Otherwise, rather than convey well informed NOS, they present a distorted caricature, readily susceptible to naive NOS preconceptions (Allchin 2004). That is, they can easily perpetuate the grossly under- or ill-informed NOS views promoted decades ago, which current instruction hopes to remedy (Kelly et al. 1993; NRC 1996). In particular, the process of scientific discovery must be properly contextualized, not ‘rationally reconstructed’ or romanticized—at least if one intends to honor such appeals as Clough and Olson’s (above) to render the nature of science accurately (Allchin 1995, 2003, 2006). NOS problems will likewise be situated in concrete contexts, not abstract metaphysical space. Accordingly, resources worth preserving—or worth distributing on a wide scale—will reflect the participation and expert review of professional historians, philosophers and sociologists of science (as exemplified in the Minnesota Case Study Collection). Complementary skills are needed and require cross-disciplinary collaboration. NOS education thus requires integrating expertise beyond the experience of most science educators, just as it requires more educational expertise than most historians, philosophers or sociologists of science can provide unassisted.

3.3 Other Aims, Other Resources

Yet other principles guided the development of the Minnesota Case Studies as NOS resources. For example, NOS learning ideally integrates seamlessly with science content and process of science skills: ‘Whole Science’ (Allchin 2011). NOS thereby emerges as a part of science itself, not as a peripheral or dispensable adjunct. When NOS lessons are designed as sidebar vignettes for textbooks, or as anecdotal asides, or possibly even as specialized lessons, one conveys significant messages to students about the (ir)relevance of NOS. A supplemental guiding principle, then, used in the Minnesota cases has been an appreciation for teaching science, process of science skills, and NOS reflection as an integrated ensemble (Hagen et al. 1996, v–vii; Minstrell and Kraus 2005; Friedman 2009). Such a broad-scope approach readily accommodates other widespread objectives, as well, such as profiling ‘science as a human endeavor’ (NRC 1996; Rutherford and Ahlgren 1990). Laboratory activities or investigations can be integrated as opportunity allows. For example, students classify organisms in ‘Picture Perfect’, weigh gases in the case on Avogadro, and explore heat as a variable in dyeing with indigo. Standard labs, such as ones on spectroscopy or exploring light and magnification of the microscope, can also be coupled with and contextualized by the historical narratives (not all the Minnesota Cases include labs). As noted recently by Clough and Olson in this journal, ‘teaching the NOS in this highly contextualized manner is important in persuading teachers that NOS instruction need not detract from, and can likely promote, science content learning’ (2008, p. 144).

Finally, perhaps, ideal resources are public, not proprietary. If available online, the “package” should be easily downloadable in one file or compressed folder (Friedman

2009). The Minnesota cases are freely available on the SHiPS Resource Center website (http://ships.umn.edu/modules).

4 Prospects

The multiple demands of ideal NOS lessons—historically informed inquiry cases that foster NOS reflection and engagement with faithfully rendered 'Whole Science'—may seem to limit the development of good resources. Advocates of NOS education, however, may be well advised to keep their eye on the ultimate goal, and proceed, like the fabled tortoise, slowly but surely—lest they stray from an ultimately productive trajectory. Still, some such resources, in addition to the Minnesota Cases, are already available. Notably, over a decade ago, Hagen et al. (1996) offered a set of seventeen historical case studies in biology, focusing on such standard concepts as natural selection (peppered moth), homeostasis, sex-linked inheritance, endosymbiosis of mitochondria, the citric acid cycle, production of antibodies, and behavior as an adaptation. One case from that collection, on Nobel Prize-winner Christiaan Eijkman and the search for the cause of beriberi, exemplifies the potential of such resources (Allchin 2001a). Namely, such cases can, as outlined more recently by Metz et al. in this journal (2007, pp. 320–321):

- engage students' prior NOS conceptions
- motivate student interest in inquiry by situating research in human and cultural contexts
- foster student reflection with questions that punctuate an investigative "narrative"
- allow students to engage in open-ended discussion and problem-solving, both individually and collectively, both orally and in writing.

Other fine recent examples, beyond those from the HIPST Project (2010, and profiled in this special issue), and exhibiting a variety of case study styles, include:

- *Modeling Mendel's Problems* (Johnson and Stewart 1990)
- *Evolution of the Theory of the Earth* (Dolphin 2009)
- *Sickle-Cell Anemia and Levels in Biology, 1910–1966* (Howe 2010)
- *William Thompson and the Transatlantic Cable* (Klassen 2006)
- *Henry David Thoreau and Forest Succession* (Howe 2009)
- *Rekindling Phlogiston* (Allchin 1997)
- *Of Squid Hearts and William Harvey* (Allchin 1993)

Other, more ambitious modules situate students in a richer historical setting suitable for simulation and/or role-playing—that is, rehearsing for scientific-literacy-in-practice:

- *Darwin, the Copley Medal and the Rise of Naturalism* (Dunn et al. 2009)
- *Debating Galileo's Dialogue: The 1633 Trial* (Allchin 2009a)
- *Debating Rachel Carson's Silent Spring: The President's Committee on Pesticides, 1963* (Allchin 2009b)

These large-scale works exemplify the virtues of work developed over several years: work that is ultimately worth sharing and using widely.

All these cases, like the Minnesota Case Study Collection, contrast notably to the short stories or vignettes frequently found in textbooks and elsewhere. First, such anecdotes, while entertaining and memorable, may not lead to the desired, more sophisticated NOS lessons. Everyone knows the story of Newton and the apple, but towards what end? Such anecdotes do not engender the explicit reflection that is needed. Second, they are not boiler-plate lessons, that merely illustrate some prescribed NOS tenets. Rather, they open inquiry into NOS and invite reflective discussion. They use problems to teach NOS, as found fruitful in other contexts. The role of case studies is to provide substantive lessons in NOS, deeper than the superficial treatment of anecdotes and stories.

Resources such as those profiled here, while essential, hardly meet all the various challenges in implementing NOS in the classroom. For example, practicing teachers often tend to follow habits and resist departures from content (Höttecke and Celestino Silva 2010). One major constraint is the trend of institutional accountability, biasing the incentive structure for teachers. Teachers inevitably teach to the tests. However, even where national or state curricula include NOS as a goal, effective tests for assessing NOS understanding are not always present. The instrument most widely used by science educational researchers, VNOS, has a disclaimer against being used in formal classroom assessment (Lederman et al. 2002). VNOS has also been widely criticized for not measuring the important dimensions of NOS (Ford 2008; Rudge 2010). However, a new alternative approach, modeled on the standardized Advanced Placement essay, probes NOS understanding through the analysis of contemporary cases in the news (Allchin 2011). It echoes aims sketched by a group of teachers, scientists, policy makers, and philosophers at the 2009 meeting of the Society for the Philosophy of Science in Practice: NOS understanding should contribute to scientific literacy in real-life settings. This approach underscores the need for NOS analytical skills, as developed through complex case studies such as presented here.

Still, from the perspective of the practicing teacher, the availability of high quality materials is a significant limiting factor. Development of such materials involves a significant investment of effort and melding of expertise. Ideally, such resources are thus shared. But they must be developed first. If one believes, for example, that Nash's account of Joseph Priestley and the gases released by plants (described above) is inadequate, one should write the case study rather than describe how *someone else* should do it (for example, Matthews 2009, pp. 951–955). As noted by Dolphin (2009, quoted in opening above), educators need resources now, not yet more declarations about how important they are. Like the HIPST Project, the Minnesota Case Study Project presented here addresses that implicit challenge.

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