ABSTRACT. The status of consensus on nature of science (NOS) education indicates the need for less pontificating and more action. Standards for NOS teaching resources, based on research to date, are reviewed. Examples, including the new Minnesota Case Study Collection, are profiled. All illustrate the dual aims of (1) historically informed problem-based learning that fosters explicit NOS reflection and (2) engagement with faithfully rendered samples of Whole Science.

Keywords: case study teaching; nature of science; historical simulation;

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), and even many facets that foster effective NOS learning. Yet 'despite this cheery consensus regarding the importance of accurately teaching NOS,' Clough and Olson caution 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). The primary challenge has shifted. The tide has turned from rhetoric to resource development.

What features does research indicate such resources should ideally exhibit (Minstrell & Kraus 2005, Klassen 2006, HIPST 2008)?

First, effective lessons promote explicit NOS reflection (Craven 2002; Schwartz, Lederman & Crawford 2004, Scharmann et al 2005, Seker & Welsh 2005). 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. Exercises must 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 & Eison 1991, NRC 1997, Mayer 2004, Michael 2006): NOS education is no exception. Ultimately, resources should be informed by the best available research in the cognitive science of learning and educational psychology (Duschl 1990).

contemporary case studies (Wong et al. 2008), a student's own investigative experience, or all combined. Black box activities, 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.

Following these two standards, one may establish further detailed objectives. For example, 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 2007). 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, nature of science education may productively be viewed in the context of problem-based learning (PBL) (Savery & Duffy 1995, Duch, Gron & Allen 2001, Hmelo-Silver 2004, Major & Palmer 2005). Here, the aim is to address problems specifically in NOS. That is, declarative nature of science knowledge needs to be problematized. One needs to reframe familiar NOS tenets (Lederman et al. 2002) as unsolved NOS problems. The problems must also be accessible: on a scale of human decisions and choices. The challenge in developing resources, then, includes contextualizing NOS issues, "motivating" the problems, and framing them for students at an appropriate developmental level (with an eye towards supporting successful problem-solving experiences).

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. Skill development needs modeling and practice (Minstrell & Kraus 2005), not just stories.

How does one identify significant or meaningful NOS problems? Just as one might turn to 'science-in-the-making' in history to profitably profile the process of science (Latour 1987), historical perspective can illuminate NOS development. Science methodology, like science itself, has a history. Even the notion of controlled experiment is a contingent result, based on resolving problems in generating research results that can be interpreted reliably and meaningfully (Boring 1954). The effect of gender or racial 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 important strategy (based on general research on learning) 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 discussion about how to remedy the mistakes and/or avoid them in other cases (Allchin 2001b).

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, Carlsen & Cunningham 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 distributing on a wide scale) will reflect the participation and expert review of professional historians, philosophers and sociologists of science. NOS education thus requires integrating expertise beyond the experience of most science educators.

One may identify yet other desiderata to NOS resources. For example, NOS learning ideally integrates seamlessly with science content and process of science skills. 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, may be an appreciation for teaching science, process of science skills and NOS reflection as an integrated ensemble (Hagen, Allchin & Singer 1996, vi-vii; Minstrell & Kraus 2005, Friedman 2009). Moreover, ideal resources will profile the full spectrum of contexts for scientific practice—from experiment and reasoning about observations to selective funding and culturally shaped cognitive blindspots: the touchstone of authentic science implies completeness. Authenticity implies Whole Science (Allchin 2010). Such a broad-scope approach readily accommodates other widespread objectives, as well, such as profiling 'science as a human endeavor' (NSES 1993, Rutherford and Ahlgren 1991). One may surely include laboratory activities or investigations where appropriate and as opportunity allows. As noted recently by Metz et al 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' (2007, 144).

Finally, perhaps, resources should be public, not proprietary. If available online, the "package" should be easily downloadable in one file or compressed (zipped) folder (Friedman 2009).

Given all these multiple demands—historically informed PBL that fosters NOS reflection and engagement with faithfully rendered 'Whole Science'—one might well imagine that the development of good resources is nigh impossible. 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.

Indeed, some such resources 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 1997a, 2001a). Namely, such cases can:

• 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
— all assets of science narratives echoed recently in this journal (Metz et al 2007, 320-321).

Other fine recent examples, beyond those profiled in this volume, include:
  • *Modeling Mendel's Problems* (Johnson & Stewart 1990)
  • *Sickle-Cell Anemia and Levels in Biology, 1910-1966* (Howe 2005)
  • *William Thompson and the Transatlantic Cable* (Klassen 2006)
  • *Henry David Thoreau & Forest Succession* (Howe 2009)
  • *Rekindling Phlogiston* (Allchin 1996)

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.

*The Minnesota Case Study Collection*

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'. Today, educators regard the NOS in his 2-
volume collection of cases as far too narrow and thus potentially misleading. 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. Still, the
Harvard case studies provide an inspiring model for new historical cases with updated NOS.
Indeed, "it is time," Stinner et al (2003) observed, "that the ideas of James Conant's case
studies be updated and revised to serve the needs of 21st century students and societies" (p.639).
That explicit challenge has now been met. 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. They address the new standards outlined above and are now
freely accessible online. The cases are hosted by the SHiPS Resource Center (ships.umn.edu),
the internet home of a network of teachers that originated at the First International History,
Philosophy and Science Teaching Conference in Tallahasee in 1989. Samples of these historical
problem-based case studies are summarized below:

**Richard Lower and the 'Life Force' of the Body**
by Erin Moran

What makes the heart beat and the blood flow, features so closely associated with life?
Even in modern times, vitalist assumptions linger. 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:

- science in personal, cultural and historical contexts
- different interpretations of the same evidence
- conceptual change.
- collaboration, both direct and indirect

Lady Mary Wortley Montagu & Smallpox Variolation in 18th-Century England
by Erika Remillard-Hagen
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 skepticism. 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:

- credibility in science (evidence versus personal testimony)
- the cultural context of scientific thought and reasoning
- controlled "clinical" study
- science and gender

Robert Hooke, Hooke's Law & the Watch Spring
by Shusaku Horibe
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:

- scientific careers (and social class)
- credit and priority (and social class)
- nature of discovery

Splendor of the Spectrum: Bunsen, Kirchoff & the Origin of Spectroscopy
by Sam Jayakumar
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
Determining Atomic Weights: Amodeo Avogadro & His Weight-Volume Hypothesis
by Lindsey Novak

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 diatomic molecules. But that concept conflicted with other theories, and chemists deferred to the views of the revered Jacob Berzelius. Now 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 at diatomic.

Debating Glacial Theory, 1800-1870
by Keith Montgomery

In the early 1800s, geologists traveled widely, documenting the landscape, asking various questions about landscapes and geologic history. By 1840, they were addressing the startling proposal that glaciers occurred 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:

- conceptual change
- nature of field work
- historical reasoning
- role of personality/politics of science

Interpreting Native American Herbal Remedies
by Toni Leland

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 with 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:
• science in different cultural contexts
• credibility
• role of experiment and controlled investigation

Picture Perfect?: Making Sense of the Vast Diversity of Life on Earth
by Katie Carter
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 elements include:
• funding
• institutions for social interaction
• visualization and documentation
• the limits to 'lawlike' ordering of nature

Freedom from Decision: The Psychology of B.F. Skinner
by Adam Gallagher
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 initially 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. Major NOS elements include:
• nature of scientific discovery and creativity
• growth of knowledge and conceptual change
• scientific ideas and cultural values

The King of Colors: The Chemistry of Indigo and other Dyes
by Deborah Gangnon
The dyeing of fabrics goes back over four thousand 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 elements include:
• science in different cultures
• nature of discovery
• science and commerce
Perfumes: Distillation for 17th-Century French Courts
by Sandy Stai

The setting for this case study is 17th-century France, the subject: perfumes. Students respond to a royal commission to develop an original perfume (or cologne) by using distillation of plant materials. They must interpret their work in contemporary terms. Advanced classes may explore the nature of specific organic chemicals (terpenes, esters, aldehydes, etc.) and Dalton's Law of partial pressures. Major NOS elements include:

- cultural context of science
- nature of investigation and discovery
- science and the arts

Maize: Indigenous Agriculture and Modern Genetics
by Shawn Kuykendall

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 GM foods.

Major NOS elements include:

- science in different cultural contexts
- ethical dimensions of scientific knowledge
- model organisms

Contested Currents: The Race to Electrify America
by Steve Walvig

At the end of the 19th century, the two titans of the new electrical age, Thomas Edison and George Westinghouse, vied in establishing widespread 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, add increasing depth of understanding to interpreting the nature and consequences of AC and DC current. Major NOS elements include:

- the role of personality in science
- competition in science
- science and commerce
'The Soul Made Flesh': An Introduction to the Nervous System
by Michelle Stanley

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 elements include:
- conceptual change
- science, class and gender
- role of social interactions in science
- ethics of experimentation

Commentary

These cases contrast, notably, to the short stories or vignettes. Namely, they aim, first, to go beyond the anecdotal mode, which while often entertaining and memorable, may not lead to the desired lessons, which require deeper reflection and engagement. Second, they are not short boiler-plate lessons, that merely serve up an illustration for students to make a prescribed conclusion about some particular NOS tenet. Rather, they open inquiry into and explicit, reflective discussion on NOS. That is, they use problem-based learning strategies to teach NOS, just as one might use them to instill scientific concepts along (loose) constructivist principles.

The role of case studies is to provide substantive lessons in NOS, deeper than the superficial treatment of anecdotes and short stories.

Finally, while resources are best viewed as tools for creative teachers in individual classroom contexts, one can be sensitive to the contexts of evaluation, especially where contexts of accountability are primary factors shaping classroom focus, activities and time management. Unfortunately for the classroom teacher, and those who would provide materials for them, the instrument most widely in use among science educational researchers, VNOS, includes a disclaimer, cautioning against use in formal classroom assessment (either formative or summative).

References


Allchin, D. 1997b, 'Rekindling Phlogiston: From Classroom Case Study to Interdisciplinary Relationships', Science & Education 6, 473-509. See also URL: ships.umn.edu/modules/
Allchin, D. 2001b. 'Error types', Perspectives on Science 9, 38-59.
Allchin, D. 2010. 'Whole science', 8th International Conference for the History of Science in Science Education, Maresias, Brazil.
Clough, M.F. 2006. 'Learners' responses to the demands of conceptual change: Considerations for effective nature of science instruction', Science & Education 15, 463-94.
Friedman, A. 2009. 'But what does it look like? Exploring the use of the history of science in one high school's bioogy classroom', 9th International History, Philosophy and Science Teaching Conference, Notre Dame. URL:
HIPST [History and Philosophy in Science Teaching Consortium]. 2008. 'Theoretical basis of
the HIPST Project'. URL: hipstwiki.eled.auth.gr/hipst_htm/theoretical_framework.htm.


Scharmann, L.C., Smith, M.U., James, M.C. & Jensen, M. 2005. 'Explicit reflective nature of science instruction: evolution, intelligent design, and umbrellaology', Journal of Science


Schwartz, M.S., Sadler, P.M., Sonnert, G., & Tai, R.H. 2008. 'Depth versus breadth: how content coverage in high school science courses relates to later success in college science coursework', *Science Education* 93, 798-826.


Wong, S.L. & Hodson, D. 2009a. 'From the horse’s mouth: what scientists say about scientific investigation and scientific knowledge', *Science Education* 93, 109 – 130.
