Chapter 32

Historical Inquiry Cases for Teaching Nature of Science Analytical Skills

Douglas Allchin

32.1 Science in Action and History

Imagine learning science alongside a famous scientist from history. Not just the concepts but also how science works. You are challenged to address the same problems and to participate in planning investigations, interpreting evidence, analyzing arguments, imagining alternative explanations, and assessing possible errors. For example, follow Nobel Prize winner Christiaan Eijkman as he searches for the cause of beriberi (Allchin 2013, pp. 165–183). Or accompany Alfred Russel Wallace as he plans a career collecting natural history specimens and puzzles about the origin of new species (Friedman 2010; see also text box below). Assume the role of Dave Keeling as he tries to measure precisely atmospheric concentrations of carbon dioxide—and secure funding to do so year after year for four decades (Leaf 2012). These are episodes of historical inquiry. The student who is able to reflect explicitly on the process learns scientific practices and the nature of science (NOS) firsthand, by modestly *doing science* (Hagen et al. 1996; Rudge and Howe 2009).

What is historical inquiry? It combines two familiar approaches to teaching NOS: (1) historical cases and (2) inquiry experience (with explicit reflection). It benefits from the merits of each approach while complementing their respective deficits (Allchin et al. 2014; see Table 32.1). First, history is valuable in contextualizing science, conveying its human and cultural dimensions. Historical narratives also show in detail how science unfolds. They reveal the complexity of laboratory and field practices, the role of chance (or accident), the fine-scale reasoning, as well as the large-scale debates. Historical stories excel especially where student inquiry activities tend to fail: they can cover long periods of

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D. Allchin (✉)
Minnesota Center for the Philosophy of Science, University of Minnesota,
Minneapolis, MN, USA

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Table 32.1 Merits and deficits of modes of NOS instruction (from Allchin et al. 2014, p. 473)

Mode	Merits	Deficits
Contemporary case	Helps motivate engagement through authenticity and "here-now" relevance	Cannot be fully resolved, leaving uncertainty and incomplete NOS lessons
	Can support understanding of cultural, political, and economic contexts of science	Cannot exhibit details of process which are not yet public or are culturally obscured
	Can support understanding of how science and values relate	
	Develops scientific literacy skills in analyzing SSI	
Inquiry	Helps motivate engagement through personal involvement	Difficult to motivate all students, especially as a group
	Fosters personal integration of lessons	May be viewed as artificial exercise or school "game," not as genuine science
	Supports understanding of constructed interpretations, models, forms of evidence, and model revision	When investigations "fail," can prompt negative emotions, alienating student from NOS lessons
	Develops experimental competences: framing hypotheses, designing investigations, handling data, evaluating results	Typically shuttered off from cultural, social, or political contexts
	Relates nature of scientific knowledge to inquiry skills and methods	
	Develops understanding of how scientific claims can be defended or criticized in contemporary SSI cases	Hard to model role of "chance," or contingency
		Requires substantive amounts of time and resources
Historical case	Helps motivate engagement through cultural and human contexts and through narrative format	May seem "old" and irrelevant
		Difficult or time-consuming for teachers to learn background or historical perspective
	Can support understanding of long-scale and large-context NOS features: especially conceptual change, and cultural/biographical/economic contexts of research problems and interpretive biases	If text-based only, limits development of hands-on experimental competences
	Can support understanding of investigative NOS: problem-posing, problem-solving, persuasion, debate	If rationally reconstructed only or presented as final-form content, does not support understanding of "science-in-the-making"
	Can support understanding of complexity of scientific practice, as well as historical contingency	
	Supports analysis of process and product, since ultimate outcomes are known	
	When framed in inquiry mode, can develop scientific thinking skills—more efficiently than with hands-on inquiry	
	Can foster understanding of error and revision—without risking emotions of personal failure	

investigation—up to decades of research. Accordingly, they help convey the important NOS concepts of tentativeness, conceptual change, and the unexpectedness of such change—notoriously difficult to teach otherwise. By following the zigzag of historical development, and by fostering conceptual engagement through inquiry questions, students can be guided stepwise to grapple with the long-term change themselves. Historical cases have long been valued for providing insights into NOS.

At the same time, historical stories can seem remote—about another time and place, other people and other values not relevant today. Here precisely is where the second approach, student inquiry, offers value. According to the now-standard educational ideal (Schwab 1962), students take an active role in their own learning. They are challenged to think creatively and solve problems. By integrating inquiry into history, what would otherwise be a stale story, from a remote third-person perspective, becomes an embodied first-person experience, more memorable and effective from a learning perspective. NOS learning becomes more personalized and more effective.

Just as inquiry enhances the role of the history, the history can enhance the role of the inquiry. Too often, students dismiss their own inquiry activities as not "real" science. In historical inquiry, the problems emerge from original historical contexts. They are rooted in cultural and biographical realities. They help motivate *authentic* engagement (in contrast to decontextualized "black-box" activities or artificially contrived classroom inquires; Klassen and Froese Klassen 2013). With history, students come to understand naturally and vividly another central NOS feature—how science emerges from its social contexts and how its practices are shaped by cultural perspectives. In addition, history can provide the student with some of the intellectual resources to solve the inquiry challenges. After student effort, the history is also a benchmark for comparison. Finally, history delineates a productive path of successive inquiry challenges, not clear when the students act on their own. History thus helps enhance conventional inquiry.

What does historical inquiry look like in a classroom? A sample case—developed by a high school teacher collaborating with a historian of science—is described in the following text box (Friedman 2010). When biology textbooks discuss Darwin's theory of evolution by natural selection, they usually mention his travels on the *H.M.S. Beagle*. Many even discuss the influence of Lyell and Malthus on his thinking. However, historians are well aware that Alfred Russel Wallace independently developed a nearly identical theory on the origin of new species. The case study adapts Wallace's story for students to follow, highlighting his middle class background, his career as a collector, and the observations and experience that led to his own insights. The 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

The basic format is a narrative built around a series of key questions (see more below). The questions—where the real learning is done—aim to engage students in explicit reflection about both the scientific concepts and the nature of science. This case also integrates optional supplemental 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.

Alfred Russel Wallace & the Origin of New Species

by Ami Friedman

First, the teacher opens the case with a brief illustrated sketch of the cultural context in Britain in 1847. This helps to situate science in an accessible human setting. It also introduces some cultural themes that will be echoed later: 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 teacher introduces the central scientific problem, along with the main character: Alfred Russel Wallace and uncertainties about how new species originate. The problem is also presented biographically: Wallace was trying to couple his personal study with collecting exotic animal specimens as a way to earn a living. The concrete human context helps to motivate the scientific inquiry by inviting the student to decide, alongside Wallace, how to finance his collecting expedition abroad. The life story also helps frame the conceptual resources available for students in their own thinking. The teacher pauses in the presentation to allow students time to think and discuss their responses.

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

The narrative strings together a series of questions to actively engage students in and guide them through their conceptual development. For example, 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 lead 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

(continued)

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 Wallace 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. For each question, the teacher acts as a fellow participant and facilitates individual reflection and group interchange. Following discussion, the students are primed to hear how Wallace and his contemporaries reasoned.

The questions are situated historically. But they are also open-ended. Multiple answers are possible. The teacher encourages the students to think broadly. Without being accountable to just one “correct” answer, students more readily contribute to class discussion. In addition, the uncertainty underscores that science is about searching for and reasoning toward answers from the data at hand, not justifying some “right” answer that is already known.

One retrospective question asks students to compare Darwin and Wallace’s ideas and histories. How should one interpret their parallel discoveries? Who should receive credit for discovering the concept of evolution by natural selection? Why? This nature of science feature—about priority and credit—involves a more synoptic perspective but again is open to several views.

As a conclusion, the teacher reprises the NOS elements explicitly. Students 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, and so on. This helps consolidate the NOS learning in the case and prepares students to apply their new knowledge to other cases. Perhaps they record what they have learned in a journal or in a written summary to submit to the teacher for review and comment.

[Summary adapted from Allchin 2012a, pp. 1264–1266]

32.2 History and Science-in-the-Making

Why not just tell historical stories? If history is a valuable source of NOS insight, why not just share NOS anecdotes or assign short vignettes or biographies to read, with the NOS concepts clearly stated and illustrated? Several websites are already beginning to make such stories readily available (www.storybehindthescience.org; www.science-story-telling.eu). While students will benefit to some degree, research on a variety of approaches to teaching NOS indicates that the most effective ones involve an element of inquiry (Bell 2007; Deng et al. 2011). This should not be surprising, given the general importance of inquiry learning. A key element is engaging the learner in the learning process and helping them make the lesson part of their individual cognitive structures. So the aim is to convert history into contextualized questions that specifically spur NOS inquiry.

Another reason to be skeptical about simple stories is the psychological tendencies of storytelling. Humans revel in telling stories. But the goal of entertainment and the desire to be viewed as informative can distort the truthfulness of the content. As a result, science stories tend to glorify scientific heroes, render their character and methods as more perfect than they really were, or monumentalize the achievement of one person at the expense of multiple contributors (Allchin 2003). Science storytellers easily fall prey to idealizations, or rational reconstructions, of the way science "should" have developed (Allchin 2000). As a result, the intended NOS lessons fall by the wayside. Teachers need to delve into the unexpected details of how discoveries actually occurred—sometimes as a result of chance encounters or unrelated developments—for students to be able to discern how science really works. So, the first challenge for teachers is to orient themselves to open questions that delve into the process of science, rather than present neatly prescribed historical "myths" about how science is "supposed to be" (Clough 2007).

In inquiry learning, the instructor's first task is to find questions or problems that will motivate students to *NOS* reflection and *NOS* learning. NOS (not just science) must be *problematized*. For example, "how do we know this evidence is reliable?" Or, "how might our reasoning be mistaken?" Teachers should demur from introducing NOS concepts pre-packaged. In addition, questions must be open-ended. No "teasers" with prescribed tenets that students are supposed to guess (or already know!). No leading the students by the nose to a target answer. History helps here. The key NOS questions are often found embedded in the history itself—another reason for replacing plain student-based inquiry with historical inquiry.

The second task of inquiry-style NOS instruction is to map an effective, loosely guided path from familiar concepts to new concepts. One recreates "science-in-the-making" (Latour 1987; Flower 1995; Allchin 2013, pp. 41–44). Textbooks provide only completed (readymade) science. In inquiry, teachers help students, like scientists, address unsolved problems, propose possible alternative solutions, and then assess and find ways to justify confidence in any answer. Working in that "blindness" is essential. It is very challenging for a teacher who already knows the textbook concept or the actual historical outcome. An instructor who adopts inquiry mode must learn to sacrifice the secure authority of already knowing the right answer or outcome. The focus instead is on the process, the reasoning, and the justifications—the very nature of science in constructing knowledge from scratch. Initially, most teachers struggle mightily to "not know" the right answer. It is hard not to give accidental clues or hints and to be as naive and full of wonder as the students. But it also generates an air of excitement, of suspense, and later the reward of insight. Again, working with this uncertainty in an inquiry environment and struggling toward developing an answer is an integral part of the NOS lesson, as modeled in history. The students are learning, through practice, just like their historical counterparts, what justifies confidence in a solution.

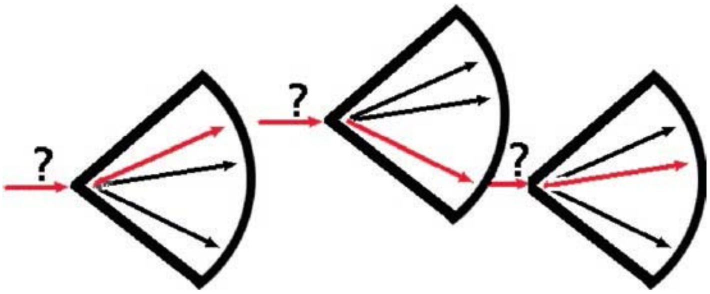

Fig. 32.1 The episodic nature of inquires—a lineage of questions—in a historical case, alternating between open questions and divergent responses

Combining history and inquiry may seem paradoxical. Inquiry learning is inherently open-ended. But the history is already done! It is closed. How can students experience the critical open-endedness in a context of closed history? The answers seem already known. Are the students merely to recapitulate, or repeat, the history, without any genuine input of their own? Are they expected to get the "right" answer—namely, just what history produced? What if they don't? Have they failed? (Without an instructor's guidance, that's exactly what students tend to think.) How can we reconcile open-ended inquiry with closed history?

Because openness and uncertainty are central to the learning process—and to the ultimate NOS lesson—the strategy is to work episodically, with a series of successive inquiries, each more narrowly focused (see Fig. 32.1). At each stage, teachers must give students complete freedom, including the freedom to "fail." It is the work on the individual problems and how they reason or exercise their creativity that matters. There are many possible ways to design a possible experiment for a given question. The history in each case can confirm this. There are usually multiple ways to interpret the results. Again, the history can confirm this. There are typically multiple potential flaws or weaknesses in any claim and multiple ways to respond to criticism. Again, history is a guide. These all enter student discussions and problem-solving. They enrich understanding of scientific practices or how science progresses somewhat blindly to produce reliable conclusions.

A major role for history is to help thread the inquiry episodes together. The history establishes the context for the first problem or question. Students engage in it. They compare solutions, even if they will *later* prove to be wrong. Then, the history is introduced. One learns the perspective of a selected central character (who need not always be correct!). One follows the narrative forward to the next occasion for inquiry. At each juncture, students are free (indeed, encouraged) to think openly. The story resumes with only one of the many possible trajectories, with the fate of all proposed solutions yet to be decided (Fig. 32.1)! The result is a lineage of *questions*, not just answers (Farber 2003).

As history unfolds, the uncertainties from early stages are resolved. Plausible alternatives are reduced as evidence accumulates. Debates are narrowed. Doubts and possible errors are addressed. Multiple forms of evidence converge. Eventually, a new concept emerges, and the students can justly celebrate having participated in its discovery. History is the episodic map for guiding students through an inquiry of science-in-the-making to its resolution.

32.3 Posing Authentic NOS Questions

As noted above, the key to any effective inquiry activity is motivating students at the outset with a good question or problem. Posing such questions is a familiar challenge for all teachers. Namely, how does one engage students in a strange new topic? Here is the great virtue of using history. History provides the critical motivation. One can usually engage student interest with a historical cultural context that makes the inquiry *concrete*, *meaningful*, and *worthwhile*. In addition, by focusing on particular scientists, one finds the biographical contexts (like Wallace's) that prompted someone to personally pursue research. These motivations—*in familiar human terms*—help shepherd students into investing effort in an inquiry activity. This contrasts with how a curriculum is typically characterized: by the *current* relevance of the concept. Ironically, the modern application is often not the original context that initiated the research that ultimately *led to* the concept. For example, the devastating 1906 San Francisco earthquake helped spur research into Earth's crustal movements (Dolphin 2009/2016). The aim was not to discover the yet-unknown plate tectonics. Carlton Gajdusek was motivated to find the cause of a strange disease among a remote tribe in New Guinea (Gros, 2011). The goal was not to discover a new mode of disease transmission. Marie Tharp—who eventually helped discover the mid-Atlantic rift—just wanted an interesting job (Elliott and Allchin 2016). Authentic historical questions help students model the process of doing science and, consequently, foster an understanding of how it works. Historical context is key.

Some popular NOS lessons are wholly decontextualized. They seem to focus on just one NOS concept, abstracted and divorced from the science which it intends to model. However, the artificial, highly contrived nature of such exercises is readily apparent to students, who tend to respond with indifference. They treat the activities as classroom games, not lessons about real science. Many educators regard these "black box" exercises as elegant, economic models of NOS. But that strong aesthetic relies on *already understanding the nature of science*. In a *teaching* context, with naive students, the abstract activities have limited effectiveness. That's why working on cases and authentic questions from history is so valuable. They are fully and richly contextualized. The motivation is real. Accordingly, students are engaged by familiar goals such as curing diseases, producing chemicals for profit, or wondering about the size of the universe.

Thus, the teacher's introduction of the historical problems or questions is not some trivial preamble to the "real" work. *Contextualizing the question through ren-*

dering the original scenario vividly is one of the instructor's most important roles in inquiry learning. So, one should not rush. Devoting ample time to setting the scene, using drama and emotion, is essential.

One fruitful way of closing a historical case is through a contemporary epilogue. How did the science from the past contribute to scientific research that is still continuing now? How did the *nature of* science from an episode in the past reflect how science functions in our society today? One needs authentic (and sometimes complex) cases to think analogically and to transfer NOS lessons to interpreting current claims about health or aging, the environment, or technological risk. Historically based NOS lessons are surely enhanced through retrospective reflection and re-contextualization in the present. That is part of completing the NOS lesson. And such meaningful connections are fostered through authentic NOS questions in real, fully contextualized historical cases.

32.4 Developing Lifelong NOS Analytical Skills

As articulated in the introduction to this volume, NOS education ultimately aims to help students interpret the reliability of sometimes contested scientific claims in personal and public decision-making. To assess those claims effectively, one needs to understand how science works. How are the claims assembled? How is their trustworthiness ensured? Equally, how can they fail? In what sense are they *tentative*? In what ways are they shaped by their *social or political milieu*? What is the *role of empirical evidence*, whether by *experiment or other form of investigation*? How are *inferences* involved and how does one gauge the soundness of the reasoning? NOS understanding is, ultimately, about supporting analytical thinking skills. It is not to recite or explain a list of NOS tenets. Active, inquiry-style learning is well adapted to the aim of developing skills for assessing the reliability of scientific claims (as discussed above). It engages students in exercising and practicing those skills. Students are also able to evaluate their own performance in reasoning and, through discussion with other students and instructors, adjust it and improve it. A focus on skills is another reason why working side by side with great scientists from the past can be so valuable.

Not surprisingly, perhaps, the dimensions of reliability in science reach far beyond the short NOS "consensus list" (Allchin 2017b). Some factors involve experimental reasoning, such as the use of controls or even ensuring that samples are not contaminated. Some involve conceptual factors, such as appropriate statistical tests or guarding against reasoning fallacies or the human psychology of confirmation bias. Others involve social dimensions, such as the credibility of the researcher or possible conflicts of interest in communicating science in the public realm. All are potentially important in assessing the reliability of a scientific claim. One can find recent cases in the news in which errors in each of these dimensions had major social consequences (see Allchin 2012b). So all are ultimately important for citizens to detect and understand. The consensus list is just an opening, highlighting some of the more significant elements. But to realize our educational vision, NOS education will cast its eye well beyond this narrow beginners' list to a much larger inventory of factors in how we ensure the reliability of scientific claims.

Historical case studies are ideal for expanding the focus on NOS, because the many different factors in assessing the scientific claims arise naturally in following each case closely. NOS questions, reflection, and problem-solving are easily incorporated into the authentic historical scenario. They each contribute to addressing the core question, "how do we know this?" "How can we be confident of the conclusion?" "Are there other alternative explanations?" "Are there potential sources of error to consider?" Cases from history are good samples of how scientific claims can be uncertain or controversial and how to address parallel claims today. Even a few historical cases each year, over a K-12 (or collegiate) education can provide a powerful foundation for addressing scientific claims in social settings. It's not just about the concepts. It's about the *skill* in analyzing scientific claims in the media.

The vast scope of NOS may seem overwhelming—and beyond the reach of even the most thorough education. That is why our deep goal should be to develop lifelong NOS thinkers. If we consistently underscore the theme of "how do we know this claim is reliable?", we can habituate students into a frame of asking the relevant questions. They will pose those questions even when they encounter NOS issues they have not experienced previously. And the very posture of asking those questions and seeking those answers is ultimately how we want to prepare students to become well-informed consumers and citizens. Historical inquiry cases help students learn NOS and NOS analytical skills.

32.5 Resources

Assembling effective case studies is exceptionally challenging. So the teacher first venturing into this realm might prudently plan, as a first step, to rely on prepared cases, rather than assemble their own. The novice should be on the lookout for cases with good, complex cultural and human contextualization. The questions should be compelling and open-ended. The scientific struggles should not seem too simple or obvious nor the characters too ideal—the history needs to be "honest" if the nature of science is also to be rendered authentically. One might also look for the role of a professional historian of science in writing or reviewing the case. Without well-written cases, one can, ironically, reinforce the very misconceptions one is trying to remedy (Allchin 2012a, 2013, pp. 46–120, 252–257). Fortunately, many good cases are already available. A sampling of cases ready for use in the classroom (already reviewed both by teachers and by professional historians and philosophers of science) is shown in Table 32.2. Other cases can be found at the SHiPS Resource Center website: http://shipseducation.net/modules.

Table 32.2 A sampling of good historical case studies for teaching aspects of NOS

Biology	
Christiaan Eijkman & the Cause of Beriberi	Allchin (2013, pp.165–183)
Alfred Russel Wallace & the Origin of New Species	Friedman (2010)
Carleton Gajdusek & Kuru	Gros (2011)
Modeling Mendel's Problems	Johnson and Stewart (1990)
Sickle-Cell Anemia & Levels in Biology, 1910–1966	Howe (2007, 2010)
Lady Mary Wortley Montagu & Smallpox Variolation in 18th-Century England	Remillard-Hagen (2010)
King D Carlos, A Naturalist Oceanographer	Faria et al. (2011)
Archibald Garrod & the Black Urine Disease	Gabel and Allchin (2017)
Richard Lower & the "Life Force" of the Body	Moran (2009)
Interpreting Native American Herbal Remedies	Leland (2007)
Picture Perfect?: Making Sense of the Vast Diversity of Life on Earth	Carter (2007)
Henry David Thoreau & Forest Succession	Rudge and Howe (2009)
Chemistry	
Determining Atomic Weights: Amodeo Avogadro & His Weight–Volume Hypothesis	Novak (2008)
Splendor of the Spectrum: Bunsen, Kirchoff & the Origin of Spectroscopy	Jayakumar (2006)
Karl Ziegler & Catalyzing Chemical Reactions	Allchin (2017a)
Physics	
Five Episodes in the History of Electricity	Henke and Höttecke (2010)
Contested Currents: The Race to Electrify America	Walvig (2010)
Robert Hooke, Hooke's Law & the Watch Spring	Horibe (2010)
William Thompson & the Transatlantic Cable	Klassen (2006)
Electromagnetism & the Telegraph	Barbacci et al. (2011)
The Snowflake Men	McMillan (2012)
Earth science	
Charles Keeling & Measuring Atmospheric CO2	Leaf (2012)
Evolution of the Theory of the Earth	Dolphin (2009)
Marie Tharp & Mapping the Ocean Floor	Elliott and Allchin (2016)
Debating Glacial Theory	Montgomery (2010)

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