Historical inquiry cases for nature of science learning

Casos de investigação histórico por aprendir o natureza da ciência

Douglas Allchin
University of Minnesota
2005 Carroll Ave., St. Paul, MN 55104, USA; allch001@umn.edu

Abstract.
History — when framed from a historical perspective as science-in-the-making — can provide occasions for inquiry into and learning about the nature of science. This paper describes how several features in episodic historical narratives help structure such inquiry: (1) cultural and biographical motivational contexts; (2) questions that problematize the nature of science and promote nature-of-science inquiry; (3) historical perspectives exhibiting science-in-the-making; (4) a narrative format; (5) an episodic structure; (6) coupled closure of both inquiry and narrative; and (7) final reflection and consolidation of nature of science lessons.

Keywords: historical inquiry; inquiry learning; case study; nature of science; history of science

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Resumo.
A história — quando formulada a partir de uma perspectiva histórica de ciência-em-construção — pode fornecer oportunidades para investigar e aprender sobre a natureza da ciência. Este artigo descreve como várias características em narrativas de episódicas históricas ajudam a estruturar tal investigação: (1) contextos motivacionais culturais e biográficos; (2) questões que problematizam a natureza da ciência e promovem investigação sobre a natureza da ciência; (3) perspectivas históricas que expõem a ciência-em-construção; (4) um formato narrativo; (5) uma estrutura episódica; (6) fechamento conjunto da investigação e da narrativa; e (7) reflexão final e consolidação dos aspectos de natureza da ciência.

Palavras-chave: investigação histórica; aprendizagem por investigação; estudo de caso; natureza da ciência; história da ciência

Introduction

History of science can provide science students with insights on the nature of science, or *NOS* (Allchin, 2013; Conant, 1947; Nash, 1951). How does one convey these lessons effectively? Educational research indicates that the most effective forms of NOS instruction involve inquiry — that is, engaging students in their own learning through questions and personal and collective investigation (Bell, 2007; Board on Science Education, 2012; Deng et al., 2011; Driver & Oldham, 1985). The strategy profiled here is to *combine* history and inquiry — namely, using a historical trajectory to guide students through successive investigative and problem-solving activities. In essence, we situate them in a historical context of science-in-the-making (Allchin, 2013, pp. 39-44; Flower, 1995; Latour, 1987). We want students to experience the science "in the shoes of famous biologists [or other scientists] and to face historically significant problems and original data, forsaking the privilege of already knowing the right answer." This perspective is adopted "to faithfully portray how scientific knowledge develops," so that students can develop skills to interpret modern scientific claims and analyze their trustworthiness (Hagen, Allchin, & Singer, 1996, p. vi). Here I describe this pedagogical model in detail and articulate its theoretical foundations, as embodied in a landmark set of historical case studies published as *Doing Biology* in 1996 (Allchin, 2012a; Hagen et al., 1996). I also integrate subsequent theoretical perspectives (Monk & Osborne, 1997; Rudge & Howe, 2009) and pragmatic classroom considerations (Henke & Höttecke, 2015) . In particular, this paper considers how to combine history with inquiry in a way that might substantively transform the teaching practices of those oriented to either historical narrative or inquiry alone.

A key feature of inquiry learning is open-ended investigation. Students work to develop and validate new knowledge on their own (even if relying on an instructor as a guide). They then reflect explicitly on the process. Everyone originally forsakes the privilege of already knowing the answer. (The instructor, too, must echo that orientation in interacting with students.) The prospect is uncertain. That is how science unfolds. The educational goal is to experience how we research questions, grope towards solutions, and justify a solution through evidence and reasoning alone (rather than through an appeal to external authority). That process differs from knowing (or imagining) the answer in advance and trying to *rationalize* it by choosing only the data and arguments that accord with it (Allchin, 2013, pp. 84–86, 94–100). The open-endedness of inquiry contrasts dramatically with history, which is closed-ended. The events have already occurred. The virtue of history, or a retrospective narrative, is that it shows exactly how the science arrived at its answers. The process is implicitly reconstructed through the key events — the decisions of famous scientists, the notable experiments, the accidents, the errors, the debates, the influences of political contexts, and so forth. The fixed trajectory of closed history seems to eclipse the opportunity for simultaneously learning NOS via a student's own inquiry experience.

Addressing that apparent paradox is central to this paper.

In what follows, I identify some of the practical challenges of assembling and leading an inquiry-style science lesson and describe how, ironically perhaps, the use of history can help resolve those problems. Several features of episodic historical narratives are important to structuring and promoting such inquiry-style learning, discussed in separate sections below. These features will be illustrated through one particular case: the work of Christian Eijkman on the cause of beriberi in Java in the late 1890s (Allchin, 2013, pp. 165-183). At many points in the narrative, students address authentic historical questions from that episode: about orienting research, responding to chance events, interpreting experimental results, reflecting on human experimental subjects, assessing the burden of proof, and so on. Each question leads to a lesson about the nature of science, summarized in a closing reflection.

Motivating Inquiry

The first aspect of any teaching — and arguably the most important — is motivating student engagement. How do students become attentive and, equally important, active in and committed to their own learning? In the standard model of inquiry learning, students select their own problems. But in practice, this is not so simple. First, students may not have any "problems." Or the level of their personal curiosity may fail to sustain a full investigation. Moreover, in large classes a focus on individual problems means pursuing multiple projects at the same time—problematic from a sheer management perspective. On the other hand, when students develop consensus on a shared project, their enthusiasm and commitment may vary considerably. In actual K-12 school settings (in contrast to the idealized theoretical models), motivating inquiry can be quite difficult.

History can help. Indeed, teachers often turn to historical anecdotes or stories to help engage students in the content, without inquiry (Henke & Höttecke, 2015). Here, however, history becomes a way to motivate *inquiry*. When reoriented to science-in-the-making, history identifies the original unsolved problem that led to modern concepts. It fully contextualizes the reason(s) for inquiry, and thus for science more generally. First, cultural contexts help to justify the value of pursuing a particular problem (Stinner, 1995; Stinner et al., 2003). For example, in our sample case on beriberi in Java, students learn about the Dutch government's military and economic interests in preventing the disease among workers and armies in their colony.

A historical narrative that focuses on one scientist also provides a more personal, biographical context. It can help humanize the science. The beriberi case focuses on Christian Eijkman, who eventually earned a Nobel Prize. Students learn about his earlier background in Java and how he became interested in medical research. Ironically, students need not have strong personal commitment to the problem at hand to appreciate its social and humanistic dimensions. Still, they can become invested in it for the sake of participating in a story. In addition, the problem was (is) real, not conjured up artificially for the sake of a classroom exercise. The first role in inquiry, then, is to render the problem as culturally and personally compelling through historical context.

The nature of motivation is specific here: to engage the student in a particular inquiry. (On teachers' concerns about staging historical cases, see Henke & Höttecke, 2015.) It is not merely to arouse the student's attention momentarily with an amusing anecdote, before turning to the "real" lesson based on the scientific content (in contrast to Kubli, 2001, and Metz et al., 2003, pp. 322–324). History here is not part of a "bait-and-switch" tactic. Nor is the underlying aim to promote a scientific career or change the image of scientists, another common use of history (promoted by Erten, et al., 2013; Hadzigeorgiou et al., 2012; Hong & Lin-Siegler, 2012; Klassen & Froese-Klassen, 2013; Seker & Welsh, 2003). The focal scientist thus need not be a hero. The primary intent is not to present romanticized role models. Rather, the aim of the history here is to elicit the student's active investment in finding or learning about a solution. History is a source of authentic and humanistic contexts to motivate inquiry questions. Indeed, this is the first lesson in nature of science: how scientific work originates and is funded.

Problematizing NOS

A second objective is posing the right questions to elicit reflection and learning — in our case, specifically about the nature of science. On different occasions, inquiry learning can be used to teach scientific concepts (through practical contemporary applications, for example) or to teach history itself (by trying to interpret original documents or historical data, say). But the objective here is to help students understand the epistemic dimension of science: how science works (or how sometimes it doesn't work!). A core task, then, is to *problematize* NOS (Allchin, 2012a, 2013; Clough, 2006; Howe, 2007). For example, what are the challenges in developing reliable evidence, or in deciding between two alternative theories, or in evaluating the credibility of someone's testimony? In general, "how do we know this?" or "how do we have confidence in our conclusion?"

Earlier historical lessons for science education, such as those developed in the 1950s by James Bryant Conant and Leonard Nash (1957), presented students with discovery *narratives* alone. They did not pose questions to engage students in their own problem-solving and thinking, especially *about NOS* (or, in their words, "the tactics of science"). They did not problematize the science or the nature of scientific work. According to the constructivist instructional principles generally accepted today, these early case histories did not actively engage students in their own learning, or invite them to reflect explicitly about how scientific knowledge develops its reliability. In other cases (by Klopfer, 1964-66, and Clough, 2009, 2011), the questions are often based on commenting on NOS characterizations or observations presented to the reader. They are highly directed and generally already allude to targeted NOS principles. The student's role is to agree or disagree, or to elaborate based on interpreting the text provided. Deep NOS inquiry, by contrast, presents open-ended problems about scientific practices for students to solve, probe in more depth, or discuss. The NOS concept should emerge as a solution to a particular challenge, say, about deciding between alternative theories or bolstering the trustworthiness of a claim. Interpreting closed history is different from engaging in scientific or epistemic problem-solving in a historical context. One primary feature of the model profiled here, then, is using history to identify key moments from the past where one can pose *open questions* or decisions to students, and invite their participation — in both scientific inquiry and NOS-inquiry.

NOS inquiry is not necessarily isolated. It can be integrated with more conventional inquiry on scientific concepts, rendering a holistic sense of scientific practice, or Whole Science (Allchin 2013, pp. 20-26, 39-40; Hagen et al., 1996, pp. v-vii, 198). This coupling has been widely recommended especially in current institutional climates and teaching cultures, where conceptual content remains the dominant focus (Clough, 2006; Heilbron, 2002; Henke & Höttecke, 2015; Monk & Osborne, 1997; Rudge & Howe, 2009). For example, in the beriberi case, students are asked standard science inquiry questions about planning investigative variables, interpreting experimental results, developing alternative theories, and designing experiments to compare two different explanations. But they are also invited to reflect on deeper NOS problems: on the burden of proof in scientific versus social policy contexts, on the nature of human subjects in experiments, on the nature of bestowing credit in science, and on the nature of error.

Inquiry and Historicist Perspective

As noted above, for the NOS lessons to be relevant to interpreting scientific claims today, the perspective, even of history, should be one of "science-in-the-making." Here, professional historians are of special value in vividly conveying historicist perspectives. How did the problems look to the historical scientists (versus how do they look today)? Not "why did Eijkman believe that bacteria caused beriberi?", but "As a contemporary of Eijkman, how might you interpret the cause otherwise?" A historical case should seem like an ongoing contemporary case merely displaced in time.

The principle of respecting historical perspective, or of avoiding Whiggish history, includes a few basic rules for teachers (Allchin, 2013, pp. 46-106). Most important, the instructor cannot divulge the ultimate answer prematurely. Nor can they provide any biasing clues (however tempting that is!). Either would undermine the intended inquiry learning. So: there can be no foreshadowing. Likewise, there can be no obvious stacking of the deck towards certain outcomes or theories. Nor anachronistic prejudicing by ascribing scientists personality traits based on later successes or failures. Phrasing of questions that subtly invites a particular "correct" response will also subvert the goal of inquiry, just as it does when an activity is not embedded in history. Any guidance to the students must be situated in the horizon of uncertainty as experienced by their historical counterparts. *No anticipatory hints allowed*. Ultimately, just as spoilers ruin the thrill of a good mystery, they also dissolve the essential motivation and rationale for inquiry. Thus, in the beriberi case, it is important not to preemptively announce, or even analyze, Eijkman's mistaken conclusion about beriberi as bacterial. Nor should one even suggest the need (a conspicuous clue) for a critical or skeptical attitude. Ironically, the lesson about the nature of error in science relies on quite the opposite: understanding how thoroughly reasonable Eijkman's perceptions were, given the context and the available information. That requires respecting the historical perspective fully, with all its potential blind spots.

The historical perspective ought not be overstated, however. Students need not work exclusively within the conceptual constraints of history, especially if such concepts seem foreign or unreasonable (see teachers' concerns documented by Henke & Höttecke, 2015). Inquiry (embodying constructivist-style learning principles) requires students to think creatively and draw imaginatively on their existing repertoire of concepts. Students may be introduced to the historical theories or background, but need not be tutored in accepting them provisionally to govern their own reasoning, especially if they will be expected soon to abandon them. Again, the goal is to foster inquiry, not repeat history exactly (Allchin, 2013, pp. 84-91).

Ironically, a teacher may need to actively suppress the role of history as an implicit benchmark. The historical scientist's work is not a standard for measuring student achievement. For the sake of inquiry, students must feel independent and responsible in pursuing their own thinking. Elsewise, students can easily "opt out" and wait for the "real" (historical) answer. Or they can perceive the historical scientists as "geniuses," endowed with privileged insight beyond their own. They can continue to believe that scientific knowledge is preformed and only delivered from authoritative sources. They will fail to appreciate how it is humanly constructed. They may also perceive the goal of science (like their own as a student) as merely confirming pre-established truths (Henke & Höttecke, 2013). In borrowing from history to guide the framing of student inquiry, one must not to let the actual historical outcomes short-circuit the work of inquiry. Again, the central NOS lessons rely on students experiencing blind science-in-the-making.

At the same time, an instructor with healthy historical awareness may well anticipate how students, echoing their historical counterparts, might variously think. They can encourage the development of alternatives within the historical horizon. Afterwards, students themselves may also possibly learn (and appreciate) how their thinking parallels actual history. For example, in the beriberi case, when students confront Christian Eijkman's problems in the 1890s, they typically introduce hypotheses or design experiments similar to his. They are also equally adept at echoing Eijkman's critics in finding potential flaws in his reasoning. Comparing student work with their historical counterparts is a form of validation — without having to characterize the work as either right or wrong. Students understand that they are doing "real" science, while still in a school setting (a frequent deficit of student inquiry exercises, as noted by Clough, 2006).

Notably, a historical inquiry, like any genuinely open inquiry, is "messy." The uncertainty is often accompanied by complexity and underdetermination, and may provoke feelings of confusion, chaos, or insecurity (Allchin, 2013, pp. 121-132). These are additional emotional dimensions for teachers to manage (in themselves and students both). Oversimplifying the history, a common tendency among novice teachers, runs the risk of destroying the essential historical perspective of science-in-the-making and erasing the very meaning of inquiry.

The Challenge of Open Inquiry

Inquiry, like science, is opportunistic. It is susceptible to context and unanticipated factors. At each moment of inquiry, then, many divergent trajectories are possible (Figure 1). One cannot predict in advance where the inquiry will lead. By contrast, institutional curricula typically dictate fixed conceptual endpoints. Ironically, the inquiry must be *resolved* with a predictable outcome. Indeed, inquiry teachers exhibit significant concerns about target lessons, control of instructional flow, and maintaining their authority in the classroom (Henke & Höttecke, 2015; Höttecke & Silva, 2011). How does one guide inquiry to the desired endpoint without eclipsing the unpredictable pathways that are so essential to understanding the exploratory nature of science? Namely, how can inquiry be open- and close-ended at the same time?

< INSERT FIGURE 1 ABOUT HERE >

Moreover, each successive step of inquiry introduces new options, new opportunities, new possible trajectories (Figure 2). There are many problems to pose, then many ways to frame any particular problem, plus many ways to design investigations, many ways to interpret results, many ways to imagine sequel investigations, and so on. One important lesson from history is that promising trajectories do not always yield expected discoveries. Likewise, unplanned connections or contingencies sometimes lead to major breakthroughs (Allchin, 2012b; Burke, 1978; Kohn, 1989; Livio, 2013; Roberts, 1989). Which trajectory does one pursue in a classroom, with what consequences? Consider that separate class periods for the same teacher may diverge, making planning and preparing for the next day's activities — especially laboratories — burdensome. Long-term scheduling and coordination become exceedingly problematic. Faced with such uncertainties, an instructor may seek efficiency and control, and turn to an idealized learning trajectory, or rational reconstruction. Such imaginary histories promise a secure teaching sequence and guaranteed solutions. Ironically, however, they also tend to convey misleading lessons about the uncertain nature of science-in-the-making and typically decrease student engagement in divergent, open-ended thinking (Allchin, 2013, pp. 77-92). "Cookbook history" does not foster NOS lessons any more than "cookbook labs" reflect genuine scientific investigation.

< INSERT FIGURE 2 ABOUT HERE >

In addition, the psychological rationale for inquiry learning tends to frame it as an individual experience. Inquiry in a group setting can be fraught with emotional and interpersonal challenges. For example, students do not all think alike. Pursuing one trajectory at the cost of other students' suggestions can easily alienate some individuals, and foster counterproductive feelings of exclusion. Also, because learning proceeds through trial and error, "failure" seems inevitable. Subsequent student feelings of discouragement may threaten commitment to the learning process. Or disillusionment may erode the trust essential to an effective teacher-student relationship. Politics and emotions can thus overrun the undisciplined inquiry classroom and erode the student's critical investment in learning. In practice, inquiry can be a very fragile learning structure.

Ironically, history can again help guide a teacher in managing the challenges of open-ended inquiry. Once students have completed their own short-term inquiry activity, the instructor can return to the historical case. The students learn a bit more of the actual history. It can offer comparison without evaluation. The historical narrative then neatly provides a way ahead. While many trajectories are possible, one follows just the decisions or choices of some central historical character (Figure 3). The choice is partly arbitrary. But it leads to a coherent and humanistic narrative. One can articulate the character's reasoning, without necessarily endorsing it, nor discounting student work. Thus, in a historical inquiry approach, historical events need not be the benchmark for "correct" responses. Subsequent history will tell the tale, with corresponding lessons about the nature of science. The particularity, especially coupled with awareness of the diverse possibilities, helps underscore that scientists inevitably practice within a personal perspective — a vital NOS lesson (variously expressed as "subjectivity," "theory-ladenness" or "social and cultural context").

< INSERT FIGURE 3 ABOUT HERE >

The core historical narrative then guides students to the next occasion for inquiry (Figure 3). There, one entertains divergent inquiry thinking again. And, again, the narrative helps the teacher through the dilemma of which trajectory to pursue. Because the history is authentic, not rationally reconstructed, students cannot always depend on the central character to reach the "right" answer. No anticipated outcome upstages the historical drama, with its twists and turns, and unanticipated events. Because the trajectory is also somewhat arbitrary, students see their own responses (when justified by evidence) as equally valid alternatives.

Again, the aim here is not for students to replicate history. Indeed, the cognitive recapitulation model, positing that students develop in direct parallel to scientists through history, has been widely discredited (Allchin, 2013, pp. 86-88; Monk & Osborne, 1997, pp. 412-413; Swanson, 1995). The history should provide occasions for inquiry, not a predetermined script. History frames instead a "lineage of *questions*" — a strategy pioneered in Mix, Farber and King's biology text (1996; and articulated in Farber, 2003).

Episodic Inquiry or Interrupted Narrative?

In historical inquiry, the story functions primarily to support successive inquiry activities. The narrative is alternately preamble and epilog, carefully crafted to spur the students' own thinking and then inform further reflection. The history/inquiry assumes an episodic character (akin to the familiar form of an "interrupted" narrative). For example, the narrative for the beriberi case is extensive. But it all revolves around contextualizing, informing, and interpreting the series of 14 inquiry questions, or "THINK" exercises, which form the primary occasion for learning. The cases in this special volume are further examples of this format (see also McMillan's "The Snowflake Men" [2012]; Howe and Rudge's [2005] case on sickle cell anemia; Dolphin's [2009] multi-week curriculum on mountain-building; and the Minnesota Case Study Collection [Allchin, 2012a]).

Episodic historical narratives differ significantly from other approaches to stories in science education. For example, Metz et al. (2007) advocate stories along with "the use of imaginative and manipulative components within the narrative," which "involves the reader in an ongoing interaction with the narrative" (p. 316). However, if the NOS lessons are primarily achieved through inquiry, the history should play the supporting, not the lead, role. The history should function to engage the student in the inquiry, rather than the inquiry activity being an adjunct to the history.

As practiced by professional storytellers, *interruption* is a key strategy. It helps involve the listener, and foster "narrative appetite" and anticipation (Norris, et al., 2005, p. 541). Wandersee recommended just such a strategy for history in the science classroom. By "participating" in the story, students would increase their stake in following the outcome.

Similarly, when role-playing historical scientists, Wandersee would ask students questions or seek their opinions on his actions (Eleanor & Wandersee 1995; Roach & Wandersee, 1993, 1995; Wandersee, 1990). While interruption can be a powerful storytelling technique, its role in inquiry cases is quite different. The emphasis is on the students' own NOS thinking, not making the story more important. Ideally, one should foster an "appetite for NOS," not merely a "narrative appetite." The students should become more interested their own creative problem-solving, than in hearing more story recited to them. In a sense, then, it is an inquiry interrupted by narrative segues, rather than a narrative interrupted by inquiry activities. The history contributes a sense of continuity and human context across the successive occasions for active thinking. The inquiry is punctuated. The epilog of one episode should segue seamlessly to the preamble of the next. The history can thus condense large spans of time, making it possible to address large-scale inquiry projects in a classroom setting. The resulting continuity underscores the episodic (rather than the canonical "interrupted") structure of the narrative.

Teachers generally find an episodic format comfortable in the classroom (Reid-Smith, 2013). Most notably, it balances opportunities for autonomous student activity with instructor control of overall instructional flow. It also changes the rhythm of a class period frequently, promoting sustained student attention and learning. Perhaps for these reasons episodic, or "interrupted," cases are the most popular among users of the Center for Case Study Teaching in Science (Herreid, 2005; Herreid et al., 2011; 2012, p. 73; although the cases are generally not historical).

The significance of an episodic structure for inquiry has an interesting consequence for how one uses historical cases in the classroom. Namely, teachers do not like relying on students reading a narrative text, especially during class time (Henke & Höttecke, 2015; Reid-Smith, 2013; Rudge & Howe, 2009, p. 565). A focus on inquiry promotes interaction with the teacher as narrator, perhaps using images that help visualize the problem, the scientists, or their work. Personal engagement contributes further to a more lively, vivid, and memorable rendering of science and NOS.

Resolving Inquiry and the Historical Narrative

Perhaps the greatest conundrum for any student-led inquiry is reaching closure. How does one shepherd the open-ended process to a known endpoint — say, the modern scientific concept at the core of a conventional lesson? The teacher who guides the students too strongly or conspicuously towards the "correct" endpoint risks destroying the core epistemic lesson: that there is no external, omniscient authority to guarantee "the truth." A teacher cannot maintain the integrity of inquiry while also intervening to save students from a crisis of confusion or the chaos of an unwieldy investigation. Any authority who resolves a troubled inquiry *deus ex machina* ultimately subverts the core NOS lessons.

As noted briefly above, the narrative informed by history is critical in achieving convergence. First, one consults history in part because one knows that there is indeed a solution before embarking on a path of "open" inquiry. Teachers can pose the original question or problem secure that there *is* some scientific closure. (In this way, a historical case differs importantly from a contemporary case or controversy.) Eventually, the historical narrative converges on a solution. Each segment of actual events yields new findings that help resolve uncertainties or debate. So the teacher has a secure and predictable closure, eve if along a zig-zag path. Notably, this allows the instructor to situate a historical inquiry lesson in a large-scale instructional plan, without forsaking the core open-ended activities.

Second, the history provides the investigations, evidence and reasoning that helped settle debates and led past scientists to select among alternative conceptual interpretations. Criticisms are answered. Exceptions are clarified. Qualified judgments wane. Possibilities narrow. Debate subsides. Confidence in a stable solution emerges. Moreover, the relevant experimental results or evidence may well be beyond the reach of a school classroom – perhaps based on expensive instruments or prolonged study. Nor do students exhibit professional levels of expertise (whether about fossil identification or seismic data or statistical models). History can conveniently collapse time. Narrative can substitute for material effort and escape the need to fund research. Students are thus able to participate vicariously in an inquiry that would otherwise not be possible in a classroom.

Third, the narrative format allows the instructor to lead the students through these encounters in an authentic way. The history gradually comes to the "rescue," but clearly not by superhuman insight or supernatural agent. Indeed, the history can reveal all the unanticipated contingencies. In the beriberi case, new investigators with different theoretical orientations provided new evidence. Results from studies on nutrition, unrelated to beriberi, emerged with additional meaningful results. Once one recounts how events unfolded, the students can participate and reach the final conclusions themselves.

Because narrative and inquiry are coupled, the denouement of the narrative parallels the resolution of the central problem that originally motivated the inquiry and launched the historical story. Closure is thus achieved in two ways at once. The scientific problem is solved. At the same time, the narrative journey reaches its anticipated destination, with associated emotions. In the beriberi case, the discovery of vitamins is marked and celebrated with the award of a Nobel Prize. In the double closure, the finished story *explains* science as a process. The narrative brings the science and the nature of science together, with an emotional knot for the student.

Closure can occur even when the ending may be wholly unexpected. At first, the story of beriberi seems to be about disease and germ theory. But it ends unexpectedly with the concept of vitamins — ironically, a concept already familiar to most students, but not obviously relevant at the outset. Like many captivating stories, the ultimate ending in science may be unanticipated (Burke, 1978; for the case of the Keeling Curve, see Leaf, 2012; on Gajdusek, kuru and prions, see Gros, 2011).

Finally, the closing offers an occasion for comparing student performance with the actual events from history. The history is not the authoritative benchmark. But it is still a valuable point of reference in retrospect (as noted by Howe, 2007, and Monk and Osborne, 1997). Students can see the variety of possible pathways forward. They can note the difference between the actual history and a perhaps idealized version of it. The roles of politics, personal perspectives, cultural values, or other contextual elements shaping science become clearer.

Consolidating NOS Learning

The final stage to any inquiry, or constructivist learning episode, is the consolidation of the lessons. Here is where one guides the students in drawing and appreciating the “morals” of the story. One cannot expect stories to “speak for themselves” as evidence for the nature of science, any more than the scientific data “speak for themselves” in forming theoretical conclusions in science. As Tao (2003) noted,

> When studying the science stories, many students selectively attend to certain aspects of the stories that appear to confirm their inadequate views; they are unaware of the overall theme of the stories as intended by the instruction. (p. 168)

Indeed, science teachers can take an entire history of science course and fail to learn much about the nature of science (Abd-El-Khalick & Lederman, 2000). Explicit reflection on NOS issues is critical (Clough, 2006; Craven, 2002; Howe, 2007; Klopfer, 1969; Kurdziel & Libarkin, 2002; Peters & Kitsantas, 2010; Russell, 1981; Scharmann et al., 2005; Seker & Welsh, 2005; Yacoubian & BouJaoude, 2010). Thus, reflection should be encouraged throughout. But the closure of the lesson, which accompanies the closure of the narrative, allows a special occasion for holistic discussion of NOS issues, especially those that emerge from comparing "before" and "after."

In closing a historical inquiry case, the teacher and students explicitly recall and identify the various historical factors that led to the outcome. But ultimately, the students must complete the NOS reflection on their own. In the beriberi case, students are invited to formalize in writing their thinking about many features of the nature of science: the cultural context of science; the role of theoretical preconceptions; the role of chance, or accident; the nature of controlled experiments; error and conceptual change; and so on. Again echoing basic constructivist pedagody (now at the level of NOS), this ensures personal cognitive integration of the NOS lessons.

Historical Explanation and Learning through Narratives

Another virtue of combining history with inquiry is the narrative format itself. Stories are an integral part of human experience and a familiar form of sharing information. Indeed, our cognitive tendency to tell stories may be shaped by our evolutionary heritage as social organisms (Hsu, 2008). Stories certainly engage students. So narratives can be valuable vehicles for rendering any science lesson (Green, 2004; Herreid, 2007), including scientific inquiry as a process (Norris et al., 2005).

But narratives also do more than entertain and inform. As philosophers of history note, they are implicit *explanations* (Bruner, 1991; Carr, 2008; Norris, et al., 2005, pp. 546–548, 557; Richards, 1992; White, 1987). They demonstrate historical causation. Stories display "a logic of the flow of actions through time, a structure of events that gives them a distinctive form." A narrative "ties the action to its background circumstances, its antecedent events, and its subsequent results" (Carr, 2008, pp. 25, 29). Indeed, humans may tend to think primarily in terms of narratives and exemplars, rather than abstract laws. Even scientists rely on case studies, model systems, and exemplars (Creager, Lunbeck, & Wise, 2007; Kuhn, 1977). By situating inquiry processes in concrete scenarios, stories cognitively support analogical thinking about NOS in other cases. For example, in the beriberi case, students participate in reasoning about Eijkman's theory about germ theory. Later they discover that he was mistaken. Even though they found it reasonable, too. The lesson in trial and error and conceptual change in science is experiential, not based on some dry or vague general statement that "science is tentative, but durable."

Ideally, then, the teacher will be well aware that historical narratives, like fables, have inherent NOS "morals." They will reflect on the narrative content and use its explanatory power mindfully. For example, because stories have a potent affective component, an ill-structured narrative can easily, as Velleman (2003) notes, instill an association of the intended lesson with the "wrong" reasons. Similarly, stereotypes and melodramatic tropes that form the basis of so much familiar storytelling can misportray the nature of authentic inquiry or scientific practice (Allchin, 2013, pp. 46-76). Effective use of the narrative format demands extraordinary care.

Yet narratives can also be powerful tools. They can vividly depict the relevance of a broad spectrum of factors that shape scientific work and its conclusions. In the beriberi case, students encounter the roles of culture, chance, evidence, criticism, and multiple investigators. Stories convey concretely how they are all integrated: contributing to what has aptly been called a Whole Science approach to science and NOS (Allchin, 2013, pp. 20-26, 39-40).

Summary

The model of historical inquiry using episodic narratives thus has several elements of structure, all supporting the aim of learning NOS through inquiry (Table 1): (1) cultural and biographical motivational contexts; (2) questions that problematize the nature of science and promote nature-of-science inquiry; (3) historical perspectives exhibiting science-in-the-making; (4) a narrative format; (5) an episodic structure; (6) coupled closure of both inquiry and narrative; and (7) final reflection and consolidation of lessons. These elements, collectively, embody or support the conventional principles of inquiry learning, and help explain why historical narratives, appropriately adapted, can be so effective for learning science and the nature of science.

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Table 1. Features of the episodic historical inquiry model.

- motivate inquiry through both cultural and biographical historical contexts
- problematize the nature of science through puzzles and questions
- foster inquiry and the uncertainty of science-in-the-making through historical perspective
- structure inquiry stepwise to follow a historical lineage of questions, linked through an episodic (“interrupted”) narrative
- resolve the scientific inquiry and historical narrative in tandem
- consolidate NOS lessons through a final and explicit reflection
- use the narrative format to provide a historical explanation of NOS

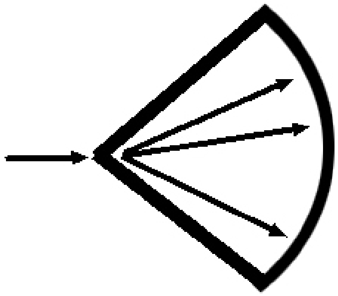

Figure 1. Divergence in inquiry.

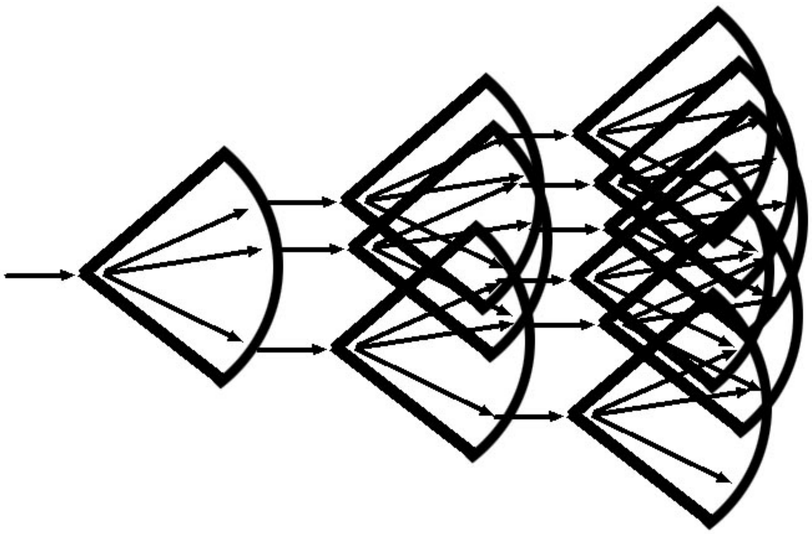

Figure 2. Potential compounded divergence in successive stages of inquiry.

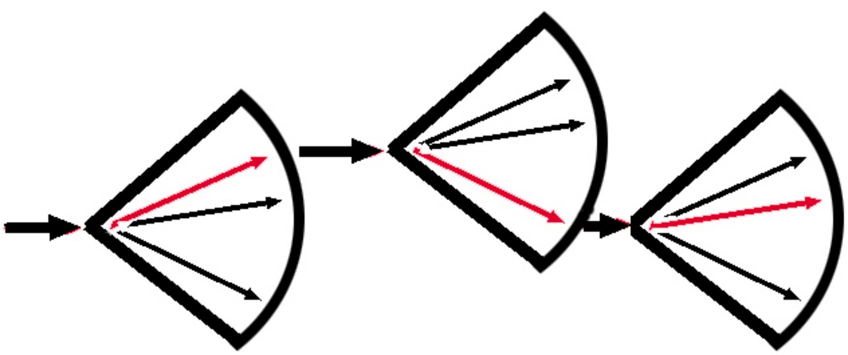

Figure 3. Successive divergences guided by an episodic historical narrative.