ARTICLE
Teaching the Nature of Science Improves Scientific Literacy Among Students Not Majoring in STEM

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Traditionally, science courses focus on knowledge and practices within specific disciplines. There has long been a call, however, to increase the focus on the nature and process of science as a way to improve scientific literacy and increase the transfer of knowledge. Despite this, there are few systematic studies that seek to understand the impact of this approach. Revising a STEM course in a liberal arts curriculum to primarily focus on the nature and process of science rather than on the content of a specific discipline increased student scores on the Test of Scientific Literacy Skills and improved perceptions of STEM. In the revised course, students self-reported higher levels of confidence in their ability to learn scientific information and their ability to contribute to scientific progress compared to traditional methods. These data and other literature suggest that the traditional knowledge-focused approach to science education is insufficient to facilitate scientific literacy and address equity gaps in STEM. Proposed is a model where scientific literacy and feelings of inclusion in STEM are the product of direct engagement in the process of science and careful evaluation of the nature of science. Long-term, a holistic approach that includes an authentic discussion of the enterprise of sciences is needed to prepare students to engage in future problems that are best solved by cross-disciplinary collaboration.

Key words: Nature-of-science, Interdisciplinary, Scientific Literacy

Historically, most introductory life science courses use a content-focused curriculum that relies heavily on textbooks. Yet, these textbooks do not accurately represent the enterprise of science nor do they accurately portray the practitioners of science (Gibbs and Lawson, 1992; Abd-El-Khalick et al., 2008; Ragusa, 2013). Further, traditional textbooks present many barriers for students from historically marginalized or excluded backgrounds, or students who have unique learning needs. These barriers may include high financial cost, lack of diversity, and an approach that often ignores cultural influences on science. One of the primary limitations of the textbook model is that it represents a biased view of the scientific process because it divorces scientific output from the environments in which knowledge is constructed.

The open educational resource (OER) movement seeks to address some of these issues by providing low-cost alternatives to traditional textbooks. Many of the OER options can be more easily edited to provide better representation in both authorship and practitioners of science. OER, however, often require the use of technological resources so these materials do not fully solve issues of access. Additionally, these materials still communicate the traditional, content-focused approach to science education.

Together, these issues result in a classroom that is not structured to facilitate a broad view of science. Rather, content heavy introductory courses may be exacerbating inequities in STEM education because they marginalize the role of experience and affect in science (Fortus et al., 2022). The goal of STEM courses should be to increase scientific literacy and encourage the generation of knowledge rather than select for competence based on prior knowledge. Alternate approaches from the content-heavy structure of many science courses are needed to encourage participation in STEM by all stakeholders.

In contrast to the potential discouragement that can result from textbook heavy and content focused courses, open discussions of the nature, process, and philosophy of science shows some promise for improving scientific literacy (Michel and Neumann, 2016; Widowati et al., 2017). There are, however few systematic studies directly addressing this approach, especially in the life sciences and neurosciences. This article seeks to report one approach to revising introductory courses—specifically for students not majoring in STEM—and the extent to which it impacts student's view of science.

COURSE STRUCTURE AND APPROACH

The understanding of science is different between STEM majors and those not majoring in STEM (Abd-El-Khalick, 2006; Liu and Tsai, 2008; Miller et al., 2010; Lederman et al., 2013); each group has different strengths related to "scientific literacy" and understanding the nature of science. Therefore, our goal was to encourage greater interest in STEM and a more complete understanding of the process of science. In our student population, non-major students not only held a different view of science than students majoring in STEM, they also scored lower on measures of scientific literacy. Therefore, our lowest level biology course, General Biology (BIOL 1100) was revised to focus more heavily on the nature and process of science. This course was selected because it is the primary course taken by students not majoring in a STEM field. Most of the literature related to teaching the nature of science is focused on the high-school level or early college levels (Abd-El-Khalick et al., 2008; Miller et al., 2010; Lederman et al., 2013; Michel and Neumann, 2016); therefore, this student population represents a next step in extending the literature. Historically, the BIOL 1100 course has utilized OER Biology textbooks such as OpenStax Concept in Biology or Lumen Learning Biology for Non-majors. These materials do come at a cost to the students for use of the platform and associated courseware. To shift the focus of the course, the traditional textbooks were replaced with books that were more focused on communicating the philosophy of science and representing a more authentic view of science. In various iterations of the course, this has included "Uncertainty: How it makes science advance" (Kampourakis and McCain, 2019), "Structure of Scientific Revolutions" (Kuhn, 1962), and/or "Ignorance: How it drives science" (Firestein, 2012). Other than the changes to the course focus and materials, other aspects of the course including enrollment caps (~45-60 students/section) were consistent with historical trends.

The general structure of the revised course was made up of the following units/modules:

Foundations of Inquiry (~4 weeks)
The goal of the first unit is to introduce the philosophy of science, to identify misconceptions about science, and to reconstruct student perceptions of how scientific knowledge is generated. To do this, course discussions focus on the role inductive/deductive reasoning and falsification in science. Included are brief discussions of the history of science and how the definitions and philosophies of science change throughout time and across cultures. These initial discussions open space to discuss epistemology and the limits of science. They also challenge the traditional view of science presented in middle/high school by examining how our current view of "the scientific method" has been shaped by reductionism, falsificationism, and other views that do not capture the breadth of scientific inquiry.

The early framework developed in the class then allows discussions about discourse across disciplines. Here, ethics in science is highlighted as a way to investigate the extent to which science is a "self-correcting endeavor". For example, students are challenged to consider the impact of retraction of peer-reviewed manuscripts on scientific knowledge and the confidence that is placed in scientific discovery.

Fundamental Principles in Science (~6 weeks)
Once students begin to understand the vocabulary and history surrounding the philosophy of science, the middle of the semester is used to place these abstract discussions in context using topic/content discussions. Topics are selected with student input via an anonymous poll. Students are allowed to vote for provided topics and/or suggest a new topic. Prior topics have included:

- Genetics and race
- Evolution: the past, present, and future
- Neuroscience and mental health
- Vaccines and the immune system
- Nutrition: beyond exercise and obesity
- Climate change and conservation
- Addiction and the neurobiology of reward

In each of these content sections, students study how the life sciences answer questions about each topic. Class assignments are focused on helping students identify how the philosophy of science has shaped the scientific progress in each of the topics. Readings in this section are taken from online resources, articles, or books that are more focused on science communication than content delivery. (e.g., "The Disordered Mind" (Kandel, 2018)). This structure allows the selection of resources with more diverse representation than typically is found in textbooks. Generally, a topic is covered in 2-3 weeks and results in ~3 topic discussions per semester.

Process of Science (~3 weeks)
In a class where students are learning about the philosophy of science, they are also encountering challenges to their existing notions of "the scientific method". As a result, projects focus on providing students opportunities to engage in scientific inquiry. Engagement at this level provides opportunities to discuss broad concepts including the use of iteration and/or recursion as well as the role of models and representation in the process of science. By the end of the semester, the students have completed at least one project where they demonstrate their engagement in the complete process of science from conception and design to analysis and communication of results. Projects range from survey-based projects that address respondent views of science or of specific topics to observation-based projects to experiments performed in a laboratory. Projects involving bacteria are common. For example, some students enjoy developing projects to explore bacteria diversity and abundance at different locations around campus. Other groups take a more experimental approach, for example by investigating the effects of essential oils on bacterial growth. Projects are all student driven so there are a wide range of approaches and topics. For example, mental health and sleep are among the most common topics for survey-based projects. The common theme is that all students are involved in the conception of the study, participate in data collection, and wrestle with decisions about data analysis.

In the first week of this unit, students design their projects and class time is used for students to receive feedback from the instructor on their ideas. Students are instructed to develop a project in which all data can be collected (but not analyzed) within two weeks. By the end of the first week, students submit a project proposal that outlines their project and resource needs. During the data collection phase, the instructor provides all equipment and resources for approved projects. Any projects that are not initially approved are revised by the student in collaboration with the instructor. The primary assessment criteria for the project proposal are feasibility and the likelihood of completing data collection in the allotted time. During data collection, students have no out-of-class assignments to ensure sufficient time for project completion. During this time, two class periods are reserved for students to receive help from the instructor or an undergraduate assistant.

Reasoning in Science (~2 weeks)
When students build new mental models of science, there is often a misconception that the quality of the data is defined by its statistical significance. To address this thinking, class assignments—including the final project that reports student-collected data—help students utilize both quantitative and qualitative evidence. There is an emphasis on differentiating between anecdotes and systematically collected observations.

The timelines listed are an approximation based on total time spent on each topic. The sections are also not independent; for example, discussions about the nature of science are interleaved with fundamental principles in science. Further, one cannot investigate the process of science divorced from the history of its methods.

ASSESSMENT AND METHODOLOGY

To explore the impact of how the increased focus on the nature and process of science impacts scientific literacy, a pre/post assessment design was used. Students completed the Test of Scientific Literacy Skills (ToSLS) (Gormally et al., 2012), a brief attitudinal survey, and contributed to a class word cloud.

Test of Scientific Literacy Skills
Students completed the ToSLS and were awarded points for completion. Their score on the assessment did not impact their overall course grade. In the post-test, however, students whose score increased were awarded bonus points on their final project; this incentive was not stated until after they completed the pre-test to avoid intentional "tanking" of the pre-test. This incentive structure meant that no student was required to take the ToSLS.

Attitudinal Survey
Students completed a brief survey on their views of science via an anonymous Mentimeter poll at the beginning of the second class period of the semester then again during the last week of the class. Students used a Likert-scale rating to respond to the prompts: "I can articulate ways in which science interfaces with my interests" and "Understanding science requires innate talent or skill". Students are not required to respond but, in all cases, all students who were present in the class responded to the poll. Students were not shown the results until after the poll closed.

Class Word Cloud
Students were prompted to identify what they needed to understand as a prerequisite to learning science by responding to the prompt: "To understand science, I have to understand ___". Each student was allowed a maximum of three entries to the word cloud.

Data Analysis
All surveys, incentives, and data analyses were approved by the Harding University Institutional Review Board prior to data collection. Data were not analyzed until after completion of the semester and only after anonymization of responses. ToSLS data were analyzed by paired t-test using GraphPad Prism v9. Students' ToSLS scores were included

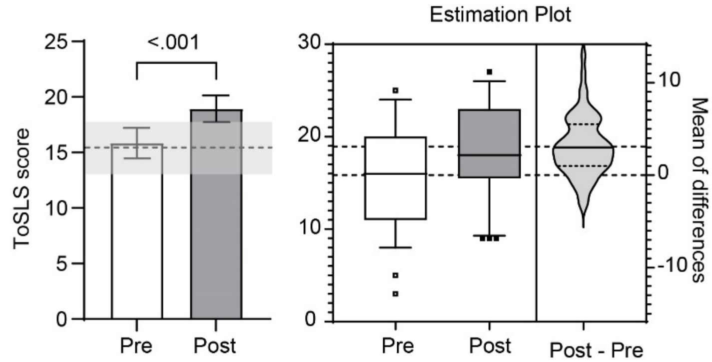

Figure 1. Student performance on the Test of Scientific Literacy Skills (ToSLS) is higher after a nature-of-science focused course. The left graph shows the total ToSLS score for students at the beginning of the course (white bar) and at the end of the course (grey bar). Dashed lines and shading represent scores for students who completed their science requirement at Harding University before implementation of the revised course. Bars represent mean ± 95% CI. n=62 students from two separate semesters who completed both the pre and post assessment. Right graph shows estimation statistics for raw ToSLS score with medians ± 5-95% interquartile range and the violin plot shows the mean differences.

only if they took both the pre- and post-class assessment, this represented 57% of the enrolled students. The remaining 43% is accounted for by students who took one but not both assessments and students who voluntarily withdrew from the course. (the high attrition rate is accounted for by a combination of students adding/dropping the course during the first week and that students were incentivized but not required to complete both ToSLS assessments). The average drop rate after the first week of class was <10%. Attitudinal survey data was analyzed using the 'wasserstein_distance' function in 'scipy.stats'. Attitudinal data was also analyzed by a Wilcoxon signed-rank matched pairs test in Program R. Word cloud responses were not statistically analyzed.

DEVELOPMENT OF SCIENTIFIC LITERACY

The Test of Scientific Literacy Skills is a well validated assessment that focuses on skills that are common across STEM disciplines (Gormally et al., 2012). It assesses specific subdomains such as quantitative reasoning, validation of arguments, and scientific design. Overall, student scores increased 3.1±3.2 points from beginning to end of the semester. (Figure 1) In these data, 83% of students increased their score by at least one point. Importantly, the dotted line and shaded region in Figure 1 represents the ToSLS score of students who completed the pre-revision version of the course and these scores are similar to the pre-class scores.

While standardized assessments such as the ToSLS are well validated, they do not capture student attitudes nor their view of the enterprise of science. To address this aspect of the course, students were asked to complete a brief Likert-scale attitude survey and contribute to a word cloud at the beginning and end of the semester.

At the end of the course, students felt more able articulate their interest in science. They also viewed science as less dependent on innate talent at the end of the semester (Figure 2). The pre-post distributions are separated by a Wasserstein Distance of EMD=0.65 (Figure 2 top) and EMD=1.15 (Figure 2 bottom). For reference, when these data are modeled with completely overlapping distributions EMD=0; survey data with the same sample size but with non-overlapping data except for 10% overlap in the '3' category gives an EMD=3.2. EMD values of 0.65 and 1.15 correlate with a Wilcoxon signed-rank matched pairs $p<0.001$ after continuity correction for both data sets. These statistics suggest highly dissimilar response distributions. Additionally, the words that students contributed to the word cloud changed over the course of the semester (Figure 3). At the start of the course students lack a common vernacular and their contributions belie logical progression (i.e., "to understand science I have to understand life" or "to understand science I have to understand science"). The submissions also represent a very pragmatic, course-focused view of science (e.g., "to understand science I have to understand *teacher*, *words/English*, *testing*). In contrast, the final word cloud shows a stronger language to describe science and a better understanding of science, as evidenced by inclusion of words such as "Logic", "Bias", and "Epistemology". Students also begin to recognize uncertainty and error as integral to the process of science.

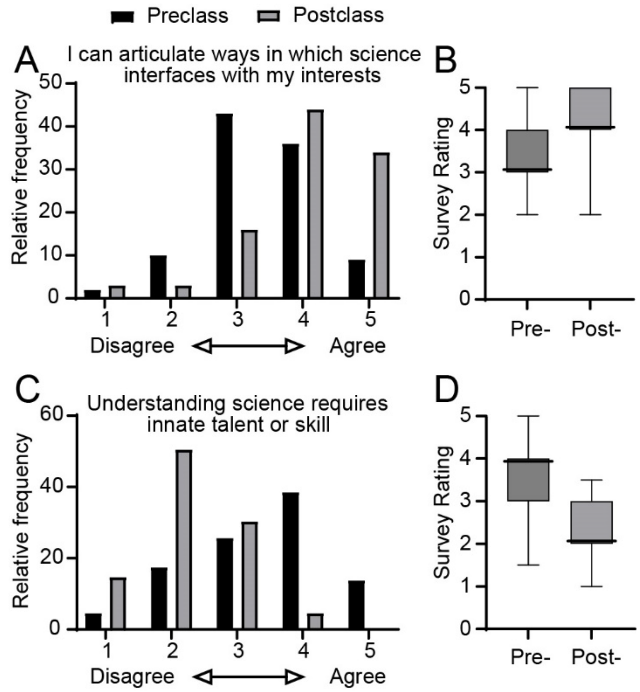

Figure 2. Student attitudes toward science change during a nature-of-science focused course. Students were asked to rate the extent to which they agree/disagree with the statements above graphs. Reported in graphs A and C are aggregate frequencies from anonymous student ratings on the first day of the semester (black bars) and in the last week of class (grey bars). Graphs B and C are box plots representing median ± 95% CI for survey responses. Pre-class n=100; Post-class n=109 student responses across three semesters.

DISCUSSION AND INTERPRETATION

Broadly, these data should catalyze a conversation about how introductory courses treat science. To what extent does the traditional content-heavy focus of science communication contribute to the decline of scientific literacy and decreasing trust in scientific data in many western cultures (Rutjens and van der Lee, 2020; Rutjens et al., 2021; Boyle, 2022)? The revised course focused strongly on vocabulary and concepts that cross disciplinary boundaries and this approach altered ToSLS scores and attitudes toward science. Therefore, data in this study, together with prior literature, should also facilitate a critical evaluation of disciplinary boundaries that often downplay the commonalities and interdependencies within STEM. Dr. Ernest Everett Just warned in 1939 against constructing artificial boundaries in the biological sciences lest it lead to a fractured understanding of the life sciences (Just, 1939). He predicted that a regimented view of biology inspires awe only because it "… connotes the abstruse too far removed from everyday life". Presently, the biological sciences are highly segmented based on model system, processes of interest, and technical approaches. His prediction about the biological sciences should serve as a warning for neuroscience educators to highlight epistemological diversity as a defining feature of neuroscience rather than identifying the field by the knowledge of its practitioners.

This report provides one approach to formalize the discussion of how knowledge is constructed. The data herein represent a first step in assessing the role of teaching the philosophy of science in promoting scientific literacy. Results suggest that scientific literacy is dependent on student conception of science more so than on their topical knowledge. Student attitudes shifted (Figure 2) and their understanding of core scientific principles increased (Figure 1 and,3) when the philosophy of science is highlighted, even at the expense of topic-based content.

These data are consistent with prior findings that addressing misconceptions about science has a greater impact on scientific literacy and engagement than increasing factual knowledge about science topics. The findings of this study suggest that emphasizing the nature and process of science is worthwhile for courses that seek to shape student engagement in science. It also suggests that a similar shift in focus may impact persistence in STEM insofar as it may provide more opportunities for students to make connections to their lived experience. Before firm conclusions are made about this effect, more data is needed to understand the impact on metrics such as retention and persistence.

The implementation of this structure does require the course facilitator to wrestle with the epistemic underpinnings of STEM and openly discuss the role of culture in the process of science. While this may seem obvious, STEM instructors are more likely to use culturally inclusive practices than have a culturally inclusive view of the enterprise of science (Shultz et al., 2022; Dancy and Hodari, 2023). Therefore, this course structure may facilitate change by encouraging instructors to interrogate their own conception of science.

Considering that attitudes about student connections to science changed in our study (Figure 2), it is important to note that this study did not directly assess belonging. Future

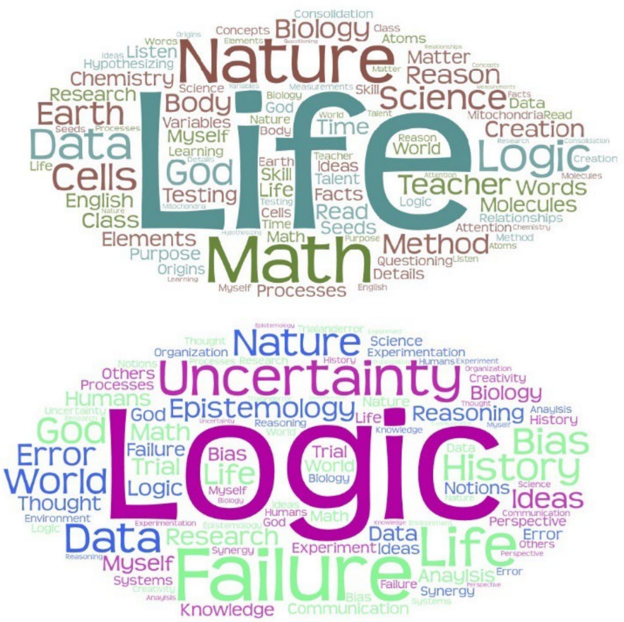

Figure 3. Student contributions to a group word cloud shift from beginning (top) to end (bottom) of the semester. Students were encouraged to contribute up to three words based on the prompt, “To understand science, I have to understand ___”.

iterations of this course should also consider representation of authors in the resources used. Belonging and self-efficacy in STEM are important predictors of persistence and should therefore be considered in the implementation of any course revisions (LaCosse et al., 2020; Hansen et al., 2023). Prior data demonstrates that identities of authors, instructors, and other contributors to the classroom impacts student belonging and, in our data, indirect measures of belonging are correlated with scientific literacy. Authors of supplemental readings and resources in the revised course described herein represent a variety of identities, but it is important to further dissect the relationship of belonging and scientific literacy.

As “scientific literacy” is a nebulous term that has a fraught history, it is important to recognize that these data are not prescriptive for course structure nor assessment. Rather, there should be an appreciation for, as science philosophers such as Rene Descartes and Michael Polanyi would suggest, the role of intuition and exploration as a way to achieve habits of scientific thought. These data promote course frameworks that focus on a holistic view of science that considers content knowledge as the extension and byproduct of “scientific literacy” rather than a mechanism to achieve it.

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