INQUIRY & INVESTIGATION

Confronting Scientific Misconceptions by Fostering a Classroom of Scientists in the Introductory Biology Lab

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Abstract

A fundamental component of science curricula is the understanding of scientific inquiry. Although recent trends favor using student inquiry to learn concepts through hands-on activities, it is often unclear to students where the line is drawn between the content and the process of science. This activity explicitly introduces students to the processes of science and allows the classroom to become a scientific community where independent studies are performed, shared, and revised. We designed this activity to be relatively independent of the chosen content, allowing instructors to utilize the presented framework for classes of various disciplines and education levels.

Key Words: *Active learning; experimental design; inquiry instruction; misconceptions; process of science; scientific method.*

The production of a scientifically aware populace is a central goal in introductory biology education at all levels. Misconceptions about the processes, products, and people in science can lead to relatively minor issues, such as failure to appreciate one's classroom time, or to more pervasive societal problems such as mistrust of scientific results (Hmielowski et al., 2014). Student understanding of the nature of science is often impeded by deeply rooted misconceptions (McComas, 1996). For instance, students view science as a stepwise, linear process with a definite beginning and end (McComas, 1996; Clark et al., 2000; Peters, 2005; Long & Wyse, 2012). This misconception may stem from the widespread teaching of the scientific method in close association with "cookbook" science laboratory exercises. Such activities include a set of steps and a description of desirable results, providing incentive for students to work toward a "correct" result. We and others (Tang et al., 2010; Brownell et al., 2012) recognize the importance of hypothesis testing and view the teaching of individual components (e.g., observations and appropriate study design) traditionally taught as "the scientific method" as an important contribution to a student's understanding of how science is done. Labs focused on content mastery can be useful in demonstrating specific biological principles but are often not representative of actual scientific investigations. Teaching the "scientific method" or even components like hypotheses and predictions *during* an otherwise cookbook lab can lead to a fostering of the misconception of a linear and formulaic scientific process. This misconception may reinforce others, such as science being a solitary endeavor, lacking creativity, and having a definite end point.

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Inquiry-based exercises can provide the necessary context in which a student can learn the scientific method while coming to appreciate the subtle nuances of how real scientists accomplish their work. For instance, allowing students to work on separate parts of a bigger question sheds light on the importance of collaborators in science. Furthermore, allowing freedom in experimental design emphasizes the inherent creativity in science, and the variable results and new ideas generated along the way show how common research goals maintain scientific communities. Rooting out misconceptions in this way meets the goal of presenting science as inquiry in the *National Science Education Standards* (National Research Council, 1996). Here, we present a laboratory exercise to be implemented early in an introductory science class that offers a small-scale representation of the entire scientific process. Our objective was to design an activity that primes students for future inquiry-based exercises early in their academic career by showing them explicitly how such labs emulate real-world science. The coupling of inquiry-based activities with explicit instruction and reflection about the nature of science is more effective than the implicit instruction in nature of science offered through discovery learning alone (Akerson et al., 2000; Bell et al., 2003). A deeper knowledge of the scientific process early on might also raise students' perceived valuing of the biological principles they learn via lectures,

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texts, and other media by first showing them the creativity, collaboration, and fun that can be involved in doing real science (McComas, 1996; Ainley & Ainley, 2011).

We designed this inquiry-based lab to allow students to challenge their own prior misconceptions about the scientific method and the real work lives of scientists (Figure 1). To begin, students are provided with media that stimulate discussions concerning what constitutes "real" science. They are then challenged to design experiments that address different aspects of a scientific problem, and the data they collect are used to generate a professional poster presentation, highlighting the creativity and sharing in science. In the example used here, we present students with a news article that raises concerns about effective hand-washing in hospitals and they design experiments to inform hand-washing best practices, but the experimental system is not the focus of this article. The framework of the lab should be applicable to almost any scientific question that can be addressed within the time frame of three biology lab sessions. If time and resources permit, allowing students to choose among possible study systems or to suggest their own ideas will further students' ownership of the exercise.

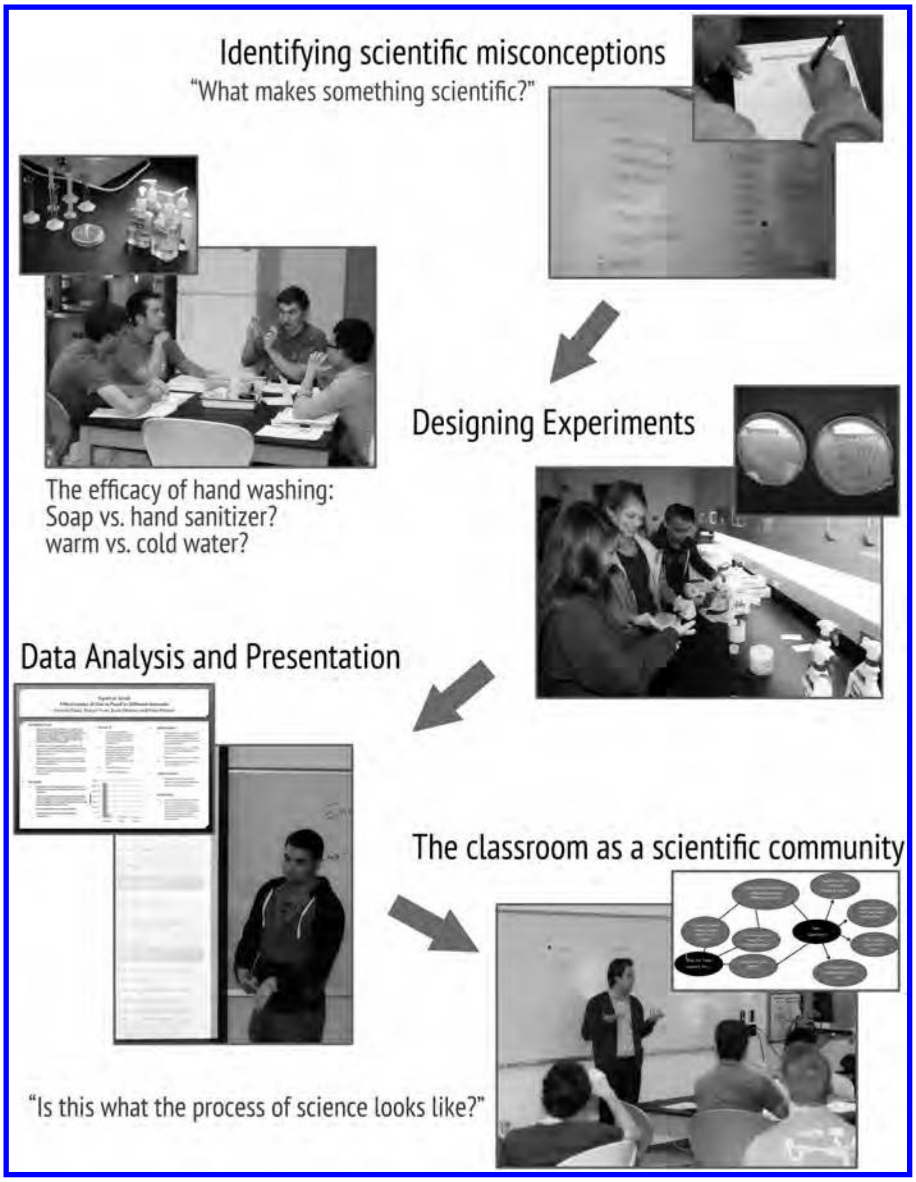

Figure 1. A visual representation of the lab activity. Students experience guided inquiry that helps them identify their own misconceptions, participate in the process of science in a realistic way, and visualize the nonlinear, creative, community-based nature of science in their own classroom.

○ Safety Considerations

- Should you choose to have students study hand-washing efficacy or otherwise carry out bacterial culture as we describe below, Petri plates should remain wrapped in plastic and closed at all times unless they are beneath an approved biological safety cabinet.
- Students should wear gloves at all times when handling plates or associated culture tools.
- Used Petri plates are a biohazard and should be disposed of in accordance with your institutional guidelines.
- Instructors who substitute another activity for those involving bacterial culture should consider student safety first.

○ Materials

We have provided open-source access to all documents associated with this laboratory exercise, which we feel are generally useful to students in other activities:

- The "How Does Real Science Work?" lab-manual text with additional teaching-assistant notes
- "An Introduction to Microsoft Excel and PowerPoint" for students
- "How to Locate and Cite Scientific Literature" for students
- (Optional) "A Guide to Basic Statistical Analyses" for more rigorous statistical analyses

These documents are available at https://drive.google.com/folderview?id=0B-OdNu2xQRXMVHUwcjBlandWOEk&usp=sharing or by scanning this QR code:

The materials provided to students to design their experiments as they wish include

- 6 agar-filled Petri plates
- Parafilm
- Instructions for inoculation of plates by sterile beads
- Cotton swabs

- Inoculating beads
- Dissecting microscopes
- Nitrile gloves
- Graduated cylinders
- 3 popular soaps or hand sanitizers
- Incubator

○ Day 1: Scientific Misconceptions & Experimental Design

Discussion of the Podcast & the "Traditional Scientific Method"

Before the class period, students are instructed to listen to the podcast episode "Fake Science" by *This American Life* (free to access online at http://www.thisamericanlife.org/radio-archives/episode/265/fake-science). The podcast provides five stories of people using standardized methods, scientific or otherwise, to reach their goals and is the starting point for student discussion about the nature of science. After listening, students need to respond to the following prompt in a brief, type-written reflection, which will be used for student reflection on learning gains at the end of the lab:

How is science done? What is the role for a scientific method in this process? What role, if any, does creativity play in the process?

The class period will begin with a discussion of the podcast itself. This is an icebreaker activity to get the students talking and thinking, and feedback from teaching assistants (TAs) at the Ohio State University (OSU) indicates that this somewhat quirky podcast gets students excited and ready to talk. It is important to make this a student-centered discussion. Example questions to get conversation started could be "Can you name a story that was real science?" or "What elements of the horse-racing portion were scientific or nonscientific?" At the end of this discussion, students will be aware that there are misconceptions and misuses surrounding the nature of science, facilitating movement into the topic of how science actually works.

Students will enter the classroom harboring diverse sets of prior knowledge regarding the nature of science, some of which will include commonly held misconceptions. By directly discussing the "steps" of the scientific method, we can activate students' prior knowledge of the subject and, subsequently, couch some important ideas (e.g., the hypotheses and predictions) in light of the way in which the students will conduct their own scientific investigations.

First, assign one aspect of the scientific method to each lab table. Have students discuss these among themselves for 10 minutes while you walk around listening and fostering discussion. Students will then present a list of important components of their step to the class, and the TA will summarize on the board (10–20 minutes of discussion). Answers will vary widely, but guidance during the group discussion should lead to inclusion of the following components:

- Question: Novel or useful, addresses old issue in new way, can be answered scientifically.
- Hypothesis: Does not make a prediction, is a statement of your explanation for the phenomenon in question.
- Prediction: Includes methodology (what is being measured), will provide support for your hypothesis if confirmed, mutually exclusive of other explanations, testable.
- Experimental Design: Control, randomization, replication, bias avoidance, intended to provide evidence specific to testing your predictions.
- Results: Attained and analyzed in a standardized, appropriate fashion, clear and concise presentation, with images and graphs when useful.
- Conclusions: Include whether hypothesis is supported or not, should be appropriate considering results, generalizes results to broader world without overextrapolation, suggests new lines of future research and compares your results with other investigations to further the field as a whole.

Designing Their Own Experiments

The perceived value of a topic and student motivation to participate are tightly linked (Ambrose et al., 2010). The introductory biology sequence at OSU begins with a course mainly focused on cell structure/function and genetics. We wanted to choose a context for student investigation that fit the course content while providing a highly relatable area for research. We chose for the students to read the *New York Times* article "Selling Soap" by Stephen Dubner and Steven Levitt (available for free at http://www.nytimes.com/2006/09/24/magazine/24wwln_freak.html?pagewanted=all). This article covers the large discrepancy between required levels of hand-washing by hospital doctors and the actual amount of hand-washing that occurs. We have students read it before coming to class, and a short discussion of its meaning facilitates transition to the students' own experiments. We do not want to convey a need for a utilitarian "value" to the work the students will do, but we do recommend outside material demonstrating the importance of the work, if only for advancing the current state of knowledge on a subject. The main emphasis is choosing an investigative context in which students already have some prior knowledge so that they can begin to ask questions without being hindered by having to research fundamental concepts.

Students will now have the opportunity to design and carry out their own scientific experiment concerning the efficacy of hand sanitizers for killing bacteria on human hands. Be sure to familiarize yourself with standard use of all materials prior to lab. Each experimental design should be checked before groups proceed, to ensure feasibility, applicability, and the possibility of some result (see Table 1). In addition to approving the experimental designs, encourage groups to review each other's work. The designs that groups generate will be diverse, and some will be outlandish or not feasible. Below is a sample of actual student questions from this lab:

- Does hand sanitizer or hand soap eliminate the most bacteria during 20 seconds of hand-washing?
- Does hand soap have greater efficacy when used with cool, warm, or hot water?

It is important to strike a balance between stifling students' imagination and guiding them toward a feasible project. Have the students explain to you how they have incorporated control, randomization, and replication into their design. Guide them to a more sound design if certain parts are missing. After students have plated their bacteria,

Table 1. Chart for experimental design, with grading rubric filled in (bold).

Component	Your Plan
Question	(1 pt) Question is based on observations and can be addressed with the given lab materials.
Hypothesis	(2 pts) Hypothesis is a simple, preliminary answer to the above interest.
Prediction(s)	(2 pts) Prediction is testable, directly related to the hypothesis, and a reasonable potential outcome.
Experimental Design	(4 pts) Design explicitly addresses randomization, replication, and control. It includes all the necessary details in order to repeat the study and addresses the avoidance of bias.
Hypothetical Graph of Anticipated Results	(1 pt) Graph is based on the prediction stated above and displays the data collected in implementing the experimental design.

they will seal the plates with Parafilm and place them agar-side-up in an incubator.

After-Class Literature Review

While their plates grow cultures between labs, students are directed toward another important part of doing science: considering what work has already been done in the field. You should assign them a brief annotated bibliography as homework. Unlike a more traditional literature review, students will be conducting this literature search after they have designed their experiment. Therefore, the focus of this assignment is to have them reflect on the potential value of searching the literature. Namely, a literature search can allow one to discern what hasn't been done and design a novel study that will add new knowledge to the field. Also, consulting previously published work is important for knowing what methods are available. Lastly, it is useful to draw comparisons with previous studies when formulating hypotheses and discussing one's own results and conclusions.

Assignment Instructions for Students: Searching for relevant primary literature is an important skill for a scientist or anyone who would like to find information on topics they are curious about. To effectively cover the previous work in your field, you must find all relevant literature and then organize and paraphrase it in a way that can be useful to you during your study. One way to do this is by an annotated bibliography. Each member of your group is to find three primary journal articles directly relevant to the question you are addressing in the study you just designed. You will then create an annotated bibliography for these three articles. After writing the short (two- to three-sentence) summary of the article, discuss how this article would have changed your approach to the experimental design phase. The information in the handout "How to Locate and Cite Scientific Literature" should be used to help you learn to find literature and then properly paraphrase the author's words and avoid plagiarism. Your instructor will also demonstrate how to perform a search for literature and discuss paraphrasing versus plagiarism.

○ Day 2: Data Analysis & Dissemination & Lab Wrapper

Data Collection & Analysis

This part of the lab should be very straightforward, as students will simply be counting bacterial colonies, quantifying colony morphology, or taking some other measurement of bacterial abundance. Students should obtain laptop computers with both presentation and data analysis software to analyze their data and make their poster. We have provided a specific tutorial for the Microsoft products we use in our introductory labs.

Poster Creation & Student Presentations

Walk around the classroom and provide guidance as needed during poster creation. Students need to divide up the work in an efficient manner. Often, students will include too much text at too small of a size. Encourage them to refer to the presentation software handout for guidelines. The poster should be a summary of their presentation, not a script. Each group will deliver a 5-minute presentation to the class of their results. Allow 1 minute for questions after the presentation. Keep to this schedule to ensure that there is time for the remaining activities. Use the provided grading rubric to assess the presentation. Encourage students to compare the results of other groups with their own to incite discussions emphasizing the role of the scientific community and collaboration in knowledge production.

Using a Concept Map Wrapper to Emphasize the Scientific Community

This is one of the most important parts of this lab. It is here that the students may be able to fully grasp the nonlinear nature of the process of science – a major goal of the lab. Have the students come up with ways in which multiple posters relate to one another and contribute to the general knowledge of the subject in synergistic ways that neither could by itself. Ask the students what new questions they have after seeing the entire class's results and comparing them with their own group's findings. These discussions result in students thinking more critically about their research questions, especially when multiple groups come to different conclusions for similar questions. The instructor should draw this discussion out as a concept map on the board to show how each group's results can be connected to those of other groups, generating new questions or different ways of testing old ones. Once the concept map is complete and connected in a nonlinear way, tell the students, "This is science, this is how it works!" As you proceed through the discussion, attempt informal assessment of the level of attainment of the first four outcomes in Table 2. Guide the discussion toward areas (e.g., the existence and role of the scientific community) that students may not have thought about yet.

At the end of this discussion, request that students read their own response to the writing prompt that they wrote prior to the start of day 1. Provide the following prompt for students and ask that they

Table 2. Student learning outcomes, misconception examples, and associated assessments. Misconception statements are modified from the Student Understanding of Science and Scientific Inquiry assessment tool (Liang et al., 2008).

Learning Outcomes	Example of Misconception	Assessments
Recognize the nonlinear nature of science (that there is no simple scientific method)	"Scientists follow the same step-by-step scientific method"	Pre- and post-instruction journal writing; wrapper discussion
Identify the creative aspects of the scientific process	"Scientists don't use their imagination and creativity when they collect data"	Pre- and post-instruction journal writing; wrapper discussion
Discuss the role of the scientific community in the advancement of knowledge	"Unlike many other professions, science is almost always a solitary endeavor"	Pre- and post-instruction journal writing; wrapper discussion; annotated bibliography homework assignment
Conceptualize the role and limits of the scientific endeavor	"Scientific investigations usually come to a definitive end, allowing the science to move on to a brand new question"	Pre-lab questions on the podcast; "What Is Science" discussion at the beginning of the lab; student discussion following each poster presentation; wrapper discussion
Formulate appropriate hypotheses, testable predictions, and a sound experimental design	"Scientists follow the same step-by-step scientific method" "When scientists use the scientific method correctly, their results are true and accurate"	Experimental plan worksheet; instructor discussions with individual groups
Execute a primary literature search and paraphrase material appropriately	"Scientists don't have different interpretations of the same observations"	Annotated bibliography homework assignment
Analyze data and make a scientific poster using common computer programs	"The same hypothesis is not tested in many different ways" "Scientists don't use their imagination and creativity when they analyze data"	Poster and group presentation

write a reflection piece on what they have done and learned over the course of the previous two lab periods:

What have you learned about the nature of science during the lab? In answering, reread your response to the first writing prompt and reflect on any differences in what you would write given what you now know.

Collect the responses to both prompts and use these to assess student achievement of desired course outcomes according to Table 2. If you wish to grade this, we recommend a qualitative evaluation based on apparent effort and focus on the prompts themselves, because free responses will vary greatly.

A useful conclusion to the lab might be to take students through the interactive "The *real* process of science" graphic on the Understanding Science website produced by scientists at the University of California at Berkeley (available at http://undsci.berkeley.edu/article/0_0_0/howscienceworks_02).

○ Considerations for Implementation

This lab has now been instituted for an academic year at OSU, following an initial pilot lab period. Feedback we have obtained from TAs and our own experiences has led to the following considerations for instructors. First, the structure of this lab allows for multiple approaches to establishing a learning context for students. Our choice of hand-washing efficacy was one option that appealed to the students of this specific introductory biology course, but other examples could be photosynthesis in plants, pesticide effectiveness on weeds, or insect behavior. Resources that provide activities to which our laboratory design could be applied include BioSciEdNet (BEN, http://www.biosciednet.org/portal/about/index.php), MERLOT (http://www.merlot.org/merlot/index.htm), and the National Science Digital Library (http://nsdl.org/). Essentially, the framework of allowing students to explicitly behave like real scientists can be used to approach most biology concepts. However, care should be taken to find materials that introduce this context in creative and entertaining ways to encourage initial discussions and allow students to make connections with their prior knowledge. Second, this lab requires instructors to actively monitor and guide students in their inquiry. Fostering student inquiry while guiding students away from unrealistic projects can be a challenging scenario for instructors, especially those with limited experience. Our interviews have revealed that most TAs find this lab exciting and liberating, while some admit to being intimidated. We highly encourage discussing the issues in teaching guided inquiry with TAs prior to this lab activity. Specifically, we suggest tailoring this activity to the instructor's desired level of learner-centered material using table 2.6 in the *National Science Education Standards* guide for teaching and learning (National Research Council, 2000).

○ Conclusion

We designed this lab to capture the excitement and curiosity that drive scientific research. Interviews with students and TAs have confirmed that the freedom of designing their own experiments and acting as a scientific community was refreshing for the students. Additionally, we began collecting survey data for both classes that have and classes that have not done the "How Real Science Works" lab, to understand how the lab influences students' perceptions of the nature of scientific inquiry. As more biological sciences curricula include student-centered activities, an early example of this type of inquiry for students entering their major could increase the value of student-centered activities in later coursework. Finally, the described method of showing students the real, nonlinear way that scientists approach problems could be a valuable experience for future nonscientists by giving a relatable, real-world perspective of a human endeavor that is often clouded by misconceptions.

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