FEATURE ARTICLE

Developing Nontraditional Biology Labs to Challenge Students & Enhance Learning

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Abstract

Laboratory experience and skills are not only essential for success in science studies, but are the most exciting and rewarding aspects of science for students. As a result, many biology teachers have become critical of the efficacy of cookbook-type laboratory activities as well as the purposes, practices, and learning outcomes of lab experiments conducted in this regimented way. In our proposed lab approach, instead of asking students to compare and contrast living cells from various kingdoms, we ask that students design and conduct lab experiments to obtain the empirical evidence to disprove both Schleiden's and Schwann's generalizations that all living things, including plants and animals, are composed of identical units called "cells." Students must then write up their findings in a paper intended for publication in a peer-reviewed scientific journal. Through this process, students learn the scientific method; concepts such as testability, falsifiability, and repeatability; and the requirements of communicating scientific findings through peer-reviewed publication.

Key words: *Scientific method; falsification; testability; repeatability; peer-reviewed publication.*

○ The Idea of the Lab

In the school setting, science labs are designed to reinforce key concepts and principles, as well as to help students understand and appreciate the process of scientific experimentation. In our approach, students are asked to use observations and experiments to draw evidence-based conclusions, and to master specific laboratory skills, methods, equipment, and measurement techniques. In order to make traditional biology labs more challenging and interesting, we engage our students in the concepts of testability, falsifiability, and repeatability by asking them to try to disprove discoveries of the past.

In the following lab activity, students are challenged to empirically obtain evidence to disprove a given scientific claim. To this end, they must develop testable and falsifiable hypotheses, design experiments, develop procedures, and conduct experiments to test the hypotheses and draw evidence-based conclusions. To learn the nuances of the scientific enterprise, they work with various samples of tissues (human cheek tissue, chicken skin, onion tissue, *Elodea* [*Anacharis*], yeast, etc.) and make slides as they conduct experiments and test their hypotheses. They also draw and examine water from ponds or rivers for single-celled living forms such as paramecia and amoebas to support their findings.

> *In our approach, students are asked to use observations and experiments to draw evidence-based conclusions.*

In addition, instead of writing a lab report, the students write a scientific paper, seek peer review from classmates, and then submit the paper to their teacher for classroom publication. To do so, they also need to know how to prepare and write a sound scientific paper and how to submit this paper for publication. In the process, they begin to understand what to expect after submission, and see the value of peer review in obtaining evidence-based conclusions and maintaining the integrity of scientific results (Belk & Borden, 2007). These additional steps help students see the relationship between scientific inquiry and scientific publication, one of the main ways to communicate scientific results and discoveries and, thus, help advance science and foster scientific integrity.

○ The Scientific Mindset

In practice, science is a construction of the mind based on actual observations; it seeks to find better explanations for natural phenomena. Science, by choice, "is limited to… questions that can be answered by the discovery of objective knowledge and the elucidation of natural laws of causation" (Futuyma, 1983, p. 170). This choice is based on the premise that science can progress only when directed toward objective observations that do not change from one observer to another. For a proposal to be called "scientific," it must (1) involve natural occurrences; (2) be testable by agreed-upon standards so that it can conceivably be proven wrong; and (3) be subject to revision or dismissal based on the outcomes of such tests or the acquisition of new,

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objective observations (Kieffer, 1985). This is why "science is the province not of geniuses who never err but of hard working men and women who are attracted to problems and determined to solve them" (McComas, 2012, p. 86).

The cornerstones of science are the concepts of falsifiability, testability, and repeatability by agreed-upon empirical standards. Falsifiability requires that hypotheses are "framed in such a way that they can be refuted by straightforward observational tests" (Sir Karl Popper, cited in Bowler, 1992, pp. 17–18). This condition is very important because in science, hypotheses are not motivated by the desire for social acceptance or commercial benefit, nor are they based on coercion or noncritical evaluation of observable facts. Rather, each hypothesis is an understanding derived from sound evidence based on existing knowledge and available tools (Janovy, 1985; Cherif, 1998). Another critical aspect of the scientific process is repeatability, the ability of other researchers to obtain the same results by using the same procedures and materials specified in a given experiment. Repeatability is central to scientific inquiry, integrity, accountability, and acceptance.

○ Setting the Stage for the Lab Exercise

In his book *Micrographia* (1665), the physicist Robert Hooke (1635–1703) described how a cork is composed of a pattern of tiny rectangular holes that he called "cells." What Hooke saw were really the dead remnants of structures that, when alive, were filled with fluid. The word and the concept *cell* became "as essential and significant to biology as the word *atom* did to physics and chemistry" (Bruno, 1998, p. 75). In 1683, the biologist Antonie van Leeuwenhoek was able to describe for the first time the unicellular organisms now called *protozoa*. In 1838, the botanist Matthias Jakob Schleiden described plants as a community of cells. Later, the physiologist Theodor Schwann made the generalization that both plants and animals are composed of identical units called "cells." In short, building on Hooke's and Leeuwenhoek's observations and their own individual discoveries, Schleiden and Schwann concluded that all living things are made of cells and that each of these cells is a discrete unit of life. Today, cell theory holds that all organisms are made of one or more cells, that the cell is the basic unit of life, and that all cells come from existing cells.

○ Lab Exercise & Activity

Instead of asking students to examine and compare living cells from three kingdoms to find out how they are alike and different, we asked students to design and conduct lab experiments that lead to observations needed to empirically disprove both Schleiden's and Schwann's generalizations that all living things, including plants and animals, are composed of identical units called "cells." Prior to conducting this exercise, students learned how to use the microscope and how to prepare slides and lab specimens to observe. By the end of the lab activity, students were able to prepare slides using, for example, human cheek tissue, chicken skin tissue, onion tissue, *Elodea*, or yeast or to use previously prepared slides of tissues in conducting their experiments and testing their hypotheses. They were also able to prepare samples and examine water from a pond or river for single-celled animals such as paramecia and amoebas to support their findings.

The following were our instructions to several student groups, including senior high school and lower-division college students, all of whom had a basic biology background.

1. Generate the hypotheses that you will test empirically to falsify Schleiden's and Schwann's generalizations that all living things are composed of cells.
2. Challenge your hypotheses one by one, using the process of reasoning, and keep only those you could not eliminate by the reasoning process.
3. Design the procedures that you will employ in your lab experiments to test the hypotheses that you could not eliminate by the reasoning process.
4. Using the materials, tools, and instruments available in the lab, determine the materials and equipment that are needed to conduct the experiments.
5. Conduct the same experiments at least twice to test your hypotheses and to obtain empirical evidence to disprove Schleiden's and Schwann's generalizations that both plants and animals are composed of identical units called "cells."
6. Upon successful completion of your experiments, communicate your findings by writing a scientific paper suitable for publication in a peer-reviewed journal. Include in your manuscript the following sections: abstract, introduction, method and procedures, results, analysis, conclusion, and references.
7. Ask three of your classmates to review your paper and suggest changes and adjustments, if any.
8. Submit your scientific paper to your teacher for review. Your paper may be (a) accepted with no changes, (b) accepted with changes and revisions, or (c) rejected for publication. To be considered for publication, your paper must obtain, on average, at least 3.5 out of 5 points, based on a scale of 1–5.
9. Upon completion of your experiments and submission of your scientific paper, answer the following questions:
   a. Were you able to generate a number of hypotheses?
   b. Were you able to eliminate most of your initial hypotheses through logic and reasoning before you selected the final hypotheses that needed to be tested empirically?
   c. Were you able to repeat the experiments for each hypothesis?
   d. Were you able to obtain empirical evidence to disprove Schleiden's and Schwann's generalizations that both plants and animals are composed of identical units called "cells"?
   e. If you were unable to disprove Schleiden and Schwann, what conclusions did you draw concerning their generalizations about cells?
   f. Why do you think that the process of peer review is important in the scientific endeavor?
   g. Was your paper:
      i. Accepted without revision? Explain why, in your opinion.
      ii. Accepted with revision? Explain why.
      iii. Rejected for publication? Explain why.

10. Why do scientists so often try to disprove, rather than prove, a discovery, hypothesis, or theory?
11. Schleiden's and Schwann's generalization that all living things are composed of identical units has become the cornerstone of cell theory. When do you think that a given hypothesis becomes a theory?
12. Explain how the design of an experiment can affect the quality of the outcome in testing a given hypothesis.
13. Explain how the repeatability of experiments can decrease our skepticism and increase our acceptance of the outcomes of experiments and discoveries.
14. What additional experiment(s) could you conduct to support your findings?
15. Why does the general public often trust the information presented in scientific journals, whereas scientists always question information presented in scientific journals (and elsewhere) instead of automatically trusting it?
16. Why is it important that a hypothesis (tentative explanation) must be testable and falsifiable?

○ Sample Student Hypotheses

To suggest the nature of our students' response to this project, we include a sample of several of their hypotheses and experimental procedures designed to disprove current cell theory.

Hypothesis A: A single cell by itself is not capable of an independent existence without combining with other cells to form a single living entity. Students tested Hypothesis A with a few simple experiments involving the collection and observation, under the microscope, of single-celled organisms in pond water. They sought to show that not all cells have the essential components of a membrane, nucleus, and cytoplasm. They also sought to prove that even when the three components are seen in closed form, this does not mean that signs of life can be seen metabolically and functionally.

Hypothesis B: The single units of prokaryotes have nothing in common with single units of eukaryotes and, therefore, both belong to different types of life structurally, functionally, and metabolically. Students pursued Hypothesis B by conducting experiments and reviewing existing literature to attempt to prove that individual bacterial cells and individual yeast or paramecium cells have nothing in common. They also sought to prove that even when common components are present, these components are not essential for life (i.e., that without them, signs of life cannot be seen metabolically or functionally).

○ Suggestions for Using This Approach

Educators who wish to adopt this pedagogical approach are encouraged to apply the following guidelines:

1. Choose less complicated investigative labs with procedures and protocols that have short learning curves.
2. Focus on subjects for which data can be collected in a short period.
3. Do not impose unrealistic expectations on your students, such as might lead to formation of negative personal attitudes.
4. Explain to students that failure to obtain empirical supportive results is acceptable as long as it is not due to lack of effort or failure to follow the specified methods and procedures.
5. Start with only one or two targeted biology labs using this approach in a given semester until instructor and students become comfortable with the approach.

We usually end this lab activity by asking students to read, and then discuss in class, Edward O. Wilson's short paper "Scientists, scholars, knaves, and fools" (Wilson, 1998). Students are asked to write one-page reflections on the paper, especially the following paragraph:

> Science, to put its warrant as concisely as possible, is the organized systematic enterprise that gathers knowledge about the world and condenses the knowledge into testable laws and principles. The diagnostic features of science that distinguish it from pseudoscience are, first, repeatability: The same phenomenon is sought again, preferably by independent investigation, and the interpretation given to it is confirmed or discarded by means of novel analysis and experimentation. Second, economy: Scientists attempt to abstract the information into the form that is both simplest and aesthetically most pleasing – the combination called elegance – while yielding the largest amount of information with the least amount of effort. Third, measurability: If something can be properly measured, using universally accepted scales, generalizations about it are rendered unambiguous. Fourth, heuristics: The best science stimulates further discovery, often in unpredictable new directions; and the new knowledge provides an additional test of the original principle that led to its discovery. Fifth, and finally, consilience: The explanations of different phenomena most likely to survive are those that can be connected and proved consistent with one another. (Wilson, 1998, p. 6)

○ Final Remarks

Our experience with this laboratory exercise has shown that students prefer the challenges of conducting purpose-driven lab experiments and strive for achieving evidence-based conclusions and outcomes. They find both the process of preparing and writing scientific papers, along with seeking publication, to be worthwhile educational experiences. As one student wrote, "It makes me a better student in terms of organizing my thoughts, solving problems, writing my term papers, and appreciating science, what scientists do and endure in the realm of doing science and achieving scientific discoveries." In short, students understand what distinguishes scientists from nonscientists, as well as distinguishing scientific from nonscientific claims or proposals. Students also learn that

> the objectivity of science lies in its willingness to subject every aspect of the hypothesis

> to rigorous testing, [and] if the predictions derived from the hypothesis are not confirmed by experiment, the hypothesis is rejected and a new model sought. (Bowler, 1992, p. 17)

While the majority of our students unfortunately still see science as a set of facts rather than an active human endeavor, it is more unfortunate that many teachers are still teaching science as an assemblage of facts. To become scientifically literate citizens, students need, in addition,

> a better window on what science is and how it is done, a clear presentation of key concepts that rises above the recitation of details, an articulation of philosophical underpinnings of the scientific discipline at hand, exercises that demand analysis of real data, and an appreciation for the contributions of science to the well-being of humans throughout the world. (Cox et al., 2012, p. xxi)

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