Teaching the Scientific Method in a Large Introductory Biology Two-Semester Lab Sequence

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Abstract

One of our goals in teaching Introductory Biology labs is to teach students the scientific method. After a two-semester Introductory Biology lab sequence, students should be able to formulate hypotheses, design a simple experiment, understand the concept and utility of experimental controls, analyze and interpret results, and communicate their findings. We have developed lab exercises during the first semester where we: 1) give students the experimental question and ask them to formulate a research hypothesis and a null hypothesis, 2) ask students to design positive and negative controls for an experiment given a choice of conditions, 3) teach students to construct line and bar graphs, calculate averages and standard deviations, perform t-tests and chi-square tests 4) ask students questions about their experiments that lead them toward interpretation of results, and 5) communicate findings by answering directed questions. In the second semester of the introductory biology sequence, we have developed an inquiry-based multi-week module based on metagenomic analysis of bacterial diversity using next generation sequencing technologies. In this lab module, students work on a real research question to obtain, analyze, interpret, and communicate their data using the skills that they developed during the first semester sequence. At the end of the second semester, students think about the next step that they would take to test their hypothesis or whether they would develop a new hypothesis based on their results. This two-semester sequence takes students through learning the fundamentals of experimental design and the scientific method in the first semester using a step-wise skill building learning approach, followed by tackling a real research question that requires more independent thinking and creativity in the second semester.

Methods

During the last few academic years, we have developed or modified lab exercises in the first semester Introductory Biology lab course (Biology 101) to gradually introduce students to some of the key aspects of the scientific method. In the second semester (Biology 102), we introduced a new metagenomics lab module, where students participated in an authentic research project where we hoped they would use and build upon the skills developed during the first semester. To assess how well our goals were achieved in both courses, we analyzed data from student evaluations of the laboratories that students complete at the end of every semester (before receiving their grades), and compared results between the old (prior to emphasizing the scientific method) and new (emphasizing the scientific method) curricula. For Biology 102, we also administered a CURE (Classroom Undergraduate Research Experience) survey, and compared survey results between students completing the old (non-research based) curriculum and new (research-based) curriculum.

Scientific Method Goals

To gain experience applying the process of science and using quantitative reasoning:

Hypothesis: To demonstrate an ability to formulate hypotheses
Design: To demonstrate an ability to design experiments based on the scientific method
Controls: To understand the concept and utility of experimental controls
Analysis: To analyze and interpret results from a variety of biological methods
Math: To use mathematical reasoning and graphing skills to solve problems in biology
Communication: To communicate findings from a study in oral or written form

Conclusions

- A gradual introduction of some key aspects of the scientific method slightly increased students' interest in and perceived quality of the lab, as well as their perceived understanding of their abilities to perform and interpret experiments in Biology 101.
- Introduction of the Leaf Metagenomics research module in Biology 102 slightly decreased students' interest in and perceived quality of the lab, as well as their perceived understanding of their abilities to perform and interpret experiments in Biology 102.
- Incorporation of the Leaf Metagenomics lab module in Biology 102 did not enhance either students' understanding of the process of scientific research or students' interest in science (based on student self reporting).

Future Directions

- Incorporate more aspects of independent research, rather than directed assignments, into the Leaf Metagenomics Module, where students develop hypotheses themselves, design at least portions of the experiment, determine proper controls to use, etc.
- Enhance students' communication skills, as well as interest and excitement in the Leaf Metagenomics module, with a poster competition where we will select the best idea for the next semester!
- Give interested students the opportunity to continue working on the Leaf Metagenomics project in other courses and/or independent study projects.

Biology 101 Lab Exercises

OLD Lab Activities	Goals Addressed	NEW Lab Activities	Goals Addressed
Microscopy		Lab Skills	Analysis, Math
Enzyme Kinetics	Analysis, Math	Enzyme Kinetics	Analysis, Math
Photosynthesis	Analysis, Math, Communication	Microscopy	
DNA Restriction Analysis	Analysis	Photosynthesis	Controls, Analysis, Math, Communication
Transformation of *E. Coli* with plasmid DNA	Analysis	UV Irradiation Session 1	Hypothesis, Design, Controls
Expression and Purification of GFP from *E. coli*	Analysis	UV Irradiation Session 2	Analysis, Math, Communication
Genetics of *Arabidopsis thaliana*, Session 1	Hypothesis, Analysis, Math	Genetics of *Arabidopsis thaliana,* Session 1	Hypothesis, Analysis, Math
Genetics of *Arabidopsis thaliana*, Session 2	Analysis, Communication	Genetics of *Arabidopsis thaliana*, Session 2	Analysis, Communication
Vegetative Plant Structure		Transposon Mutagenesis, Session 1	Controls
Plant Transpiration	Hypothesis, Controls, Analysis, Math	Transposon Mutagenesis, Session 2	Analysis
Lower Plant Diversity		Transposon Mutagenesis, Session 3	Design, Controls
Flowers to Seeds		Transposon Mutagenesis, Session 4	Analysis, Communication

Biology 102 Lab Exercises

OLD Lab Activities	Goals Addressed	NEW Lab Activities	Goals Addressed
Bacterial Mutagenesis	Hypothesis, Analysis, Math, Communication	Bacterial Mutagenesis	Hypothesis, Analysis, Math, Communication
Barcoding Life	Analysis	Leaf Metagenomics, Session 1	Hypothesis, Design
Invertebrate Diversity, Session 1		Leaf Metagenomics, Session 2	Controls
Invertebrate Diversity, Session 2		Invertebrate Diversity	
Animal Development		Mammalian Anatomy	
Mammalian Anatomy		Plant Anatomy	
Neural Function	Analysis, Math, Communication	Neural Function	Analysis, Math, Communication
Cardiac Function	Hypothesis, Design, Controls, Analysis, Math, Communication	Plant Physiology	Hypothesis, Controls, Analysis, Math
Disease Tracking ELISA	Controls, Analysis	Renal Function	Hypothesis, Controls, Analysis, Math, Communication
Renal Function	Hypothesis, Controls, Analysis, Math, Communication	Decision-Making in Ants and Humans	Hypothesis, Analysis, Math, Communication
Decision-Making in Ants and Humans	Hypothesis, Analysis, Math, Communication	Leaf Metagenomics, Session 3	Hypothesis, Design, Controls, Analysis, Math, Communication
Analysis of Metagenomics Data	Controls, Analysis, Math, Communication	Leaf Metagenomics, Session 4	Hypothesis, Design

Results

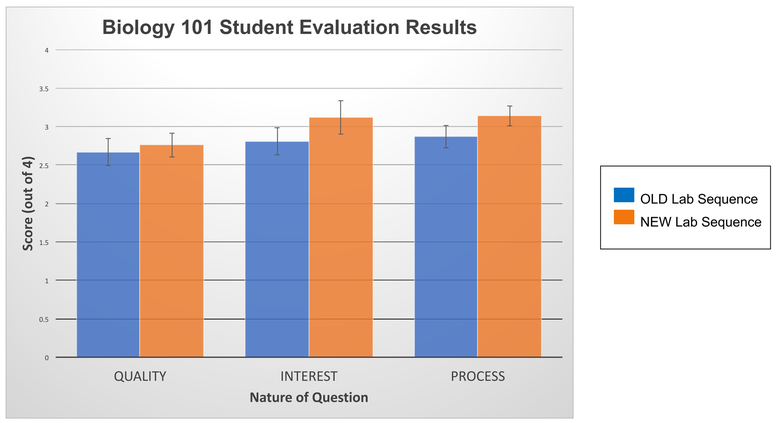

Figure 1A: Scores from Student Evaluations of Biology 101 Labs

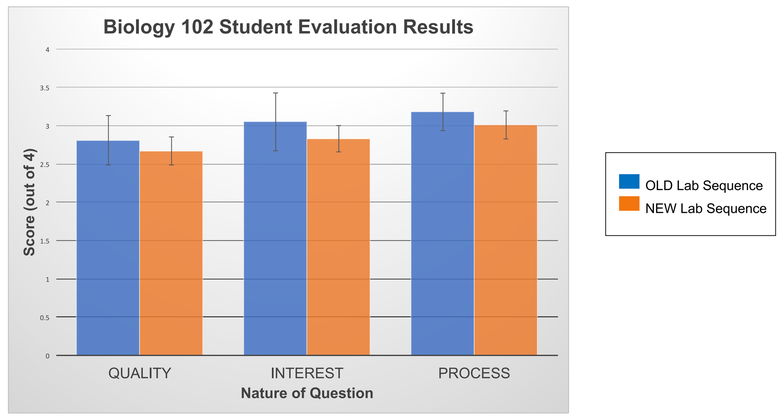

Figure 1B: Scores from Student Evaluations of Biology 102 Labs

Figure 1(A and B): Average scores with error bars plotting 2X SEM (standard error of the mean). A score of 0 indicating the worst rating and a score of 4 indicating the best rating. Evaluations were worded as follows:
QUALITY: Overall quality of the lab.
INTEREST: The TA effectively stimulated my interest in the lab.
PROCESS: In this lab I developed my abilities to perform and interpret experiments.

Student Evaluation Comments

From new Biology 101 Labs:
- I especially enjoyed the sessions where we used those websites to pick restriction enzymes and see the sites on the plasmid. I really enjoyed that process, and it has helped me to see that even though the concept is complicated, it's easy to do it in a lab.
- The lab was effective in expanding on class material and helping us learn biological lab methods.
- Great lab section that helped me learn the concepts of biology better while stimulating my interest in the experiment.
- The labs effectively stimulated my interest and also were good at teaching lab skills while doing experiments that were things that scientists practically use.

From new Biology 102 Labs:
- The lab was organized terribly. We ended up just doing the grunt work for a Penn lab that was doing some metagenomics experiment. We were just part of a big project and spent an entire lab picking leaves so that people next year could do experiments with them. This did not help us learn in any way at all, and did not pertain to the material we learned in lecture.
- I have learned many new lab techniques that I will retain during my years at Penn.
- This was a very enjoyable lab and helped me understand the concepts from the lectures. The course was structured well and made research seem more accessible by incorporating the projects of Penn professors.

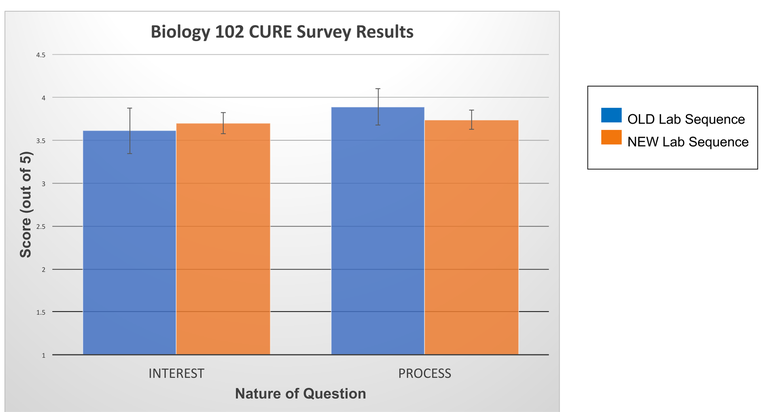

Figure 2: CURE (Classroom Undergraduate Research Experience) Survey Scores
Average scores with error bars plotting 2X SEM (standard error of the mean). A score of 1 indicating the most disagreement and a score of 5 indicating the most agreement. Evaluations were worded as follows:
INTEREST: This course had a positive effect on my interest in science.
PROCESS: This course was a good way of learning about the process of scientific research.