Tested Studies for Laboratory Teaching
Proceedings of the Association for Biology Laboratory Education
Vol. 35, 132-139, 2014

Uncooking the Lab: Laboratory Designs for Engaging Students in the Process of Science

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We all know that the study of biology, or any other science, involves more than assimilating factual information. It also involves learning how to effectively use that information for problem solving, posing hypotheses, conducting experiments, and interpreting experimental results. Given this, if we want our students to understand what science is, we need to provide them with both conceptual knowledge and we need to give them opportunities to actively practice science. The question then becomes: How do we accomplish these goals? One solution: design our student lab activities to provide experiences similar to what goes on in actual research labs.

Keywords: Active learning, laboratory research modules, practicing science

Link to Supplemental Materials
http://www.ableweb.org/volumes/vol-35/v35/heitz/supplement.htm

Introduction

We all know that the study of biology, or any other science, involves more than assimilating factual information. It also involves learning how to effectively use that information for problem solving, posing hypotheses, conducting experiments, and interpreting experimental results. Given this, if we want our students to understand what science is, we need to provide them with both conceptual knowledge and opportunities to actively practice science. The question then becomes: How do we accomplish both of these goals?

One solution is to design our student lab activities to provide experiences similar to those in actual research labs. The "Research Project" labs I have designed:

- are all offshoots of what were previously cook book-type labs.
- last more than one week.
- mirror real-life research problems.
- are open-ended (do not have known or expected outcomes).
- allow students the opportunity to learn from their "mistakes".
- are inexpensive to run with a just few students or with as many as 1400 students per year.

In developing these labs, I started by asking myself: "What skills and abilities do scientists (and many other professionals) use on a regular basis?" I asked the same question of over 200 faculty from across the US and Canada. I also asked over 2000 introductory biology students. With some variation, both faculty and student lists include the following skills and abilities.

- Problem solving skills
- Communication skills (both written and oral)
- People skills, e.g. ability to work well in groups
- Ability to think critically
- Organizational skills
- Ability to learn from one's mistakes and a willingness to continue learning
- Ability to be flexible, to think on your feet
- Having a good base knowledge of the material

I find it very useful to have my students generate this list for me. Once it is obvious that they recognize the need for these skills, I can use their own words to support specific goals of our courses. This list also aligns very well with the Essential Learning Outcomes and the Principles of Excellence, published by Liberal Education and America's Promise (LEAP) in association with the Association of American Colleges and Universities and many key businesses and professional schools. It also aligns with *Bio 2010: Transforming Undergraduate Education for Future Research Biologists* (NRC 2003) and more recently the document *Vision and Change in Undergraduate Biology Education: A Call* *to Action* (AAAS 2011).You can easily do a web search of what skills and qualities employers want and come up with a wide range of sites proposing similar lists. In other words, we know and our students know the skills and abilities they will need in the future.

The questions then become: Are we helping our students build these skills and abilities in our intro courses? And,what role(s) can the lab play in helping our students build these skills and abilities? In trying to answer these questions I examined the types of research scientists perform and grouped them into categories. From these categories, I focused on three types, listed below along with an example of a student lab I developed for each type:

- Contractual research projects – e.g. D*ead or Alive?* A preliminary analysis of unknowns for evidence of life
- Research projects which may result in specific answers – e.g. *Genetic Analysis of Population of Organisms*
- More complex open-ended research projects– e.g. *Gravitropism and the Hypocotyl*

Because the labs I developed are not what students consider "normal labs", I discovered I had to "sell" this type of lab. To do this, as noted above, at the beginning of the semester I have the Teaching Assistants (TAs) start each lab by asking the students: "What skills and abilities do you feel you will need to use on a regular basis in your future career?" The TAs collect this information in a word document or take a picture of what they collect on the blackboard. Then they note: "Wouldn't it be valuable if you got a wide range of practice in all of these before you enter your future career?" and point out that providing this practice is among the key goals of the laboratory experiences in our introductory biology courses.

All that being said, I discovered when I first started developing and teaching these labs that it is very difficult for introductory biology students to start the semester with a full-blown research module. Instead, it was better to ease the students into it by fronting the work with what I call a few "Tools and Techniques" labs. The format of these labs was more familiar to the students – but each lab also included a small investigative experience. Following the first three Tools and Techniques labs we go to total immersion as the students meet their first investigative lab, *Dead or Alive? A preliminary analysis of unknowns for evidence of life*.

Contractual Research Projects

Example: Dead or Alive? - A preliminary analysis of unknowns for evidence of life

Students are given the following overview of the project:

- A major US oceanographic survey has discovered new forms of life in one of the deep oceanic trenches. To pinpoint key areas for future study the survey team did a perimeter search and took thousands of grab samples from nearby areas.
- The grab samples need to be analyzed. Doing a complete analysis would be prohibitively expensive and time consuming. Therefore, the first step is to determine which of the thousands of samples (and as a result the areas they came from) contain evidence of life.
- The National Science Foundation plans to give the contract for the initial analysis to one research lab. The NSF has provided competing labs with sets of test samples. The lab that gets the contract will be the one that develops the most cost effective and accurate methodology to determine which of the thousands of sample areas are worthy of further study and analysis. The protocol for determining which samples are most likely to contain evidence of life forms has been left up to the competing labs.
- Your lab has requested and received one of the sets of test samples. If you get the contract, you will be able to support yourself and your employees for the duration of the contract. In addition, the national recognition the contract provides will help your lab gain future contracts.
- You call a lab meeting to brainstorm how to determine which samples are most likely to contain evidence of life forms. Your staff, time and budget are limited.

As is evident from the overview, *Dead or Alive?* is basically a work-for-hire-type research project. The purpose and end result are defined, but the methods for getting there are left up to the researchers. Like most of the modules, this is a three-week lab. During Week 1 the TA begins the session by having the students meet in small groups and then in large group to go over a series of questions designed to prepare them for the research project. To foster communication among the groups the TAs let the students know: "We are a research lab working together to get the grant. We're going to have different groups work independently to come up with what each feels is the best proposal. If one of them gets the grant we will all benefit." By the end of Week 1 each group of three to four students in the lab produces a proposal for the research. In Week 2 the students conduct the research. In Week 3 they share and analyze their results and write a proposal to get the contract to conduct the research.

Research Projects with Specific Answers

Example: Genetic Analysis of a Population of Organisms.

In this lab, students mate or cross organisms to determine if specific traits are genetically inherited. They use a software program (Classical Genetics Simulator or CGS) to analyze their crosses in ways similar to those used by practicing geneticists and genetics counselors. This gives students the opportunity to develop the logic and thought processes needed to solve real-life problems in genetics. This lab is described in detail in a previous ABLE publication (Heitz et al. 2011)

Open-Ended Research Projects

Example: Gravitropism and the Hypocotyl - Developing and testing a hypothesis concerning the mechanism(s) affecting the gravitropic response of the hypocotyl in Brassica oleraceae (broccoli)."

This example is described below in the Student Outline section. This third type of lab addresses complex problems in which no single experiment will answer the question. In this type of research scientists investigate multiple possible avenues and often seek to eliminate possibilities. We start this (and in fact all) lab session(s) with three questions.

- What are we doing?
- Why are we doing it?
- How are we doing it?

We point out that these three questions are the foundation of scientific inquiry. We can ask all types of questions, scientific, metaphysical, etc., however, scientific questions (What are we doing?) must have a rationale (Why are we doing it?) and must be testable (How are we doing it?)We further point out that students must be prepared to answer these three questions at the beginning of each lab session. The keys for me in developing these labs were:

- I lacked money and manpower so I had to be inventive.
- I realized a lab experience can go on for more than one 3 hour period. (To most this is not an earth-shattering realization but it made all the difference.)
- I took existing labs and "turned them on their ears". Instead of spending the entire lab walking students through techniques alone, students had to learn techniques to answer open-ended questions. In other words, I made the lab experience mirror real research.

Effects of the Lab Redesign on Student Learning

For those of you who are worried about changing your labs and making mistakes – Don't worry – you will make mistakes. I made a lot of them, but I learned a lot from the mistakes I made. For example I learned:

- Before I attempt to teach my students anything, I better have a very clear idea of what I want them to learn from the process: i.e. the types of scientific processes, thought processes, thinking, and methods I want them to learn. Then I need to develop the lab exercise in a format that gives my students the opportunity to learn these things.
- If student learning is the goal, I need to take the focus off of the instructor and put it on the student.
- If I want my students to be able to deal with uncertainty, I need to let them experience situations where uncertainty exists and let them deal with it.
- If I want students to be able to learn from their own mistakes, I have to give them that opportunity in a setting where their grade is not affected by the initial mistakes but rather is determined by what they learned as a result of making and dealing with the mistakes.

I have also learned that real learning is the responsibility of the individual and that the majority of this occurs outside of the classroom. However, what goes on in the classroom and what I require of my students should set the stage for and give students practice in the learning I want them to achieve.

Student Outline

Example of an Investigative Lab

Gravitropism and the Hypocotyl -
Developing and testing a hypothesis concerning the mechanism(s) affecting the gravitropic response of the hypocotyl in *Brassica oleraceae* (broccoli)

Student Protocol

Before coming to the lab, students complete a reading assignment and use the information in it to answer a set of pre-lab questions. For the gravitropism lab,the reading assignment discusses factors that can affect gravitropic and phototropic responses in roots and stems. These can include:

1. Hormone concentration differences, e.g. auxin
2. Movement of starch granules/statoliths
3. Second messengers stimulated by altered orientation, e.g. calcium
4. Wavelength of light, e.g. blue vs. green vs. red

For the gravitropism lab, the pre-lab questions are the following.

1. List three factors (parts or substances found in the plant) which are thought to be involved in the gravitropic or phototropic responses.
2. Where and how is each of these factors thought to affect gravitropism or phototropism?
3. Select one of the factors you listed above (or any other you think is reasonable) and develop an hypothesis concerning the mechanisms involved in the gravitropic response of the hypocotyl in Brassica.

   (Note: We are asking you to look at only one factor, or a very few closely related factors, to determine what effect it may have on gravitropism in the hypocotyl. We are not asking you to determine all of the factors which may affect gravitropism in the hypocotyl of Brassica.)
4. Write the hypothesis you plan to test here and in your lab notebook. Be sure to include a brief rationale for your hypothesis.
5. What kinds of equipment or supplies will you need to conduct an experiment to test the hypothesis you propose above?

As the students enter lab they hand in their pre-lab questions. The TA uses these to establish student research groups with similar interests/ideas for projects.

TA Protocol

The TA starts the lab by introducing the experimental system and the research project. The experimental organisms are five-day old seedlings of *Brassica oleraceae* – broccoli, a dicot. (We purchase the sprouting broccoli seed for about $50/kilo).
The TA reminds the students about basic plant anatomy. For example:

- In this lab we're using *Brassica oleraceae* (broccoli), a dicot.
- Like a peanut seed, the broccoli seed contains two cotyledons (the two halves of the peanut) and an embryo (that little hard crunchy thing between the two halves of the peanut that you were suspicious about and often flicked out before eating).
- In development, the root emerges first. Next the hypocotyl, the region below the cotyledons, elongates and pulls the cotyledons and apical meristem out of the soil. The cotyledons open up and become photosynthetic to support early growth.
- In Fig. 1 you can see a cross section of the stem, with the vascular tissue arranged around the periphery.
- In the cross section of the root, the vascular tissue is central.
- The hypocotyl is the organ that connects the root and stem.

The TA then asks the students: What does the cross section of the hypocotyl look like? (Students will generally volunteer that it must be a transition zone between root and stem.)

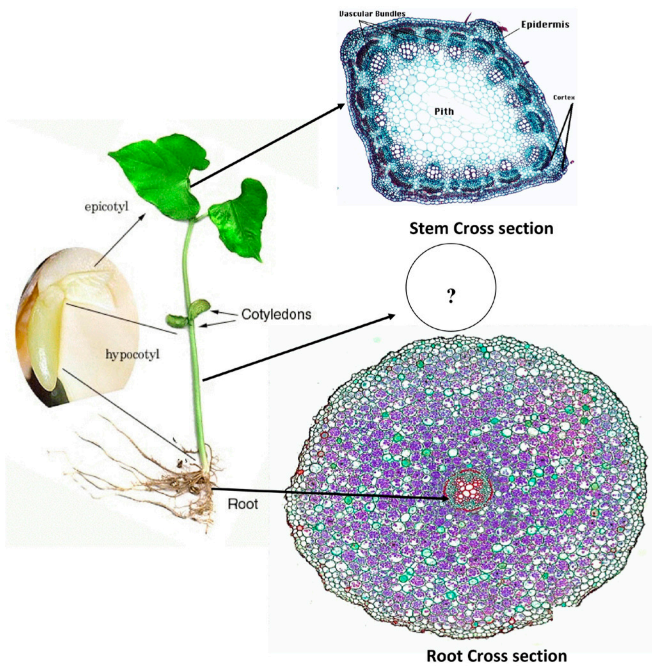

Figure 1. A cross section of a stem shows xylem and phloem arranged in a ring around the periphery. A cross section of a root shows xylem and phloem centrally located. How would these be arranged in the cross section of the hypocotyl?

The TA follows up this question by additional questions that are left hanging. For example: Will the hypocotyl respond more like a root than a stem or vice versa? Do regions closer to the root respond more like root and regions closer to the stem respond more like stem?

The TA then notes that no good scientist would start an investigation without doing some preliminary experiments and tells the students that some preliminary experiments were set up in advance of the lab to test the gravitropic response:

- We use simple light proof chambers (35 mm film canisters) as shown in Fig. 2.
- We wet a strip of filter paper and inserted it into the chamber.
- We cut off some 5-day-old seedlings at soil level and attached them to the filter paper (Figure 2). Surface tension/adhesion properties of water allow this.
- We cover the canisters and leave them alone for 4 or 5 hours (or overnight).

The TA then directs the students to work in their small groups to predict what will happen:
- How do you predict the hypocotyl will respond in this system—Will it angle up, down, stay straight, other?
- Come up with a prediction and a rationale for your prediction.
- Draw your prediction on the board.

Once all predictions have been written on the board, we ask the groups for their rationales. After all predictions are up on the board and all rationales are stated, the TA gives all groups an experimental canister, asks them to observe the response and asks the group to draw the actual response on the board as accurately as possible, using a different-colored chalk and without erasing their initial prediction.

We don't stop there—the TA introduces one more preliminary experiment, in which seedlings were arranged in what Paul Williams (Fast Plants developer, University of Wisconsin) calls a crucifer cross (Fig. 3), a reference to the plant family Cruciferae, to which Fast Plants belong. This experiment was also set up in a lightproof canister and left for 4 to 5 hours (or overnight). The students are asked again to predict what they think each of the hypocotyls will do and to provide a rationale for their predictions. As above they diagram their predictions and then the actual results on the board.

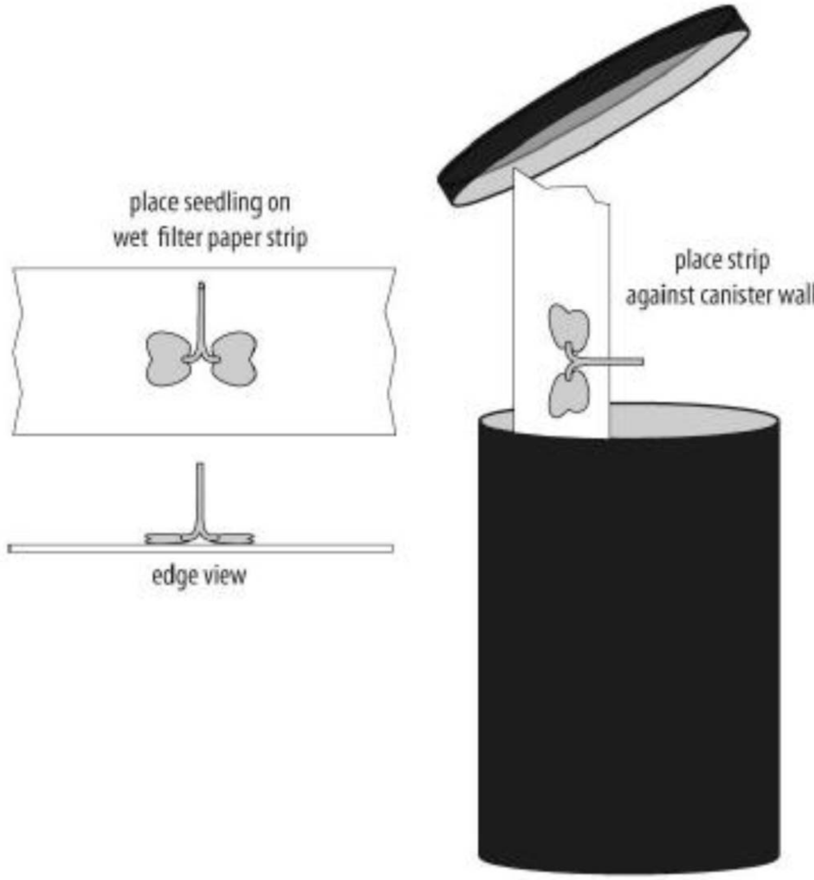

Figure 2. The basic experimental apparatus and setup for preliminary Experiment 1 is shown here. The canister remains in the upright position for 4 to 5 hours or overnight.

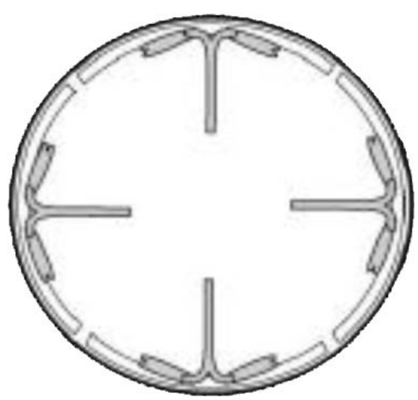

Figure 3. The "Crucifer cross" arrangement for preliminary Experiment 2 is shown here. Note in this case the canister is placed on its side for 4 to 5 hours or overnight.

In this introduction to the research project we don't answer any questions but instead raise questions. We also point out that:

> "Whoever set up these canisters was a bit sloppy because the hypocotyls are all different lengths. What effect might this variation in length have on the ability of the hypocotyls to curve? Remember there is no cell addition in this part of the plant. All growth in this region is the result of cell elongation."

Raising this point allows us to talk about controls. Often some of the seedlings have fallen off of the filter paper, which allows us to talk about the need for replicates. The type and degree of curvature will differ among the seedlings. This difference leads to a discussion of methods for measuring (using Image J) and analyzing (using Excel) the responses as well as the issue of timing (i.e., when to observe the responses).

We give students some idea of the available supplies and equipment, but we don't try to limit them. A list of the available supplies is included in the Instructor's Notes in the resources associated with this paper (see Notes for the Instructor below.) After this introduction we ask the student groups to choose a factor they think might affect the response and develop an experiment to determine what effect it may have. The format for the proposal is as follows:

1) Introduction (brief) - State the purpose or hypothesis of the experiment and the rationale for it.
2) Materials and Methods - State what equipment will be needed and explain the experimental design. This section should include discussion of controls to be used.
3) Results - State what type(s) of data will be collected and how the data will be analyzed once collected. Include a discussion of the responses you would expect to see if your hypothesis is supported.
4) Students are also asked to include a list of needed supplies with their proposal.

TAs review the proposals and at the beginning of Week 2 they provide their comments in the form of Socratic questions, e.g. Is the number of replicates sufficient to allow for random loss of hypocotyls and to allow for statistical analysis? Have you developed a method to measure the response and if so, what is it? Have you included sufficient controls?, etc. Students are given some time to discuss proposals, controls, number of replicates needed and methods for measuring response. Following this they set up their experiments and work out a schedule for collecting data.

In week 3, we revisit methods for evaluating data, e.g. using Image J for measuring and Excel for statistical analysis and graphing and students analyze their data and write up their results as a standard journal-style article.

Notes for the Instructor

Instructors' Notes be found at the following URL:
https://uwmadison.app.box.com/HeitzUncook-Lab

This site contains:
- The intro pages to my lab manual (These explain how and why the lab manual is organized the way it is.)
- The full text of the labs discussed in this article (plus others) and the full Instructors' Notes for the Dead or Alive and Gravitropism labs.
- A primer on use of ImageJ for measurements and of Excel for statistical analysis and graphing.

Acknowledgments

The author thanks the University of Calgary and all of the ABLE volunteers for their generous help and for creating a wonderful opportunity to share ideas.

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About the Author

Jean Heitz is a Distinguished Faculty Associate in Zoology at the University of Wisconsin-Madison and has worked with a two-semester Introductory Biology sequence for majors since 1978. Her key roles have been in development of active-learning activities for discussion sections and open-ended investigations for laboratory sections. Jean has also taught a graduate course in *Teaching College Biology* and is the author of *Practicing Biology: A workbook to accompany Biology by Campbell and Reece*, 10th Edition and *Practicing Biology: A workbook to accompany Biological Science by Freeman*, 2nd edition (Benjamin Cummings, 2010).

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Citing This Article

Heitz, J. 2014. Uncooking the Lab: Laboratory Designs for Engaging Students in the Process of Science. Pages 132-139 in *Tested Studies for Laboratory Teaching,* Volume 35 (K. McMahon, Editor). Proceedings of the 35th Conference of the Associa-tion for Biology Laboratory Education (ABLE), 477 pages. http://www.ableweb.org/volumes/vol-35/?art=9