Supplemental Material

CBE—Life Sciences Education

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Supplemental Material A

The three courses that comprised the new introductory biology curriculum each had a 1-credit discussion integrated as part of the course. The organismal and ecological biology course (OEB; 3 credit hours) was held in large lecture format for two 50-minute class sessions per week, and then divided into nine GTA-led small group (approximately 25 students each) discussions for one 50-minute session per week (in a separate location). Similarly, the cellular and molecular biology (CMB) course also had nine sections of GTA-led small group discussions for 50 minutes of the 150 minutes of class time per week. The new 2-credit lab course (Skills of Biological Investigation) alternated between two weeks of lab work and one week of discussion to reinforce learning about the concepts and skills targeted by the lab. This coursewas approximately 25 students per section and led by GTAs, with faculty oversight. Regardless of course, the philosophy of the discussions was to practice interpreting or applying biology in a collaborative context, with the support of primary literature being especially prominent in the OEB and CMB discussions. All discussions were guided by explicit sets of learning objectives designed by the curriculum community who designed each course.

The following represents an overview of each of the discussions associated with the new introductory courses.

OEB Discussion

The goal for the OEB discussion was to support student understanding of modern scientific research and knowledge generation by improving their ability to read and interpret scientific literature. OEB focused primarily on the introduction, methods, and results portions of scientific articles, although entire articles were read by the end of the course. Specifically, the OEB discussion had five overall learning objectives:

1. Identify the purpose of a scientific study
2. Describe and evaluate a study's methods
3. Interpret figures
4. Synthesize scientific results and draw conclusions
5. Use a model to describe a system and make predictions

The curriculum was designed in three modules, with the first module focused on research with simple experimental designs that were best suited for mastering the first three learning objectives. The second module introduced articles that used more complex experimental designs and focused more intensely on the fourth and fifth objectives. During the third module, students worked in pairs on a final poster project, which required them to read two related research articles, interpret each, and then synthesize the findings of both articles into one overall conclusion. Modules one and two were either three or four weeks long and each ended with a quiz to test student understanding of the learning objectives. The third module ended with a poster presentation. These quizzes and poster presentations comprised 140 points out of the 250 points for the discussion portion of the course. The rest of the points were either homework assignments (50 points) or in-class group assignments (75 points), with 5 points for a dropped homework.

For each class session, students had a homework assignment that prepared them for the activities that would be done in class. The homework was completed individually. During the in-class session students reviewed the homework, and then participated in small group work related to the scientific article. To scaffold the development of skills necessary to read a scientific article, parts of an article were often presented to students to read and then figures and other results were revealed incrementally, versus expecting students to read the entire article at one time. Class always ended with an assignment of homework for the next session.

To demonstrate the sequence of the course and the objectives, Table 1 below shows the specific learning objectives (often sub-objectives of the 5 overall objectives above) and activities for each week of class.

Table 1: OEB course summary

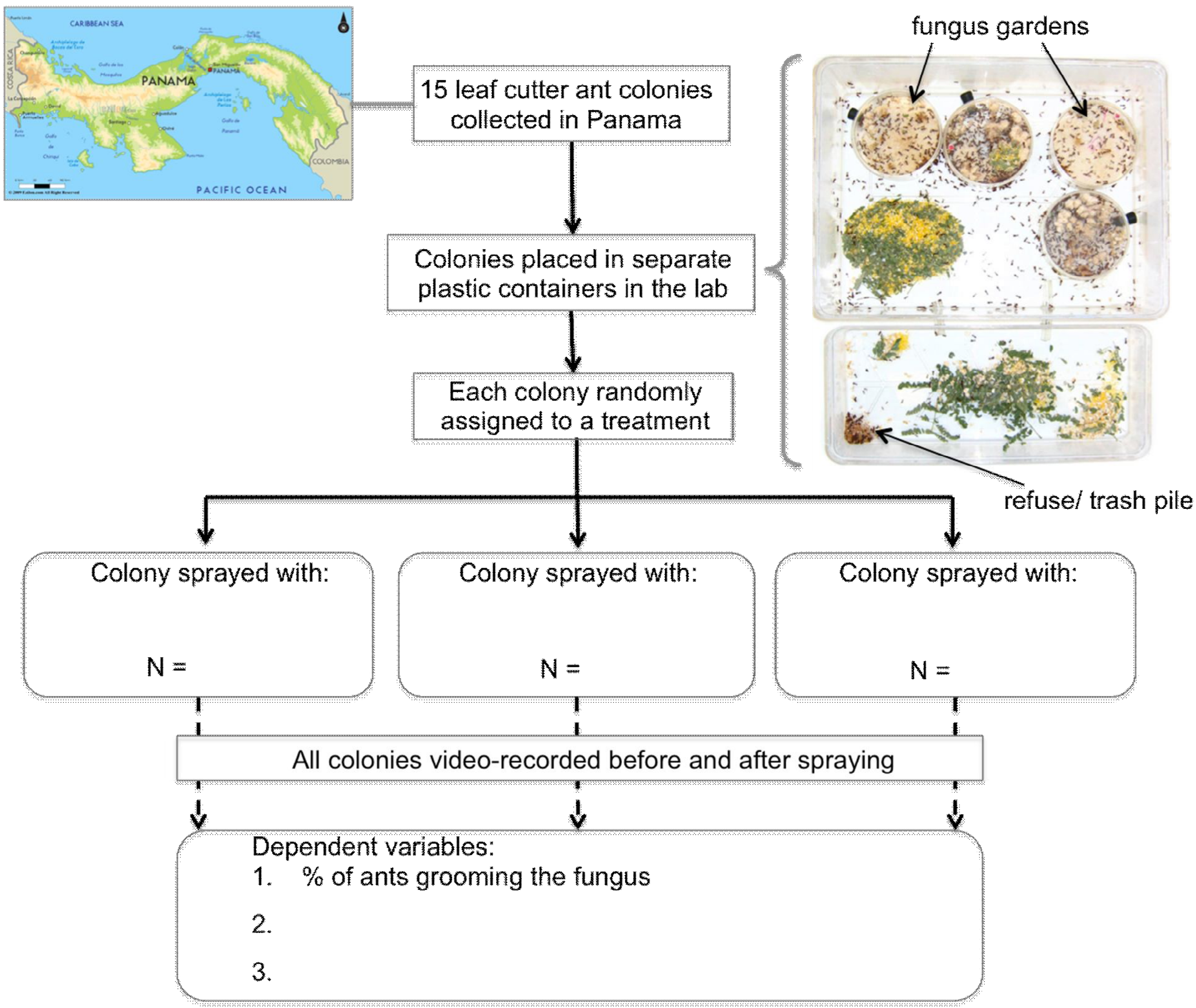
Week	Specific learning objectives	Activities
1	1a: Explain how a hypothesis is related to a scientific question.	Introduction to discussion; What is a hypothesis?
2	1a: Explain how a hypothesis is related to a scientific question. 1b. Explain the purpose of a hypothesis. 2a. Use a diagram to illustrate the design of a study or experiment. 3a. Identify and interpret the basic components of a graph 3b. Interpret the relationship between variables presented in a graph by explaining the results in your own words. 3c. Connect figure elements to experimental design 4a. Determine whether data support or refute a hypothesis.	Fecal transplants (van Nood et al 2013) Identify the hypothesis, independent and dependent variables, and how the design related to the hypothesis. Interpret a visual model of the research design and relate it to the hypothesis Interpret one figure from the study results.
3	2a. Use a diagram to illustrate the design of a study or experiment. 3a. Identify and interpret the basic components of a graph. 3c. Connect figure elements to experimental design 4a. Determine whether data support or refute a hypothesis. 2b. Explain why authors designed their study the way they did. 3b. Interpret the relationship between variables presented in a graph (including significance).	Leaf cutter ants and fungal pathogens (Currie and Stuart 2001) Review the experimental design of the study. Interpret three figures from the study in small groups. Class discussion of the implications of the results. (See example of the in-class activity below this Table)
4	Covered all learning objectives presented in the class so far.	Quiz 1
5	1c. Given a body of text from a scientific paper, identify the hypothesis being tested.	Plants and insect herbivores (Agrawal 1998)

	2a. Use a diagram to illustrate the design of a study or experiment. 2b. Explain why authors designed their study the way they did. 4a. Determine whether data support or refute a hypothesis. 1e. Generate a graph of predicted results based on a hypothesis. 4b. Propose or identify a plausible mechanism to explain the results of an experiment/study. 4c. Synthesize multiple figures from a paper	Explain the concept of plant defenses. Review the purpose of the study, experimental design, and draw the expected results (given the hypothesis). Review the actual results and discuss whether they support the stated hypothesis. Synthesize the results of three figure panels.
6	3b. Interpret the relationship between variables presented in a graph (scatterplot, and bar graph), including significance. 4b. Propose or identify a plausible mechanism to explain the results of an experiment/study. 4c. Synthesize the results from multiple figures. 2c. Determine whether a study is observational or involves a manipulative experiment. 4d. Make an inference about causation or correlation based on the results of a study. 4e. Identify the 'take-home message' from a paper 5a. Identify important components of a system and how they interact. 5b. Develop a simple visual model to describe a system or process the student has read about.	Recreational fishing and trophic cascades (Wilmer and Stone 1997) Create a visual model of the species interactions in the article. Review the purpose, methods, and results of each part of the study in small groups. Jigsaw to share results.
7	1c. Given a body of text from a scientific paper, identify the hypothesis being addressed 2c. Determine whether a study is observational or involves a manipulative experiment. 4d. Make an inference about causation or correlation based on the results of a study. 2d. Identify the strengths and weaknesses in study design (realism, logistics, level of control, causality)	Recreational fishing and trophic cascades (Altieri et al 2013) Design a manipulative experiment to test an observation from the article. Create a model of the species interactions for this ecosystem. Analyze the methods of the study.

		Choose groups and articles for final project (course leaders pre-identified 14 pairs of articles from which students select).
8		Quiz 2
9	All learning objectives	Final Project Group Work Work with final project partner on interpreting the methods of the articles.
10	All learning objectives	Final Project Group Work Work with final project partner on interpreting the results of the articles.
11	All learning objectives	Presentation of Final Projects Students present a poster in which they interpret each article individually and then synthesize the two articles together.

Week 3 in-class activity

The following figure illustrates the experimental design used by Currie and Stuart (2001) to investigate weeding behavior by leaf cutter ants. Use this figure to answer the questions below. Note that for some of the questions you will need to fill in missing information on the diagram.



1. What treatments did they use in their experiment and what was their sample size for each treatment? Fill in the *basic* description of each treatment and the sample size on the diagram above. In the space below, explain why they included each specific treatment in their experiment. (2.5 pts)

The following figure and represents one of the main results from Currie and Stuart (2001). Use this graph to answer the questions below and turn this in to your TA before leaving discussion.

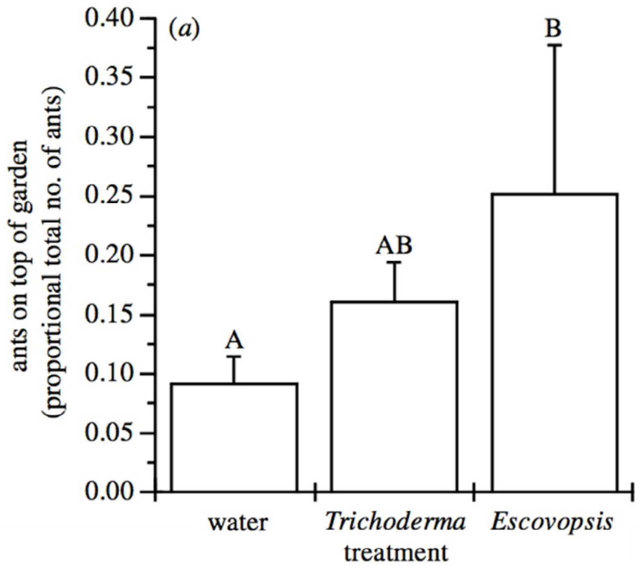


Figure 1. Frequency of different behavioral responses to the presence of water, *T. viride* and *Escovopsis* in intact colonies of *A. colombica*. (a) The average proportion of workers located on the top surface of the garden (n=5). Bars sharing letters are not significantly different and error bars represent standard errors.

1. Annotate the figure using the following questions as a guide: (1 pt)
   i. Indicate which axis shows the independent variable.
   ii. Indicate which axis shows the response they measured (dependent variable).

2. Interpret this graph. (Summarize the results in your own words, including whether any differences are statistically significant.) (2 pts)

3. Assuming that the ants on top of the garden were engaging in "weeding" behavior, do the results above support the authors' hypothesis that: (1 pt)
   i. Ants "weed" their fungus gardens to remove *Trichoderma* fungi?

   ii. Ants "weed" their fungus gardens to remove *Escovopsis* fungi?

4. Assuming that colonies with a higher proportion of ants on top of the garden were working harder to control fungi, do the results above support your hypothesis about which fungus the ants would work harder to control? <u>Which treatments did you compare to come to this conclusion</u>? (1 pt)

CMB Discussion

The overall goal for the CMB discussion was the same as the overall goal of the OEB discussion: to support student understanding of modern scientific research and knowledge generation by improving their ability to read and interpret scientific literature. The discussion associated with the CMB course was structured to be similar to how the OEB course functioned (including the same module, quiz and final project structure, homework and in-class activity structure, and general assessment structure), except it focused more on arguments made from scientific data (often found in the discussion section of papers) and had a stronger focus on conceptual topics. The specific learning objectives for the course were:

1. Write and analyze scientific arguments from data
2. Use an argument to make predictions about future research directions
3. Explain the contribution of multiple sets of data and arguments to the progression of scientific knowledge
4. Articulate an understanding of the cellular and molecular aspects of DNA, photosynthesis, and disease

The sequence of the course by week is shown below, along with the learning objectives and overview of activities.

Table 2: CMB course summary

Week	Learning objectives	Activities
1	Write and analyze scientific arguments from data Articulate an understanding of the cellular and molecular aspects of DNA, photosynthesis, and disease	Hershey and Chase, 1952 Students learn the four components of an argument (claim, evidence, qualifier, inference). Students work in groups to write the argument Hershey and Chase would have made about their experiment. They then read the discussion of the Hershey and Chase article and identify the argument components from it.
2	Write and analyze scientific arguments from data Explain the contribution of multiple sets of data and arguments to the progression of scientific knowledge Articulate an understanding of the cellular and molecular aspects of DNA, photosynthesis, and disease	Franklin, Vischer and Chargaff, and Chargaff Students receive data from three famous early DNA experiments and write the arguments that each should have made from their data sets. Students work together to create a table of what pieces of data each group had and why each on their own was not able to solve the puzzle of the structure of DNA.
3	Write and analyze scientific arguments from data Use an argument to make predictions about future research directions Explain the contribution of multiple sets of data and arguments to the progression of scientific knowledge Articulate an understanding of the cellular and molecular aspects of DNA, photosynthesis, and disease	Watson and Crick and Pauling Students bring in their homework where they have dissected either the arguments for Watson and Crick and Pauling's articles. In small groups, finalize the arguments and then form jigsaw groups so that each group has members who analyzed Watson and Crick and who analyzed Pauling. Discuss the soundness of the arguments that each made, and why Watson and Crick's model was ultimately correct and Pauling's was wrong.

		Students discuss what experiments they thought Watson and Crick should have done next. (See example in-class activity after this table)
4	Write and analyze scientific arguments from data Explain the contribution of multiple sets of data and arguments to the progression of scientific knowledge Articulate an understanding of the cellular and molecular aspects of DNA, photosynthesis, and disease	Gutman et al., 2014 Students read an article on telomere length and aging as homework, and then interpret figures from the paper as a group at the beginning of class. Different groups then receive different data sets about factors that impact telomere length (such as diet, sleep, etc.) and interpret the data and write the argument that should be made from those data. Students then engage in a class discussion about the integration of these data sets to inform their understanding of factors that impact aging and telomere length.
5	All learning objectives	Quiz 1
6	Write and analyze scientific arguments from data Use an argument to make predictions about future research directions Explain the contribution of multiple sets of data and arguments to the progression of scientific knowledge Articulate an understanding of the cellular and molecular aspects of DNA, photosynthesis, and disease	Schulze et al., 2013; Willuda et al., 2012 Students read about C3 and C4 photosynthesis and come into class and create a conceptual diagram that represents the two processes. They then identify the location of a critical enzyme called Glycine decarboxylase (GDC) in the C3 and C4 pathways. Students interpret two figures from the articles that show activity of this enzyme with each pathway, and localization of this enzyme in the plant leaves.

		Students then discuss the implications of these figures to the development of the C4 pathway. The homework for the next week is to brainstorm what they think the authors of these studies did next in their research.
7	Write and analyze scientific arguments from data Use an argument to make predictions about future research directions Explain the contribution of multiple sets of data and arguments to the progression of scientific knowledge Articulate an understanding of the cellular and molecular aspects of DNA, photosynthesis, and disease	Students start by trying to predict what questions the authors of last week's articles would try to answer in their next research articles. Students are presented with figures from the next research the authors did, and interpret and write arguments for these data.
8	Write and analyze scientific arguments from data Use an argument to make predictions about future research directions Explain the contribution of multiple sets of data and arguments to the progression of scientific knowledge Articulate an understanding of the cellular and molecular aspects of DNA, photosynthesis, and disease	Students read an article about how scientists are trying to engineer C4 pathways into crop plants to make them more drought tolerant. Students have to search the literature and find an abstract of an article where they are doing this type of engineering. In class, students work in groups to synthesize the state of the field and make predictions about the future research directions in this area. Students select groups and paper sets for the final presentations.
9	All learning objectives	Quiz 2
10	All learning objectives	Group work related to the methods of the two articles
11	All learning objectives	Group work related to the results of the two articles

12	All learning objectives	Final project presentations

In-class session, Module 1, Week 3

In small groups, discuss the following and turn in at the end of class

Use the table below to structure/guide the discussion on Question1:

	Pauling	Watson / Crick
What was the data used in the argument?		
Was the quality of the argument (based on the data) sound?		
Why was the argument right or wrong?		

1. Given the two models and associated arguments (based on the data sets), choose the most sound argument and give your reasoning. Why was Pauling's model incorrect? Did he have bad / unsound data or a bad / unsound argument?

2. How did Watson and Crick use multiple sets of data and arguments to contribute to the progression of scientific knowledge?

3. What arguments were used by Watson and Crick to support the claim that Pauling's model was incorrect?

Lab Discussion

The goal for the lab discussion was to support student performance of their own scientific investigations, and come to an understanding of how the scientific literature supports these investigations. The specific learning objectives for the course were:

1. Distinguish between and develop your own scientifically-appropriate hypotheses and predictions
2. Find and use scientific literature to frame your experimental designs
3. Organize, analyze, and interpret your scientific data
4. Communicate your scientific results in written and verbal forms (including creation of figures and tables)
5. Design and carry out your own scientific investigations

There were four discussion periods and four two-week long lab experiences in the course, as well as a two week long final oral presentation period. The points in the course consisted of written lab communications (90 points), lab quizzes (60 points), in-class assignments and participation (77 points), student final oral presentation (60 points), and in-class mini-oral presentations (28 points), which added up to 315 possible points, with a course maximum of 300 points. The two-week long labs were guided inquiry in nature, where students were introduced to the research system in week one, collected and analyzed preliminary data, and then were given additional variables that they could choose to manipulate. They then either set-up or designed their own investigation at the end of week one, and then implemented, collected and analyzed data, and presented mini-oral presentations of their results in week two.

Table 3: Summary of lab discussions

Week	Learning Objectives	Activities
1	Distinguish between and develop your own scientifically-appropriate hypotheses and predictions Use scientific literature to frame your experimental designs Organize, analyze, and interpret your scientific data Design and carry out your own scientific investigations	Meter stick drop activity Students measure the distance that a meter stick drops under different conditions (visual or oral cue for re-capture) and then design their own experiment on this system. Students make hypotheses and predictions, design an experiment (based on a brief literature review of factors that impact reaction time), collect data, enter data into Excel to produce summary statistics and figures, and come to a conclusion.
2	LAB	Fungal and plant interactions lab week 1
3	LAB	Fungal and plant interactions lab week 2
4	Organize, analyze, and interpret your scientific data Communicate your scientific results in written and verbal forms (including creation of figures and tables)	Written communications Students bring their analyzed data from the fungal and plant interactions lab and come to class having read one article related to this lab. They are given an overview of the sections of a written communication, and then work with their group to produce an outline a written communication for the lab. They look up scientific literature to cite in discussion. At the end of class, students are introduced to the topic of the next lab.
5	LAB	Bacterial growth
6	LAB	Bacterial growth

7	Distinguish between and develop your own scientifically-appropriate hypotheses and predictions Organize, analyze, and interpret your scientific data	Inferences Students start the discussion by peer reviewing the written communications they produced for their bacterial growth lab. Students are introduced to the idea of empirical data versus inference by an activity where they infer a phylogeny from empirical characteristics of a group (first with the chordate group as a class and then mammal skulls in small groups). Groups present their inferred mammal skull phylogeny and then compare their findings with a recent phylogeny produce by genetic data. They discuss models in science and uncertainty. Students are then introduced to the mammal skull lab they will be doing in class.
8	LAB	Mammal skull lab
9	LAB	Mammal skull lab
10	Distinguish between and develop your own scientifically-appropriate hypotheses and predictions Find and use scientific literature to frame your experimental designs Design your own scientific investigations	Experimental design Students are introduced to experimental designs that are more complicated than just a manipulation of one variable. They are also introduced to an experimental system involving the behavior of flour beetles. Students observe the beetles, search for and read literature on animal behavior, collect preliminary data, and then propose an experiment or set of experiments that they will conduct on the flour beetles next week.
11	LAB	Flour beetle lab
12	LAB	Flour beetle lab (build on the findings from week 1)

13	Distinguish between and develop your own scientifically-appropriate hypotheses and predictions Find and use scientific literature to frame your experimental designs Communicate your scientific results in written and verbal forms (including creation of figures and tables)	Final oral presentations In pairs, students select a topic that has been discussed in lab over the semester and are challenged to present a research proposal on an experiment they would conduct to investigate this system further. They must present primary literature to support their hypothesis and experimental design, and show results that would be expected if their hypothesis was correct. The presentation is done in the form of a powerpoint.

*The full curricula for these discussions is available by contacting the project PI: Elisabeth Schussler. The curricula were created as part of an NSF TUES Project (DUE 1245215).

Supplemental Material B

Test of Scientific Literacy Skills (TOSLS; Gormally, Brickman, & Lutz, 2012) question numbers (from the original instrument) used in this study and how they aligned with each skill category.

TOSLS Skill	TOSLS Question Number
Identify a valid scientific argument	1
Understand elements of research design	4, 25
Make a graph	5
Read and interpret graphical representations of data	2, 6, 7, 18
Solve problems using quantitative skills	16, 20, 23
Understand and interpret basic statistics	3, 19, 24
Justify conclusions based on quantitative data	21, 28