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The "Anti-Cookbook Laboratory": Converting "Canned" Introductory Biology Laboratories to Multi-week Independent Investigations

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We converted a series of "canned" biology labs into multi-week, guided-inquiry laboratory investigations. In our labs, students work in research "Teams" of 3-5 students on multi-week, guided-inquiry experimental "Streams". Using an example 12-week long PCR Stream, we describe several aspects of the "Teams and Streams" model, including: i) how we guide students' development of testable hypotheses; ii) how cooperative group interactions within Teams are promoted; and iii) activities that we use in the laboratory, including assessments. Significantly, the learning goals associated with inquiry-based investigations involve higher order cognitive skills and behaviors than those associated with "cookbook" labs.

Keywords: Inquiry-based learning, cooperative learning, learning goals, assessment, multi-week investigations

Link to Supplemental Materials

http://www.ableweb.org/volumes/vol-34/luckie/supplement.htm

Introduction

In 1999, our faculty began asking the question: "Are undergraduate science laboratories teaching students the art and trade of science or simply leaving them with a memory of trivial exercises done for unknown reasons? From our conversations with students in biology, it certainly appeared as though the latter was the consensus. Students used words like: "boring", "restrictive", "pointless", and so on, to describe the biology laboratory. In fact, very few of our students characterized the lab as a good learning experience. Even our 'best and brightest' students agreed that while our new cutting-edge DNA genomics labs were fun, structured labs really didn't help them learn. In fact, they indicated that they often didn't really understand what they were doing until the week *after* completing the experiment, when they wrote the lab report.

In an effort to remedy this problem, we began a long-term redesign of the biology sequence in the Lyman Briggs College of Science at Michigan State University. Combining what educational experts have found about active and cooperative learning with a challenge to our biology faculty to make the lab as realistic as possible (i.e., a place to 'do science'), the lab curriculum departed from numerous 3-hour traditional labs that each student performed on their own, to what we now term "Teams and Streams." Now, we use student research teams to pose a scientific question/hypothesis, propose an experimental design to set about gathering evidence regarding said hypothesis, perform multi-week experimental investigations and then present findings in vari-

ous forms (web sites, interviews, multiple drafts of a scientific manuscript, posters) to their peers and their instructors.

The idea that the biology teaching lab should focus on inquiry is not new. The role of the lab course is to teach students how to "do science"! Thornton's (1972) edited volume represents the seminal "call to arms" for getting our students involved in actually practicing doing science in their undergraduate science labs. Sundberg and Moncada (1994) also provided a practical "how-to" for moving to inquiry-based laboratory investigations. However, we hadn't embraced these ideas in a formal way prior to 1999.

While inquiry-based labs are key for learning science, another critical element is having students work in cooperative teams, an endeavor that is much employed but often with mixed results. Johnson et al.'s (2006) book illustrates how college faculty can use cooperative learning to increase student achievement and help ensure that their students actively create their own knowledge. These authors provide a set of practical strategies for structuring cooperative learning and the conceptual framework needed to understand how to create a truly cooperative learning community in college classes. Smith and Imbrie (2007) provide a guide that prepares students for the teamwork, group projects, and collaborative problem solving that are necessary for success in science. Written from the perspective of an engineering professor, this book, especially the first few chapters, is especially useful for helping students in college biology courses understand the what and how of being part of a successful team.

The benefits of active and cooperative learning strategies are well established (see Prince et al. 2004 for review) and reach beyond the single course in which they are employed. For example, Derting and Ebert-May (2010) found that a freshmen level course that used active and cooperative approaches had a positive effect that grew over time. Wright et al. (1998) utilized an innovative method to assess student learning and showed that if you use a rigorous evaluation of student learning (in this case, have research faculty perform interviews of students who complete introductory chemistry) you will see that active and cooperative approaches lead to greater content learning than passive traditional lecture.

All of these types of learning activities fall under the category of "scientific teaching" (Handelsman et al. 2004, 2007) that is based on how students learn (Zull 2002) and has become well established as "good practice" among many within the STEM education community. More recently, attention has been given to the depth versus breadth issue. Schwartz et al. (2009) reported that students who studied one particular science topic (e.g., photosynthesis or respiration) in great depth in High School did much better in that corresponding science topic (e.g., biology) in college. As a result, many STEM instructors have cut back on the volume of content delivered in an effort to increase student learning. However, even with all of this increased educational understanding, simple pedagogical strategies, such as designing logically reasoned instructional activities (Wiggins and McTighe 2005) that are tied to explicit student learning goals (Gronlund and Brookhart 2009) have not been universal practice at the college level.

In this paper, we present the lab model that we employ across the Lyman Briggs College Biology program in an effort to meet the challenges described above and increase student learning, especially in the arena of "thinking and acting like scientists". We redesigned our laboratory curriculum using a "Teams and Streams" model that emphasizes research *teams*, multi-week experimental *streams*, and *inquiry*-based instruction. Our model was first employed in a single course in the late 1990's (Luckie et al. 2004), and gradually was adapted by the other instructors in our program (e.g., Smith and Cheruvelil 2009). We now have six separate instructors in biology who use Teams and Streams in both the Introductory Organismal Biology and Introductory Cell and Molecular Biology course, which comprise our year-long curriculum. The only other published model that we are aware of in which inquiry has been used as the basis for program-level curriculum reform is that of Spronken-Smith et al. (2011), who redesigned the undergraduate Ecology curriculum at the University of Otago in New Zealand to refocus efforts towards more inquiry and more research experiences for students.

We begin by exploring how we go about putting students in research *teams* at the beginning of each semester with the assistance of student data collected via the online Team-Maker tool (Get from **http://catme.org**). We also present some of the rationale for the use of teams, and some of the tools and techniques that we use to promote the establishment and maintenance of highly effective teams (e.g., Comprehensive Assessment for Team-Member Effectiveness (CATME; **http://catme.org**). These aspects include the physical layout of the lab and the individual workstations for the student teams. We next describe the elements of the "PCR and Genetic Disease" *stream* as employed by Dr. Doug Luckie in fall semester 2011. Sample lessons and activities are described and compared to the types of lessons and activities that one might find in a typical "cookbook" lab. Learning goals take the spotlight here; it turns out that more sophisticated learning goals become possible when you spend more time exploring a topic (depth versus breadth). Finally, we focus on *inquiry*, and how inquiry is crucial in the development of students as scientists. Special emphasis is placed on science process skills and student activities geared towards hypothesis formulation and the design of an experimental plan.

Student Outline

We provide as a pdf the Lab Book that was used in Dr. Doug Luckie's Introductory Cell and Molecular Biology course in fall semester 2011 (*Introductory Cell and Molecular Biology (LB145), Fall semester 2011*, Dr. Doug Luckie (**http://www.msu.edu/user/luckie/ABLE2012/lab-book.pdf**). In this iteration of the Teams and Streams laboratory model, student teams carried out a single 14 week long experimental stream in which they developed a PCR-based diagnostic assay for the mutant form of a gene that causes a disease.

This Lab Book will provide the reader with the best and most complete picture of the materials provided to students as they set-up and carried out their experimental work.

Materials

Staffing

Each laboratory section has a maximum enrollment of 24 students, yet a section with 20 students is more typical. In fiscally lean years, each laboratory section was taught by either one graduate student (graduate assistant) or two undergraduate students (learning assistants). In years with greater financial support, a laboratory section would have three instructors present, either a graduate assistant and two learning assistants or the lecture professor and two learning assistants.

Equipment and Supplies

What is necessary to have on hand when you perform the Teams and Streams laboratory depends upon the stream(s) that one wishes to do. Generally, our laboratory rooms have 4-6 laboratory benches that can be used by each team of four students and each bench is each supplied with set of standard equipment and supplies as well as a computer that runs either Windows or Mac OS (Fig. 1). For the cell and molecular biology course, this includes common items like a small microcentrifuge, a set of pipetmen, and a vortex genie mixer, as well as pipet tips, labeling tape, microfuge tube racks, Eppendorf tubes, Sharpie® markers, etc. When we do the 14-week PCR Stream, we place equipment in the room at side benches that will be shared by all student groups such as a UV-Vis spectrophotometer that allows students to quantitate DNA template concentrations, thermal cyclers for doing PCR, as well as DNA gel electrophoresis equipment, and a transilluminator with digital camera for capturing gel images under UV light. Each term, we purchase PCR reagents. Interestingly, students order (and pay for) the PCR primers they design.

When we implement the Ecology Stream in the organismal biology course, each student team comes up with their own hypothesis to test. We then beg, borrow and steal whatever that team might need to carry out their work. We have amassed a variety of field and lab equipment this way through the years, including aquaria, basic equipment for water testing, measuring DBH of trees, and measuring soil moisture and pH. We also have microscopes equipped with digital cameras, and a computer at each team's lab station.

Forming and Evaluating Teams

In order to form functional teams, and solicit and collect feedback to track their success during the semester, we use

Figure 1. Student groups of four are assigned a bench space and set of equipment. In the photo, these students work in the cell and molecular biology laboratory and they have a set of pipetmen, a vortex, ice bucket, power supply, gel box, micro-centrifuge, labeling tape, sharpie markers, etc. Notice that the benches are designed for teams of four students, with no physical barriers and plenty of space.

web-based software developed by the Purdue Engineering faculty (**http://catme.org**). Instructors are welcomed from all institutions to set up an account and use CATME free of charge. At the beginning of the semester, the Team-Maker software provided on this website allows faculty to more deliberately, based on the educational literature, and more easily form teams in their laboratory sections. The software allows each instructor to choose which of many survey questions they would like their students to answer, and then how their answers should be weighted (labeled simplistically as low, medium, or high in Fig. 2) when forming teams. Some aspects of team formation focus on creating a team with a variety of skills or perspectives (heterogeneous grouping; labeled "Heterogeneity" in Fig. 2). Other information is used to build teams that have something in common (homogeneous grouping; labeled "Homogeneity" in Fig. 2). The overall goals are to have the best-functioning and happiest teams possible.

In our experience, we find certain characteristics and questions particularly important when forming semester-long student teams. For example, using answers to a question about sex and ethnicity, we can protect women and ethnic minorities from isolation that has been shown to reduce their success (Oakley et al 2004). We also find it very important when forming groups that teams have: a) common times outside of class when they can meet; and b) relative homogeneity in self-reported hours that students plan to spend working on this class. After forming teams using Team-Maker, the companion CATME software provides tools to collect and disseminate regular team assessment via peer feedback. Students answer surveys and receive feedback that shows how they rate themselves as compared to their other team members (on average). Faculty are also presented with well-organized set of information, including confidential written comments, for their own analysis (Fig. 3).

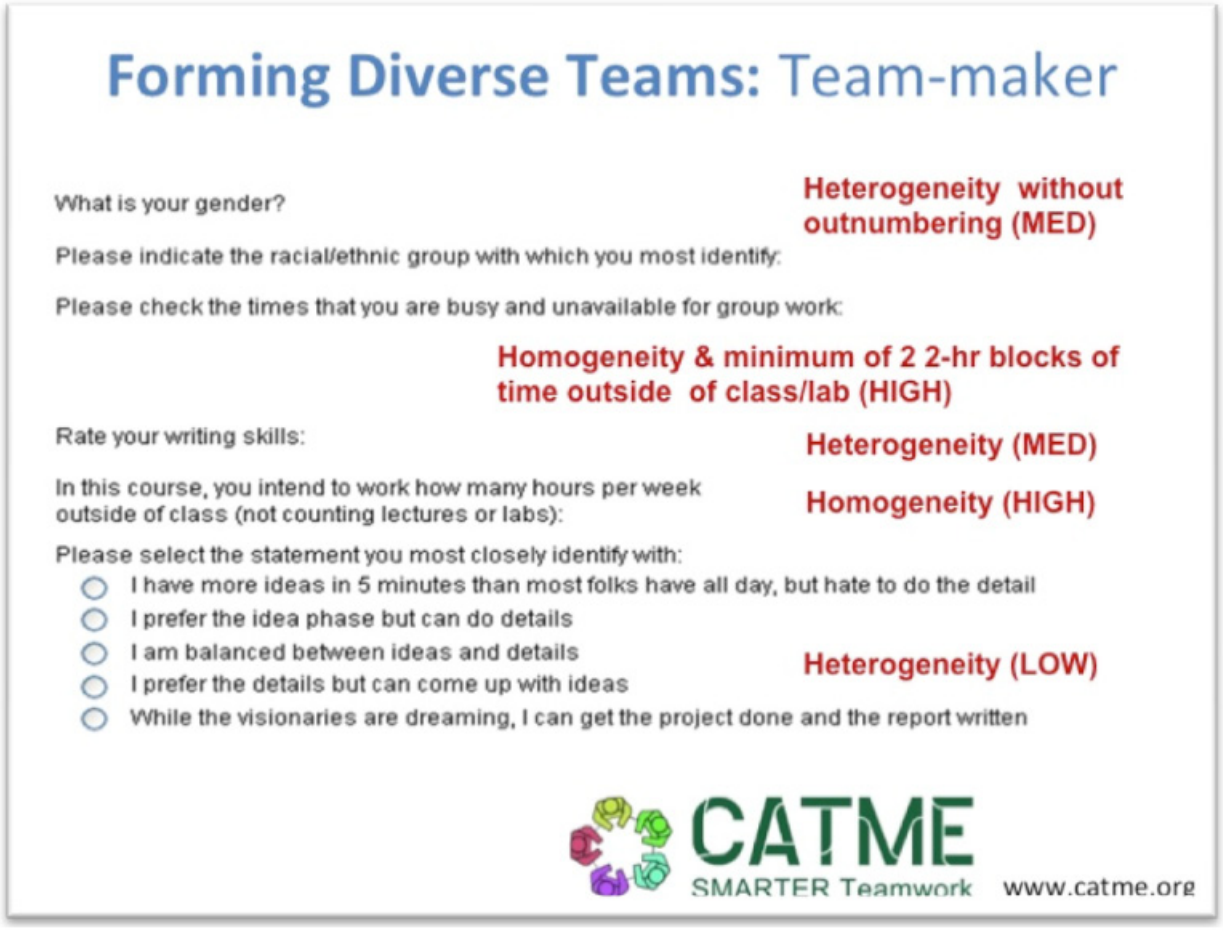

Figure 2. Online software built and hosted by Purdue University called Team-Maker (catme.org). Team-Maker provides assistance building more effective student teams. Survey questions are chosen and responses are weighted by the instructor. In this example, the software will build teams based on shared open times for group meetings in student schedules as well as diverse skills and perspectives in each team. The companion software, CATME, provides great assistance in team assessments via automated student peer evaluation (see Fig. 3).

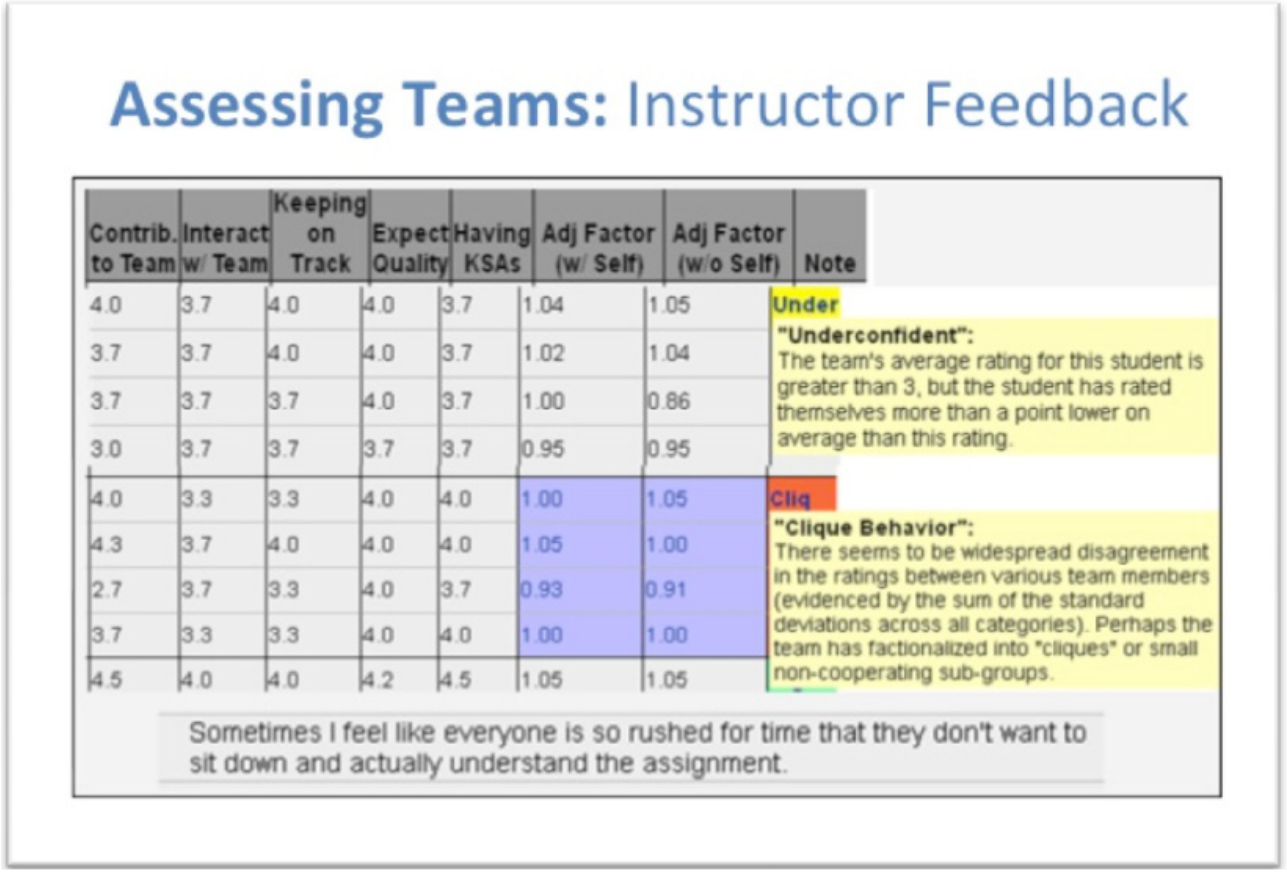

Figure 3. Examples of CATME team assessments via an automated student peer evaluation online survey. Instructors choose what questions to ask the students and then feedback from what **the mem**bers of a team said about each other is automatically formatted and funneled to both students as "Student Feedback" and instructors as "Instructor Feedback"**.**

Notes for the Instructor

Overview and Timeline for the PCR Stream

(Assessments are shown in blue)

In the 14-week PCR Stream, student teams choose a disease and develop a PCR-based diagnostic assay for the mutant form of a gene that causes it. They are also required to find and replicate a similar PCR-based assay published previously (a form of control). The outline of the 14-week time period of the project is shown in Figure 4. During week 1, we form student teams, assign roles, start with an orientation to PCR & genetic disease, and the goals of the semester. We also use a film [IDEO segment from Nightline] to model optimal creative and group behaviors. During week two student teams are introduced to basic lab equipment and skills (pipets, spectrophotometers, lab notebook, graphing, etc.), and students **propose their research plan** via a formal slideshow talk, "Plan A vs. Plan B", from which they receive verbal feedback. During week three, student teams submit a written proposal in the form of a traditional manuscript [**DRAFT1**], participate in a **formal interview,** and perform a cookbook PCR lab with water baths. If manual PCR does not work the first time, then they may try again using automated thermal cyclers. Students are encouraged at this stage to begin contacting researchers to obtain DNA samples with their disease mutations and mentored with respect to what to say in the emails that they send to solicit research materials. In week four, students may repeat the PCR experiment if it did not yet work. They must get the PCR experiment from the cookbook lab to work before they are permitted to continue in their own independent research. If the team is ready to move forward they may perform experiments, inside or outside of the classroom, associated with their social experiment, the so-called "30 Days." In "30 Days" they design an experiment and collect data regarding the history, philosophy, sociology or psychology related to their disease and create a short documentary film.

Starting in week five, student teams are taught and then may use a DNA genome preparation kit to extract human DNA from frozen cell cultures. Starting in week 6 groups may initiate their independent experiments if they succeed with both PCR and genomic DNA preparation experiments, and otherwise repeat either or both. Student teams

Week	Laboratory Investigation
1	*Orientation and project introduction*
2	Basic lab skills, group's **Proposal Presentation**
3	PCR Lab, group's ***Draft 1 due*****, In-lab Prof/LA Interview**
4	PCR Lab (continued) and 30 Days Lab
5	30 Days Lab (continued) and Genome Lab
6	Genome Lab (cont.), group's ***Draft 2 due*** (5 copies), **Prof Interview**
7	Independent Investigations, Ordering, **Verbal & Written *Peer Review* due**
8-9	Independent Investigations [PBAs, Notebooks checks and troubleshooting]
10	Independent Investigations **Verbal & Written Status Report due**
11-12	Independent Investigations [PBAs, Notebooks checks and troubleshooting]
12-13	In-lab **Presentation** (short practice talk about your findings)
14	***Final paper due and Presentation at Briggs Research Symposium***

Figure 4. Outline of the 14-week PCR and Genetic Disease Laboratory Stream.

are required to submit a revision of their first manuscript [**DRAFT2**] with a required rotation of who authored which sections of the paper. The Teams then make an hour-long appointment with the professor to have a second **group interview** outside of the scheduled lab meeting times. In week 7 each student submits a written **Peer Review** and short verbal feedback on another group's manuscript before proceeding with experiments. This week is usually also the deadline to order oligonucleotide primers for independent projects. Each week students are randomly chosen to participate in **notebook checks** and performance-based assessments (**PBAs**), which are used to keep each student accountable. In week 10, groups are expected to present a brief written **progress report** and an oral presentation in the form of a slideshow talk, consisting of only an abstract and figures. In weeks 12-13 a draft/practice **final presentation** is given in the form of a slideshow talk in lab, and student films from "30 Days" are shown. During weeks 14 and 15 the **final manuscript** is submitted and student teams give a **final formal presentation** at public forum on the MSU campus.

Learning Goals and Assessment of Student Learning

(Assessments are shown in blue, above)

Implementation of the Teams and Stream laboratory model has allowed us to devise and work towards an amazingly rich and complex set of learning goals for our students in the Introductory Biology laboratory. Instead of focusing on a narrow set of content and lab skills goals, we have been able to focus much more on "Doing Science", in the vein of the original ideas of Thornton (1972) and Sundberg and Moncada (1994). For example, we are able to practice to a much greater extent cognitive science-process skills such as hypothesis formation, experimental design, and data analysis.

A comparison of the learning goals one might expect to find in a typical one-week long PCR cookbook lab and a multi-week Teams and Streams lab is shown in Appendix A.

Students author and revise several drafts of a research manuscript focused on their project, participate in two formal interviews, complete a peer review, present several verbal talks, as well as a handful of PBAs and Notebook checks. Student groups are also expected to present a poster at a public forum in week 15 or at the end of the following semester. Attendance and participation is tracked and CATME online software aids in group functioning and evaluation of individual performance.

Beyond Teams and Streams: Moving to Inquiry

When thinking about adding inquiry to labs, it is helpful to consider the four different levels of inquiry defined by Fey and Bretz (2008) that can be achieved in the student laboratory. Labs that provide no inquiry (Level 0) are characterized by experiences in which student verify known outcomes, with instructors providing the problem and all methods and procedures. On the other end of the spectrum are Level 3 Inquiry Labs, in which a phenomenon is provided to student, who then choose the problem they wish to explore, develop their procedure for doing so, decide what data to collect, and then interpret their data in the context of the phenomenon. Level 3 is basically real research with someone providing the topic. Our labs tend to be somewhere in between Levels 0 and 3; some of our experimental streams are highly structured, while others approach Level 3. That said, our experience has been that students in teams working together for longer periods of time affords the opportunity for meaningful, higher order inquiry investigations.

Figure 5 outlines the elements that need to be addressed in the process of converting a cookbook-style lab to a lab that has a higher level of inquiry. This worksheet is based both on the characteristics of inquiry as well as the backward design model of curricular development.

The first item of business is the "Topic" (Fig. 5, top chevron). In the case that we have developed in this paper, the

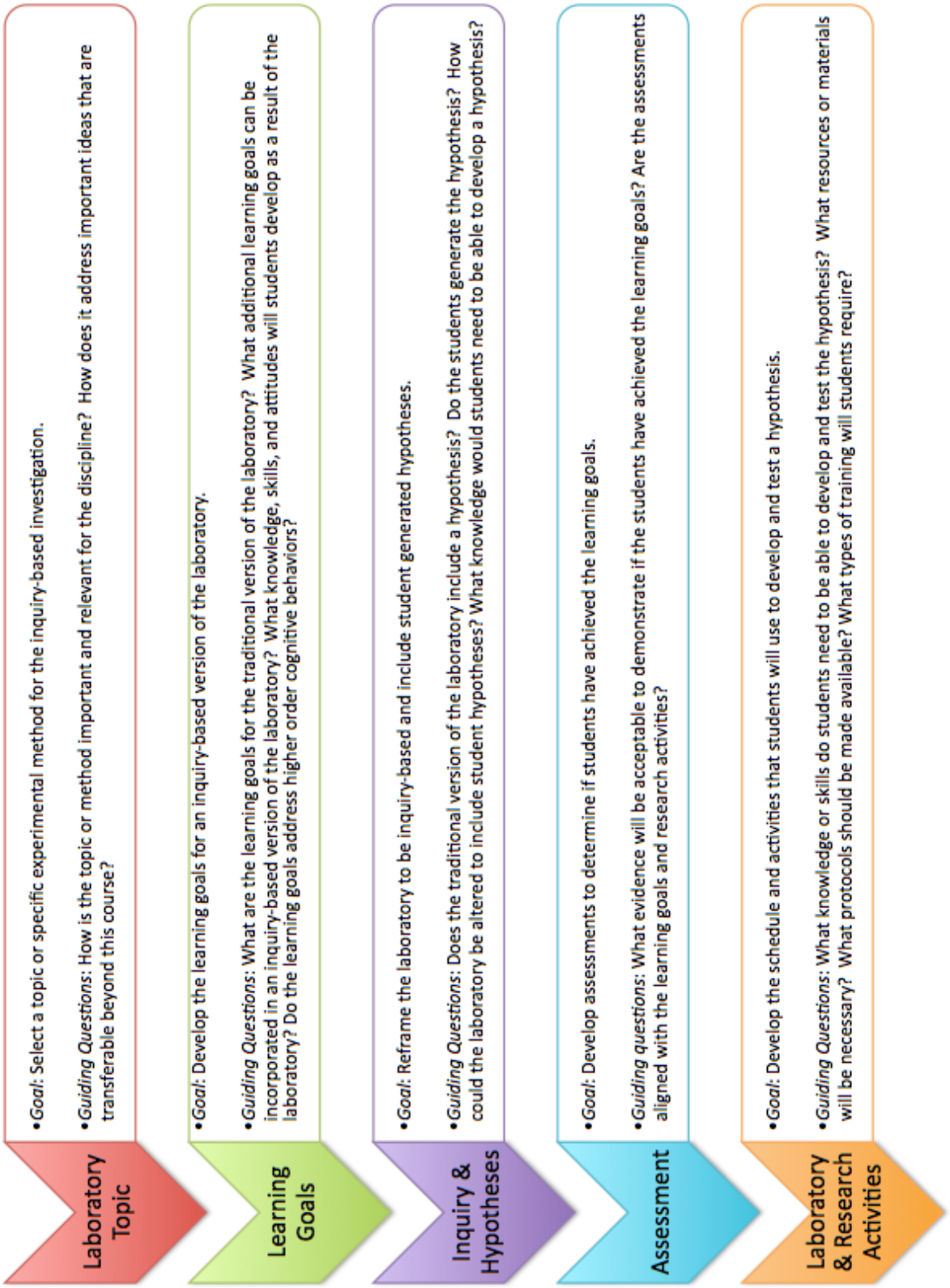

Figure 5. Elements that need to be addressed in the process of converting a cookbook-style lab to a lab that has a higher level of inquiry. Each chevron is associated with a goal and a set of guiding questions.

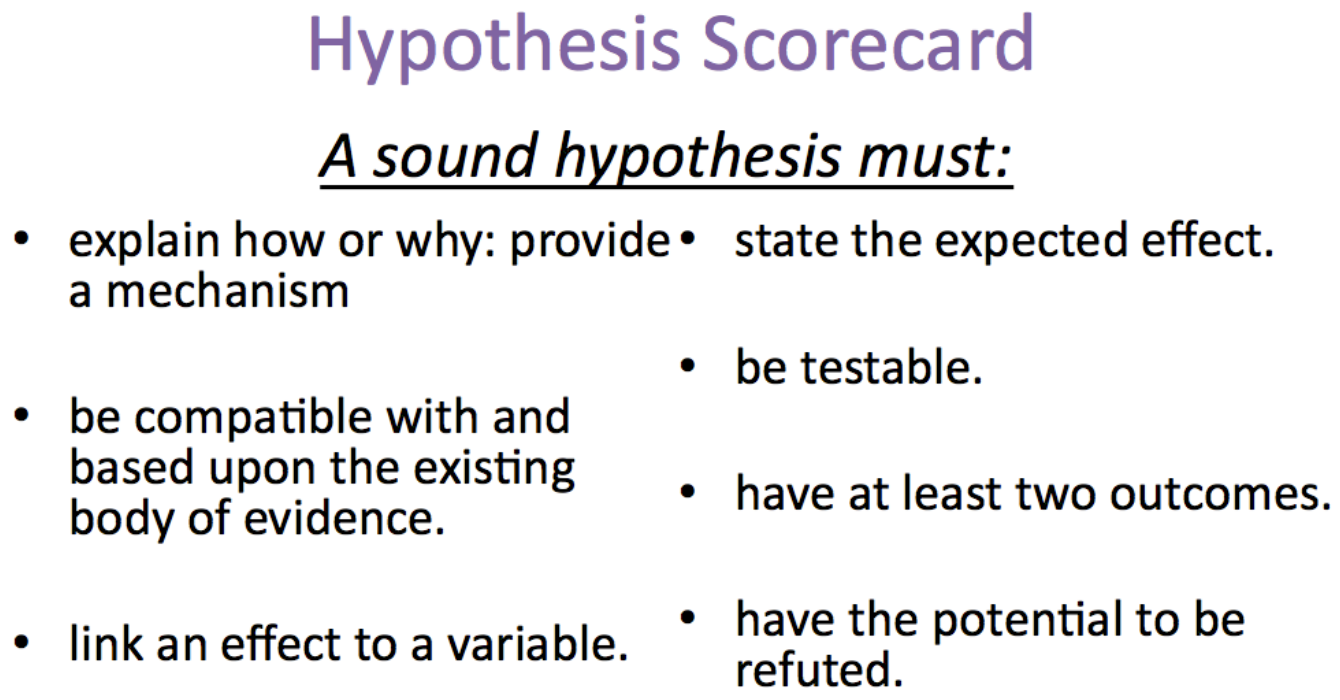

Figure 6. The Hypothesis Scorecard: A tool for developing and assessing hypotheses. Hypotheses can be assessed by assigning one point for each characteristic. An *accomplished hypothesis* will have a score of 7. An *incomplete or developing hypothesis* will have a score of 5-6. A score below 5 is an *attempted hypothesis or not a hypothesis*. The scoring procedure can be used by students when they develop their own hypotheses or when they evaluate other examples of hypotheses. The scorecard can then be used by instructors to assess and grade student generated hypotheses.

Topic is DNA, PCR and Genetic Disease. In the course of doing their lab work, students will learn a lot about DNA, PCR and genetic disease, just as you would in your own research if you were investigating a particular topic area. Students are challenged to explain why the chosen topic is important and relevant, not only for the discipline, but also beyond the walls of the classroom lab.

The next step is to develop learning goals for the inquiry-based laboratory (Figure 5, second chevron). There is no need to back off on Content Learning Goals: the students in the DNA, PCR and Genetic Disease lab stream spend time comparing and contrasting PCR to in vivo DNA replication, and they learn how to differentiate between silent, missense, frameshift, and nonsense mutations. However, the expanded timeframe allows us to incorporate additional learning goals into the inquiry-based version of the laboratory, with an emphasis on knowledge, skills, and attitudes that address higher order cognitive behaviors. In the case of the DNA, PCR and Genetic Disease lab, students create their own research plan and their own experimental design (with appropriate controls) to test a hypothesis (with associated predictions) that they have proposed.

Where once we may have had the goals of having students set up and run a PCR, and analyze products by agarose gel electrophoresis, we now amplify that goal by asking them to develop a PCR-based diagnostic assay for the mutant form of a gene that causes disease. Student-generated hypotheses are particularly important to an inquiry-centered lab (Fig. 5, third chevron). There is a lot of content that students need to know in order to be able to develop a hypothesis, and we work with our students quite a bit in this area.

This leads us naturally to the next step in the process, which is developing assessments to determine if students have achieved the stated learning goals, both with respect to the content knowledge associated with our labs as well as science process skills (Fig. 5, fourth chevron). One of the things we have tried to address as we continue to refine our laboratories is how to teach and assess hypothesis formation. Most of us now use the hypothesis scorecard, or rubric, shown in Figure 6, and we have found this to be a very useful tool for helping students to develop hypothesis formulation skills.

Finally, we are ready to develop the schedule and activities that students will use to develop and test a hypothesis (Fig.5, last chevron). In doing so, we need to consider what knowledge or skills students need to develop to formulate and test a hypothesis. What resources or materials will be necessary? What protocols should be made available? What types of training will students require?

Some Other Examples of "Teams and Streams"

We have put together summaries of a set of four other experimental streams used in the Lyman Briggs College Biology program. These are included as Appendix B, and the set includes: "The Comparative Biology Stream", in which students explore animal biodiversity in an inquiry-based phylogenetic context (Appendix B #1); "Exploring the interaction between mutation and environment using *Pseudomonas fluorescens*", an exploration of evolution in action (Appendix B #2); "Friendly Foes: A search for novel bacteriophage", with students isolating and characterizing phage from bacteria sampled in different environments (Appendix B #3); and "The Plant Protein Stream", in which students determine the effects of a chemical compound on total protein levels in plant tissue (Appendix B #4). Other Streams in the Lyman Briggs Biology Program include "Doing Biology", with students practicing research skills, "The Ecology Stream", in which students carry out independent investigations for 5-7 weeks culminating in a poster presentation, and an "Antibiotic Resistant Bacteria" stream, a semester-long experience in which student teams compare antibiotic resistance and community composition of bacteria sampled from two environments.

Potential Roadblocks and Pitfalls

It would be great if all biology students everywhere could have laboratory experiences that incorporate all of the features of the lab streams that we've described in this paper. However, some critics of this approach suggest that such inquiry-based laboratories require high levels of staffing, excellent facilities, motivated students, and institutional support. Thus, critics of this approach can claim that what we do won't work in a less than ideal environment. However, we suggest that small, simple steps can begin to improve learning in all biology laboratories. It took us several years to convert our original cookbook-style lab sequence to our inquiry based-teams and streams model. We took baby steps, first starting by converting a one-week lab into a two-week lab by adding inquiry. Then, we eventually added another week to the same topic, and so on. Each time, we assessed student learning and with student learning improvements came administrative support and buy in from the students and teaching assistants.

We argue that any biology program can do this. Find something in your lab sequence where your learning goals are not what you'd like them to be. Then add a lab that will allow you to do inquiry and use your labs to teach students how to do science, just as Thornton (1972) suggested 40 years ago.

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Appendix A

Comparison of Learning Goals of a "Cookbook" PCR Lab versus a 14-week Inquiry PCR Lab

Learning Goals in the One-week-long PCR "Cookbook" Lab

Content Goals:

1. Learn how to design a PCR reaction cocktail and what each ingredient does.
2. To learn enough about PCR to design your own primers to target a known mutation.
3. Learn how to calculate annealing temperatures for primers given only the DNA sequence.
4. To develop a PCR reaction to be used as a positive control.

Experimental Goals:

1. To learn how to set up and run PCR reactions and the role of the reaction ingredients.
2. Learn how to mix a PCR reaction cocktail with correct concentrations diluted from stock solutions.
3. Learn how to mix and make an agarose gel for electrophoresis.
4. To further gain expertise in working with DNA laboratory equipment (e.g., micropipettors, thermocycler, agarose gels).

Learning Goals in the Semester-long PCR and Genetic Disease Stream

Mental (Cognitive) Skills

- **Hypothesis:** You can read a published scientific article on a PCR-related topic and identify an author's hypothesis, and how the evidence (observations, data) presented is supposed to support it. You can create a testable hypothesis and propose a mechanism for your hypothesis. You can create a visual model to illustrate your hypothesis.
- **Experiment:** You can read a published scientific article on a PCR-related topic and identify the author's research plan. You can determine the experimental design, i.e. identify methods, variables and controls. You can create your own research plan, an experimental design, to test a hypothesis with appropriate controls as well as make predictions of results [before performing any experiments]. You can make a visual model to illustrate your experimental predictions
- **Analysis:** You can evaluate the results of your PCR experiments e.g. what bands in a gel should indicate, or whether the absorbance of a solution indicates how much DNA should be in it. You can use your findings to make conclusions to the result of the experiment, to troubleshoot and postulate appropriate changes in the experiment that should happen next. You can create figures, tables, and any other useful visual models to represent the data you obtain or conclusions you propose based on data.
- **Connections:** You can identify connections between this research and other topics you study in science and non-science courses. You experience some aspect of your malady and to connect your research to real-world impacts. To gain a greater focus and ability to write/speak about your disease as a result of a more profound understanding of the field of your research.
- **Teamwork:** You can learn how best to work and behave in a scientific research team. Being flexible. Practicing social skills. Patience. Leading. Following. Talking. Listening.

Physical (Motor) Skills

- **Equipment Operation:** You can find in lab and know how to use standard equipment as a result of repeated experience including: power supply, vortex genie, digital spectrophotometer, agarose gels, spectrophotometers, micropipetters, thermocycler, baths, heating blocks, pipette aids and computer programs.
- **PCR Protocols:** You can find protocols, reagents, and mix a PCR reaction cocktail with correct concentrations diluted from stock solutions and run a PCR reaction experiment in the thermocycler. You find protocols, reagents, and mix, make, run and photograph a LB or TBE agarose gel for DNA electrophoresis.
- **Records & Accuracy:** You can measure, prepare and pipette stock solutions, like LB or TBE buffers, accurately. You can create a graph by hand as well as by using computer software. You can to keep a daily entry based laboratory notebook.

Content Knowledge

- **Disease:** You know the terminology, mutation, gene information, chromosome information, cellular effects, organ effects, health effect and changes of your [genetic] disease. What is a point mutation? Differentiate between silent, missense, frameshift and nonsense mutations.

- **PCR:** You know the terminology and details of how polymerase chain reaction (PCR) works in a simple explanation as well as in a very deeply detailed fashion. You can evaluate DNA sequences of oligonucleotide primers designs and create your own. You can explain how the polymerase enzyme interacts with both the primer (e.g. 5' vs. 3') and DNA template strand during PCR. Learn how to design a PCR reaction cocktail and what each ingredient does. Learn how to calculate annealing temperatures for primers given only the DNA sequence. You understand all the reagents contained in a PCR cocktail, their roles, and can explain the use of differing temperatures, salt & Mg concentrations and how the use of a "master mix" aids in PCR experiments. You understand how agarose gel electrophoresis works.
- **DNA:** List the three components of a nucleotide. Distinguish between deoxyribose and ribose, pyrimidine from purine, "base-pairing rule." Describe the structure of DNA, which is 3' and 5' ends, and explain what kind of chemical bond connects the nucleotides of each strand and what type of bond holds the two strands together. Which strand is 'sense' and which is 'antisense?' Describe the in vivo process of DNA replication and explain the role of helicase, single strand binding protein, DNA polymerase, ligase and primase. Be able to compare and contrast PCR to in vivo DNA replication.

Appendix B

Outlines of Four Example Teams & Streams Inquiry Laboratories

1. The Comparative Biology Stream

Course: Introductory Organismal Biology

Content & skills learning goals:

a. Develop an understanding of phylogenetic trees as hypotheses for proposing and testing evolutionary relationships within and between groups of organisms.

b. Read, understand, and synthesize the peer-reviewed primary scientific literature.

c. Be able to describe basic features and name representatives of these nine invertebrate phyla (and be aware that there are others): Porifera, Cnidaria, Platyhelminthes, Nematoda, Annelida, Mollusca, Arthropoda, Echinodermata, Chordata.

d. Demonstrate the ability to use technology (e.g., digital cameras, PowerPoint) and communicate scientifically to others orally and visually.

Student Team Composition: Teams of 4-5 students each.

Duration of Stream: 4 weeks (each lab 3 hours in duration)

Overview & Timeline for Stream: In the Comparative Biology Stream, student teams explore the similarities and differences among groups of animals. During week 1, we start with an orientation to animal phyla and an exploration of how phylogenies can be used to propose and test hypothesized evolutionary relationships among organismal groups. Student teams practice phylogenetic tree thinking and how to compare organisms morphologically and in a historical context. During weeks two and three, student teams explore these ideas in depth by collecting some comparative (mainly morphological) data on representatives of nine invertebrate phyla, including some key dissections, and use these data to explore different phylogenetic hypotheses about the ancestor-descendent relationships of these nine phyla. The teams take and annotate digital photographs of their observations of this set of animals that are incorporated into each team's PowerPoint file that is presented orally at the end of the Stream (during week 4). These data are also analyzed within a phylogenetic framework, with teams comparing two competing phylogenetic hypotheses for these same nine animal phyla and arguing the relative merits of each.

Assessment of Learning Goals: During week 1, student teams conduct an exercise that requires them to collect morphological and behavioral data on five animals and then use that data to compare alternative hypotheses of evolutionary relationships (phylogenetic trees). This assignment is completed and turned in during lab. For homework, each student individually reads and responds to questions regarding a scientific journal article that focuses on phylogenetics (example paper below in citations). At the end of lab during weeks 2 and 3, students turn in drafts of their oral & visual PowerPoint presentation that is a photolibrary of their dissections and observations of the nine animal phyla. For homework during each week, student teams work on their complete photolibrary that also includes slides that compare characteristics across phyla; this photolibrary is due before lab during week 4, at which time each student gives a short (2-4 minute) oral presentation of their ppt slides that compare across animal phyla. During week 4, the student teams also work on an analysis of these same 9 phyla within a phylogenetic framework, with teams comparing two competing phylogenetic hypotheses for these phyla and arguing the relative merits of each. Finally, after completing the stream, there is a lab exam that includes the Phylogenetic Assessment Tool.

Relevant Citations:
Li, C., X. Wu, O. Rieppel, L. Wang and L. Zhao. 2008. An ancestral turtle from the Late Triassic of southwestern China. *Nature*, 456: 497-501.
Smith, J.J. and K.S. Cheruvelil. 2009. Using Inquiry and Tree-Thinking to "March Through the Animal Phyla": Teaching Introductory Comparative Biology in an Evolutionary Context. *Evolution Education and Outreach*, 2: 429-444.

2. Exploring the interaction between mutation and environment using Pseudomonas fluorescens

Course: Introductory Organismal Biology

Content & Skills Learning Goals:

a. Formulate alternate hypotheses for how the environment and mutations interact to allow for adaptation.
b. Understand how population size affects manifestation of mutations.
c. Apply the scientific method and perform an experiment using *Pseudomonas fluorescens* to test hypotheses.
d. Master pipetting, dilutions, plate streaking and Chi-square statistics.
e. Write a scientific report that describes experimental design and results that provide support for or against their hypotheses, and incorporates appropriate literature sources into the discussion.

Student Team Composition: Teams of 4 students are formed at the beginning of semester using CATME. Each team performs one portion of the experiment and contributes results to the entire laboratory section. Each team will write a research paper that includes their data as well as data collected by the entire laboratory section.

Duration Of Stream: Four weeks – one lab session (1-2 hours duration) each week for three weeks, plus an extra week for writing.

Overview & Timeline for Stream: This is an adaptation from an experiment reported by Rainey and Travisano (1998). Students set up an experiment to determine what happens to an ancestral phenotype of *Pseudomonas fluorescens* when placed in a heterogeneous environment and how population size can affect outcome. Students discuss the scenario and come up with alternative hypotheses, for example: mutation is spontaneous, or that mutation is induced by environmental change.

In the first week, students are introduced to pipetting, dilutions and plate streaking and are given a pure culture of the smooth (ancestral phenotype) *Pseudomonas fluorescens.* They streak a plate with the pure culture to view a few colony phenotypes a few days after incubation, and then add the culture to one of three different medium concentrations (1/4, 1/8, 1/16 strength). They then setup a controlled experiment, where they set a subset of tubes in a shaking incubator as a control, and set another subset in a stationary incubator – tubes are not sealed to allow oxygen to enter. The stationary environment is considered the heterogeneous environment because an oxygen gradient forms from top to bottom. In week 2, they score how many tubes show the formation of a film (indicating the presence of another phenotype), and then perform dilutions and streak cultures from each group to determine the number of phenotypes and the number of colony forming units of each phenotype of the *Pseudomonas fluorescens* in week 3. In week 4, teams compile the data from other groups in the lab (number of tubes that showed divergent phenotypes from the ancestral smooth phenotypes), and compare the frequency based on medium concentration. They perform a statistics to determine differences, and write a scientific manuscript.

Assessment of Learning Goals: The major assessment piece in the *Pseudomonas fluorescens* stream is a research paper (week 4, graded as a team project, data collected from both the individual team and the entire lab section is included) consisting of a Title Page, an Introduction, Methods, Results and Discussion section, a set of Tables and Figures, and Literature Cited. The paper goes through a first draft that is reviewed (with feedback) by the teaching team, and the team is allowed to resubmit after feedback to improve their grade.
Other assessments in the *Pseudomonas fluorescens* stream include weekly lab quizzes (to ensure engagement with material *before* lab), a pre- and post-test, and a lab exam (covering lab skills and process skills goals) to provide individual accountability.

Relevant Citations:
Kassen, R., Llewellyn, M. and Rainey, P.B. 2004. Ecological constraints on diversification in a model adaptive radiation. *Nature* 431:984-988.
Rainey, P. B. and Travisano, M. 1998. Adaptive radiation in a heterogeneous environment. *Nature* 394, 69–72.

3. Friendly Foes: A search for novel bacteriophage

Course: Organismal or Cell/Molecular Biology

Content & Skills Learning Goals

a. Develop the skills to perform a serial dilution series and to understand the applications/purpose of such a dilution series.
b. Develop the skills to perform a plaque assay and become familiar with working with bacteria and bacteriophage.
c. To relate the general bacteriophage life cycle to the plaque assay procedure.
d. Develop the skills to isolate nucleic acids from biological samples.
e. Develop the skills to perform agarose gel electrophoresis.
f. Relate the molecular characteristics of DNA to the laboratory methods used to isolate and analyze it.
g. Demonstrate understanding of microbial communities and the role of bacteriophages in those communities.
h. Create a research hypothesis that is supported by evidence from the primary literature.
i. Develop an experimental plan to test the hypothesis.
j. Identify an experimental procedure to further characterize the novel bacteriophage beyond what is presented in the lab manual.
k. Communicate the results of the research in a scientific paper.

Student Team Composition: 4 students per group

Duration of Stream: 7 weeks (2x2hour lab periods per week)

Overview & Timeline for Stream: This Stream was based on previously published examples of high school and undergraduate student laboratories in which students isolate and characterize potentially novel bacteriophage. I adapted the idea to become a 7-week project for 4-person research groups in a course for 80-100 students. The overall goal of this research was to isolate and characterize a potentially novel bacteriophage from environmental samples that the students selected. Besides completing training laboratories as directed, students must learn about bacteriophages by reading and engaging in the primary literature. First, the research group selected the environment to sample based on evidence from the literature. Locations selected included dairy farms, agriculture research plots, sewage drains, and natural areas. In addition to isolating phage from an environmental sample, students made a virus stock and performed experiments to characterize the phage. Phage genomic DNA was isolated and subjected to restriction enzyme analysis. Additionally, students proposed and performed a Design It Yourself (DIY) experiment, whereby, they used the literature to identify an experiment that would contribute to the further characterization of the newly isolated bacteriophage. DIY experiments included examples such as host range, improving isolation techniques, and electron microscopy.

Assessment of Learning Goals: Research group progress toward the learning goals was assessed by a variety of assignments over the course of the project. The research groups completed a research proposal and participated in an interview with the instructor at the beginning of the project. Students took quizzes prior to each training lab. Students then completed post-laboratory assignments after each training lab to practice and get feedback on how to prepare figures and write sections of a scientific article. Finally, the research group authored a journal style scientific article describing their research.

Relevant Citations:

Phage Finders: **http://www.drjreid.com/phagefinders.htm**
Bacteriophage Discovery and Genomics HHMI Program in Research and Education: **http://www.pitt.edu/~gfh/**
Bacteriophage Research: Gateway to Learning Science: **http://www.microbemagazine.org/index.php/06-2010-home/1866-bacteriophage-research-gateway-to-learning-science**
Hatfull, G. F., M. L. Pedulla, D. Jacobs-Sera, et al. 2006. Exploring the mycobacteriophage metaproteome: phage genomics as an educational platform. *PLoS Genetics*. 2: e92.

4. The Plant Protein Stream

Course: Introductory Cell and Molecular Biology

Learning Goals

Lab Skills - At the end of this experimental lab stream, students will be able to:

a. Plant and nurture plant seedlings;

b. Prepare a concentrated stock solution of a chemical reagent (self-chosen) and prepare a dilution series (5-fold) based upon it;

c. Use a spectrophotometer to carry out a Bradford Assay for total protein in a tissue sample by making a standard curve and then applying it to a tissue homogenate.

Science Process Skills - At the end of this experimenta lab stream, students will be able to:

a. Propose a high quality hypothesis to test;

b. Conduct a search of the primary literature to find articles pertaining to the effect of a chemical reagent on plant growth and development;

c. Design an experimental plan (w/ guidance) including replication and controls;

d. Carry out a statistical test (ANOVA) to test for significance of observed differences across treatments;

e. Prepare an Introduction section and a set of Figures and Tables similar to those found in a scientific manuscript;

f. Make an oral presentation in class of one aspect of their team's research project.

Student Team Composition: Teams of 4 students each. CATME employed to establish teams.

Duration of Stream: Five weeks (two lab sessions of 2 hours duration each week).

Overview & Timeline for Stream: Our Plant Protein lab stream is an adaptation of a lab sequence described by Howard and Miskowski (2005). In our version of this lab stream, students use a Bradford assay of total protein to test for differences in the protein content of plants treated with differing concentrations of a chemical reagent. We run this as a five-week exercise, which serves as a vehicle for teaching an array of lab techniques and science process skills. During week 1 (typically the first day of lab in the semester), student teams are established, students learn how to use the pipettors, and the teams prepare flats and sow plant seeds. In addition, students are oriented to the lab environment and brainstorm a chemical reagent. In week 2, students make a dilution series and are introduced to spectrophotometry and Beer's Law by creating a graph of absorbance versus concentration. We help the teams get started on a primary literature search, and we explore with them the elements of a good hypothesis. In week 3, students prepare stock solutions of their reagents and prepare dilutions to appropriate working concentrations. Students also use the "Orange Problem" to explore standard curves and to estimate how much protein is in an orange. In week 4, students extract protein from their experimental plants and calculate how much protein is in their samples. This leads into the statistical tests to determine the significance of observed differences. In week 5, students do their oral presentations and we polish manuscripts, which are submitted the following week.

Assessment of Learning Goals: The major assessment piece in the Plant Protein stream is an abbreviated research paper (summative, week 5, combination of individual and group grades) consisting of a Title Page, an Introduction, a brief Results and Conclusions section, a set of Tables and Figures, and Literature Cited. The paper goes through a first draft that is reviewed (with feedback) by the teaching team before submission of the final paper. Other assessments in the Plant Protein stream include weekly lab quizzes (to ensure engagement with material *before* lab), the Orange Problem, a lab exam (covering lab skills and process skills goals) to provide individual accountability, and an oral PowerPoint presentation to the entire lab class.

Relevant Citation:

Howard D. R., and J. A. Miskowski. 2005. Using a Module-based Laboratory To Incorporate Inquiry into a Large Cell Biology Course. *Cell Biology Education*, 4: 249–260.

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