The Advantages of Inquiry-Based Laboratory Exercises within the Life Sciences

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There has been a recent and strong advocacy to introduce inquiry-based laboratory instruction into biological science courses. Traditional life science curriculum taught basic biological concepts that utilized “cookbook” type experimental procedures in which students follow a pre-described methods resulting in well established and validated results (Domin 1999). Clearly execution of these types of laboratory exercises enforced lessons learned in the classroom but did very little to enhance critical thinking skills. It is believed that developing laboratory exercises that have a research orientated focus will not only teach science, but will develop students to think like a scientist. There is no clear consensus on the function and purpose of laboratory instruction within an academic curriculum (Russell 2008). Leading purposes include: bridging the gap between theory and practice, illustrate material taught in lecture, increase enthusiasm and foster scientific attitudes, and to develop skills of observation, reasoning and critical thinking. Additionally, the perceptions on the importance of laboratory exercises differ greatly between professors and students (Hofstein 2003).

It is quite ironic that we teach science to students that aspire to become scientists; however there clearly is a differentiation between earning a science degree and developing the skills necessary for scientific achievement. The discrepancy is even further pronounced and ironic because the ‘scientific method’ which enforces keen observation, hypothesis generation, and experimental design is taught as a cornerstone dogma to being a good scientist however traditional didactic laboratory exercises fail to develop these skills. Recent publications from the National Research Council, American Association for the Advancement of Science and National Academy of Sciences have encouraged the need to introduce research-driven exploration in lieu of “cookbook” exercises (National Research Council (2003), American Association for the Advancement of Science (2010), National Academy of Sciences (2010). The term “cookbook” refers to experimental procedures in which students follow a step-by-step method reminiscent of a cooking recipe. Furthermore, the expected end result of the experiment is often provided to the students before they even initiate the experiment. Unfortunately these laboratory approaches encouraged students to intellectually disengage from the experiment and follow the protocol to completion without any regard to understanding the methodology or the acquired outcome (Igelsrud 1988). Evaluation of student performance is often based on how well they follow the protocol. Because the laboratory exercise was validated with repeated data output, any discrepancy in the results was attributed to student’s inability to follow the protocol. Failure to obtain satisfactory results is a common occurrence of the scientific research process and is acceptable. What is unacceptable however is the inability to troubleshoot and explain the possible errors or circumstances that yielded unexpected results. The students that do
obtain the pre-determined results often lack the conceptual understanding and significance of individual steps of the experiment. For many students this led to frustration and often, for non-science majors, discouraged them from pursuing their education within the natural sciences. Student perceptions and attitudes towards science have been shown to improve if laboratory instruction is taught with a connection to the real world and students are provided an opportunity to participate in the experimental design (Mathews 2010).

Educators have understood the shortcoming for many years regarding “cookbook” laboratory exercises (Handelsman 2004). Therefore, why would such practices continue throughout university life science programs? Redeveloping lab programs into an inquiry based exercise that provides a sense of authentic research experience is not an easy task and may explain why didactic laboratory programs exist throughout the university system, even in the face of data suggesting that research focused laboratory exercises enhance learning. Laboratory instruction must go beyond measuring student achievement as a learning outcome and focus on laboratory formats that promotes conceptual understanding, retention of knowledge, reasoning skills, higher-order cognition, hands-on experiences and enthusiasm for scientific achievement (Domin 1999). Using these outcomes as a guide for comparison, the advantages and disadvantages of “cookbook” and inquiry-based instruction was evaluated.

The **advantages** and **disadvantages** of utilizing “cookbook” laboratory exercises within the life science curriculum include:

**Advantages**
1. Laboratory exercises are easily designed to fit into restricted student schedules
2. The results of the exercise are predetermined allowing assessment of the students performance
3. Conducive and manageable for courses with large student enrollment
4. Can cover multiple biological concepts within a course
5. Laboratory exercises can be created into modular exercise that correspond with classroom lecture

**Disadvantages**
1. Students easily lose enthusiasm for science education and an interest in ongoing and future scientific achievements
2. Students quickly learn what steps of the procedure can be ignored or fail to thoroughly read the protocol for complete understanding
3. Critical thinking skills are not developed
4. There are little opportunities to apply problem-solving strategies
5. Students feel disconnected from the exercise and lack “ownership” of the collected data
6. Collaboration among peers is discouraged
7. Students do not plan the experiments and results are not properly interpreted
8. Scientific concepts are “verified” rather than “discovered”
It is clear that “cookbook” laboratory exercises persist manly due to a logistic advantage. The bottom line is that they are easier to manage and setup. With limited budgets and laboratory support personnel, these types of laboratory instructions are favored. They tend to be advantageous to the instructor but place the student at a disadvantage for enhanced learning. The major strength of “cookbook” exercise is that numerous biological concepts can be taught by using independent modules that can be interchanged and aligned with classroom lectures. In this regard students are solely validating concepts learned from the lecture. Critical thinking and reasoning skills are not developed and students easily lose enthusiasm for the process of scientific investigation. Recent studies have indicated that students believe that “cookbook” lab formats are trivial and are executed for unknown reasons (Luckie 2004). Students want to be challenged in the laboratory and therefore “cookbook” laboratory exercises fail both the student and the intent of a scientific education.

The advantages and disadvantages of utilizing “inquiry-based” laboratory exercises within the life science curriculum include:

**Advantages**
1. Students take “ownership” of the laboratory exercise
2. Students experience the scientific method and acquire an appreciation and understanding for scientific achievement
3. Students become interested in ongoing and future scientific achievements as it relates to current events
4. Students experience the successes and failures of scientific research
5. Students are encouraged to collaborate to obtain successful results
6. Students learn critical thinking and problem solving skills
7. Students retain the learned concepts

**Disadvantages**
1. Difficult to manage in courses with large student enrollment
2. Requires significant amount of time that students must be in the laboratory
3. Students can become easily frustrated

Laboratory exercises that utilize an “inquiry-based” approach instill scientific skills that are desired in life science majors (Wood 2003). The inquiry-based approach boosted the development of critical thinking and problems solving skills in students. Current analysis has demonstrated that “cookbook” laboratory exercises fail to develop these skills. Furthermore, inquiry-based exercise promotes scientific curiosity (Haury 1993). Curiosity is the foundation of the scientific method. Students who ask questions, make the proper observations and can formulate a hypothesis are the ones that will succeed in the field of science. Recent trends indicate that students want instant feedback on their educational progress and need to be actively involved in the educational process (Lord 1999). Students, who are given the opportunity to design
experiments and execute them, regardless of the whether or not the proper results are obtained, are more likely to become “self-educators” and maintain curiosity and enthusiasm for scientific achievement. These students are likely to pursue advance science degrees and become the next generation of scientists.

The evidence supports the mandate by the National Research Council, American Association for the Advancement of Science and National Academy of Sciences to redesign laboratory instruction into an inquiry-based format. The inquiry-based instruction can be either instructed-guided discovery or authentic research based. These redesign laboratory approaches will 1). Bridge the gap between theory and practice 2). Illustrate material taught in lecture 3). Increase enthusiasm and foster scientific attitudes and 4) Develop skills of observation, reasoning and critical thinking. Additionally they will provide students with the type of challenges that they are requesting from a laboratory-based course.

References


**Annotated readings**


-This article reports the comparative results between “cookbook” and inquiry-based laboratory exercises. Although there has been a push to introduce more inquiry-based laboratories into the science curricula, few studies have actually conducted a head-to-head comparison with traditionally taught laboratories. It was found that students within the inquiry based laboratories had positive attitudes towards research, developed greater self-confidence with experimental procedures and their intellectual abilities and conveyed an enthusiasm to continue scientific research in the future. These attributes were not evident from students performing the “cookbook” laboratory exercises. The methods to make the comparison between the two groups used questionnaires and instructor observations.


- The authors redesigned a cell biology laboratory course with emphasis on authentic research and inquiry-based exercises. Using student questionnaires, it was found that students improved their critical thinking skills, developed an appreciation and enthusiasm for research, became interested in ongoing and current cell biology research and had a desired to conduct more inquiry-based laboratory exercises. The main complaint from students was that the labs were time consuming so therefore they felt rushed and it was difficult to remain totally independent when performing the experiments. The authors designed the course into modules in which each module highlighted a different cell biology concept.

-The authors put forth a model in which investigators can incorporate their laboratory research efforts into the laboratory exercises within biology courses. This approach may create unique opportunities to expose students to ongoing and relevant research. Six factors are proposed and discussed that should be considered when utilizing authentic research for student education: 1) Must contain a low barrier of expertise that foster data collection 2) Data collected should be verified and repeated by other students 3) There should be enough variables in the research to allow students to develop a diverse hypothesis 4) All data should be collected in a central database and shared among all students 5) Students must report data in the proper scientific format as if it is going to be published in a peer-reviewed journal 6) The instructors must utilized their general and specific training and skills to encourage high level discussion from the students

Lord, T and Orkwiszewski, T. (2006). Moving from didactic to inquiry-based instruction in a science laboratory. The American Biology Teacher, 68(9), 342-345. -In this article the authors report a side-by-side comparison of students participating in either “cookbook” laboratory exercises or inquiry-based exercises. This study supports the need for more inquiry-based laboratory instruction as evident from the student outcomes. Students in the inquiry-based laboratories developed better critical thinking skills, learned and retained more biological concepts, increased their enthusiasm and attitudes towards science and overall enjoyed these types of laboratory exercises over “cookbook” protocols. The authors also highlight that the current generation of students require constant stimulation and need to be mentally engaged in their science education. An inquiry-based laboratory format satisfies the needs and scientific curiosities of the student.

Luckie, D. B., Maleszewski, J. J., Loznak, S. D. and Krha, M. (2004). Infusion of collaborative inquiry throughout a biology curriculum increases student learning: a four-year study of “Teams and Streams”. Adv. Physiol. Educ, 287, 199-209. -This article reports the comparison of an inquiry based laboratory exercises to “cookbook” laboratory exercise. Using Bloom’s Taxonomy as a guide, an inquiry-based laboratory program was developed and then assessed. It was found that students in the inquiry-based program performed better on a modified version of the medical school entrance examination (MCAT) and developed enthusiastic attitudes towards science education and authentic research. The authors emphasize that “controlled chaos” in the laboratory must be encouraged and that faculty need to resist the urge to fix the laboratory mistakes of students. Trial and error are the hallmarks of scientific inquiry.

Myers, M. J. and Burgess A. B. (2003). Inquiry-based laboratory course improves students’ ability to design experiments and interpret data. Adv. Physiol. Educ, 27(1), 26-33. -A comparison was investigated between students enrolled in a lecture-only or a lecture + inquiry-based course. Students were evaluated for their ability to properly analyze data and properly design experimentation protocols. Students were assessed before and after completion of the course. It was found that students taking the lecture
inquiry-based laboratory course improved critical thinking and reasoning skills. It is concluded that students enrolled in lecture-only courses (without a laboratory component) struggle with data analysis and experimental design.

- This work describes a comparison between “cookbook” and inquiry-based laboratory exercises. Unlike many other comparative studies, the investigators tested students before initiating and after completing the laboratory exercises to gauge how much knowledge was gained from the exercise. Although both laboratory exercises covered the same material (basic enzymology) the students in the inquiry-based group learned significantly more upon completion of the exercise. Interestingly, the “cookbook” format was based on four learning objectives but the inquiry-based laboratory had no explicit objectives. Instead, the inquiry-based group was presented with one open-end question followed by several specific questions. The authors acknowledge that one disadvantage of the inquiry-based method is that it requires considerable more time to execute than the “cookbook” procedures.

- Laboratory exercises and instruction can be categorized as “cookbook”, inquiry-based or research-based however there has not been very many evaluations that compared all three formats. In this study, the authors found that research-based formats outperformed both traditional “cookbook” methodologies and inquiry-based approaches. Inquiry-based approaches however did out perform “cookbook” formats in terms of increased conceptual learning and a deeper understanding of the nature of science. Furthermore, it was found that students engaged in inquiry-based or research-based laboratory exercises have a better appreciation for what it means to be a scientist. They also were more likely to undertake an undergraduate research project.

- The study aimed to introduce a laboratory program that consisted of inquiry based research that directly associated with relevant real world situations. The investigators found that student’s interest increased significantly if laboratory exercises focused on answering questions relevant to experiences of the student. It was also found that participation in inquiry-based exercises dramatically increased the student’s confidence in their abilities to design experiments and interpret data. This studies suggest that inquiry-based laboratory exercises are most productive in terms of
educational gains, if the data collection aids in the understanding of real world situations relevant to the student.


- The authors redesigned an introductory biology laboratory course into an inquiry-based laboratory format. They also related the lab to a known and common real-world health problem. The authors observed that students gained a greater appreciation for the laboratory when they were working on a relevant project and that data generated was potentially novel and not previously reported. Students reported that they were frustrated at the beginning of the project as they were making mistakes and were unsure if their data was correct. As the semester progressed, the students embraced and appreciated the aspects of troubleshooting experiments and stumbling their way through the protocols.