Magazine

Easy ways to promote inquiry in a laboratory course: the power of student questions.

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To teach students to think like scientists, we modified our laboratory course to include regular opportunities for student practice of inquiry and the scientific process. Our techniques are simple; they can be implemented without rewriting lab manuals, require little additional grading beyond typical lab reports, and are applicable across the science curriculum.

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An overarching goal in science education is to teach students to think as scientists. However, many lab manuals provide concise directions that guide students step by step through an experiment, thereby turning students into technicians, not scientists. Alternatively, inquiry- and discovery-based activities not only teach the scientific process but also increase student engagement and understanding (Lawson 1992). The importance of inquiry is clear in the National Science Education Standards, which state "Students' understandings and abilities are grounded in the experience of inquiry, and inquiry is the foundation for the development of understandings and abilities of the other content standards" (NRC 1996, p. 103).

[ILLUSTRATION OMITTED]

A large body of literature on increasing inquiry and investigation in lab classes exists. Inquiry activities specific to particular biological, chemical, or physical phenomena are readily available [e.g., on the heat of fusion of water (Arce and Betancourt 1997), seed germination (Crandall 1997), yeast respiration (Glasson and McKenzie 1997), leaf stomata density (Grant and Vatnick 1998), and seedling emergence (Silvius and Stutzman 1999)]. In addition, various authors report dramatic revisions in which entire lab courses have been restructured to focus on student-designed investigations (Boersma et al. 2001; Dimaculangan et al. 2000; Lunsford 2002). These are exciting strategies for involving students in the process of doing science.

In addition to the advantages of student-driven experiments, asking questions is a critical aspect of thinking about science. To quote biology education researcher M. Shodell (1995, p. 278), "The essence of 'thinking' is really question asking." Students typically focus on the facts of science rather than the questions that lead to the discovery of those facts. In many science classrooms, questions come primarily from the instructor so that students have little experience generating their own questions (Dillon 1988).

Several science educators have proposed ways to increase the emphasis on student questions during lecture, homework assignments, and even exams (Zoller 1987; Shodell 1995; Dori and Herscovitz 1999; Marbach-Ad and Sokolove 2000). The benefits of an inquiry approach and an emphasis on student questions have been discussed at all levels of science education, including as early as elementary and middle school (Harlen 2001). The laboratory is an ideal environment for students to develop skill in asking scientific questions.

Our goal was to emphasize inquiry throughout a lab course without large-scale changes in course organization. Sundberg et al. (2000) discuss a number of practical problems to overcome in developing investigative labs, including resistance of colleagues, lack of time and money, TA training, technical support for lab preparation, and changes in appropriate grading approaches; they suggest that revamping a semester-long lab course to include more inquiry could take between one and two years. Many faculty interested in increasing inquiry in the lab have neither the time nor money for such a large transformation. Thus, our article provides teachers practical, easy, and almost-free techniques to increase student inquiry in every lab section.

We present two basic approaches to emphasizing inquiry in the lab--written student questions before and after each lab and student-designed experimentation. Our approach to student-driven experiments is to start with mini-experiments within a directed activity and build up to an independent experiment. Similar approaches have been described by others (Adams 1998; Crandall 1997; Knabb 1997; Leonard 1991), and we present our version as another example of a successful approach. The emphasis on written student questions is a particularly easy way to promote scientific thinking by students. Our techniques do not require rewriting the lab manual, nor do they require major changes to course curricula. Although the examples we provide are from a senior-level cell biology course with 25 to 50 students, our techniques could be used in any science lab and are appropriate for high school science classrooms as well.

Written student questions

Pre-lab questions. The purpose of pre-lab questions is to focus student thinking on the upcoming experiment and potential results. Students must write three specific, concrete questions; at least one must be a question they think will be answered in lab. These questions are due at the start of lab.

Students are advised to think about what questions the experiment addresses and what questions students develop as they think through the experiment. Pre-lab questions account for about 5% of the lab grade and can be graded quickly; most students receive full credit unless they ask meaningless questions (e.g., "who was Robert Hill?" for an experiment on the Hill reaction). Feedback is provided by brief marginal comments, and particularly thoughtful questions earn extra credit.

Requiring students to write pre-lab questions reinforces the nature of science as a process that begins with questions. It increases critical thinking because students must consider predicted outcomes and possible alternatives. Identifying a question to be answered in lab forces students to understand the type of data that will be collected and enhances the value of performing experiments. Additionally, writing about the lab in advance allows students to formulate early connections between the current exercise and other knowledge. Students who think about the experiment in advance are more comfortable in lab and take more ownership of the experiment and its results. In addition, as with any pre-lab assignment, there is the added benefit that students come to class better prepared.

When students are allowed to ask any question, they write a variety of diverse questions (Table 1). Some students ask questions that demonstrate curiosity about the procedure or the organism used. Other questions draw connections, analyze the methods, or suggest further experimentation.

Post-lab questions and experimental proposal. The post-lab questions are designed to encourage students to reflect on what they accomplished in the lab investigation and to stimulate thinking about new questions that derive from the experiment. Students must suggest a new question that has arisen from their lab observations and briefly propose an experiment to answer it. Post-lab questions reinforce the questioning nature of the scientific process. Students realize that an experiment starts from questions and ends with new questions. Likewise, students are not finished with an experiment once they have collected and analyzed data; by reflecting on what they have learned, students end the experiment by asking a new question. Post-lab questions are required on a weekly basis, and thus our students are given regular practice at thinking about experiments to answer questions.

The questions and experimental proposal account for about 5% of the lab grade and can be graded quickly, with most students receiving full credit; brief marginal comments provide feedback and suggestions for improvement. Post-lab questions have the added benefit of requiring critical thinking, as students must analyze self-generated questions to determine if those questions are practical to answer within the classroom. See Figure 1 for examples of student questions. Note that the last three questions would be difficult to answer in a three-hour student laboratory; students receive feedback on practicality, which prepares them for the independent experiment discussed later.

The continual practice of generating questions allows students to ask better, more critical questions. Marbach-Ad and Sokolove (2000) found that, with practice, their introductory biology students asked more questions that demonstrated higher-level thinking. In our approach, students generated at least two specific types of questions on a weekly basis throughout the quarter, resulting in many opportunities for instructor feedback. We are currently in the process of analyzing the effect of such frequent student practice on the prevalence of higher-level questioning abilities.

Student-designed experiments

Mini experiments. The mini experiment is an opportunity for students to conduct a short experiment embedded within a longer lab investigation. It requires students to manipulate some variable or method they have just used. For example, during one lab, students collect drops of their own blood and incubate them with bacteria to observe phagocytosis. The mini experiment in this lab challenges student teams to optimize phagocytosis by choosing a variable to test.

The benefits of mini experiments are severalfold. They require students to think about procedures instead of simply following a recipe. Because the variables each team chooses to manipulate differ, the class is provided with diverse and interesting results for analysis. Mini experiments provide guided practice in experimental design. Whereas post-lab questions provide practice in experimental design on paper, mini experiments allow students to design, carry out, and analyze the results of a clearly defined experiment. Furthermore, students learn that experimental methods should fit the question being investigated and that procedures may be flexible to optimize results.

Mini experiments do not require changing the lab manual or course preparation. To implement mini experiments, we simply identify experimental variables or methodological steps that can be altered and encourage students to explore by altering that variable or step. These variations may or may not affect the outcome; either way, a lesson about experimentation can be learned.

Independent experiment. Of the approaches we use, the independent experiment is the most open-ended inquiry our students practice. Students choose a question to investigate, usually an extension of a previous lab exercise, and often related to one posed as a post-lab question earlier; for example, the first two questions in Figure 1 are common ones chosen for independent experiments. Examples of other independent experiment questions can be found in Figure 2. Students work primarily in pairs and are provided guidelines emphasizing the importance of a focused question, inclusive of appropriate controls. We encourage students to think about possible problems in advance and emphasize the need for quantitative data.

To assist students in designing experiments, we require that one week in advance, students submit their question, a brief summary of their planned approach, and a detailed list of materials. For two weeks before the experiment there are more office visits as individual students seek assistance in planning. In addition, the lab setup is more complicated than usual because different kinds of experiments are done in the same session. The day of the experiment (usually the eighth week in a 10-week quarter) students submit detailed methods. After students have completed their experiment, they submit a final report including an analysis of the results and the experimental design.

Watching students conduct their independent experiments is watching science in action. The independent experiment provides genuine practice in experimental design and troubleshooting. Students do not simply follow a recipe to achieve "correct" results, but often must modify their planned approach in the face of unexpected technical problems; although this makes the lab session more chaotic, it is incredibly satisfying to watch. Students who investigate their own questions take pride in their investigation and its results. Finally, independent experiments provide something that traditional lab activities cannot--unique and individual data. Students are challenged to analyze and present their own data using appropriate graphs and tables.

Summary

Revising lab curricula to focus on inquiry does not require large-scale revision of established lab manuals. Here, we provide four simple ways to emphasize questioning as a critical part of the scientific process. Pre- and post-lab questions are particularly easy to implement, requiring no modification of written lab manuals, no change to supplies or equipment, and no class time. They provide students with weekly practice in critical thinking and experimental design, opportunities for instructor feedback without a large increase in grading, and increased engagement in the lab activity. Mini experiments allow students to genuinely investigate questions without changing lab logistics or requiring large amounts of lab time. An independent experiment requires a full lab session and more preparation by the instructor but provides students with the invaluable experience of asking and answering their own scientific question--i.e., doing science.

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TABLE 1 Examples of student-generated pre-lab questions.

Student's question	Quality demonstrated
How do the internal structures differ among the amoebae, paramecia, and stamen hairs?	Ability to identify questions that should be answered in lab
How does the cell know the exact length	Curiosity and thinking about

of a normal flagella; is there a stopimplications
cap at the end? And what places the cap
on the end, if there is a cap?
What would happen if a person had a Curiosity and thinking about
bacterial infection causing a fever? implications
Would the rate of phagocytosis be high?
Is the smaller size of red blood cells Analysis and ability to relate
(RBCs) relative to white blood cells concepts from lab experiment to
(WBCs) due solely to isotonicother information
constraints on how much hemoglobin may
be inside the RBC, or is it more a
result of maximizing surface area for
gas exchange?
Can the number of WBCs vary enough Application of the scientific
throughout a 24-hour period such thatprocess
taking one sample can be misleading as
a standard healthy representative?
When making beer or wine, does Application to the real world
Saccharomyces cerevisiae stop at one
spot within the cell cycle, and if so,
where?
How does DAPI get into the nucleus and Thinking about experimental
get to the chromosomes? procedures
How is yeast budding similar or Ability to relate concepts from
different from mammalian cytokinesis?lab to lecture
If cells have checkpoints to prevent Thinking about implications
abnormalities, how is it that things
still go wrong (e.g., nondisjunction)?
What is more important, the Evaluation and rationale for
concentration or length of exposure future experimentation
when it comes to environmental insults
affecting the cell cycle?

FIGURE 1 Examples of student-generated post-lab questions.

* What is the effect of temperature on flagellar regeneration?
* How do wavelength and intensity of light affect the Hill reaction?
* Is length of flagella related to speed of movement?
* What determines the direction of motility of the cells?
* Do different uncouplers have the same effect on the rate of the Hill reaction?
* Would the age of the spinach make a difference in the rate of photosynthesis?
* Would flagellar regeneration be affected if the tubulin genes were over-expressed?
* How is movement produced by the flagella?
* What structures of the cell wall give it the greatest durability?

FIGURE 2 Examples of student-generated questions for independent experiments.

* What is the rate of phagocytosis of Staphylococcus epidermis by neutrophils (bacteria/neutrophil*min)?
* What effects do pH changes have on RBCs, amoebae, and paramecia?
* What cytoskeletal protein is involved in maintaining organelle position?
* Does cytoplasmic streaming in stamen hair cells of

Tradescantia
virginia use actin, microtubules, or both?
* How would the rate of electron transport in chloroplasts be different
if the light source used for photosynthesis were covered with colored
filters?
* What will be the effects of different calcium concentrations on
flagella and cilia function in Chlamydomonas and Paramecium caudatum?
* Does temperature change the rate of motility of single-celled
eukaryotes? At what temperature does motility stop? Does temperature
change affect different modes of locomotion (ciliary, flagellar, or
amoeboid) differently?
* Are the isotonic ranges and rates of plasmolysis different for
different cells?
* What are the effects of temperature on membrane permeability? How will
different temperatures affect the rates of permeability of different
alcohols?