SERIAL LABORATORIES TO TEACH RESEARCH SKILLS

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A major challenge lies ahead for science educators. We must do a better job in recruiting students to science and retaining them from the moment they enroll in their first science course. Several task forces, professional societies and conferences have addressed the challenge by articulating goals of science education at all educational levels. Being from a liberal arts college, I find of particular value the "Oberlin College Ohio Report, 1986; Maintaining America's Scientific Productivity: The Necessity of Liberal Arts Colleges" (see also Walsh, 1986). Of several goals suggested in the report, this paper offers an idea pertinent to this one: "to engage students in the research process."

In our enormous discipline, we nearly universally accept the tenet that the lab/field is the place to do science, and so we may ask: How can we engage students in research in our laboratory courses? If our laboratory courses are effective at engaging and preparing students for research, then students should be both eager and able to conduct directed research during their senior years.

So how do we plan our laboratories to engage students in research? Numerous skills, processes and attitudes have been identified in the literature as being part and parcel of the research process. One study (Tamir and Amir, 1987) suggests that such processes reduce to 7 major activities:

- handling quantitative relationships
- explaining and assessing data
- conceptualizing and planning investigations
- summarizing results
- interpreting and concluding
- selecting form of and presenting findings
- designing experiments

Providing students with experiences that develop these skills should be evident in any lab designed to teach the research process.

We might ask ourselves how our existing laboratories are designed and whether they effectively teach these skills. College biology laboratory education typically has three major goals (von Blum, 1975). Students:

- observe and/or experiment with biological materials to gain first-hand knowledge and to develop or reinforce fundamental concepts
- receive training in the use of techniques, equipment, methods and procedures of the discipline and
- develop a functional understanding of the investigative nature of science.

Nearly every lab manual that I have read claims to have similar goals. Yet the
design of most of our laboratories is closed-format or "cookbook" style, in which the student repeats the past successes of research biologists and rarely experiences the excitement of having a genuine question. While the first two goals are usually attained, and most of the above science processes are engendered,

few students become engaged in investigation to the extent that they will develop a functional understanding of science.

A response to the shortcomings of cookbook-style laboratories has been an assortment of investigative laboratories that has emerged over the past 10-15 years. These range in form from term-long projects, with which most of us are familiar, to one period inquiry sessions, such as some activities of BSCS Green Version. Recently, open-ended laboratories incorporating elements of the guided inquiry model have been introduced (Leonard, 1988; Leonard et al., 1988). These labs generally achieve the third goal above and, for the most part, develop science process skills.

However, there are some problems associated with investigative laboratories (see for example, Rubin and Tamir, 1988). For example:

• Term-long investigations are often too unstructured for the concrete learner.
• Frequently, the questions that are asked by students are rather trivial.
• Students often feel overwhelmed by all of the procedures that have to be synthesized to complete the investigation. Though science process skills are "taught" in investigative laboratories, they may not be learned by students having certain learning styles. In short, the effective communication of the excitement of research may still elude us.

This paper offers a laboratory scenario -- the serial laboratory -- that attempts to overcome some of the problems of both the cookbook and open-ended investigative laboratories. Serial laboratories address all three of the goals of laboratory education while teaching research process skills.

In serial laboratories a single topic is investigated for sequential laboratory periods in the manner that a research project is conducted.

The Serial Laboratory

Typically in a research project, protocol is developed with a known system before trying it out on an unknown system. Less guidance is given to students as they progress from the first lab period to the final period, which is a small-scale independent investigation. The first laboratory period involves a typical "cookbook" experiment, in which student instructions pose the background, the research question and the experimental design, and specify procedures for conducting the experiment and recording, analyzing and summarizing the results. Students are guided through the design of the second experiment, which relies on the results of the first period. Procedural details are intentionally omitted, thereby leaving students to apply protocol learned from the first lab. Instructions are given to guide the students in their analysis of results, which are presented in a second post-lab session. Results inspire questions for the third lab experiment.
which can be planned and performed in small groups. Procedural details are worked out between the group and the instructor in a pre-lab session before the third and final lab period.

A summary of the goals and contexts of each lab period and activities of pre- and post-labs is shown in Table 1. In this scenario, the focus of the first lab is to assist students in conceptualizing the area of biology being studied, to develop laboratory techniques and to develop data analysis skills. Several research skills, such as designing experiments, selecting form of data for presentation, etc. are deliberately not addressed until later sessions. In the second lab, students must plan the investigation, but the scope is narrowly defined so the planning skills develop in a structured context. Most of the activity centers on application of skills and concepts learned in the previous lab to address a slightly different problem. Because the students are required to present these results to the class, they begin to develop skills in selection and presentation of data.

The second post-lab and subsequent pre-lab are critical periods in the development of the serial lab. Following second lab, a class discussion of the student-presented results, interpretations and conclusions will invariably lead to questions about the biological phenomenon being studied. In preparation for the pre-lab period, small

<table>
<thead>
<tr>
<th>LAB I.</th>
<th>GOAL: DEVELOP SKILLS IN CONDUCTING AND ANALYZING RESULTS OF AN EXPERIMENT USING SPECIFIC METHODS, PROCEDURES AND PROTOCOLS CHARACTERISTIC OF THE DISCIPLINE</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CONTEXT: PREPLANNED, PREDESIGNED, PACKAGED &quot;INVESTIGATION&quot; OF SEVERAL COOKBOOK LABORATORIES</td>
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<td></td>
<td>TYPICAL</td>
</tr>
<tr>
<td>POSTLAB I.</td>
<td>GOAL: GUIDE DATA ANALYSIS, SUMMARY AND INTERPRETATION</td>
</tr>
<tr>
<td>LAB II.</td>
<td>GOAL: APPLY PROCEDURES AND PROTOCOL TO INVESTIGATE BIOLOGICAL PHENOMENA</td>
</tr>
<tr>
<td></td>
<td>CONTEXT: STUDENTS ARE GUIDED THROUGH PLANNING, DESIGNING AND PERFORMING AN INVESTIGATION. SPECIFIC PROCEDURES ARE BASED ON OUTCOME OF FIRST LAB. LEARNED CONCEPTS, DEVELOPED PROTOCOL AND/OR SPECIFIC RESULTS ARE APPLIED.</td>
</tr>
<tr>
<td>POSTLAB II.</td>
<td>GOAL: GUIDE ANALYSIS, SUMMARY, INTERPRETATION AND PRESENTATIONS OF DATA</td>
</tr>
<tr>
<td>PRELAB III.</td>
<td>GOAL: GUIDE DESIGN AND PLANNING OF INDEPENDENT INVESTIGATION</td>
</tr>
<tr>
<td>LAB III.</td>
<td>GOAL: CONDUCT AN INVESTIGATION</td>
</tr>
<tr>
<td></td>
<td>CONTEXT: OPEN-ENDED OR GUIDED INQUIRY OF BIOLOGICAL PHENOMENA. GUIDING QUESTIONS DIRECT THE DEVELOPMENT OF AN HYPOTHESIS AND THE DESIGN OF THE TESTING EXPERIMENT.</td>
</tr>
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</table>

NEW RESOURCES ARE PROVIDED AS NECESSARY.
groups are assigned the task of selecting a question to investigate and designing an experiment. They are provided with guiding questions to help them plan details of the experiment, though most of the design occurs in the class session or in small group sessions with the instructor.

The serial lab model can be applied to laboratories in lower or upper division courses. I have used this approach in several courses -- most successfully in general (cellular and molecular) biology and plant physiology. An approach I use is to find an excellent cookbook type laboratory exercise (we all know of dozens, I suspect) with several opportunities for application in areas in which I wish to develop subsequent concepts in the course. Typically, the lab exercise I select for modification is one that is interesting for the method, but which may leave students with the usual "so what" feeling after finding what they felt they "should have found."

Such exercises are well suited for serial lab development.

The Serial Laboratory in Enzymology

The serial lab example described here is used in a general (cellular and molecular) biology course. The labs are based on modifications of the laboratory on phosphatase by Abramoff and Thomson (1976) and Clark and Switzer (1977). Reference is also made to the Worthington Biochemicals manual (1977) and Torriani (1966). Table 2 summarizes the questions and activities of each lab, pre-lab and post-lab period in the enzymology sequence. Traditionally, all of the activities through post-lab II are scheduled for a single lab period. In the serial lab, these are extended to two lab periods, mainly because several of the directions are eliminated, leaving the students to fill in protocol details based on their learning from the first week's experiences. When the students are asked in preparation for prelab III to plan an investigation, they are instructed to:

- generate research questions
- select one question and formulate an answer in the form of a hypothesis
- make predictions
- identify all variables, and
- design a protocol for an experiment to test the hypothesis.

I have received an assortment of student-generated questions, which may be categorized as follows: One kind of question simply asks whether the enzyme can be found in some tissue. For example, is there phosphatase activity in barley cytosol? Another kind of question is equally shallow, simply asking to do the same thing on another source of phosphatase. For example, what effect does phosphate have on plasma phosphatase? Generally, there are no predictions offered from such hypotheses because the question, at least as asked by most students, is not driven by any hypothetico-deductive reasoning. If the student can provide a rationale for thinking, for instance, that plasma phosphatase is expected or not expected to be inhibited by phosphate, then reasoning to develop a prediction is usually offered and the question should be tested. The most difficult aspect of guiding students at this point is to get them to think about the biology (what would be interesting to test?) rather than the methodology (what can I test?).

The following kinds of student-generated questions exemplify thought about biology and are the type that I desire. One kind asks to investigate a
A SERIAL LABORATORY IN ENZYMOLGY

GOAL: TO INVESTIGATE THE CELLULAR CAPACITY TO HYDROLYZE PHOSPHATE ESTERS WITH PHOSPHATASE

LAB I. QUESTIONS:
- HOW IS AN ENZYME ASSAYED?
- WHAT IS THE EFFECT OF SUBSTRATE CONCENTRATION ON ENZYME ACTIVITY?

PROCEDURES:
- PREPARE A STANDARD CURVE TO MEASURE PRODUCT FORMED
- DETERMINE OPTIMAL ENZYME CONCENTRATION AND REACTION TIME FOR ASSAY (FAMILIARIZE)
- DETERMINE THE EFFECT OF SUBSTRATE CONCENTRATION ON ENZYME ACTIVITY

POSTLAB I. ANALYZE DATA (correct for controls, graph results, calculate kinetic parameters)
EXPLAIN DATA
BRIEF, INFORMAL SUMMARY AND REPORT OF RESULTS

LAB II. QUESTIONS:
- HOW DO TEMPERATURE, PH AND PHOSPHATE EFFECT PHOSPHATASE ACTIVITY?

PROCEDURES:
- PERFORM 3 ASSAYS

POSTLAB II. INTERPRET RESULTS
DRAW INFERENCE AND CONCLUSIONS
RAISE QUESTIONS

PRELAB III. PLAN INVESTIGATION
DESIGN EXPERIMENT

LAB III. QUESTION (for example):
- IS A CELL'S ABILITY TO PRODUCE PHOSPHATASE INFLUENCED BY PHOSPHATE CONCENTRATION IN THE GROWTH MEDIA?
PROCEDURE:
- GROW E.COLL, ESTIMATE CELL DENSITY, HARVEST CELLS, AND PERFORM ASSAYS AS REQUIRED BY THE DESIGN

POSTLAB III. ANALYZE AND SUMMARIZE DATA
SELECT FORM OF PRESENTING DATA
REPORT RESULTS OF INVESTIGATION

Table 2. Questions and activities of each stage in a serial laboratory on enzymology for a course in general (cellular and molecular) biology.
specific question raised during experimentation. For example, does pH affect substrate affinity? When the question is raised in the context of wondering, the prediction is easy for the student to produce: if pH affects three-dimensional changes in the enzyme structure, then substrate affinity should change with pH. Another kind of question brings other aspects of biology from their past experience. For example, usually at least a few students have had some physiology and may wonder as follows: Does phosphate concentration in a cell's growth environment affect phosphatase? If phosphatase functions to provide phosphate as a nutrient, then production of phosphatase may not occur when phosphate concentration in the cell's environment is high (non-limiting). When students think this way, I jump at the opportunity to channel some groups to test this. Without knowing that they may be repeating the work of Jacob and Monod, they have thought in parallel to those Nobel laureates!

In this example, the identification of variables and design of protocol requires both a class session (the same session in which students are offering their questions) and a meeting with individual groups. This time is taken in lieu of lecture. But when my next lecture is intending to address the operon model, I feel successful rather than "behind." Table 3 illustrates the factors that students should consider in designing one possible experiment. The responses given to student questions about experimental protocol in Table 3 are developed in advance of the unit. Those given in Table 3 are a combination of some that have worked in past student experiments and some that have been taken from the literature. The literature used for such searches included both lab manuals and primary literature in molecular genetics and microbiology. In order for the third lab to be successful, there must be a balance of open-endedness and guidance. The instructor must anticipate the student questions and have a few up her/his sleeve for which details of protocol have been researched and materials have been ordered. Yet the instructor must be prepared to accept student alternative suggestions for protocol as long as they seem reasonable (e.g. there are several ways to lyse cells, even though some may not work as well as others).

The third lab becomes one of the most exciting educational settings I have ever experienced.

However, unlike the previous two labs, there is much uncertainty and the instructor should be prepared for anything. Sounds like research, doesn't it?

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**Students have respectable questions, experience with related protocols, and motivation to gather, analyze and interpret results.**

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**Evaluation of the Serial Laboratory**

The lab series may be used once or several times in a course. For example, I have designed my plant physiology course to consist of two or three serial laboratories, a couple of closed-format labs and a final independent project in which students, alone or in pairs, can put together an entire short project from scratch.

The serial laboratory offers a means to
Table 3. Variables that students should consider in planning the details of a typical experiment. In this experiment, the research question being asked is:  *Does phosphate concentration in a cell’s growth environment effect phosphatase?*

<table>
<thead>
<tr>
<th>Factors to be considered include:</th>
<th>Workable systems to which students can be led:</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. what cells to use</td>
<td><em>E. coli</em></td>
</tr>
<tr>
<td>2. media for growth</td>
<td>minimal salts plus glucose; no phosphate in some and a range of phosphate concentrations in other tubes (9 mg/ml KH₂PO₄ saturates the induction response)</td>
</tr>
<tr>
<td>3. how long to grow cells</td>
<td>2 days at 37°C</td>
</tr>
<tr>
<td>4. buffer to use</td>
<td>0.1 M Tris HCl pH 8.2</td>
</tr>
<tr>
<td>5. how to collect cells</td>
<td>centrifuge 5 min at 8000g to remove phosphate and resuspend cells in buffer</td>
</tr>
<tr>
<td>6. how to control for variation in cell number in different treatments</td>
<td>measure A₅₄₀ of blank and either (a) express results per A unit or (b) calibrate turbidity with a hemocytometer and express results per cell</td>
</tr>
<tr>
<td>7. how to make enzyme accessible</td>
<td>add 1 drop toluene 15 min before assay to lyse cells</td>
</tr>
</tbody>
</table>

Teaching the concepts and methodology similar to that offered by the cookbook lab exercises. However, it provides follow-up experiences to those already known to be productive. So, relative to cookbook labs, the open-ended excitement of the inquiry process is maintained. The problemsolving tasks, concept development and familiarization with new procedures or apparatus are emphasized in different sessions so the inquiry process does not become burdensome. Furthermore, structure is retained in the early stages of the sequence thereby providing guidance for learners that need structure before progressing to open-ended experiences. Yet, relative to one-period investigative labs, the question that is pursued in the serial labs can be non-trivial, relying on contemporary methodology.

The investigations may even offer answers that might otherwise be "presented" in lecture but instead can be discovered in lab.

Serial laboratories can simulate research in several respects. They provide a progression in which conclusions drawn from one laboratory investigation inspire the inquiry process and subsequent concept development. The serial laboratory scenario presented here also defines the place in the curriculum for methodological training—as a means to the end of inquiry rather than an end in itself.

The serial laboratory has some obvious problems. Perhaps the most significant is that a topic which may have required one laboratory period in a traditional lab course now becomes two to
four weeks of study. Activities in other areas of course content must be cut or reduced in scope. I have found that to compensate for this, I spend less analytic time on other course concepts and more analytic time on concepts related to the topics of the serial laboratories. I have also come to realize that no matter how we define the content of our courses, something important will have to be omitted due to the expanse of the subdisciplines of biology. Having accepted this premise, it is easy to justify spending more time to teach processes as long as the topics on which I focus complement the other departmental offerings and the student’s whole education.

Some of the problems of the cookbook laboratories are still evident in the first week of the serial laboratory. Detailed, structured activities are retained in this period. This tends to be difficult for some students. Having to focus on one topic for a long period can be tiresome. Yet usually by the end of the sequence these individuals understand the necessity and importance of detail. Despite the difficulties of the open-ended investigation for some learners, those that persist see the excitement of research that many of us did not experience until we were in graduate school.

LITERATURE CITED


