AN INVESTIGATIVE APPROACH TO CELLULAR/MOLECULAR INTRODUCTORY BIOLOGY

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Many of us have had the opportunity to involve undergraduate students in our research and have seen the development that occurs when students become actively engaged in the intellectual and technical challenge of solving a scientific problem. This experience often stands in stark contrast to the students' experience in more traditional courses where they adopt a passive role, taking notes from an authority in the lecture component and following technical instructions in the laboratory. While this system apparently does not deter students who enter college with strong interest in science, it does little to attract undecided students to the field. In fact, traditional science courses seem to select and reward students who tolerate passivity well and who readily accept information delivered by those in authority. A scientific work force selected for these traits would be a sterile lot, lacking creativity, intellectual drive, skills in critical analysis, and the courage to take intellectual risks.

Much has been written and presented about the success of investigative laboratories in engaging students intellectually and infusing life and excitement into undergraduate science courses. Many of us have used investigative formats in our intermediate level courses with great success. With funding from the Howard Hughes Medical Institute, we have planned and, last year, implemented a completely investigative format in the laboratories of Introductory Biology I (Introduction to Cell and Molecular Biology). We administered an evaluation instrument at the end of the course and found that the lab experience was decidedly positive for most students in the course. Seventy-three students completed the instrument. When asked "Was the lab educationally worthwhile?", 60 answered yes, definitely; 12 answered yes, with reservation; and 1 answered no. While it is tempting to detail the structure of the laboratory component of this course, many protocol-level ideas are not widely exportable to other institutions. I think a more useful discussion will center on the highly successful design of the laboratory, which is widely exportable across different institutions and disciplines.

Overview of the Laboratory in Introductory Biology

The labs in Introductory Biology were based on a design used successfully in several intermediate level labs at Macalester in which each experiment is performed through a series of steps taking 3-4 weeks to complete. Students work in groups of three (I thank John Jungck at Beloit for this suggestion). In this way, students are never stuck in pairs with completely incompatible partners, yet groups are still small enough that all students must participate. All lab work is evaluated on a group basis and, when work is handed in, students rate each other on the percentage of work each of them contributed toward the various aspects of the project (I thank the biolo-
gists at Hope for this idea). Students are never lectured to in lab. All information is disseminated in hand-outs, in textbook assignments or through library reserve readings. Students learn the needed information by reading and discussing with each other.

After initial skills in group process (see below) and computer use are established, students begin the first experiment. The first week is spent discussing the nature of the experimental system (e.g., photosynthesis), understanding the tools available for investigation (e.g., spectrophotometry, micropipets, balances, centrifuges, etc.), defining an experimental question (e.g., what is the optimal wavelength of light for photosynthesis in this organism?) and developing a working protocol for the experiment. For more naive students (e.g., the first experiment in the first introductory course) this phase may take two weeks.

At the beginning of the next lab, students have their protocols checked by an instructor and they receive some points for having completed the protocol. (N.B. A flawed and an unflawed protocol receive the same grade. We try to reward effort, creativity and willingness to accept outside suggestions rather than correctness.)

The staff acts as consultants to the students along the way, giving as much information as students request, but trying not to impose our ideas about how the experiment should be designed or performed.

This is especially true if a student group develops an unusual experimental approach. We look for soundness, not adherence to convention. The students then perform their experiment and discuss how the results should be graphed and presented the following week.

The next week, students come to class prepared to give a short oral presentation on their findings. Students usually use overhead transparencies to give their presentations and we try to leave enough time for student discussion about findings. Since the entire class is working on the same experimental system (e.g. photosynthesis) but on different problems (e.g. wavelength, temperature, pH), they have a common basis for understanding one another's presentations, but the presentations are different enough from one another to maintain interest.

The following week we begin a new experiment and each group turns in a written paper on the completed experiment. They also turn in an evaluation of the percent effort of each member of the group (including themselves) on various aspects of the task (design, performance, presentation, written report). The written reports increase in difficulty throughout the semester. The first report includes a protocol, graphs and a paragraph summarizing results while the last report is a full scientific paper with introduction through discussion.

A note about our emphasis on honesty:

We continually tell students throughout the course that it is not important to get "the right" answer (in fact, the labs are designed such that the staff has minimal information about what a "right" answer is.) When they collect and analyze their data, students know that they will have to support their conclusions solely from the quality of their data (supplemented with any reading they have done) and will not be able to rely on the judgement of an authority in the course. This frees them from trying to second guess the staff, places them in the sole position of authority with respect to their own work, and allows the more insecure students to relax a bit about experimental performance. Students are never penalized for mistakes in lab and they are told that they must report their results exactly as they occurred, no matter how dreadful.

Students reported being grateful for this approach. On the last day of class this term, the students viewed the Nova presentation "Do Scientists Cheat?" Afterward, we had a discussion about the true definition of scientific cheating and fraud and whether they had cheated in this course. They said there was virtually
no pressure to cheat in this course because of the emphasis on honesty. Surprisingly, however, students volunteered that they frequently cheat in other science courses where the emphasis was on obtaining a correct answer. Virtually all the students said they cheated in their science courses in high school for the same reason.

An overemphasis on getting the “right” results may, in fact, not be that different from the actual practice of science where publications at any cost mean success, but it sends the wrong message about what is ideally most important about the scientific enterprise. When good scientists make mistakes, they try again until they get it right because they have the time to do so, unlike most undergraduates in courses. They do not pretend that their experiment worked. Given the pressures on young scientists today to publish, this is a dangerous message for students to receive early in their scientific careers.

| When we penalize students for not getting it right on the first try (either by lowering their grade or placing unrealistic demands on their time), we misrepresent the practice of science and may send a message to students that science is about getting the right answer by legitimate or, if necessary, illegitimate means. |

What Works in the Investigative Format?

Focus on group work: During the first week of lab, we focus directly on group process. We talk to students and do exercises that demonstrate differences in learning styles and problem-solving styles. At the end of the lab, students generate a list of behaviors for themselves and the instructors that will facilitate good group interactions. They also share their ideas about grievance procedures and a process for staff intervention if group work is going badly. We only had one case of intervention during the semester, although 7 members of the class complained on the evaluation that group work detracted from the educational value of the lab. Although we do not have hard data, I do think that making group process an explicit part of the learning experience, rather than simply letting it happen, helped to make students more accountable for their behavior and facilitated their group interactions.

Student involvement in experimental design, protocol development, and data analysis: Overwhelmingly, this aspect of the course was reported by the students to be the most educationally beneficial. Typical student comments about this aspect of the lab were as follows:

“Experiments made sense because I was involved in planning the experimental design, in performing the actual experiment, and in analyzing the results. This format helped me understand the experiment as a whole.”

“This type of lab approach certainly requires much more thought and analysis than less investigative approaches. Therefore, it taught me a lot about how to analyze, compare and contrast results to reach a conclusion. It helped me think not only in this field, but it will help in many others.”

“I had hoped that college biology would be like this. This course is a bridge between high school biology and real science. My group work skills improved immeasurably and I really liked the way the labs made you think out each step to make the lab a success. At the end of the lab, I really felt like I had accomplished and learned something worthwhile.”
Forty-one percent of the students reported that experimental design and analysis was the most educationally valuable aspect of the lab component.

Students reported again and again that they understood the experiments well and that they were genuinely interested in the results. This is quite different from reports in previous years when we offered "cookbook" labs. Students frequently reported that they did not understand the point of the lab exercises and complained that lab was a waste of time. Ironically, design and analysis, the most successful part of the investigative format, is the part that is almost entirely missing from traditional formats. The actual performance of the experiment received much lower marks from students. Fifteen percent of the students actually reported that the performance of the experiment was the least educationally valuable part of the lab component.

Oral reports: Speaking in public is, by far, the most common fear of Americans. So we were not surprised when students reported being intimidated by oral reports. However, they also reported that they benefited from the experience. Twenty-nine percent of the students said it was the most educationally valuable part of the lab component. The oral reports in Introductory Biology worked, in part, I think, because they were relatively informal (although visual aids were required) and they were frequent (four per semester). This lowered the anxiety level considerably. What we did wrong in this iteration of the course was to make the topics of the presentations (and the experiments) too similar to one another, and therefore students got bored with some reports. Reports need to be on a common topic, but about different aspects.

Concerns about this Format.

Lack of coverage: The most frequently voiced concern about this format by colleagues in biology (not by students in the course) is that we cannot cover many lab experiments or techniques in one term if it takes at least three weeks for each experiment. This is certainly true. However, rather than focusing on classical experiments which demonstrate various aspects of cell and molecular biology, we have chosen to focus on important and widely-used experimental tools and on the intellectual process of scientific investigation. The tools, most of which are used in several experiments during the term, include the centrifuge, analytical balance, pH meter, micropipets, serological pipets, spectrophotometer, and gel electrophoresis equipment. We feel that repeated use of these tools in different experimental contexts will reinforce student skill with the equipment and will build student confidence in their ability to use scientific instruments. The intellectual elements include reasoning skills in experimental design, protocol development and data analysis; use of information resources in seeking answers to questions through reading and interviewing the staff; organizational skill in design, data collection and experimental performance; communication skills in the writing of four papers and presentation of four oral reports; skills in mathematics and graphical analysis in analyzing data and presenting it in appropriate graphical form; interpersonal skills in working effectively in groups; and simple manual skills in the accurate performance of the experiment.

The emphasis on tools and skills, rather than on the coverage of certain illustrative experiments, seem to us to make better educational sense for many types of introductory courses. In the former case, students play an active role in lab, interacting with the instruments and practicing the skills of the professional scientist. In the coverage model, students play a passive role, performing experiments that have been chosen and designed and, in some cases where elaborate data collection sheets are handed out to students, analyzed by the instructor. In my experience with this approach, students frequently "successfully" complete the lab without understanding why they were performing the experiment or what it was designed to illustrate.
In this model, we present science to students stripped of its basic nature; intellectually rich, oriented toward problem-solving, complex, messy, frustratingly dependent on detailed technical success, and dependent on communication skills at every level. As professional scientists, this is what we love (and sometimes hate) about our disciplines. If we had to do science that way we teach science, I suspect many of us would be looking for different jobs.

It is tempting for us to believe that a lab is successful if it "works", i.e. if students are able do the experiment and get positive results. However, I think this approach does great disservice to our students and our disciplines.

Lack of connection to the lecture component: Although students understood very well the purpose of the lab and did not complain about its disconnectedness to the lecture, I do think that the lab and lecture can enhance one another if designed to correspond. In the future, we plan to try to tie the lecture and lab material together into units around central themes (see "Future Directions" below).

Method for placing students into groups: This is a significant problem in a lab where group process is an explicit part of the students experience. We have not found an ideal way to do this. This term, we randomly assigned students to new groups for each new experiment. Students did not complain about changing groups often (some actually enjoyed it), but they did complain when they were placed with people with whom they had difficulty working. Because all lab grades are group grades, incompatibility in groups is a significant problem. Next year we plan to try allowing students to self-assign to groups but giving students the option to change groups at the beginning of each new experiment. Our rationale is that, in a course where students must endure a lecture section of 80-100 people, we would like to give them as much power and autonomy in decisions as possible. Allowing them the simple freedom of choosing their own working groups, we think, would significantly improve student morale and enhance learning.

Time commitment by staff: This lab approach appears to be more labor intensive than it actually turned out to be. Some time benefit is gained by having to "prep" lab only once every third week. Given that, there are three areas that require a major time commitment. First, when labs are prepped, a bit more time is required in planning, since each student group is doing a different experiment. The amount of latitude given students in experimental choice is certainly a function of how ably the staff can handle the chaos this induces. Secondly, staff must work closely with students in groups to help design experiments, develop protocols and analyze data. In our experience, most of this work (=75-80%) can be done during the lab period. Finally, student written work must be carefully graded. However, this task can be dramatically reduced by having all reports produced by groups. Using this model, in a class of 85 students, we graded only 28 papers every three weeks. This was not excessive.

The teaching staff for the 80-100 student course at Macalester (one lecture section, four lab sections) is comprised of one professor, one full-time laboratory instructor (master's level) and 12 upper class biology major teaching assistants. The professor and laboratory instructor do all the evaluation and grading for the course. Student aids help prep lab and assist the students in all aspects of their work in lab.

Future Directions

We will continue to make modifications in the lab design in the future. We are always looking for good experiments that are fairly straight-forward, can be easily done in one lab period and are robust enough to allow multiple student projects on a single theme. We are especially interested in experiments that can
One of the benefits of working closely with students in research is that, once they get to know you, they can candidly tell you things about what doesn’t work in your courses.

be integrated with themes being developed in the lecture component.

My major interest in the next years, however, is to focus on the lecture component of the course. My junior and senior research students have repeatedly told me that the coverage-oriented, linear model, used in Introductory Biology lectures, does not work. Students tell me they need more context, they need to know why they are learning something, they need to know what it relates to, and they need to be able to insert their own questions into the direction of the course.

Ultimately, I would like to see us move completely away from the lecture format. Priscilla Law’s much acclaimed “Workshop Physics” model should be an inspiration to us to design alternative methods to the lecture format in science courses. When we impart information in a lecture format, we force students into a passive role, a kind of receptacle for information. The information we give is chosen by us (and frequently textbook authors) and therefore is disconnected from the personal experience, intellectual context and curiosity of the student. This is in stark contrast to the actual practice of science in which information is acquired because it is needed to solve a problem or because the investigator has an interest in knowing. I think wanting to know is an essential prerequisite for true learning, and when we deliver standard lectures to passive audiences, we disconnect our students from this essential prerequisite.

However, ideals aside, in the fall of 1991, I will face 80-100 primarily first-year students in a lecture hall. So what am I going to do? For several years, I have been threatening to drop the linear, coverage model (Biochemistry, then Cell Biology, then Genetics) and organize the course around topics, drawing in information on a need-to-know basis. I intend to use this model next term and have developed a tentative outline for the teaching of Cellular/Molecular Introductory Biology in context. For example, I plan to cover four topics in the semester term: Photosynthesis, The Life Cycle of the Cell, Intracellular Communication, and Biotechnology. Each unit will draw on the traditional disciplines previously taught in linear array as well as other disciplines. For instance, to study photosynthesis, students need to understand the cell membrane, protein structure, oxidation-reduction reactions, the physics of light, the chemistry of pigments, enzyme function, the carbon cycle, plant structure, etc. In addition, biotechnology, bioethics and standard experimental approaches will be incorporated into each unit. By focussing on topics and spending time talking about why each topic is of significance in science and society, I hope to help students make the learning process more personal and, therefore, deeper and longer-lasting.

Both the investigative laboratory format and the contextualized lecture approach are based on the notion that we ought to teach science the way we do science.

Summary
Our own lab work is powered by our own interests and creativity, we learn on a need-to-know or interest-in-knowing basis, and we constantly communicate our ideas to our students and colleagues both orally and in writing. We discuss, we argue, we make mistakes, we reason, we perform technical tasks, we work on things together, and we care about the importance of our work. If our jobs entailed passively acquiring knowledge chosen by others as important and simply following technical directions in the lab, we would soon become bored and disillusioned with our disciplines and would seek other forms of employment.

Reference