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Science teachers all face the same basic set of challenges: we wish to get our students excited about and involved in the subject, and we hope that the material will make a lasting impression. We also want students to understand the investigatory, hypothesis-testing nature of science. Thus, our general goal is to impart our own enthusiasm for science while teaching students both the information of science and how scientists go about obtaining this information. Using active-learning and cooperative-learning techniques to involve students in their own learning process helps instructors address these teaching challenges (Sundberg and Moncada 1994, Morgan et al. 1995, NSF 1996, Caprio and Micikas 1998, Hason and Wolfskill 1998, Herreid 1998, Howard Hughes Medical Institute 1998).

Most of the literature on active learning at the college level focuses on introductory courses and their laboratories (e.g., Deutch 1994, Sundberg and Moncada 1994, Stukus and Lennox 1995, Adamo and Gealt 1996, Arce and Betancourt 1997, Norton et al. 1997, Tichenor 1997, Chaplin et al. 1998, Glasson and McKenzie 1998, Herman 1998, Knabb 1998, Markstein and Posner 1998). However, advanced (junior, senior, and graduate) laboratory classes offer an excellent opportunity to take the approach a step further, to simulate the entire research process. Upper-division students are generally more experienced and sophisticated than their lower-division counterparts; upper-division labs can therefore be taught in a manner that is closer to the way science actually happens.

The idea of including active learning in upper-division lab courses is not new; indeed, upper-division courses commonly include an active-learning component, such as independent or small-group projects and semester-long investigations (Deutch 1994, Stukus and Lennox 1995, Norton et al. 1997). These semester projects do allow students to apply information from other parts of the course and often involve a great deal of active learning. However, they are only one portion of the course; other components of the lab are often taught in a more "cookbook" style, requiring little thought on the part of students about the questions being explored, the experimental design, or the analysis and interpretation.

We decided to structure our upper-division laboratory course so that it would model the entire scientific process. In our experience as scientists, much of the observation and hypothesis portions of the scientific method are generated from the scientific literature. Thus, we decided that primary literature would play an important role in the course. Furthermore, we wanted to emphasize experimental design, presentation of results, and the generation of new hypotheses from current understanding. Our aim, therefore, was to create an upper-division laboratory course (specifically, for animal behavior) that would extend the active-learning component beyond simply a required independent, semester-long research project. We wanted all of the lab activities to teach creative and critical thinking and to mimic the scientific process as closely as possible.

In this article, we present an active-learning technique that we have found to be successful in meeting these goals in our animal behavior laboratory course. Our basic approach, which we have implemented for the past 3 years, is to have general laboratory topics that the class as a whole investigates. For each topic, the students critique a relevant journal article and then design and conduct a study focused on the general topic. Small groups of two to four students are in charge of each topic. These "Principal Investigators" (PIs) analyze the data collected by the class and give oral and written reports based on the results. The group-oriented nature of the laboratories reduces the instructors' preparation time, and students benefit from the time saved by delegating tasks within the group. As we show in this article, students seem to like the approach, are more knowledgeable about what the study is trying to accomplish, and become interested in many other aspects of the scientific process.

The laboratory approach

The laboratory portion of the course has three basic components: structured, technique-oriented exercises early in the semester; open-ended, student-designed investigations; and semester-long, independent projects. Because we are at different campuses, our courses are not identical. However, in both courses there are fewer than 24 students per semester, and a student receives one grade resulting from his or her combined effort in the lecture and laboratory portions of the course (with lecture and laboratory weighted equally). In addition, both courses have a single

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3-hour laboratory section per week. We explain to students at the beginning of the semester that they may have to collect data outside of the 3 scheduled hours. However, we typically design laboratory exercises so that they can be completed within the allotted time.

Technique-oriented exercises. Because most of the experiments are designed by students, we dedicate the first sessions to "Technique" labs, which introduce students to the fundamental skills needed to design and conduct subsequent studies as well as the semester project. For animal behavior, students need to learn basic techniques for collecting data and analyzing these data statistically. Accordingly, the first exercise focuses on the quantitative measurement of behavior. One of us (P. V. S.) conducts this exercise around the behavioral theme of territoriality. Students are given a brief lecture and some handouts based on background readings (e.g., Martin and Bateson 1993), and the class then heads to the campus pond to observe the territorial behavior of dragonflies. Initially, the students simply observe dragonfly behavior and create categorical descriptions (i.e., an "ethogram"). They then discuss the pros and cons of their different behavioral descriptions, brainstorm possible questions that they could ask about dragonfly territoriality, quickly design a study (including sampling techniques and data sheets) around one of these questions, and collect the data. As homework, students interpret the combined data, an assignment that prepares them for the second laboratory exercise.

The second session concentrates on how to analyze behavioral data statistically and how to present summarized results in appropriate graphs and tables. The behavioral theme for this session is orientation, and the study animal is the mealworm beetle, *Tenebrio molitor.* In contrast to later exercises, the protocol for this exercise is designed by the instructor so that students can focus on recognizing and applying appropriate statistical tests and on learning how to use computer software to analyze data and present results. Although students work together while gathering data for these first two exercises, each student analyzes the data separately and prepares his or her own report to ensure that everyone has experience with the techniques.

Although these two initial topics are specific for animal behavior, instructors of other biological subjects could easily modify these early labs to cover other essential techniques. For example, microbiology laboratory courses could introduce plating techniques and spectrophotometers, and laboratory courses in population genetics might start with sampling methods and electrophoresis techniques.

Student-designed investigations. Student-designed "PI laboratories" follow the Technique labs. The PI labs operate on a 2-week schedule: the first week is "Design Week," and the following week is the "Data Week." The Data Week for one topic is followed by the Design Week for the next topic, with this pattern being repeated for the rest of the semester. At the beginning of the semester, students sign up to be part of small groups of PIs, and each group is in charge of a particular topic. Some of the topics we have used include fighting, foraging, group behavior, habitat selection, predator avoidance, and sexual behavior; we illustrate our general approach using the topic of sexual behavior.

Class sessions during Design Week have two parts. The first part consists of discussing a journal article assigned for the topic. The article, which is selected by the instructor, both introduces the topic and provides students with ideas and some direction for designing their own study. Students come prepared with a written critique of the article, in which they analyze the appropriateness of the article's methods, conclusions, and presentation (see Janick-Buckner 1997 and Koprowski 1997 for information on teaching students how to critique). The class as a whole then discusses the article under the leadership of the PIs. Because the students have prepared the critiques beforehand, they have already been exposed to the background material, which makes it more likely that each student will contribute to the discussion.

During the second part of Design Week, the class designs the study that they will conduct during the following week. Along with the article critique, each student is required to bring a written, suitable study design to class. They develop the study design based both on the article and on information from the instructor about the general goals for the experiment and the species that will be used. Most, although not all, of the students design studies whose general questions and approach are similar to those in the article they critiqued. To start this section of the Design Week lab, students present their particular study question to the rest of the class. The students then choose the particular question they will attempt to answer and work out the protocol they will use, including the specific questions to ask and the working definitions, methods, data sheets, and types of analyses.

During this discussion, the instructor must be able to steer the students toward a study that has a likelihood of success while maintaining the flexibility to go in the direction that the class decides. This guiding process can be both exciting and beneficial for the instructor, and we have found that practice has improved our ability to guide these discussions. In addition, brainstorming possible ideas before the laboratory period helps us anticipate the range of designs that students may come up with, which in turn helps us guide the class toward suitable study designs. If we know that some suggestions simply will not work, we act as a "voice of reason" and explain the rationale to the class. The main reasons for eliminating suggestions are time constraints or potential difficulties given the subject's biology; we do not eliminate suggestions simply because we think that the study will not yield the anticipated result. As instructors, we also periodically make "command decisions" on particular aspects of the design (e.g., which data to record out of several possibilities) if the class cannot reach a consensus; this approach helps ensure that the design will be completed within the allotted period. Any details of the design that are not covered during the Design Week laboratory session (e.g., because of a lack of time) are worked out by the PIs and the instructor before Data Week.

For the sexual behavior lab, we have taken several approaches, dictated in large part by weather. During the fall semester, one of our (P. V. S.) classes critiques Höglund (1989), a relatively broad paper that discusses sexual selection, mate choice, and male–male competition in the common toad (*Bufo bufo*). In the spring semester, the other of our (W. M. S.) classes critiques Collins (1995), a laboratory study of how recent experiences affect female choice in the zebra finch (*Taeniopygia guttata*). Both papers are solid overall but have enough debatable points to allow the class discussion to cover both pros and cons of the studies. The study species for the laboratory investigation in P. V. S.'s course is the Japanese beetle (*Popillia japonica*), an abundant species in eastern Illinois during early autumn. W. M. S.'s students use Siamese fighting fish (*Beta splendens*), a fish easily obtained from pet stores and maintained in the lab. The species used in the student-designed studies is different from that used in the article; this intentional difference forces students to apply concepts and adapt methods to a new situation.

The PIs bear the brunt of the responsibility for their particular lab. In addition to leading the discussion of the journal article in Design Week, they work with the instructor between the Design and Data Weeks to finalize the data collection sheets, write out the specific protocol, obtain the necessary materials, and set up any experimental equipment. They analyze the results of the study and give a 10-minute oral presentation on their results to the rest of the class, either at the beginning of the next Design Week or during a lecture period. Following the presentation, the entire class interprets and discusses the results. The PIs' final responsibility is to write up the study in the form of a scientific paper that incorporates a few additional references; this paper is generally due a week after the presentation so that the PIs have a chance to incorporate the comments made by the class during the presentation. PIs are graded on the effort and quality of the preparation materials, their oral presentation, and their written paper. In our courses, all PIs for a laboratory topic receive the same grade for each of these components (see Herreid 1998 and Weld et al. 1999 for other references and suggestions on grading cooperative groups).

The rest of the class also has graded responsibilities for each lab. Everyone must bring in a written critique and potential study design to Design Week, participate in data collection during Data Week, and provide written answers to "extension questions" developed by the instructor following the PIs' presentation. For example, the extension questions used in the sexual behavior laboratory are: "1). What was the consistent, but nonsignificant, trend observed between male and female Japanese beetles in our study? Give a reasonable, proximate explanation for this trend. 2). Briefly describe a study (observational or experimental) that would allow you to test whether your proximate explanation is correct." Because the sexual behavior laboratory is early in the semester, these two questions were designed to emphasize to the students that they need to pay attention during the PIs' presentation, as well as to connect lecture concepts (e.g., "proximate" versus "ultimate" explanations) with laboratory results. PIs are not required to answer the extension questions based on their lab; we expect them to concentrate on their written report during this time.

Semester-long research project. As an additional part of the course, students conduct a semester-long research project, either individually or in pairs, on a topic of their choosing. Past project titles have included "Fox and Gray Squirrel Habitat Selection," "Influence of Gender and Plumage Coloration Differences on Dominance and Aggression in House Finches," and "Toad Prey-Catching Behavior in Relation to Background Color and Size." Rather than providing details on our requirements for semester research projects, we refer the reader to other in-depth treatments of the topic (e.g., Deutch 1994, Stukus and Lennox 1995, Norton et al. 1997, Weld et al. 1999). In brief, we require students to submit assignments at various stages of their project's completion, including an initial proposal, design, results, and final paper; each assignment is graded, and students may submit them early if they wish to have feedback before handing them in for credit. These projects culminate in a poster session party for the entire class to which other faculty and students are invited; these posters are graded, as are the final scientific papers describing the projects. Thus, these independent projects provide students with an additional experience in taking a project from the "question" to the "presentation" stage.

Does it work?

Although we do not have quantitative data to compare our approach with other types of animal behavior laboratories, our anecdotal impression is that this approach engaged students better and helped them learn more about science than the laboratory approaches we have used in other courses. Students were interested in the research questions, probably because they helped decide which questions to ask. They were enthusiastic during the data collection process, and, because the class combined data, they were able to generate a large amount of data quickly; collecting equivalent amounts of data individually or in small groups would have taken days instead of hours. Students also seemed to learn a lot from each other; their skills in critiquing articles, designing studies, analyzing data, and presenting results improved as the course progressed over the semester. When asked to evaluate the course at the end of the semester, the majority of students indicated that although it was a lot of work, they liked being able to design their own experiments and they learned a great deal about conducting a scientific study. Some students specifically mentioned that they found this lab approach more enjoyable and educational than previous "cookbook" laboratory courses they had taken.

In addition, although students found critiquing articles to be challenging, they also often found this aspect of the course to be especially rewarding. Early in the semester, even when given explicit instructions to the contrary, students tended to accept the articles' results at face value. For example, student critiques initially tended to focus on the quality of the writing rather than on more critical questions, such as whether the conclusions were justified based on the results. With experience, however, they learned to question results, methods, and interpretations, and the class spent much of the time discussing whether particular problems with a study's design or interpretation would affect the overall conclusions expressed in the article. Furthermore, discussions of the articles often led to discussions of particular concepts (e.g., mate choice) with more depth and specificity than lecture treatment alone would have allowed. By the end of the semester, the critiques were much better, and most students expressed satisfaction at their improved ability to read and think critically about primary literature.

Another benefit of the course was that, by being totally immersed in the design of an experiment, students became curious about the results and willing to look for scientific explanations when the answer was not what they had expected, rather than relying on less creative possibile explanations, such as technical difficulties or sample size. They also often discovered that even the best-designed study may need to be modified to succeed. Most students believed that the study designs were perfect going into Data Week; however, the frequent problems they encountered and the resulting need to alter protocols as they were collecting data told them otherwise. For example, Japanese beetles were difficult to mark, escaped readily from experimental arenas, and seemed to be affected by light; the crayfish used in one fighting lab did fight, but apparently not over the refuge that had been provided as a "resource." Furthermore, the results were not always what the students had "logically" anticipated before the study. Thus, the students experienced the way "real science" occurs and learned just how challenging (and frustrating!) it can be.

In addition to becoming aware of and interested in the scientific process, students became curious about the "nuts and bolts" of publishing (see also Janick-Buckner 1997). For example, students wanted to know how to determine authorship on a paper, how to decide which journal to send a manuscript to, and how the resulting editorial process works. The overall experience helped make science more "real" to them and gave more meaning to the amount of work that goes into obtaining and presenting any information in science.

Potential drawbacks

Despite the apparent benefits of the approach, some students were confused in the beginning as to what they were expected to do and when they were expected to do it because the approach was so different from what they were used to. This initial confusion is common when active-learning approaches are implemented (Stukus and Lennox 1995, Herreid 1998). However, students quickly learned the pattern of the course, and we now give them a timeline that lays out the pattern of the student-designed exercises and helps them grasp the process more quickly (Table 1).

Another potential drawback is that, because of the use of PIs, each student is not required to analyze the data for each lab. As a result, students get less practice using statistical equations and developing graphs. Nevertheless, the general approach may have given students better experience in many aspects of data analysis and interpretation than they would have obtained from highly structured laboratory exercises. During each Design Week, we emphasized thinking about data and types of analyses, and students had to determine which statistical tests and graphs would be appropriate for each question they wanted to ask. Thus, they were thinking about and applying statistics rather than simply solving equations. In addition, because all students participated in the design and interpretation of the results of each study, they were actively participating and thinking about the data and relationships between variables for every laboratory study. Furthermore, we measured their individual progress in analytical thinking through questions on exams that required the students to interpret graphs and to assign appropriate statistical tests to hypothetical research questions. The analysis portions of their semester projects were generally solid, which we attribute to the students' experiences applying different data analysis approaches.

A major concern about all active-learning approaches is the time commitment necessary for the instructors and the students (Herreid 1998). As with more traditional laboratory courses, the approach we developed requires instructors or lab assistants to organize and maintain any captive animals used in the studies. For example, for the sexual behavior labs it was necessary to collect and sex approximately 200 Japanese beetles before the lab and to establish a separate aquarium for each fighting fish. Other time requirements, however, are different from those of traditional lab courses. For the class investigations to be successful, the instructor needs to give the PIs feedback on study protocols and data sheets, while also helping them prepare any necessary equipment. Following data collection, the instructor often needs to assist the PIs with their data analysis and oral presentation. Thus, for each topic the instructor generally meets with the PIs for approximately 2 hours outside of class. Because the PIs help with the preparation, running, and cleanup of the lab, however, we have found that this time is generally repaid. Such repayment would likely hold for other institutions with

Week	Principle Investigators (PIs)	Rest of class	Instructor
Week 1 (Design Week)	Bring a written critique of the assigned article and a potential study design to class; come to to class prepared to lead the class critique of the journal article (i.e., bring questions on the article); develop a written protocol and data collection sheets; prepare equipment for the next week	Bring a written critique of the assigned article and potential study design to class	Be prepared to help lead the critique discussion and design the study; help PIs develop the protocol and data sheets and prepare the necessary equipment
Week 2 (Data Week)	Help organize and lead the data collection laboratory and participate in data collection; collect data from the rest of the class and analyze the results; discuss the analysis, results, and oral presentation with the instructor to get feedback.	Help gather data	Help guide data collection; give feedback to PIs on data analysis and oral presentation
Week 3[a] (Oral Presentation)	Give oral presentation and answer any questions from the class; write up the results in the form of a scientific paper—due the following week	Listen to and discuss the oral presentation; answer the instructor's extension question(s)—due the following week	

[a]Week 3 occurs during the Week 1 of the next PI group.

Table 1. Timeline for the Principal Investigator laboratories. A modified form of this timeline is given to the students at the beginning of the semester.

similarly limited teaching assistant support.

The approach also requires a significant time commitment on the part of the students. During the weeks that they are PIs, the students put in considerable time outside of class on their group's lab and often get less work done on their independent projects. However, they are PIs for only one topic; during the rest of the semester they can spend more time on their project and the lecture portion of the course. Furthermore, efficiently delegating work among the members of each group of PIs lessens the effort required by each individual in the group, although we sometimes found it necessary to assist groups in delegating tasks. To take some pressure off the students, we also let them drop one or two scores from their critique and design assignments, which allows them either to do poorly on a critique without penalty or to not hand in a critique while working on their PI lab. We also keep outside requirements in the lecture portion of the course to a minimum. To free up even more time for students, some instructors may opt not to include the semester project; we feel, however, that such projects are critical for reinforcing what students are learning in the other components of the course. Overall, we have found that the time commitments are reasonable for both the instructors and the students; however, we have noticed that students sometimes need to be reminded that traditional laboratory classes also have significant time commitments.

Another aspect of our approach that may be viewed as a drawback concerns the number of topics that we treat. Because of the high degree of student involvement and discussion, it is not possible to cover as many topics as would be covered in structured laboratory courses, a common tradeoff with active-learning approaches (Sundberg and Moncada 1994, Stukus and Lennox 1995, Gallet 1998, Herreid 1998). The specific tradeoff in our approach is to have students understand fewer topics in greater detail. More important, our emphasis is clearly on the scientific process and thinking about results, rather than the particular content items. However, because we prepare students to ask and answer research questions in animal behavior, they should be able to develop studies for any of the other topics that we cover in the lecture portion of the course. We hope that what they have learned in our laboratory helps them with other subjects as well.

As with any class that stresses active student participation, our approach works best in classes with relatively few students and with experienced instructors. Nevertheless, we believe that this approach will work in any laboratory class, although it may be necessary to divide classes with larger numbers of students into small groups with specific goals (Eisen 1998). In the case of animal behavior lab classes, such goals might include critiquing a certain part of an article or identifying the behavioral measurements the class will need to make. Our approach may also work with graduate teaching assistants leading sections of large laboratory courses, although specific training may be necessary for such assistants; as we mentioned above, it takes some skill to lead the discussions during Design Week.

Conclusions

In this article, we have presented a technique for creating a laboratory experience for advanced students—one that models the scientific process more completely than traditional, highly structured approaches. In our experience, after an initial training period students responded well to the approach and were highly engaged in the inquiry. In addition to providing students with the opportunity to more fully experience the scientific process, our approach creates a dynamic course that changes each semester, ensuring that it remains interesting in the long term for both students and instructors. For example, the instructor can easily change a laboratory's topic or emphasis by choosing a different journal article for the class to critique. Even if the topic and article are not changed, the student-based design makes it unlikely that any two studies will be the same; in the 3 years we have been teaching our classes, we have yet to repeat a topic as a class.

Despite the advantages of the current approach, it is still in its infancy and there are many ways in which to further model the scientific process. For example, students could peer review the written critiques and study designs, an approach that has the added benefit of simultaneously reducing instructor workloads (Koprowski 1997). End-of-term publication of a "journal" that includes the reports from the student-designed experiments and independent research projects would provide students with a permanent product while also reinforcing their status as members of a scholarly community. Online publication of the journal would add additional depth to that community (Mathis et al. 1999).

Although our initial trials at this approach occurred in animal behavior classes, the approach would work in any discipline in biology, or even in science in general. For instructors considering adopting this approach for their courses, we have several suggestions. First, to remain on schedule, the instructor should focus on questions that can be answered in a single laboratory period. As a related point, because adverse weather may affect field studies, the instructor should be prepared to give a backup schedule to the students with modified due dates for the data and results. Second, for those disciplines that are more equipment intensive than animal behavior, the instructor should make clear to the students what equipment is available so that students can design their studies appropriately. Third, if completely overhauling an entire laboratory course seems daunting, we suggest trying a reduced version of the approach, perhaps choosing one trial topic and focusing only on the paper critique and the student-designed investigation. Finally, instructors should strive to be flexible enough to pursue the directions taken by their students. Although the uncertainty inherent in our approach can be unsettling, the rewards are great—students and instructors remain engaged and excited by the process of science and become stimulated by the sense of discovery that motivates scientists in all fields.

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