2001

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ABSTRACT

Full engagement in science includes observation and asking questions, the development of a hypothesis, designing and conducting an appropriate experiment to test that hypothesis, data acquisition, appropriate analysis, revisiting initial questions, and dissemination of results. Here, I report on efforts to engage undergraduate students in all of these elements of science by integrating inquiry, investigation, and research in four intermediate biology courses for all majors. The project-based courses include Plant Ecology, Scanning Electron Microscopy, Molecular Genetics, and Physiological Ecology. Students conduct semester-long, experimental research projects and present their results at a public poster session on campus. Using computers, peripherals, and software funded by an award from the National Science Foundation, efforts were made to enhance the data acquisition, analysis, and presentation aspects of student research. The quality of the student research was improved, and student pride and ownership over the work increased. Students exhibited a greater understanding of science and quantitative analysis. One student project was published in a peer-reviewed journal, and many others were presented at regional and national meetings. The number of students taking elective courses in related areas, continuing research and senior honors projects, and applying and being accepted to related graduate programs significantly increased. Student poster sessions served to create a campus-wide culture of science.

INTRODUCTION

The national call for reform in science education in the late 1980's and early 1990's (National Commission on Excellence in Education, 1983; AAAS, 1990; Project Kaleidoscope, 1991) has most recently caused many at colleges and universities to rethink how science is taught at the undergraduate level (Gibbons, 1994; Good and Lane, 1994). As reform has begun to pervade undergraduate science programs, emphasis has shifted from the tradition of teaching science as a stagnant body of knowledge to a more dynamic approach emphasizing critical thinking. Reform has resulted in a change from the dualistic approach to teaching and assessment in the sciences as either correct or incorrect retention of content to a pedagogy that emphasizes the process of science (Hartman and Dubowsky, 1995). New strategies have included open-ended, investigative laboratory experiences (Sundberg and Moncata, 1994; Grant and Vatnick, 1998); inquiry-based approaches to lecturing (Uno, 1990; Ebert-May, Brewer, and Allred, 1997), small group and collaborative learning opportunities (Eisen, 1998), and the development of meaningful undergraduate research opportunities (NSF, 1996).

All of these approaches view science as a way of knowing. They serve to teach science by offering students opportunities to do science, and they represent a shift from passive to active learning and expose students to the meaningful uncertainty of the scientific process. Outcomes from this new pedagogy include increased ownership and empowerment (Grant and Vatnick, 1998), more positive attitudes towards and increased confidence with science, and more opportunities to use material in creative ways and to place it in a larger context (Sundberg, Dini, and Lee, 1994; Eisen, 1998). Ultimately, this pedagogy results in increased scientific literacy and is presumed to lead to greater retention of students in the sciences. Additionally, engaging students in science allows them to develop important skills that are typically valued across an undergraduate curriculum. These skills include effective group work, oral and written communication, library and reading skills, and critical thinking and analysis. Some have argued that all of this comes at the expense of exposure to course content, but evidence suggests that total retention of scientific information is greater with the new pedagogy even though slightly less content is delivered (Ebert-May, Brewer, and Allred, 1997).

Full engagement in science includes observation and asking questions, the development of a hypothesis, designing and conducting an appropriate experiment to test that hypothesis, data acquisition, appropriate analysis, revisiting initial questions, and dissemination of results. Despite efforts to engage students in the process of science, depending on the approach, some of these elements are often lacking or superficially introduced. For example, we found in our curriculum that students lacked opportunities to conduct quantitative analyses and to disseminate their results in the same way that professional scientists do. Here, I report on efforts to engage undergraduate students in all of these elements of science by integrating inquiry, investigation, and research in four intermediate biology courses for all majors, and I focus on efforts that were made to enhance the data acquisition, analysis, and presentation aspects of student research.

PROJECT-BASED LEARNING FOR ALL MAJORS

Similar to that at most institutions, the biology major at Muhlenberg College begins with an introductory core sequence that includes a laboratory experience. In this sequence students are exposed to the scientific process through inquiry and collaborative exercises in lecture and recitation, and laboratory exercises that offer students opportunities to learn important skills and experience open-ended investigation. These short-term experiences constitute introductions to the various components of the scientific method but do not allow students to be fully and meaningfully engaged in the entire process. Class size and student preparedness preclude this opportunity. However, as a department, we firmly felt that all majors should be engaged in longer-term research projects. We met this objective by establishing four intermediate to advanced project-based courses. These are Plant Ecology, Scanning Electron Microscopy, Physiological Ecology, and Advanced Molecular Genetics.

In these courses we have departed from the traditional undergraduate mode of lecture and laboratory to that of research and seminar. Each of these courses exposes students to research methods and to the primary literature relevant to that field and offers opportunities to be fully engaged in science. Semester-long research projects are presented in the form of a scientific paper and at public poster sessions that are similar to those held at professional meetings. The limitations that we were confronted with in these courses were technology based and primarily had to do with data analysis and presentation. Although we were satisfied with the quality of the research that our students conducted, we felt that what we could offer in terms of quantitative analysis and graphing and presentation were not as sophisticated as what typically occurs in most research laboratories. To remedy this lack we solicited funds from the National Science Foundation through the Department of Undergraduate Education's Instrumentation and

Laboratory Improvements Program (NSF-ILI). The objective of this project was to develop an undergraduate computing facility, including computers, software, and peripherals, in an effort to expand the use of data analysis and presentation in the four project-based courses. Below I focus on one course, plant ecology, to offer a more detailed description of a project-based course and to illustrate the impact of these technological improvements on our pedagogical objectives.

PROJECT-BASED LEARNING IN PLANT ECOLOGY

Course Activities

The course, taught at the College's arboretum, introduces students to scientific thinking through inquiry. With inquiry or discovery-based exercises students reach an understanding of concepts for themselves (Uno, 1990). For example, rather than being taught how a plant grows and develops, students can be led to discover this through direct observation of plants in the field. Next students are taught how to make observations and develop questions based on those observations. Students generate a list of observations and questions, and by interacting with their peers generate some very reasonable hypotheses. Students are also required to maintain a herbarium as means of developing a taxonomic vocabulary, which they most often will find essential as they become engaged in their research projects.

Next the students develop research projects. Project development occurs in conference with the faculty member and with feedback from the class, which has effectively become a research group. This is typically based on earlier observations and questions, and is often shaped by the specific interests of each student. For example, students with environmental interests often are most interested in applied questions dealing with environmental assessment or impact. Premedical students often explore medicinal aspects of plants. The diversity of backgrounds and interests that the students bring to the class is a plus and results in the development of many different kinds of research projects. Students who have trouble developing a project idea can be directed or prompted primarily through questioning by the professor.

The class is then run like a research laboratory. Weekly journal club activities offer students opportunities to develop library skills and to gain experience reading and discussing the primary literature. Class is often held like a lab meeting where students informally present some aspect of their research. The focus here is to discuss and view science as a work in progress. Students might present and get feedback on a statistical analysis or a way to graph their data. This course is also a part of a college-wide writing program. Throughout the semester students are learning how to put their questions, objectives, and hypotheses in writing as they would in a scientific paper. They are taught how to integrate quantitative results into text and how to discuss results appropriately and place them in the context of the existing literature. Ultimately, students write up their project in the form of a professional paper and present their work at a college-wide poster session much like those that occur at major scientific conferences.

The Role of the Technological Improvements

The addition of the new technology in our NSF-funded undergraduate computer facility greatly improved the quantitative aspects of the student work. The common statistical software and graphing packages allowed students to gain expertise within the context of their own research. The quality and sophistication of the student presentations and papers were greatly improved. Students exhibited greater ownership and pride with their own work. Students have been more motivated to continue their research after the course with the objective of submitting their work to a professional journal. The use of the technology itself is an essential skill, and students had the opportunity to further develop their technical expertise.

Outcomes

The research-based approach in this course has resulted in significant increases in elective enrollment in botany, which is typically under enrolled in departments where the majority of students have interest in the health professions. Assessment of student learning primarily through the evaluation of their written work indicated a greater understanding of science and quantitative analysis. Students enrolled in this course were more likely to pursue research outside of class. This includes participation in a yearlong honors research program in their senior year. Students are publishing and presenting their work. One student project has been published in a peer-reviewed journal and another is currently being revised for submission. Three student projects have been presented at regional or national scientific meetings. Since the inception of this course, significantly more students have applied to and have been accepted to fully funded graduate programs in ecology and botany. One former student, as a graduating senior, received honorable mention for the National Science Foundation Graduate Fellowship.

Challenges

One obvious challenge with project-based instruction within the confines of a semester is project failure. This is inherent in the process of science and can be a valuable teaching tool. However, working closely with students and helping them to redirect if their project becomes unworkable can minimize negative impact on the student. Many students, at least initially, experience some discomfort from this non-traditional form of learning. Another challenge can be the limited and diverse background of the students. Many students in these courses have not had more than an introduction to the area in which they are now asked to read the primary literature and conduct research. However, I have found that with time and patience the lack of background can be dealt with and is often advantageous in that their naiveté permits an unbiased approach to observation, problem solving, and discovery. Because students are not lectured to directly in this type of course, there is reasonable concern that this type of experience comes at the expense of important content. Lastly, this type of teaching is much more time consuming and places greater demands on the faculty member than more traditional modes.

SOMETIMES A DIFFERENT APPROACH IS REQUIRED

As mentioned previously, this same pedagogical approach is employed in our Advanced Molecular Genetics course. However, because of the inherent technical nature of molecular biology a slightly different approach has been taken. In this class one technique is central to every student project. All students are taught microarray technology in conjunction with yeast molecular genetics (Wallack, 2001), and students ask different questions that can be addressed using that specific experimental system. Another model is for all students to work on different aspects of the same question. This is particularly useful in broader, interdisciplinary fields. The outcomes and the challenges of these modified approaches appear to be very similar to those of the project-based model presented above.

THE CULTURE OF SCIENCE

One of the greater contributions of this kind of pedagogy is that it offers students and faculty opportunities to participate in the *Culture of Science.* Most limit their notion of culture to the humanities, and science faculty and students do not hesitate to attend a campus play, musical event, or art opening. However, science is a cultural activity involving process, creativity, and discourse. We use our public presentations and poster sessions to promote this notion. Students are asked to invite faculty and friends from non-science departments to attend their session. As a result there is a greater appreciation of science across the campus. Our diverse college community is learning that participation in and talking about science is stimulating. They learn that science is not just a complicated body of facts but offers a way to think, to interact, to create, and to discover. This wider appreciation of science perhaps has been the greatest success of our project-based curriculum.

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