

Inquiry, Investigation, and Integration in Undergraduate Science Curricula



Kelley McConnaughay
Department of Biology,
Bradley University

Ian Welsford
Department of Biology,
Keene State College

Erich Stabenau
Department of Biology,
Bradley University

Science Education Today: The Challenge

One of the most important challenges we will face in the next century will be that of increasing science literacy, particularly within the next generation of scientists. Historically, scientific and mathematical training has emphasized known facts: students were expected to master subjects as diverse as human anatomy and calculus through a mastery of facts associated with these disciplines. For example, students enrolled in human anatomy and physiology may be expected to memorize the 206 bones in the body and recall the specific mechanisms of bone formation. While the scientific method has been stressed, often from primary school on, little emphasis has been placed on the actual pursuit of science. As our scientific knowledge is increasing, mastery of a subject via mastery of “the facts” is unattainable, unless one defines the subject narrowly. Today’s “facts” are being refined or disproved rapidly; thus factual knowledge changes rapidly, necessitating frequent remastery of a new set of “facts.” More disturbing is that a method of presenting scientific concepts as a set of prescribed facts inaccurately portrays science. Science is an action sport; it is an engaging, dynamic, social endeavor.

How do we enable people to become more scientifically literate in the best sense? How do we promote their ability to understand how scientific knowledge is generated; that every scientific data set has inherent, but seldom flagrant, flaws; how disagreements among scientists are commonplace, and that scientific debate is not only common, but provides the very life-blood of the

scientific process? The actual pursuit of scientific inquiry can reveal much about the theory, culture and practice of science that cannot be realized through a study of scientific content alone.

Science Education Standards: Shifting Emphases

Current research suggests that educating students through the approaches of investigative and cooperative learning improves knowledge generation and acquisition skills as well as enhancing recruitment and retention in the sciences (ACE 1985, Hodson 1986, NSF 1990, Tobias 1992). This is particularly true for minority students and women, who often have not experienced the same degree of exposure to research as some others (ACE 1985, NSF 1990, PHERP 1991, Weiss 1978, 1987). We need to train young scientists in the pursuit of science *per se* to improve science literacy beyond mastery of a set of currently known facts. We need to work towards building skills in knowledge acquisition and generation, rather than focusing on any specific body of knowledge itself.

Recently, several national scientific societies and agencies have examined science education as practiced today, publishing numerous position papers, policy statements, and specific guidelines for science education standards for the next century (e.g., AAAS 1989, NSF 1996, NRC 1996). From these publications comes an emergent theme: science educators need to rethink our basic approach to “teaching science.” Previously, science was

This article first appeared in 1998 in *The University as a Learning Community: Tradition, Innovation, Prospects* published by the Office for Teaching Excellence and Faculty Development, Bradley University, Peoria Illinois. Reprinted with permission.



Student comparing carbon dioxide excretion in rats and turtles. Notice the proper use of replication which was determined by the student's laboratory group.

taught from within a rigidly defined curriculum, where all students were treated alike. The material provided in classroom or laboratory settings was content-based with structured lectures and readings from texts. The students were tested, in part, on their ability to reproduce certain facts on end-point exams. Finally, the previous education ideals dictated that the teacher worked alone and was an authority figure, so that students seldom disagreed with the instructor out of fear or embarrassment (i.e., the "Sage on the Stage" model of instruction).

Current science education standards (e.g., NRC 1996) reflect decreased emphasis on teaching science "facts" and increased emphasis on teaching how those facts are generated, how they are used to understand complex systems, and how they may be applied to new and complex situations. In a recent report on National Science Education Standards, the National Research Council of the National Academy of Science (NRC 1996) recommended that students be treated as individuals, with their own prior backgrounds and knowledge, and thus their own approaches to the theoretical aspects of the course. Further, the report recommended that, along with this increased emphasis on educational diversity within the curriculum, the curriculum should be as flexible as possible. The information covered during a course should be based on the students' ability to think and process information. This inquiry-based or research-based approach offers more avenues for discussion and debate among students and teachers. In addition, students should be provided with continual feedback and

assessment. Lastly, the NRC (1996) suggested that there should be more emphasis on shared responsibility for learning by students and teachers, and that more team teaching be utilized in classroom and laboratory settings to facilitate connections among traditionally isolated disciplines.

Undergraduate research participation programs have demonstrated considerable success in exposing undergraduates to current research paradigms. However, several studies suggest that comprehensive instructional programs, which acquaint students with the culture, theory and practice of science, are more effective in retaining students' interest. This is particularly true for minorities and women, who often have not experienced the same degree of exposure to research as some others (e.g., Hodson 1986, PHERP 1991, Bently 1993). Making research an integral tool within the curriculum (as opposed to an optional, even if encouraged, form of enrichment outside the curriculum) would provide all students with opportunities to participate in research, in collaboration with faculty mentors, in the context of specific "course knowledge." Further, embedding research pedagogy within the curriculum should simultaneously enhance the direct appreciation of the scientific process as well as make the content covered more relevant to students' own experiences, since much of the content is covered in student-directed investigations (Zorfass and Copel 1995).

Organismal Biology: A Model for Change

We have developed a novel sophomore-level core course for all biology majors that compares and contrasts the functional and morphological adaptations of plants and animals. The course, entitled Organismal Biology (BIO 223), is based on constructivist epistemology (Fleer 1992, Sigel 1984, Yager and Lutz 1994) and Kolb's model for instruction of differing learning styles (Svinicki and Dixon 1995). As such, the course allows students to approach material using their own, dynamic, conceptual framework, rather than forcing them to accept a predetermined framework. It is laboratory-based and, unlike classically structured courses, lacks frequent, extensive in-class lectures. The course relies almost exclusively on hands-on investigation in which the students are afforded substantial independence. Students examine the anatomy and physiology underlying basic life-processes across a

focus
on research courses

variety of organisms. For example, water movement in plant and animal cells occurs by distinctive mechanisms based on differing abilities of plants and animals to transport ions and solutes into or out of cells. Rather than handling these alternative mechanisms in separate plant or animal sections of the course, students are exposed to the principles underlying water movement in all organisms. Through direct examination of both the inherent similarities (shared constraints) and differences in the execution of basic life functions among a variety of disparate organisms, students gain a deeper and broader understanding of the basic biological principles governing all organisms. The integration of plant and animal systems is facilitated by the collaborative efforts of two instructors, one trained primarily as a plant biologist and the other as an animal biologist. The instructors are present concurrently in both the classroom and laboratory, and collaborate on the design and development of all aspects of the course.

Content is revealed through a combination of textual readings (such as textbook and/or handouts), laboratory investigations, classroom discussions and, as needed, lectures. Students are introduced to the next "topic" through laboratory handouts, which provide a summary of the "topic" to be investigated, and the organisms and equipment available to the students. The handouts also contain several thought-provoking questions designed to generate investigative ideas, refine investigative techniques, and/or to facilitate the students' ability to interpret, extend, or apply the results of their own investigations. The following is an example of one such question:

Sally wants to investigate the influence of leaf hairs on transpiration rates. She looks around the campus and finds a species of flowering herb that has six to eight oblong leaves, all from a basal rosette. She looks for a non-hairy-leaved species as similar in all possible ways to Mr. Hairy. She finds a similar looking plant, with six to eight oblong leaves, all from a basal rosette, only the leaves are smooth. She notes, however, that Mr. Smooth has larger leaves. Can Sally use Mr. Smooth and Mr. Hairy to test her hypothesis? Will her data be unduly compromised?

In small research teams of three to five students, students then decide what aspects of the topic they will investigate. In consultation with the instructors, they develop a hypothesis to investigate and a detailed experimental protocol. The variety of students' interests generally ensures that a variety of "content" will be revealed through their collective investigations. Following each week's investigation, the students present their results to classmates and the instructors. What follows are lively

debates that reveal not only a breadth of organismal principles, but also numerous meaningful and very tangible examples of "real science". Students learn first-hand that subtle differences in experimental design or measurement protocol can sometimes dramatically affect experimental results; that experimenter bias can, without appropriate training and constant vigilance, affect one's interpretation of a body of data; that even a well-designed experiment often reveals more questions than answers; that well-educated, ethical scientists often disagree, and often do so happily and without rancor.

As students are revealing basic organismal principles through their own investigations, we liberally supplement the student-derived content with a combination of lectures and thought-provoking exercises. The exercises are designed to provide the students with the opportunity to demonstrate mastery of content, to aid students in bridging related content areas (e.g., water relations and gas exchange), and/or to challenge students to apply organismal principles revealed in class to novel situations. The following is one example of this latter type of question:

A former BIO 223 student is rushed into the ER. Drs. Stabenau and McConnaughay are prepped and scrubbed, and ready to cut. They realize that the patient's lungs need to be replaced. Luckily, transplant lungs are available, and Dr. McConnaughay deftly removes the damaged lungs from the patient. Suddenly, Dr. Benton (the anesthesiologist) knocks over the tray containing the transplant lungs, and kicks them across the floor. While Dr. Stabenau starts to size up Dr. Benton's chest cavity for a possible fit, Dr. McConnaughay states, "Wait! There's a sushi party on the maternity ward. Let's use gills!" The former 223 student comes out of anesthesia long enough to hear this. Quickly, the student begins to plan his/her post-operative recovery. Give us the details of the post-operative lifestyle that will enable this student to maximize his/her recovery chance of being able to live with gills.

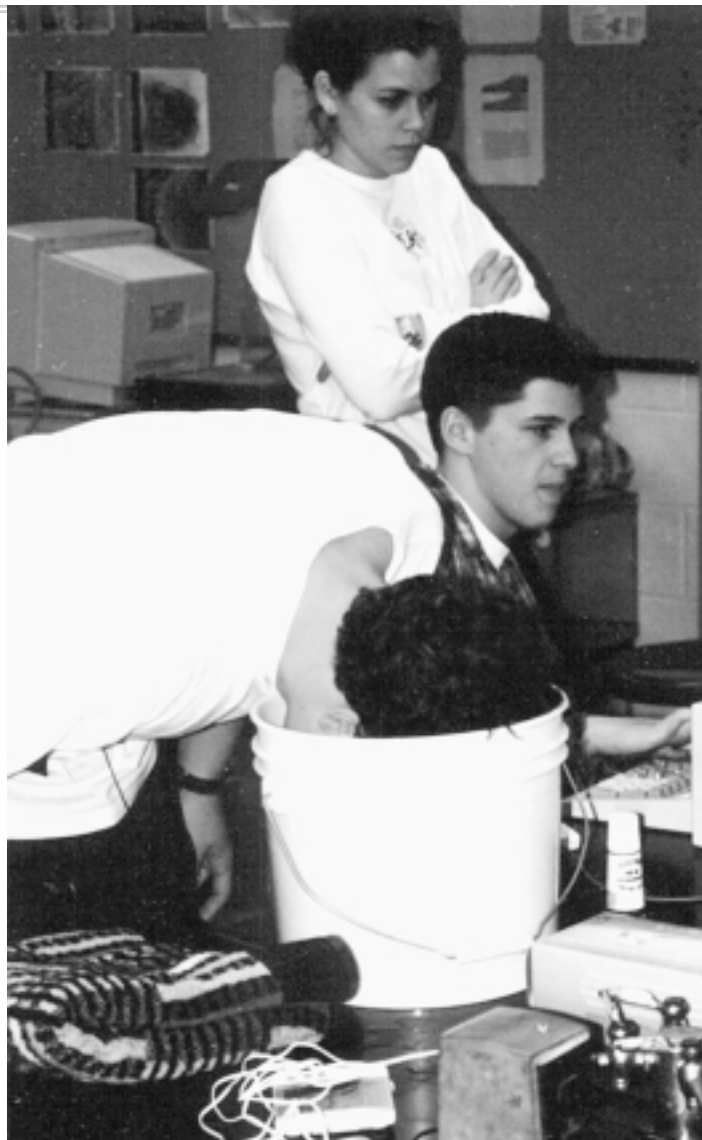
This question cannot be answered directly from information contained in any textbook. To our knowledge, gills have never been transplanted into humans in place of their normal lung respiratory units! However, students in BIO 223 are exposed to gas exchange in a variety of animals ranging from gill to air-breathers. Thus, they can take basic principles learned on the role of gills in respiration, and try to apply those principles to a "gill-transplanted" human.

The structure of the class ensures shared responsibility for learning, both during the weekly laboratory sessions and

during the class discussions. The instructors provide the investigative topics, a basic introduction to the topic, a basic protocol, a list of materials available (organisms, environments, etc.), and feedback and troubleshooting during the lab, but are not the sole foci of investigation or information (i.e., the "Guide on the Side" model). The topic investigated in the laboratory sessions is related to material covered in the classroom exercises and lectures. In addition, there is a transition of basic principles from one week to the next. For example, students investigate water and solute movement via renal mechanisms in humans, followed the next week by transpiration in plants, which is also influenced by water and solute potentials. In the laboratory sessions, students provide the question to be investigated, a specific hypothesis, the experimental protocol, data collection, analysis and interpretation, and the students disseminate their results in a weekly laboratory report.

Students in Organismic Biology are evaluated in many ways. Grades are determined by three end-point exams (two 100 point exams, and a comprehensive 200 point final), ten weekly exercises (10 points each), ten weekly laboratory reports (20 points each), a final research poster presentation (50 points), and a laboratory performance evaluation (50 points). Exams are written (the comprehensive essay exams are comprised of 10-15 questions of varying point value, ranging from factual recall to synthesis and application, from which students chose five to eight questions to answer.) However, it must be noted that students are afforded continual assessment. The first five exercises and laboratory reports are graded with substantial comments provided to the students. The students have one week to rewrite the exercise or laboratory report. The ability to redraft assignments is a crucial component in modeling the "real" world of science as well as affording students the possibility of incorporating "peer" review in a meaningful way.

As with any novel approach, there are drawbacks. First, the course is extremely time consuming for the students and the instructors. Students spend an extraordinary amount of time preparing weekly exercises and lab reports, while simultaneously rewriting the previous week's exercise and laboratory report. Instructors spend a great deal of time grading, regrading, and working individually with groups. Second, the investigative nature of the laboratory sessions ensures that it is impossible to stock all of the necessary supplies. Third, students work with other individuals in small groups to complete weekly exercises and laboratory reports in which the group dynamics may fall apart due to personality conflicts or from lack of perceived effort by other group members. We agree that more material could



Submerged undergraduate student during an experiment on "diving" bradycardia in college-aged students.

be "covered" using structured lectures, yet the question arises of whether mastery of material is significantly improved since the material is covered more at the instructor's pace than that of the student. Fifth, the course is unlike any other the students have been exposed to. This fact may make some students feel uncomfortable, since many might have experienced substantial success in the past under a more didactic model. A great deal of effort is expended by the instructors to ameliorate any such discomfort through personal and group interaction. Finally, the approach requires a commitment by the faculty in place at the institution to support such a constructivist course. All faculty, particularly those

focus
on research courses

engaged in instruction at the upper-division level, need to understand that simple coverage and/or overview of the “big” issues in organismal biology is not the sole stated goal of the course, and thus need to adjust their content expectations of students enrolled in later courses accordingly.

While there are negatives to this approach, we feel the benefits outweigh them. First, students emerge as active learners, participating at each stage of the course whether it be in laboratory or classroom sessions. Second, the investigative approach ensures variety. Many students have told us that conducting the same experiment as forty other individuals is boring and produces individuals who are simply going through the motions. Third, students are provided continual feedback and assessment. The extensive comments on their laboratory reports and exercises allow the students to learn and correct their mistakes, rather than simply looking at a grade at the top of their papers. Fourth, the course provides the students with an interdisciplinary analysis of biological concepts. Thus the students can investigate biological principles from the organismic point of view, rather than by the phylogenetic and/or strictly cybernetic/teleological view. Fifth, the organismic biology course ensures that students, as a result of working weekly in small groups, cooperate rather than compete. The overall performance of the group is extremely important to each individual. Finally, students learn science, not just facts. This ensures that if the scientific facts taught today are refined or disputed, the students will be able to critically evaluate the science and technology of tomorrow.

Conclusion

This unique sophomore level course fosters the development of basic skills needed to actively pursue science as a career: students learn to acquire, apply and generate scientific knowledge; to critically evaluate data and concepts; and to think critically in an interdisciplinary format. Performance-based assessment of students exposed to this investigative format suggests broader comprehension of the basic principles of organismal biology and better preparedness for advanced coursework and independent research in our curricula.

References

American Association for the Advancement of Science [AAAS] (1989). *Science for All Americans. A Project 2061 Report on Literacy Goals in Science, Mathematics, and Technology*. The American Association for the Advancement of Science.

American Council on Education [ACE] (1985). *National Priorities for Undergraduate Science and Engineering Education*. Report of the National Higher Education Associations Task Force, American Council on Education.

Bently, B., chair (1993). *Mechanisms to Increase Recruitment and Retention of Women and Other Underrepresented Groups in Ecology* (draft). Report of the Strategic Planning Workshop, Ecological Society of America.

Fleer, M. (1992). Identifying teacher-Child Interaction which Scaffolds Scientific Thinking in Young Children. *Science Education* 75(4): 373-397.

Hodson, D. (1986). The Nature of Scientific Revolution. *Social Science Review* 16(2): 17-30.

National Research Council [NRC] (1996). *National Science Education Standards*. National Academy Press, Washington, D.C.

National Science Foundation [NSF] (1990). *Undergraduate Science, Mathematics and Engineering Education*. Report of the National Science Board Task Force on Undergraduate Science and Engineering Education, National Science Foundation.

National Science Foundation [NSF] (1996). *Shaping the Future: New Expectations for Undergraduate Education in Science, Mathematics, Engineering, and Technology*. A Report on its Review of Undergraduate Education by the Advisory Committee to the National Science Foundation.

Pew Higher Education Research Program [PHERP] (1991). *Policy Perspectives, III*. Report of the Pew Higher Education Research Program.

Sigel, I.E. (1984). A Constructivist Perspective for Teaching Thinking. *Educational Leadership* 42: 18-21.

Svinicki, M.D. and N.M. Dixon (1995). The Kolb Model Modified for Classroom Activities. *College Teaching* 35(4): 141-146.

Tobias, S. (1992). *Revitalizing Undergraduate Science: Why Some Things Work and Most Don't*. Research Corporation, Tucson, Arizona, USA.

Weiss, I.R. (1978) *Report of the 1977 National Survey of Science, Mathematics, and Social Studies Education*. Center for Educational Research and Evaluation, U.S. Government Printing Office, Washington, DC.

Weiss, I.R. (1987). *Report of the 1985-86 National Survey of Science and Mathematics Education*. Center for Educational Research and Evaluation, Research Triangle Institute, Research Triangle Park, NC.

Yager, R.E. and M.E. Lutz (1994). Integrated Science: the Importance of “How” versus “What”. *School Science and Mathematics* 94(7): 338-346.

Zorfass, J. and H. Copel (1995). The I-Search: Guiding Students Toward Relevant Research. *Educational Leadership* 53(1): 48-51.