Cell Biology Education
Vol. 2, 112–116, Summer 2003

Inquiry-Based Undergraduate Teaching in the Life Sciences at Large Research Universities: A Perspective on the Boyer Commission Report

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Submitted February 1, 2003; Revised April 16, 2003; Accepted April 17, 2003
Monitoring Editor: Jeff Hardin

The 1998 Boyer Commission Report advocated improvement of undergraduate education at large research universities through large-scale participation of undergraduates in the universities' research mission. At a recent conference sponsored by the Reinvention Center, which is dedicated to furthering the goals of the Boyer Commission, participants discussed progress toward these goals and recommendations for future action. A breakout group representing the life sciences concluded that independent research experience for every undergraduate may not be feasible or desirable but that transformation of lecture courses to more inquiry-based and interactive formats can effectively further the Commission's goals.

Keywords: Reinvention Center, independent research, assessment, course transformation.

INTRODUCTION

In 1998, a commission of educators sponsored by the Carnegie Foundation and chaired by its president Ernest L. Boyer released its report, entitled *Reinventing Undergraduate Education: A Blueprint for America's Research Universities* (Boyer, 1998). The Boyer Commission Report (BCR) pointed out that undergraduates at large research universities were often inadequately taught, due in large part to high student/faculty ratios, a predominance of lecture-based courses, and the many demands on faculty besides teaching. The Commission argued that to improve this situation, research universities should not try to emulate the teaching practices of small liberal arts colleges with lower student-to-faculty ratios. Rather, universities should take advantage of their unique research-related resources, integrating undergraduate education into the ongoing process of inquiry that already involves graduate students, postdoctoral researchers, and faculty. In the Commission's words: " . . . Undergraduates can become junior members of the research teams that now engage professors and graduate students" (BCR, p. 17). The report challenged universities to transform their undergraduate courses, currently taught primarily in large lectures, into a primarily inquiry-based curriculum.

To promote and further the Boyer Commission's recommendations at U.S. universities, the Reinvention Center (www.stonybrook.edu/reinventioncenter) was established at SUNY Stony Brook soon after publication of the BCR. In November 2002, the Center sponsored a conference at the University of Maryland, College Park, in order to assess progress toward the goals of the BCR and discuss future directions. Faculty, administrators, and students from a variety of universities attended the conference, as well as representatives of several educational funding organizations. This essay is based on the author's presentation and the ensuing discussion at a breakout session on biological sciences.

INVOLVEMENT OF UNDERGRADUATES IN INDEPENDENT RESEARCH

Goals

The focus of the biology breakout session was on the role of independent research in the undergraduate life sciences curriculum. Although the BCR does not specifically recommend independent research for every undergraduate, we began by examining this possibility, with the questions, Is it a realistic or desirable goal we should strive for? What are the constraints? and Can existing resources be better utilized? What new resources and incentives are needed? and Can other inquiry-based activities substitute for independent laboratory research?

As a sample department for discussion, I took my own, the Department of Molecular, Cellular, and Developmental Biology (MCDB) at the University of Colorado, Boulder (CU Boulder). CU Boulder is a large research university, with ~27,000 total students, ~16,000 in the College of Arts and Sciences, and a total faculty of ~2000. Its total research expenditures in 2002 were ~$220 million, placing it near the top of AAU

DOI: 10.1187/cbe.03-02-0004
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institutions in level of grant and contract research funding. The Department of MCDB has 26 research-active faculty, with a total of ~$10 million annually in extramural research support. There are currently over 800 undergraduate MCDB majors at CU Boulder, and over 100 of these students graduate each year with a B.S. degree. Although the course offerings are largely traditional (lecture-recitation) in terms of content and teaching approaches, the department encourages undergraduates to undertake independent research in faculty laboratories as part of the curriculum. Among the 107 students who graduated in 2002, 48 of them (45%) had at least one semester (or summer) of research experience, carried out as independent study for credit, as participation in a research seminar course with 6 students, or as a traineeship with a small stipend. Traineeships were funded by either an Undergraduate Research Opportunities Program (UROP, sponsored by the Hughes Foundation and the University); a Summer Cancer Fellowship Program administered by the UC Health Sciences Center in Denver (sponsored by the National Cancer Institute), or a faculty grant.

Is this glass half-full or a half-empty? On the one hand, 45% is an admirably high percentage. Representatives from the University of Delaware, which has instituted a major undergraduate research initiative and documented the effects of independent research on undergraduate learning (www.udel.edu/RAIRE/), estimated at the conference that only about 10% of their graduating seniors have had an independent research experience. On the other hand, 45% is still far from involving every student.

Constraints

Should we be striving for 100% participation? In MCDB, although research space and research support may be an issue in deciding to take on an undergraduate researcher, they are generally not a major constraint. Neither, for most faculty, is faculty time, because graduate students or postdocs usually are responsible for the day-to-day mentoring of research undergraduates. For this reason, training of beginning undergraduate researchers does take valuable time from the members of a research group, which may or may not benefit in the long run from undergraduate contributions to the work. However, the principal limiting factor is the number of motivated, qualified undergraduate students. Even in a demanding and selective major such as MCDB, it is not surprising that a significant fraction of the students does not choose to spend time in a research laboratory or is not adequately prepared to do so productively. For these reasons, most of the participants in the session agreed that 100% research participation was not a realistic or desirable goal.

Developing the Research Mindset

How, then, can we move toward the goals of the Boyer Commission? We can do so if our emphasis is not on making every student into a researcher but, rather, on graduating students, in all disciplines, with the *mindset* of researchers. As the Boyer Commission recommended, we should develop an inquiry-based curriculum that will "produce a particular kind of individual, one equipped with a spirit of inquiry and a zest for problem solving" (BCR, p. 13).

What are some characteristics of the research mindset? Researchers are skeptical of claims not supported by empirical evidence. They are good at, and get enjoyment from, solving problems. They know how to gather and organize data, critically analyze it, and draw conclusions from it. An education with this emphasis benefits all students, not only those heading for academic or professional careers. As the Commission stated, "For those who do not enter graduate school, the abilities to identify, analyze, and resolve problems will prove invaluable in professional life and in citizenship" (BCR, p. 17).

The Boyer Commission recommended undergraduate involvement in research as a supplement to or partial replacement for the standard lecture-based curriculum. However, we concluded above that this may not be an appropriate solution for all students. What, then, besides independent research can we offer to help all students develop the research mindset? A general answer is that we, meaning those of us who teach undergraduate science courses, must become more knowledgeable and better educators.

Many academic scientists in research and teaching departments at large universities are unaware of the current ferment in the education community that has been generated by recent progress in understanding the learning process (e.g., NRC, 1999a) and by promulgation of the National Science Education Standards (NRC, 1996, 2000). Most of the concepts in this understanding are not new; they have been intuitively grasped or learned from experience by the best teachers of every era, but in the last two decades they have been validated by a substantial body of evidence from educational research (NRC, 1999a). One of the clear conclusions for undergraduate teaching is that standard lecture courses, in which listeners are passively exposed to information that they later try to assimilate on their own in preparation for a high-stakes test, are for most students not an effective means of acquiring deep understanding of a discipline.

The ineffectiveness of standard lecture-based curricula has been particularly well documented in physics. In the early 1990s, physicists at Arizona State University developed a test called the Force Concept Inventory (FCI), designed to examine students' understanding of basic concepts in mechanics (Hestenes *et al.*, 1992). This and similar tests have been used to compare the prevalence of common misconceptions before and after taking an introductory physics course or completing a physics major. Here is a sample question:

> You are standing on the moon, holding a pencil in one hand. If you let go of the pencil, it will
>
> a) float upward toward outer space.
> b) remain floating where you let go of it.
> c) fall to the moon's surface.

At one large university, 75% of beginning physics students chose a or b. Using such instruments, physicists could show that taking traditional lecture–lab courses improved understanding somewhat but that other teaching approaches, discussed below, did much better (Hake, 1998; M. Zeilik, personal communication).

Physics education researchers have demonstrated some of the reasons for ineffectiveness of standard curricula by analyzing students' perceptions of physics learning in traditional lecture courses (e.g., Hammer, 1994). Students in such courses tend to view learning as memorization of a disconnected collection of facts, terms, laws, and formulas. They have little opportunity or motivation to integrate these into a coherent view of how the world works. Furthermore, they perceive facts and concepts as dictates of authority, rather than as the results of scientific investigation by real people; i.e., they acquire little understanding of the research process by which new knowledge is generated.

Much more effective learning results in classes where there is active give-and-take between students and the instructor and between students in small groups. Particularly helpful are interactions designed to assess student understanding on the spot, during class, in a low-pressure environment. Such assessment provides immediate feedback to the instructor as well as to the students on their level of comprehension. And it transforms the class into an inquiry-based learning experience.

Therefore, a more specific answer to our question about what to do is that we can incorporate inquiry into all of our teaching. Inquiry-based teaching includes any process in which problems or questions are posed—by the students themselves, by their instructor, by their textbook, or by the professional literature—and students attempt to solve or answer them during class time. Rather than taking notes on factual information to be memorized later, students in such classes are actively engaging in the process of inquiry by which science progresses. By doing so in groups, they are learning to share their resources with those of others in solving problems. Independent laboratory research is not the only form of inquiry that will enhance student understanding.

Transforming Standard Courses

Again, the physicists took the lead in putting these ideas into practice. Eric Mazur at Harvard pioneered the use of "ConcepTests," posing questions during a lecture to assess student understanding, allowing contiguous groups of students to discuss the answer, and then displaying the distribution of group responses to the class by various means (at first colored index cards, more recently electronic devices). Differences in the responses lead to more discussion as students work toward consensus answers (Mazur, 1996; Crouch and Mazur, 2001). Robert Beichner, at North Carolina State University, has presented evidence on the effects of transforming his physics classes in this manner to an entirely inquiry-based format (www.ncsu.edu/per/scaleup/html), using redesigned, electronically equipped classrooms that facilitate student interaction in small groups and allow them to access the Internet during class for help in solving problems (see Figure 1). Using pre- and posttesting with quantitative assessments like the FCI (Hake, 1998), as well as interviews and other qualitative techniques, he can show clearly that the transformed classes are far superior to standard courses in promoting student understanding, as reviewed in a recent issue of *CBE* (Dancy and Beichner, 2002).

These ideas are also being used to transform teaching in undergraduate chemistry courses. For example, concept tests have been developed, disseminated, and used widely for in-class assessment of student understanding and promotion of active discussion (http://www.chem.wisc.edu/~concept/). In biology, there have been laudable innovations by isolated individual instructors, some reported in *CBE*, but as yet no concerted efforts directed at teaching in research universities

Figure 1. The Beichner classroom before and after transformation. (From http://www.ncsu.edu/per/scaleup/html, with permission.)

like those described above for the physical sciences. Recently, encouraging progress has been made toward developing biology concept tests (Anderson *et al.*, 2002; M. Klymkowsky, personal communication), which should help to lay the groundwork for more systemic change. We need to develop and publicize effective inquiry-based approaches to biology teaching, similar in concept to those described above for physics. At the same time, we must not lose sight of the real epistemological differences between these disciplines in crafting our approaches. How should we proceed?

Transforming Undergraduate Life Sciences Courses

Although some of us in university life sciences research departments have experimented with teaching innovations, we have seldom assessed their effectiveness in any objective way. One of the founding premises of this journal was that we need to apply the "research mindset" to our teaching as well as to our scientific research (Ward, 2002). That is, we must take an inquiry-based approach to our own pedagogy—posing questions about how we teach, doing experiments, collecting data, drawing conclusions, putting them into practice, perhaps even publishing them in educational journals such as this one. In short, we must become educators (NRC, 1999b).

How difficult will this be? Dancy and Beichner (2002) provide several helpful practical guidelines and sources that can facilitate getting started. However, faculty members of research-oriented departments that teach undergraduates are generally already overburdened with multiple responsibilities. The prevailing reward structure does not encourage them to spend more effort on their teaching, which is often viewed as an impediment to research. Many faculty believe that they are doing quite an effective job of teaching using standard lectures, and they may not be receptive to suggestions for change. On the other hand, many faculty would like to teach more effectively and are open to new ideas. Some possible ways to help promote reform are suggested below, under Conclusions.

In presenting the case for change, it is important to emphasize that course transformation can be done incrementally, without the need for cataclysmic revisions of either one's syllabus or one's teaching style. Transformation can begin, for example, by breaking up a class period into several short stretches of lecturing, punctuated by questions from the instructor to the class, based either on the lecture material or on problems or reading assigned to the students in advance. The more time students have been assigned to prepare in advance for class, the more time in class that can be spent on such questions. Encouraging students to consult with their neighbors about a question will generally help to get discussion started. These minor deviations from continuous lecturing can easily lead to the kind of ongoing in-class give-and-take described above that takes place in more completely transformed courses (NRC, 1997). A good introduction to these ideas can be found in the NRC (1997) study *Science Teaching Reconsidered: A Handbook*.

Teaching in this manner does not necessarily require more work for the instructor than do standard lectures appropriately updated from year to year, but in my experience such teaching is a lot more fun. There is more work up front, such as providing students with problems or study materials prior to class, but this is greatly facilitated by the use of a course Web site that students can access at any time. At least some of the drudgery of lecture preparation is replaced by anticipation of lively discussion with the students, whom one comes to know better as a result of the interactions in class. Students tend to appreciate the more interactive, participatory classes, which can have beneficial results for one's teaching evaluations.

How Far Should We Go?

Given the power of inquiry-based teaching to promote deep understanding, should all of our instruction be inquiry-based? The BCR first implies that it should, when it quotes the educator John Dewey to the effect that "learning is based on discovery guided by mentoring rather than on the transmission of information" (BCR, p. 15). However, a more reasonable statement appears subsequently: ". . . Students should be taught by those who discover, create, and apply, *as well as transmit*, insights about subjects in which the teacher is expert" (BCR, p. 16; italics added). The woman in a hunter-gatherer society who knows the identities of hundreds of wild plants and their uses has prodigious learning, most of which was transmitted to her by female ancestors. For the life sciences in particular, information transmission must continue to be an important part of our teaching. Biology is not physics; a large component of biological understanding is descriptive. Although the evidence indicates that teaching predominantly by lecturing is unsatisfactory, occasional lecturing seems not only desirable, but also essential. Most of us retain unforgettable ideas that were transmitted to us by a skilled and inspiring lecturer. Particularly when a concept test or other in-class assessment indicates that students lack important information, a "lecturette" of explanation or background may be necessary. We should not scrap the tradition of lecturing, but simply learn to use it much more sparingly and in small doses.

On the other hand, it became apparent in discussion during the biology breakout session at the Reinvention Center Conference that perhaps the notion of an actual research experience for all life sciences undergraduates is not so unrealistic after all. From transformed courses that are largely inquiry-based, it is only a short step to project laboratory courses in which students carry out real research. In such courses, where groups of students formulate their own research projects, present them for approval to a "study section" of instructors and teaching assistants, carry out the proposed experiments, write up the results, and present them to their peers, students are experiencing much the same process that scientists experience in their research work. We heard about one such course at West Virginia University, which is *required* of all sophomore biology majors. It was reported that students hate the course at first, but eventually rate it as their most important learning experience in the major (K. Garbutt, personal communication)! To the extent that this is real research, we must modify our earlier assumption: 100% participation in at least this level of research may indeed be a feasible and desirable goal in attempting to fulfill the objectives of the Boyer Commission.

Conclusions

In a final "Future Directions" session at the end of the Reinvention Center Conference, the biological scientists presented the following conclusion and set of suggestions.

> Life science departments should institute transformations toward inquiry-based teaching across a broad spectrum of research-related experiences, ranging from student-centered, inquiry-based introductory courses to project laboratories to faculty-mentored independent research.

These transformations will require substantial reform. Several ideas were presented in this session for activities we might promote to help motivate our colleagues toward change.

1. Try to obtain evidence for how well or poorly the current system is working, by persuading faculty to define learning goals for their courses and helping to develop objective methods (the equivalent of a Biological Concepts Inventory) to assess whether these goals are being met.
2. Present reform as an incremental process, not a revolution. Start small, and start early, with freshman courses. Consider project laboratories in the freshman year.

3. Bring outside speakers on pedagogy into the departmental seminar program to introduce examples of how to develop transformed courses and how to assess their effectiveness.
4. Start an in-house pedagogy discussion group that includes postdocs and graduate students, and perhaps undergraduates as well.
5. Invite faculty from the local School of Education to consult or collaborate in new course development and assessment.
6. Encourage faculty to participate in the growing number of education sessions at meetings of their professional societies.
7. Encourage administrators and departments to reward faculty who develop innovative and successful inquiry-based courses, particularly if these faculty appropriately assess and publish the results of their work in respected educational journals.

Becoming educators will not be painless, but the implementation of more inquiry-based teaching in our undergraduate biology courses can result in substantially increased understanding among our students and perhaps, for us the instructors, more rewarding teaching experiences.

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