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Biology Education Research: Lessons and Future Directions

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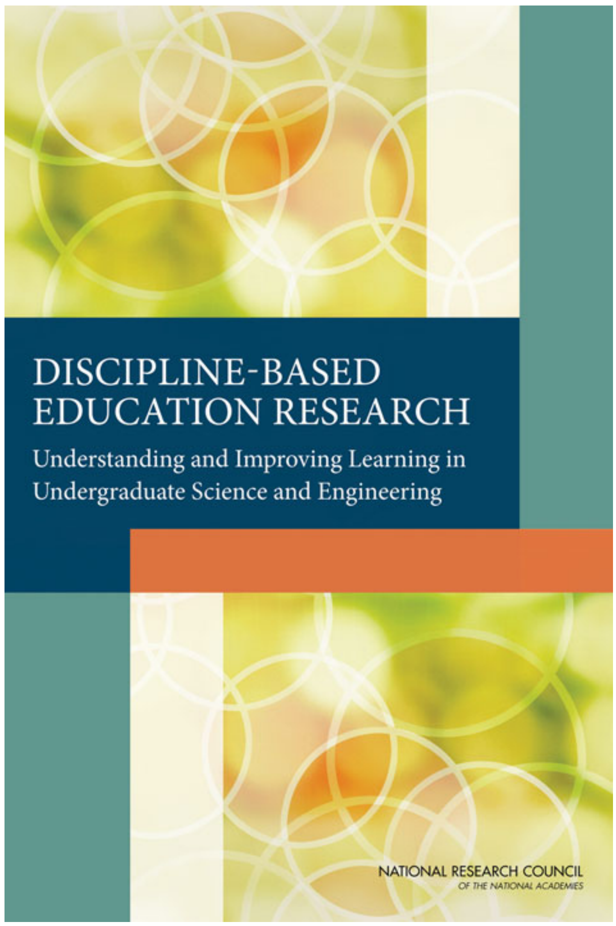
Biologists have long been concerned about the quality of undergraduate biology education. Indeed, some biology education journals, such as the *American Biology Teacher*, have been in existence since the 1930s. Early contributors to these journals addressed broad questions about science learning, such as whether collaborative or individual learning was more effective and the value of conceptualization over memorization. Over time, however, biology faculty members have begun to study increasingly sophisticated questions about teaching and learning in the discipline. These scholars, often called biology education researchers, are part of a growing field of inquiry called discipline-based education research (DBER).

DBER investigates both fundamental and applied aspects of teaching and learning in a given discipline;our emphasis here is on several science disciplines and engineering. The distinguishing feature of DBER is deep disciplinary knowledge of what constitutes expertise and expert-like understanding in a discipline. This knowledge has the potential to guide research focused on the most important concepts in a discipline and offers a framework for interpreting findings about students' learning and understanding in that discipline. While DBER investigates teaching and learning in a given discipline, it is informed by and complementary to general research on human learning and cognition and can build on findings from K–12 science education research.

DBER is emerging as a field of inquiry from programs of research that have developed somewhat independently in various disciplines in the sciences and engineering. Although biology education research (BER) has emerged more recently than similar efforts in physics, chemistry, or engineering education research, it is making contributions to the understanding of how students learn and gain expertise in biology. These contributions, together with those that DBER has made in physics and astronomy, chemistry, engineering, and the geosciences, are the focus of a 2012 report by the National Research Council (NRC, 2012).[1] For biologists who are interested in education research, the report is a



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[1]To download a free PDF version of the report, visit www.nap.edu/catalog.php?record_id=13362.

useful reference, because it offers the first comprehensive synthesis of the emerging body of BER and highlights the ways in which BER findings are similar to those in other disciplines.

In this essay, we draw on the NRC report to highlight some of the insights that DBER in general and BER in particular have provided into effective instructional practices and undergraduate learning, and to point to some directions for the future. The views in this essay are ours as editors of the report and do not represent the official views of the Committee on the Status, Contributions, and Future Directions of Discipline-Based Education Research; the NRC; or the National Science Foundation (NSF).

CHALLENGES TO UNDERGRADUATE LEARNING IN SCIENCE AND ENGINEERING

DBER and related research on teaching and learning have illuminated several challenges undergraduate students face in learning science and engineering. Indeed, "these challenges can pose serious barriers to learning and acquiring expertise in a discipline, and they have significant implications for instruction, especially if instructors are not aware of them" (NRC, 2012, p. 191).

One major challenge is accurate conceptual understanding. In every discipline, students have incorrect ideas and beliefs about concepts fundamental to the discipline. They particularly struggle with the unseen and with very small or very large spatial and temporal scales, such as those involved in understanding the interaction of subatomic particles or natural selection. As an example, many students believe the mass of a tree trunk comes from the soil, rather than the CO_2 in the air, because they have difficulty believing that air has mass (Koba and Tweed, 2009).

Students' incorrect knowledge poses a challenge to learning, because it comes in many forms, ranging from a single idea to a flawed mental model that is based on incorrect understandings of several interrelated concepts(Chi, 2008). It is less complicated to identify and address incorrect understandings of single ideas (e.g., all blood vessels have valves) than flawed mental models (e.g., the human circulatory system is a single loop rather than a double loop). Still, given that our goal is to help students progress toward more expert-like understandings, it is important for instructors to be aware of the misunderstandings that stand in the way of that goal and to have strategies for addressing those misunderstandings.

Understanding and using representations such as equations, graphs, models, simulations, and diagrams pose another major challenge for undergraduate students. Developing expertise in a discipline includes becoming familiar with representations unique to that discipline, such as evolutionary trees in biology, depictions of molecular structures in chemistry, and topographic maps in the geosciences. Experts in a discipline (here, professors) have long since mastered these representations and might no longer remember a time whenthese equations and images were new and confusing. However, in every discipline of science and engineering, students have difficulty understanding, interpreting, and creating representations that are unique and central to a given domain.

SOME INSTRUCTIONAL STRATEGIES FOR IMPROVING LEARNING AND CONCEPTUAL UNDERSTANDING

DBER has shown that specific instructional strategies can improve students' learning and understanding. For example, the use of "bridging analogies" can help students bring incorrect beliefs more in line with accepted scientific explanations in physics (Brown and Clement, 1989). With bridging analogies, instructors provide a series of links between a student's correct understanding and the situation about which he or she harbors an erroneous understanding. Another approach, interactive lecture demonstrations—in which students predict the result of a demonstration, discuss their predictions with their peers, watch the demonstration, and compare their predictions with the actual result—have been shown to improve students' conceptual understanding in chemistry and physics (Sokoloff and Thornton, 1997).

DBER and related research also point to several strategies that can be used to improve students' ability to use and understand diagrammatic representations. To this end, Hegarty (2011) suggests that instructors might:

- Explicitly point out the relationship among different displays of the same information to help students see the similarities.
- Explain the strengths and weaknesses of different representations for different purposes.
- Provide extensive opportunities for students to practice creating and interpreting diagrams of the desired type.

More generally, DBER and related research provide compelling evidence that student-centered instructional strategies can positively influence students' learning, achievement and knowledge retention, as compared with traditional instructional methods, such as lecture. These strategies include asking questions during lecture and having students work in groups to solve problems, make predictions, and explain their thinking to one another. As noted in the NRC report on DBER, the point is not to abandon lecture entirely, but to use a range of carefully chosen instructional approaches that can include lecture. When lectures are used, they should be designed with attention to how best they can support students' learning.

Despite compelling evidence for the effectiveness of student-centered approaches such as interactive lectures and collaborative activities, these practices still are not widespread among science and engineering faculty. In fact, science and engineering faculty are more likely than faculty in other disciplines to rely on lecture (Jaschik, 2012). Considering the many factors that influence decisions about instructional practices, it is not hard to understand why many faculty members hesitate to embrace more interactive classroom approaches. Even those who are interested in adopting research-based instructional methods might find challenges in departments and institutions that do not provide the needed supports for faculty to change their practices, from students who are resistant to change, and in reward systems that do not prioritize teaching. Still, with support from colleagues, professional societies, and others, many faculty members have overcome these and other challenges to transform their instructional practices.

THE CONTRIBUTIONS OF BER

What role has BER played in identifying students' challenges in learning biology and in helping to promote the use of research-based practices among biology faculty members? Most BER since the mid-1990s has focused on identifying students' conceptual understandings, developing concept inventories that measure students' understanding of a given concept, and studying the effectiveness of different types of instructional approaches that promote greater student engagement (Dirks, 2011). BER scholars use a variety of methods to study these problems. Depending on the questions being examined, these methods range from interview studies or classroom observations with a few or perhaps dozens of students, to quantitative comparisons of learning gains made with different instructional approaches across many courses or institutions. Much of this research focuses on students in the first 2 years of their undergraduate careers, typically in classroom settings in the context of large, introductory courses—the setting that provides the greatest challenge for generating engagement.

As the examples in the preceding sections illustrate, research in BER has produced some important insights into learning and, in some cases, guidance for improving teaching. A notable case of the latter comes from evolutionary biology, a field in which cognitive scientist Laura Novick and biologist Kefyn Catley have conducted extensive research about how students understand evolutionary relationships when different types of evolutionary tree representations are used (Catley and Novick, 2008; Novick *et al*., 2010). Their research shows that the form of representation that is most commonly used in undergraduate biology texts leads to the least understanding of this important evolutionary concept. As a result of their research, almost all introductory biology texts have now been changed to more effectively support undergraduate learning of evolutionary relationships, impacting the learning of hundreds of thousands of students each year.

These contributions notwithstanding, many opportunities exist to enhance the value of BER, and of DBER more generally. For example, despite the importance of fieldwork to biology, comparatively little BER has been conducted in the field. Other emerging areas of research in DBER—and in BER by extension—include longitudinal studies, studies that examine similarities and differences among different student groups, research related to the affective domain and the transfer of learning, and the development of assessments to measure student learning. According to the NRC's 2012 report on DBER, a specific challenge for BER scholars is to "identify instructional approaches that can help overcome the math phobia of many biology students and introduce more quantitative skills into the introductory curriculum, as computational biology and other mathematical approaches become more central to the field of biology" (NRC, 2003).

As BER grows, clarity about supporting BER scholars versus implementing BER findings to improve undergraduate biology education will be helpful. Regarding the support of BER scholars, the Society for the Advancement of Biology Education Research (SABER) provides a venue for BER scholars to share their research and support the development of early-career BER scholars. Several life sciences professional societies, including theAmerican Society for Cell Biology, the American Society for Microbiology, and the Society for Neuroscience, already offer professional development opportunities for faculty members to consider how to integrate BER findings into their teaching; others could use these models to do the same.

Findings from BER studies are increasingly accessible to those who are interested in using them to inform their teaching, as well as to those who might be interested in pursuing BER research programs. BER scholars publish their research on teaching and learning in a wide variety of journals. In a review of the BER literature from 1990–2010, Clarissa Dirks (2011) identified ~200 empirical studies on college students' learning, performance or attitudes. Although these articles appeared in more than 100 different journals, most were published in just four: the *Journal of Research in Science Teaching*, the *Journal of College Science Teaching*, *Advances in Physiology Education*, and *CBE—Life Sciences Education* (*LSE*). The past decade has seen a particularly rapid increase in the number of BER articles, especially in *LSE*.

Regarding the implementation of BER findings to improve undergraduate biology teaching, efforts are under way in several disciplines to help increase current and future faculty members' use of research-based practices. In biology, two notable examples are the National Academies Summer Institute for Undergraduate Education in Biology and the NSF-sponsored Faculty Institutes for Reforming Science Teaching (FIRST) program. The Summer Institute works with teams of university faculty, emphasizing the application of teaching approaches based on education research, or "scientific teaching." FIRST supports postdoctoral students interested in strengthening their teaching approaches. Although participants of the Summer Institute workshops reported substantial increases in their use of research-based instructional strategies over time (Pfund *et al*., 2009), an analysis of videotaped lessons from participants of the Summer Institute and the FIRST Program yielded mixed results concerning changes in practices (Ebert-May *et al*., 2011). It is important to note that alumni of the Summer Institute frequently reported that it took three or more years of experimentation before they could effectively implement learner-centered strategies (Pfund *et al*., 2009). As the NRC's 2012 report concludes, "These results suggest that measuring the influence of DBER and related research on teaching requires a nuanced, longitudinal model of individual behavior rather than a traditional 'cause and effect' model using a workshop or other delivery mechanism as the intervention" (p. 173).

Individual scholars in the BER community can promote the acceptance and use of DBER findings to improve undergraduate biology learning in two significant ways. One way is to enhance the quality of BER. As with any field, DBER has strengths and limitations. The greatest strength of DBER is the contribution of deep disciplinary knowledge to questions of teaching and learning in a discipline. In all disciplines, DBER could be enhanced by linking to other bodies of relevant research (including DBER in other disciplines), being explicitly grounded in theories of teaching and learning, using standardized measures for assessing learning gains and student attitudes, and conducting research on a larger scale than a single classroom and over longer periods of time than a single course. To link to other bodies of research, BER scholars could ask their DBER colleagues in physics, chemistry, and the geosciences to review draft manuscripts. SABER could help by establishing mechanisms to connect BER scholars to DBER studies in other disciplines; examples exist in engineering and the geosciences. And journal editors and reviewers could encourage the authors of BER articles to include citations of similar work in related fields.

BER scholars also can help to promote change at the departmental and institutional levels without assuming responsibility for sweeping reforms. Relatively straightforward strategies include disseminating key findings to colleagues or getting together on campus to discuss and strategize possible changes. BER scholars seeking a more active role in promoting institutional change might also help department chairs understand how to evaluate the research of BER faculty.

Given the unusually large number of diverse life sciences professional societies, the emerging coherence and focus of the biology undergraduate community on BER and improving learning in biology is notable. The growing body of BER literature and the professionalization of the field in the context of SABER in less than half a decade are cause for celebration. The American Association for the Advancement of Science Vision and Change in Undergraduate Biology (http://visionandchange.org) efforts and the associated Vision and Change Leadership Fellows program (www.pulsecommunity.org) to drive department-level change in biology education emphasize implementation of widespread adoption of BER findings. The trajectory is promising.

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