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Many stakeholders must cooperate to improve STEM undergraduate education.

The Climate for Undergraduate Teaching and Learning in STEM Fields

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Undergraduate education in the STEM fields (science, technology, engineering, and mathematics) needs improvement, a conclusion that multiple national reports over the past two decades have reached (American Association of Physics Teachers, 1996; National Research Council, 1989; National Science Foundation, 1996; Steen, 1987). In 2007, Brainard argued that efforts to enhance teaching in STEM fields continue to encounter resistance. Critiques of STEM education may emphasize different aspects of the STEM undergraduate education problem. Nevertheless, each delivers one clear and consistent message: undergraduate education in STEM fields is not adequate to the task of preparing workers for our technologically driven economy or developing a scientifically literate citizenry capable of engaging in informed dialogue and decision making on important public policy issues.

The report of the National Research Council's Committee on Undergraduate Science Education (1999) describes a nation divided into a technologically knowledgeable elite and a disadvantaged majority (National Research Council, 1999). The challenge facing educators in STEM is great. They need to "teach large numbers of students with diverse backgrounds and interests" (National Research Council, 2003, p. 2) and prepare them for a rapidly changing world where science and technology are increasingly important. As Nobel laureate Carl Wieman (2007) observed, "We need a more scientifically literate populace to address the global challenges that humanity now faces and that only science can explain and possibly mitigate, such as global warming, as well as to make wise decisions, informed

by scientific understanding, about issues such as genetic modification” (p. 9). To fulfill these objectives adequately, STEM teaching practices need to be more inclusive and flexible as the United States becomes increasingly diverse. If STEM education maintains a business-as-usual stance, our society will lose talent that we need in a competitive global economy (National Science Foundation, 1996) and an increasingly interdependent world.

Status of Teaching in STEM Fields

Many institutions are working to enhance teaching and learning in their STEM classrooms and laboratories, and many individual STEM faculty members and instructional teams are working hard to improve their instructional strategies. Harvard’s Eric Mazur and the University of British Columbia’s Carl Wieman are prominent examples. Each has implemented widely acclaimed innovative instructional strategies in undergraduate physics education (Brainard, 2007). At the same time, reports on the overall status of teaching in STEM fields are a source for concern. They tell us that a large proportion of STEM faculty have received little formal training in effective teaching techniques or how to assess learning. Generally STEM instructors teach as they were taught. Their approach to instruction is rarely influenced by learning theory or recent research on cognitive science (National Research Council, 2003).

Detailed studies of STEM teaching practices (Seymour and Hewitt, 1997) paint a fuller picture of the underlying problem with STEM undergraduate education. Many undergraduate classes occur in large lecture halls where instructional practices are constrained by architecture and seating arrangements. In addition, students complain about the poor quality of STEM teaching, especially in large lower-level classes, where student-teacher dialogue is limited. Undergraduate education in many STEM classes is heavily lecture based, encouraging students to be passive learners (National Research Council, 2003). In this environment, many students rely heavily on memorization of facts and formulas to pass tests (Brainard, 2007) and may fail to achieve genuine understanding of the STEM subject matter. Research shows that students retain only a fraction of the information presented in the typical lecture. Moreover, the traditional lecture is not an effective way to help students master the basic scientific concepts essential to advanced study and work in STEM fields (Wieman, 2007).

Specific criticisms Seymour and Hewitt report include instructors’ limited use of illustrations to clarify their points and achieve understanding of scientific concepts and processes. Similarly, they note the sparse discussion in many STEM classes of the practical applications and implications of the subject matter covered. Derek Bok, in *Our Underachieving Colleges* (2006), explains that teaching in basic mathematics courses is “likely to emphasize memorizing abstract rules, employed in formal, abstract ways, with little opportunity to consider applications to real life” (p. 130). Reports on the

nature of STEM teaching also describe the ineffective use of instructional technology in classes and mechanical lab exercises that fail to emulate the challenging and engaging process of scientific discovery. Bok also criticizes “cookbook problem solving” (p. 261) in undergraduate STEM courses.

Equally troubling is the climate that pervades many STEM classrooms and educational programs. Many introductory STEM classes have a competitive atmosphere that assumes a lot of students are not capable of succeeding. Bok’s comprehensive analysis of undergraduate education highlighted one likely source of this problem. Many introductory science courses are designed to build a foundation for students who intend to major in the field and possibly obtain a doctorate. Often these courses cover vast quantities of information that is considered essential for advanced study but is not necessary for a basic understanding of the field (Bok, 2006). Such courses can act as a filter, weeding out less desirable students whose interest in the subject matter is less certain or less intense. The atmosphere in such classes can signal many potential students that they do not fit in STEM fields or are not welcome. Hence, many students who could benefit from studying science and mathematics choose to transfer into other academic fields (National Research Council, 2003; National Science Foundation, 1996).

Forces Promoting Change in STEM Undergraduate Education

In spite of ongoing problems, there is good reason to be optimistic about the long-term future of undergraduate education in STEM fields. Many forces are advancing the cause of change and reform. Research in cognitive science and education has advanced understanding of the teaching and learning process (National Research Council, 2003). Brainard (2007) concluded from his investigation of the state of science teaching that new teaching models “have shown success in engaging and retaining undergraduates” (p. 16). A good example is North Carolina State’s Scale-Up teaching method, which provides a highly collaborative, hands-on, computer-rich, interactive learning environment for large-enrollment courses (Physics Education Research Group, 2007). Scale-Up reduced the failure rate to one-third of what is normal and dramatically reduced the failure rate of women and students from underrepresented groups (Brainard, 2007; Physics Education Research Group, 2007).

There is a great demand for scientifically trained workers to fuel our technologically driven economy. This need is compounded due to increasing global competition. Changes in the U.S. economy make clear that workers with strong backgrounds in science and technology fare much better in the workforce than do workers who lack scientific knowledge and skills.

Our ever more diverse population demands scientific education that is welcoming and accessible to many types of learners. Awareness is growing of the need to include diverse types of students in STEM fields if our society is

to have the skilled labor force it needs to enhance our standard of living and remain competitive in a global marketplace.

A large cadre of educational leaders and leading professional associations strongly advocates improvements in STEM education at the undergraduate level. Many influential groups and organizations acknowledge the need to reform STEM education and are working to improve undergraduate teaching and learning in STEM fields. A host of articles, reports, and books have appeared in recent years critiquing current practice and advocating improvements in STEM undergraduate educational strategies. Many professional organizations and disciplinary societies have joined the reform chorus, imploring their members and stakeholders to adopt more flexible, active, collaborative, and welcoming pedagogical practices that will reach out more effectively to diverse learners. The American Chemical Society is one example of an organization that promotes dialogue and action to improve undergraduate education in scientific fields. It publishes a journal on chemical education, provides instructional resources, and sponsors a variety of workshops on strategies to enhance chemistry instruction and student learning. Likewise, some accrediting organizations, such as ABET (Accreditation Board for Engineering and Technology), the chief accreditor of engineering education programs, are now heavily involved in efforts to strengthen undergraduate education in their specific fields.

Together these powerful developments and influential organizations comprise a potent force for change in the standard ways that STEM undergraduate education is delivered. Their combined efforts have promoted a national dialogue on the STEM education challenge as well as many institutional and individual faculty efforts to improve undergraduate education in STEM fields. It would seem that the synergy created by these many complementary efforts to improve undergraduate STEM education would be irresistible. However, reform has been slow and erratic, taking root in some places but not others. Often creative new initiatives have lost momentum over time as forces of inertia (which every scientist knows are both natural and inevitable) take hold.

Barriers to Reform in STEM Undergraduate Education

Many factors account for the slow, sporadic pace of reform in undergraduate STEM education. Certainly the limited training of STEM faculty for their teaching roles is a factor. The lack of knowledge of the teaching and learning literature and the many types of instructional strategies places limits on what many STEM faculty do in their classrooms and laboratories to encourage undergraduate learning.

The faculty evaluation and reward system in place in many higher education institutions also discourages efforts to enhance undergraduate education in STEM fields. With the faculty reward system balanced in most STEM fields on the side of research (National Science Foundation, 1996), many fac-

ulty members choose to invest their limited discretionary time in their research and writing for publication rather than their teaching.

Overall, the climate in many colleges and universities and in the academic profession as a whole does not seem conducive to enhancing undergraduate education in STEM. Many reports discuss the lack of resources to support pedagogical development in STEM (National Science Foundation, 1996) and the absence of incentives to study the literature on teaching and learning (National Research Council, 2003). Similarly, the limited rewards for course and instructional improvements discourage STEM professors from investing the time and energy required to update and upgrade their approaches to instruction (National Science Foundation, 1996). The National Research Council, National Science Foundation, American Chemical Society, and other organizations advocate reform in STEM education and publish materials on how to implement educational improvements. At the same time, this information on good instructional practice has not had a widespread impact on STEM education at the undergraduate level. The autonomy of discipline-based departments and the freedom of faculty members to run their classrooms as they wish certainly inhibit widespread change.

Today many of the efforts to strengthen undergraduate education in STEM continue to rely on individual faculty or small faculty groups who are committed to the cause of improving science or technology education in their department or institution. Daniel Udovic's Workshop Biology at the University of Oregon, which replaced traditional science lectures with a series of active, inquiry-based modules, is a good example of one's professor's effort to improve teaching and learning in his discipline. Another is Janine Trempy's course, *The World According to Microbes*, at Oregon State University. This problem-based, cross-disciplinary course integrates science, mathematics, and engineering and serves both majors and nonmajors (Handelsman and others, 2004). Trempy equated her own experience as an undergraduate student in general science courses to "long-winded lectures, intimidating tests and non-applicable lab experiments" (Oregon State University News and Communication Services, 1996). A citation naming her the 1996 Oregon Professor of the Year explains Trempy's determination "to create courses where students acted, rather than just listened. Where they worked together to solve real problems. Where they remembered what they learned. And where students ranging from philosophy to physical education worked together to share their expertise and learn directly from each other" (Oregon State University News and Communication Services, 1996). Regrettably, individual science teaching innovations like these have been slow to catch on. "Reform has been initiated by a few pioneers, while many other scientists have actively resisted changing their teaching (Handelsman and others, 2004).

Fortunately, the innovative teaching strategies of some STEM professors have gained considerable attention and influenced the instructional practices of colleagues far beyond their own campuses. Carl Wieman's experiments

with personal-response systems (“clickers”) and Eric Mazur’s peer instruction technique are noteworthy examples (Wieman, 2007). However, it is doubtful that profound change in STEM undergraduate education can be achieved through the bold and creative initiatives of single professors working hard to enhance the learning of students in their STEM classes. The history of STEM undergraduate education shows that reform at the level of the individual professor is not sufficient to implement the holistic change needed to transform STEM undergraduate education. This fact does not minimize the important role individual professors and faculty groups must play in creating a climate for enhancing teaching and learning in STEM fields. However, as Susan Millar, a senior scientist in the School of Education at the University of Wisconsin–Madison, has observed, “I don’t know that you can take these kinds of [innovative STEM education] programs to scale when the unit of change is the individual” (Brainard, 2007, p. A17).

Improving the Climate for Strengthening Undergraduate Education in STEM

Many elements of the formula for implementing comprehensive reform of STEM undergraduate education are in place. Yet the climate for enhancing STEM undergraduate education remains challenging, if not hostile. No single action or initiative, no matter how substantial or well meaning, seems adequate to catalyze widespread reform of STEM undergraduate education that reaches the level of specific STEM departments and individual classrooms and laboratories. Many actions, inside and outside higher education, are needed to improve the environment for enhancing teaching and learning in STEM.

The lone wolf approach to improving STEM undergraduate education is not sufficient to meet the challenge of preparing a technologically competent workforce and a scientifically literate citizenry. Many STEM education innovations and improvements will not survive, let alone proliferate, without major changes in the STEM culture and the policies and practices of higher education.

This analysis of the current climate surrounding STEM undergraduate education suggests that a number of complementary initiatives are necessary to make that climate more conducive to widespread and lasting reform. First, STEM faculty need ready access to practical, easy-to-apply information on how students learn. They also need opportunities to learn about effective instructional strategies. Dialogue with colleagues on teaching challenges and opportunities to experiment with varied instructional techniques is one way to foster a climate receptive to STEM educational reform. Revisions of evaluation and reward policies, including the criteria for tenure and promotion, are another step necessary to improve the climate for strengthening undergraduate STEM education. Until investments in improving teaching yield consequential recognition and rewards, faculty will favor

research when they set priorities and distribute their limited time. Rewarding scholarship on teaching and learning in STEM fields is another way to enhance the climate for strengthening undergraduate teaching and learning. Giving meaningful professional credit to STEM educators for studying the learning process in their classes and labs will reinforce their efforts to improve their teaching. Incentives for experimentation and innovation in the classroom are also needed to improve the climate for undergraduate education in STEM. Moving beyond conventional instructional methods in STEM requires professors to try out new and unfamiliar techniques that may or may not work with their students. The culture of science values a spirit of risk taking and innovation in the laboratory or the field. It should also promote experimentation in the classroom by rewarding faculty for their efforts and not penalizing them when well-intended educational innovations do not live up to their original promise.

Creating a climate for improving undergraduate STEM education requires a collaborative effort at many levels. Scientific organizations and professional societies are an important part of the equation for success. They should examine the effectiveness of their efforts to communicate with STEM educators and ask how they can be more helpful in promoting change. In particular, influential organizations such as the National Science Foundation, National Resource Council, STEM accrediting agencies, and others have an important role to play as agents of cultural change. They can use their considerable resources and influence to stress the importance of enhanced undergraduate education to the future vitality of STEM fields.

Institutional leaders, including presidents, provosts, and deans, also have a critical role to play in creating a climate that supports improvements in STEM undergraduate education. They can focus attention on the STEM education issue and allocate resources to support key reform initiatives. By publicly identifying STEM education as a priority, they can promote useful dialogue and action. Without the stimulus that key institutional leaders can provide, the status quo in STEM education is likely to prevail on most campuses.

Genuine reform of STEM undergraduate education must take root at the department level, or all other efforts to promote improvement will be meaningless. Individual departments, led by their chair and respected colleagues, must engage the STEM education issue within their own environment. They should look for barriers to educational improvements and identify concrete actions they can take to strengthen the undergraduate education they provide. If sustainable reform is to occur, departments must consider how they can use their teaching assignments, faculty and budgetary resources, evaluation criteria, and rewards to promote innovation and improvements in their undergraduate programs.

Professors who experiment with educational improvements in their classrooms and share their experiences and outcomes with colleagues help to develop a culture of improvement in their departments and institutions.

Similarly, STEM faculty members who meet regularly to talk about teaching and learning issues or to discuss books or reports on effective teaching practices also help to build a climate that supports improvements in STEM undergraduate education.

Conclusion

A meteorologist looking at the climate for undergraduate teaching and learning in STEM fields might conclude that the forecast is mixed. There are positive signs on the horizon as well as some threatening conditions. This forecaster might conclude there is a 50 percent chance that the climate for STEM education will improve substantially.

When the weather forecast is less than favorable, all we can do is complain or take a defensive stance and seek shelter. Fortunately, the climate for improving undergraduate STEM education can be improved substantially by the actions of many concerned stakeholders: professors, educational leaders, professional societies, and government agencies, among others. We hope that each will choose to play a role in this important effort to strengthen undergraduate education in STEM fields.

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