Improve undergraduate science education

It is time to use evidence-based teaching practices at all levels by providing incentives and effective evaluations, urge **Stephen E. Bradforth**, **Emily R. Miller** and colleagues.

Undergraduate students are not being taught science, technology, engineering and mathematics (STEM) subjects as well as they need to be[1]. Too often, faculty members talk at students rather than engaging them in activities that help them to learn and apply core scientific concepts and skills. Despite growing scholarship about effective teaching methods and meaningful ways to assess them[3], research universities rarely provide adequate incentives, support or rewards for the time that faculty members spend on improving teaching. And faculty members assign a low priority to undergraduate teaching compared to research[4]. Efforts to improve undergraduate STEM education have been slow and piecemeal at best.

The time is now ripe for change. Today we can collect, analyse and assess individual and institutional data on teaching effectiveness and student outcomes in ways not previously possible. There are also successful models for supporting and rewarding scientists to be both excellent teachers and researchers.

We write as representatives of the Association of American Universities (AAU) and the Research Corporation for Science Advancement Cottrell Scholars, a group of research-active science faculty members. We call for immediate change at all levels of research universities to improve the quality of university STEM education. It is no longer acceptable to blame primary- and secondary-school teachers for the deficits in STEM learning at the university level.

To facilitate change, we outline here rigorous examples of best-in-class pedagogical practices, programmes and policies. Many of these ideas are not new — but the robustness of implementing and evaluating them is.

Although our experiences are in the United States, these principles are more broadly applicable. No single tool will work for all universities, but every university now has at its disposal the tools to improve undergraduate STEM teaching, and no defensible reason for not using them.

Valuing teaching must move from rhetoric to reality. Too many students at North American universities who intend to major in STEM fields do not end up doing so, often because of the traditional teaching practices used[5].

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The Yale Center for Engineering Innovation and Design is used by engineering as well as art students.

Active learning interventions improve achievement for all students; those with disadvantaged and ethnic-minority backgrounds gain the most[6]. Administrators and faculty members have a responsibility to ensure that introductory classes do not push students away from STEM courses but promote critical thinking, problem solving, engaged learning and knowledge retention for all students, whether they intend to major in STEM fields or not. Effective STEM teaching is crucial to developing a science-literate population that can address the complex and interdisciplinary health, energy, security and environmental challenges of our time.

CLASS ACTION

For decades, North American universities have relied almost exclusively on end-of-term student surveys of little use in assessing teaching performance[7]. Unfortunately, other nations have followed suit. Faculty members tend to be assessed and promoted mainly on the basis of research success, which, unlike teaching, is readily quantified — through grant funding, the number and perceived importance of publications, and citation metrics. These systemic obstacles have proved resistant to change.

There are indications, however, that we are approaching a tipping point. Scientific knowledge about effective teaching methods has increased, as outlined in a 2015 report by the US National Research Council[7], which follows up on a 2012 report[3] that synthesized literature from several fields on how students learn, particularly in scientific disciplines, and ways to improve instruction.

Policy-makers are increasingly questioning the value of an undergraduate education from a large research university given its rising costs, and they are calling for accountability and efficiency measures. And faculty members are re-evaluating their teaching methods in response to competition from the increasing number and quality of massive open online courses (MOOCs) and other online offerings.

Past efforts to improve teaching have focused on individual faculty members. The AAU Undergraduate STEM Education Initiative, launched in 2011, has been exploring a more systemic view of educational reform. It is based on understanding the wider setting in which educational innovations take place — the department, the college, the university and the national level. Thus, it emphasizes the separate roles of senior university administrators (who can implement top-down change), individual faculty members (bottom-up change) and departments (change from the middle out), all of which are necessary for sustained institutional improvement to undergraduate STEM teaching and learning[8].

We suggest strategies that target changes at each of these levels, inspired by what we have learned from the initiative and from individual faculty members' experiences.

BOTTOM UP: FACULTY MEMBERS

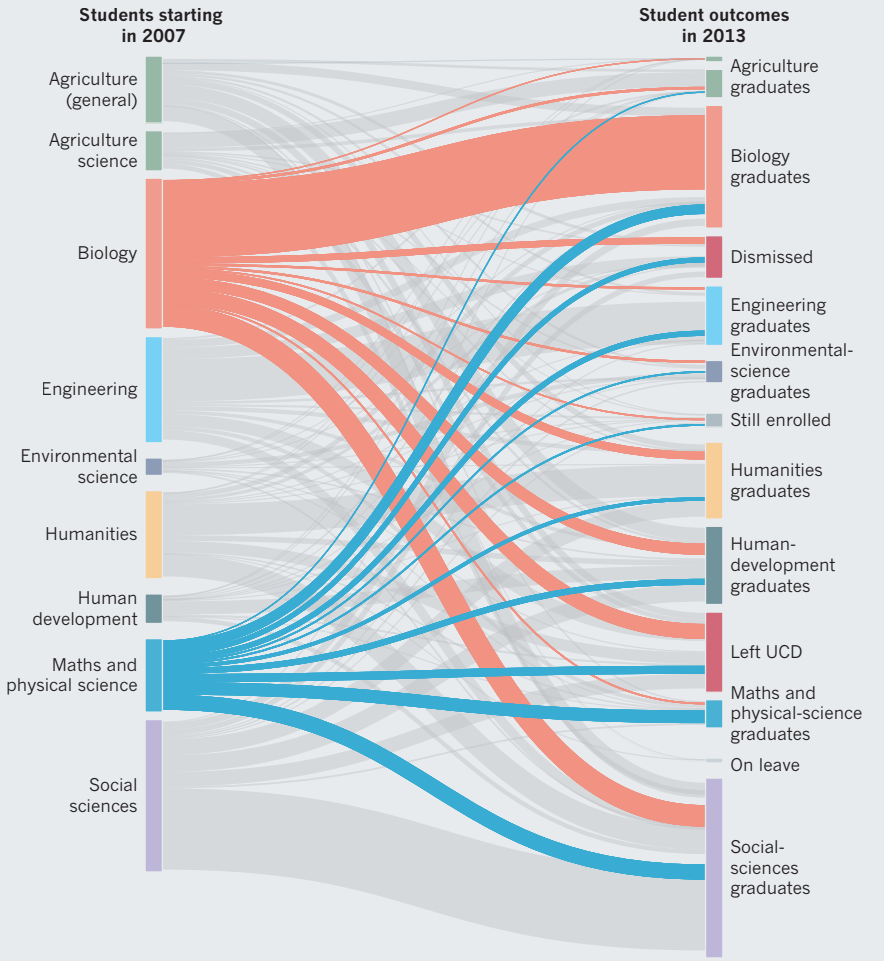
Effective teaching begins with faculty members, who maintain significant autonomy over their practices. Most care deeply about teaching, in addition to their strong interest in research. However, they rarely obtain informative feedback about their students' learning and often are unfamiliar with improved teaching practices. Moreover, they lack the resources and support to devote a significant proportion of their time to change their current practices.

Increase scientific and reflective teaching. Faculty members need to shift their perspective from "What did I teach?" to "What did my students learn?" They must aim to create engaging learning environments in which students are participants rather than passive note-takers or followers of 'cookbook' laboratory experiments. Faculty members should experiment with evaluation strategies such as classroom observation protocols and pre- and post-course testing, which can guide mid-course adjustments. The Yale Center for Scientific Teaching in New Haven, Connecticut, has demonstrated the value of such strategies, and trains faculty members, instructors, postdocs and graduate students in their use.

Increase student engagement in learning. Students learn better when they participate in and reflect on their own learning process. One way to assess students' project ownership is linguistic analysis. In responses to open-ended course-evaluation questions, the use of first-person personal pronouns and emotional words — for example, "my research made me excited about science" — correlate with student ownership of learning. Excellent teachers facilitate this, and it is one of the psychosocial factors involved in retaining students in the sciences[9]. Exemplary programmes using this tool to measure student engagement in STEM education are the University of Texas at Austin's Freshman Research Initiative and Yale's Rainforest Expedition and Laboratory courses.

CHARTING A PATH

Visualizing students' educational journeys has informed recruitment and retention efforts at the University of California Davis (UCD). The tool was developed by the iAMSTEM HUB in Undergraduate Education.



SOURCE: UCD

TOP DOWN: SENIOR ADMINISTRATION

Beyond the classroom, institutional infrastructure — physical and organizational — is required for effective teaching. Senior university administrators have crucial roles in creating a culture that values teaching and a support structure that drives continuing improvement and innovation. Value and mission statements are not enough.

Recognize and reward good teaching. To influence how faculty prioritize their efforts, university administrators must promote excellent teaching at all levels. A powerful example of this concept is the establishment of endowed chairs for educational excellence in STEM departments, such as the professor of STEM education in the chemistry department at Washington University in St. Louis, Missouri. This chair acknowledges and funds faculty members' innovative research and teaching. Industrial and alumni benefactors can support such chairs.

Encourage faculty buy-in. Senior university administrators must support deans and department heads with professional development, assessment tools and other resources to improve teaching. This is crucial if faculty members are to step out of their comfort zones and introduce proven teaching techniques, some of which students may initially resist, being accustomed to traditional 'chalk-and-talk' lectures. The Nucleus programme at the University of Virginia in Charlottesville seeks proposals from departmental teams to promote significant and sustained change in introductory STEM courses. Funds are awarded to both the faculty members and chairs to support the changes.

Centralize and make accessible data and analytics. Universities accumulate volumes of longitudinal data that have been underused in assessments of student learning and degree progress. Robust, scalable and centralized

campus-wide analytics leverage existing data and reduce the need for multiple assessment tools. For example, the iAMSTEM HUB at the University of California, Davis, offers tools to visualize student pathways through courses and programmes. At its most basic level, the ribbon-flow tool (see 'Charting a path') informs recruitment and retention efforts by visualizing the starting and ending disciplines for student year groups.

Findings should be shared with departments and faculty members to inform discussion and action. The iAMSTEM HUB formed a community of institutions to share analytical and visualization tools, called Tools for Evidence-Based Action. The Committee on Institutional Cooperation is an academic consortium of 15 research-intensive universities that includes the University of Michigan in Ann Arbor and the University of Wisconsin–Madison. It has embarked on a learning and research analytics project and shares results on a common set of student success measures.

Use teaching improvement as a fund-raising lever. Alumni, as well as private and public-sector employers, have direct interests in enhancing the university teaching and learning experience. Senior administrators should incorporate into their fund-raising campaigns well-articulated initiatives to improve STEM education.

MIDDLE OUT: COLLEGES AND DEPARTMENTS

Improvements at the top and bottom are sustainable only if combined with changes at the colleges (subsets of universities) and departmental levels that foster a team culture of continuous teaching improvement.

Develop learning objectives for introductory STEM courses. Curriculum design must include appropriate learning objectives for introductory service courses and those required for major subjects. For example, the Force Concept Inventory — broadly adopted by the physics discipline — identifies core concepts that should be mastered by all first-year undergraduate physics students. Faculty members need to align their course curricula to these departmental learning goals, in both content knowledge and skill development.

For example, Michigan State University in East Lansing is changing how introductory biology, chemistry and physics are taught, by redesigning course curricula and assessments. Faculty members have debated core disciplinary ideas, cross-cutting concepts and scientific practices. Each discipline has generated a list to transform the introductory curriculum and is now developing assessments for all three dimensions of learning.

The chemistry department at the University of Arizona adopted a course called Chemical Thinking, a redesigned general-chemistry module that has improved students' learning, retention of information, and performance in advanced courses. The course focuses on group discussions and problem solving. Faculty members spend less than ten minutes lecturing in an hour-long class.

Give faculty members the time and resources to improve teaching. Teaching assignments should accommodate the challenges and time necessary to improve methods and integrate new assessment techniques. Departments should reallocate funds to support teaching innovation and encourage staff to use campus centres for teaching and learning. At the University of Kansas in Lawrence, the STEM departments and the Center for Teaching Excellence have partnered to fund teaching postdocs to help redesign courses.

Encourage peer support and cross-departmental dialogue. Colleges and departments need to stimulate discussion of and respect for teaching. Such discussions can be strengthened through co-teaching arrangements, in which two people share course instruction and mentor each other. This approach has been successful in the College of Biological Sciences at the University of Minnesota, Twin Cities, and the University of North Carolina at Chapel Hill. Both co-teachers receive full workload credit.

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Evaluate teaching with meaningful metrics. Departments and schools should supplement alternative student evaluations with metrics for teaching performance. Methods can be chosen on the basis of the needs and resources of each institution and include pre- and post-course testing, classroom observation and reflective teaching statements or portfolios. The emphasis on student evaluations must shift from reflecting the popularity of instructors to effectively assessing learning. Macquarie University in Sydney, Australia, has established a teaching index to recognize and financially reward departments for the volume and quality of faculty members activity dedicated to teaching.

Make teaching count for promotion and tenure. Review committees must be trained to evaluate, use and weigh up data on teaching and learning, following carefully crafted guidelines. In 2007, the University of British Columbia in Vancouver, Canada, launched a major science-education initiative led by Nobel-prizewinning physicist and educator Carl Wieman with the goal of transforming undergraduate science and mathematics. From this initiative emerged a tenure track for teaching faculty, whose promotion depends on excellence and leadership in education, with much less emphasis on research. This has generated guidelines for measuring teaching effectiveness. These measures should be examined for research faculty as well.

SCHOLARLY TEACHING

Progress is likely to be slower than many of us would prefer. Moving forward will require a commitment at all levels to share and adapt the practices highlighted, to achieve systemic and sustainable change in undergraduate STEM education. It will require a reallocation of funds — not just priorities.

As a first step, institutions, colleges and departments must expect and enable their faculty members to be scholarly about teaching. And they must assess, recognize and reward those who are. ■

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