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Critical Steps Toward Modernizing Graduate STEM Education

Maintaining US leadership in graduate STEM education will require a focus on a wider range of skills beyond those needed for academic research.

The US system for graduate education in science and engineering is widely regarded as the best—or at least among the best—in the world, as evidenced in part by the many thousands of students from other countries who come to the United States each year for their graduate training. At the same time, there is wide recognition that in many institutions the US model of graduate education has failed to stay current with trends in the way science is conducted and with the nature of the student population and their career interests and opportunities. In fact, since a major report by the National Academies of Sciences, Engineering, and Medicine in 1995, over 20 studies and reports on graduate science, technology, engineering, and mathematics (STEM) education have come to that same conclusion: graduate STEM education in the United States needs to be modernized. The changes recommended in these studies have been quite consistent, and include the need to create a more inclusive and equitable environment to enable all members of a very diverse student population to thrive; to improve the quality of teaching, advising and mentoring; and to modernize the curriculum and capstone projects to better focus on core competencies and better reflect the way science is now being done.

Why has there been so much inertia in the system, and what needs to be done and by whom to help make the graduate STEM education system move forward? We were recently involved in a new National Academies report—*Graduate STEM Education for the 21st Century*—which directly confronted these questions.

This report differed from the many earlier reports in that it laid out what would constitute an ideal graduate STEM education and an action plan for achieving that ideal, including specific steps to be taken by all stakeholders. We here discuss some of its major points, including what is needed to stimulate system change at a national level.

Central to making any pervasive change in STEM graduate education will be significant attitudinal, behavioral, and cultural changes throughout the system. The ways that faculty approach graduate education must be fundamentally reoriented to include a greater focus on the interests and needs of the students. The purpose of graduate education can no longer be exclusively, or even predominantly, to produce more academic researchers. Graduates today are using their training to pursue a much wider range of careers than in the past, and the nation needs well-trained scientists in government, industry, and other settings. The fundamental skills needed in all these settings are basically the same—broad technical literacy as well as deep specialization in an area of interest, an understanding of the ethics and norms of the enterprise, and the ability to communicate findings both to colleagues and the broader public. However, in addition to these capabilities, students need to learn about or at least become familiar with the wider range of skills needed in the nonacademic settings where they want to work, so less retraining is needed when they get there.

An ideal graduate program

What would an ideal graduate education look like, and what actions need to be taken to begin to approach that ideal? In the first place, graduate programs should publish very clear data about the outcomes and career paths of their alumni, so that prospective students can make more informed and relevant choices about where to go to graduate school. The ideal program would then provide opportunities in the first year for students to sample a variety of laboratories and mentors before they make final choices about what professors they should work with. Higher education institutions should provide training for all prospective mentors and advisers, and retraining when needed for current faculty, to ensure students have appropriate and consistent faculty support. Opportunities such as internships, special courses, and professional development activities would be provided for students to learn what it might be like to pursue a career in a nonacademic setting—in business and industry, government, and the nonprofit sector. Particular attention would be paid to the needs of students from diverse backgrounds, and they would be educated in inclusive and equitable environments that maximize the probability of their success. Institutions would increase availability of mental health services and similar supports for students and would provide faculty, administrators, and leadership with strategies to improve campus environments and do a better job fostering success for all students.

Central to achieving this proposed ideal STEM graduate education is the concept of "core competencies"—the skills and knowledge base that are the essence of what it means to be a master's or doctoral graduate, competencies that all students must achieve, no matter what their career goals or interests might be. These core competencies would be the main focus of graduate education, with other experiences and coursework supplementing them. For master's students, the core competencies include a foundation in the content and research practices aligned with the student's disciplinary focus, as well as a set of transferrable, professional skills. Examples of core competencies at the doctoral level include, as one might expect, both broad and deep scientific and technological literacy and the ability to do original research. The core competencies would also include a set of leadership, communication, and professional skills, including an understanding of the norms and values of the STEM enterprise and the ability to communicate both to one's peers and to the broader public community.

Students would gain experience working in teams, preferably multidisciplinary teams, since that has become so typical of modern scientific research. Moreover, dissertations or capstone projects might well take different forms—for example, using narrative or multimedia approaches—again to better reflect trends in both modern science and professional opportunities.

Local control makes systemic change difficult

There is a good reason that 25 years of agreement about the need for graduate STEM education reform has yielded such little progress: cultivating change across a broadly distributed system is hard. Like virtually all US higher education, STEM graduate education is locally controlled, both at the institutional and even the departmental level. Importantly, and as it should be, the curriculum is controlled at the level of the faculty, and top-down attempts to order changes in curricula from academic leaders have typically been failures. Although there are some constants within graduate schools, such as the apprenticeship or mentorship model that seems pervasive, no single body controls what goes on across all of them. There is no set of rules that prescribes exactly what graduate programs will look like. There is national accreditation, but also great diversity both across and within institutions. That variation is both a strength and a limitation. The diversity among programs allows for adaptation to the local context and unique characteristics of departments, disciplines, and their individual faculties. It is also a limitation in that "no one is in charge": if there is a need for change, there is no body or organization that can dictate the nature of change across the system. Faculty do learn from their own graduate experiences and then from colleagues in other departments and institutions, but ultimately the lack of any controller makes it very difficult to move the system into new directions.

Academic incentives are critical

What makes achieving the ideal particularly difficult is that the incentives that currently drive so much of academic culture and faculty behavior are misaligned with achieving the goals outlined in the National Academies' report. Criteria for promotion and tenure typically are too heavily weighted toward research productivity in the form of publications in prestigious journals and research grants received from federal agencies, with far too little emphasis given to the quality of graduate student teaching and mentoring. The balance between research activities and education and mentorship must be readjusted to give more emphasis to quality education. Doing so would also provide a mechanism for more appropriately rewarding those faculty who have consistently dedicated significant attention to the development and growth of graduate students, at times at a cost to their own research productivity. This would be a radical change for many institutions, and it will come about only with clear commitment from every level of the university, including the president, provost, graduate dean, and other administrative leaders, and including all levels of the faculty, particularly department heads and promotion and tenure committees.

Yet academic incentives are not solely under the control of academic institutions because the state and federal agencies that fund academic research and training also often employ granting criteria that are biased against the sorts of changes we are advocating, even for purported education and training grants, and these criteria significantly influence faculty behavior. Grant review criteria—and, frequently, peer reviewer behavior whatever the stated criteria—typically emphasize the traditional research productivity measures, such as number of papers published, numbers of citations, and journal impact factor. Faculty looking for grant support, understandably, then respond by focusing their efforts most heavily on producing and publishing research results, at times at the expense of their educational responsibilities. To help modernize the system, funding agencies will need to realign their award criteria, particularly for training grants, but also for research grants that include support for graduate research assistants, to give more emphasis to the quality of teaching and mentoring. Such realignment is entirely consistent with the missions of government agencies that fund graduate STEM research, which always include a commitment to assuring that the nation has a vibrant future STEM workforce. Adjusting the weights assigned to their funding criteria would have a domino-like effect on incentives employed throughout the higher education system.

The student-mentor relationship is critical

The quality of all students' graduate experience depends highly on the nature of their relationships with their mentors and other advisers. The National Academies committee that produced the new STEM report held focus groups and met with many graduate and postdoctoral students during its work. Those discussions revealed great variability in mentor relationships. Although some students reported positive experiences, many cited relationships ranging from benign negligence to well-intentioned yet ultimately unsupportive behavior to more problematic and frustrating behaviors. Too often students felt as if their mentors saw them as employees or research technicians, rather than as students they had a responsibility to serve. As harsh as such criticism may seem, it is not surprising, given that the academic incentive system is so heavily weighted toward research productivity and against quality mentorship. The mentors and advisers who commit themselves to providing quality guidance to their students often do so without their efforts being counted toward promotion, tenure, grants or other funding, and general career advancement and recognition.

But better mentoring is not just a matter of incentives; it is also a question of skill, and fortunately effective student mentoring is a skill that can be taught. Of course, some people are naturally more empathetic and nurturing than others, but those traits are not enough. Mentors need to be willing and able to teach effectively and to advise their students on career paths and opportunities. Because better mentoring can be learned, higher education institutions should require formal training for all new mentors and provide ongoing professional development for those more experienced mentors who seem to need it.

Incoming graduate students, in turn, should be exposed during their first year to multiple laboratories and mentors, before they are required to choose among them for the rest of their graduate programs. Many institutions are now doing this, and they and their students report great satisfaction with this approach.

Diverse, inclusive environments are essential

Graduate institutions must also ensure that they are providing a learning environment in which all students can thrive. Over the past decades there has been a major shift in the student population, with more women and members of underrepresented minorities interested in joining the scientific workforce. However, many women and minority students report that they do not feel included in the same way as are men or nonminority students. Faculty and administrators need to develop, implement, and continually assess strategies, starting with admissions policies, that not only increase diversity and inclusion of graduate students but also assure retention of such students throughout the process of achieving an advanced STEM degree.

Real change requires a systems approach

Modernizing graduate STEM education will require a systems approach that includes actions from each relevant member of the system. For example, all institutions and departments should collect and make easily available data on student outcomes and career paths, so that incoming students can select their graduate programs in an informed way. Faculty should regularly reevaluate the curriculum to ensure it accurately reflects the way science is currently conducted in their field. Departments should also ensure they are providing students with a full array of core competencies necessary for professional development and examine carefully what might be extraneous course requirements that may not really matter to eventual success as a scientist. Employers from all sectors should engage with higher education institutions to help them shape curricula and other educational experiences to maximize their effectiveness in preparing graduate students for future careers. And graduate students should themselves seek opportunities to work in cross-disciplinary teams that promote multidisciplinary learning, team collaboration, and a variety of problem-solving approaches.

Change is under way

Fortunately, institutional stakeholders in graduate STEM education have started working intensively to improve the enterprise's capacity to serve students and the national interest. For example, the National Institutes of Health's National Institute for General Medical Sciences updated its training grant solicitation to have a greater focus on students and on encouraging the development of skills for careers in the broad biomedical research workforce. Its requirements are consistent with our recommendations. More recently, the National Science Foundation sent out a "Dear Colleague Letter" announcing a program that enables any graduate student it funds to apply for supplemental support for exploring career opportunities in any sector to "ensure graduate students are well prepared for the 21st-century STEM workforce." Private funders, such as the Howard Hughes Medical Institute, have also made changes to support a more student-centric graduate education experience with a focus on increasing mentoring resources, training, and requirements for faculty fellowships.

The Association of American Universities in December 2017 announced the PhD Education Initiative to ensure that diverse career pathways are "visible, viable, and valued" through shifts in the culture of graduate departments, increase the transparency and use of PhD program data, and share effective practices among its member institutions. Twenty-nine members of the Council of Graduate Schools have joined the Understanding PhD Career Pathways for Program Improvement effort, in which participating institutions collect data from current students and alumni to understand career trajectories. The aim is for those data to inform incoming graduate students on the professional development and career services provided on each campus. Universities participating in the Coalition for Next Generation Life Science, an agreement of nine research universities and a cancer institute to improve transparency and trainee outcomes in the life sciences, have committed to publishing data on life science PhD and postdoctoral programs, with an added emphasis on postdoctoral researchers. The coalition is also emphasizing career support for diverse career paths, improved doctoral and postdoctoral mentoring, and improved diversity and retention of life sciences graduate students.

These ongoing efforts are a significant start on modernizing the system, and they reflect an encouraging, growing recognition of the need for reform. However, the changes these efforts will produce will inevitably be small relative to the scale of the entire graduate education system. Many more such efforts will be needed to make pervasive system change that can push graduate STEM education toward the ideal that we have outlined here. If we were to select the one set of actions that could most effectively catalyze such pervasive change, it would be for state and federal funding agencies to adopt funding criteria that can help shape academic incentives and culture. We realize that the necessary changes will not be easy to make, and that they will require new investments in both money and human resources, but these are the costs of assuring both graduate student success and the future of the United States' STEM enterprise.

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