Summary

The U.S. system of graduate education in science, technology, engineering, and mathematics (STEM) has served the nation and its science and engineering enterprise extremely well. In many ways, it is the "gold standard" for graduate STEM education in the world as evidenced by, among other measures, the substantial number of international students coming to the United States to study. Over the course of their education, graduate students become involved in advancing the frontiers of discovery, as well as in making significant contributions to the growth of the U.S. economy, its national security, and the health and well-being of its people. However, continuous, dramatic innovations in research methods and technologies, changes in the nature and availability of work, shifts in demographics, and expansions in the scope of occupations needing STEM expertise raise questions about how well the current STEM graduate education system is meeting the full array of 21st-century needs. Indeed, recent surveys of employers and graduates and studies of graduate education suggest that many graduate programs do not adequately prepare students to translate their knowledge into impact in multiple careers.

To respond to these issues, the National Academies of Sciences, Engineering, and Medicine appointed the Committee on Revitalizing Graduate STEM Education for the 21st Century. The committee was charged with examining the state of U.S. graduate STEM education, last fully reviewed by the Academies in 1995, and how the system might best respond to ongoing developments in the conduct of research on evidence-based teaching practices[1] and in the needs and interests of its students and the broader society it seeks to serve. Over the course of 18 months, this committee examined a wide array of data about the U.S. graduate STEM education system and held focus groups and discussions with diverse stakeholders, including students, faculty, university administrators, industry leaders, and policy makers. The committee also commissioned specialized analyses to review the scholarly research on educational practices at the graduate level to help inform its work.

[1] The committee was unable to explore graduate-level teaching practices in STEM in great detail during the course of this study as a result of the limited available research; however, the committee did consider the translation of undergraduate STEM education practices such as the Association of American Universities framework for effective STEM teaching at the undergraduate level.

ABOUT THIS REPORT

This is not the first—nor will it likely be the last—report focusing on American STEM graduate education. A combination of elements, however, make it unique. First, this report calls for a systems approach to moving graduate STEM education forward. The goals laid out in this report will only be accomplished with a consistent and robust commitment from all stakeholders in the nation's scientific enterprise and in its STEM graduate education system. Chapter 6 articulates the actions needed by each stakeholder group.

Second, this report proposes an ideal graduate STEM education and then recommends action steps for each stakeholder in the system to help achieve that ideal. A central element of the strategy laid out here is to make the system more student focused while maintaining the central attributes that have made it the gold standard for the world.

A critical element is the report's articulation of the core competencies that all students who have been through U.S. graduate STEM education should acquire, at both the master's and the Ph.D. levels. While the report recommends that students be offered some supplemental coursework and training experiences, the committee feels strongly that instilling those core competencies should remain the American graduate STEM education system's primary task.

After laying out the reasons for the committee's work in Chapter 1, the report, covering both master's and doctoral STEM education, lays out its analysis of the current education system in Chapter 2. Chapters 3, 4, and 5 offer findings, conclusions, and recommendations to ensure that the system remains dynamic by addressing current needs and anticipating future contexts in graduate education. Chapter 6 presents a summary of what an ideal graduate education system would be like if all the recommendations in this report were to be implemented. It also provides a listing of the committee's recommendations organized by stakeholder, to make clear what each must do to actualize the revised graduate STEM education system the committee envisions.

AN IDEAL GRADUATE STEM EDUCATION

Implementing the recommendations in this report would produce a U.S. graduate STEM education system that better enables graduate students of all backgrounds to meet the highest standards of excellence in 21st-century STEM fields and to use their knowledge and sophistication across the full range of occupations essential to address global societal needs using science- and technology-informed decision making. These recommendations build on the current strengths of the graduate STEM enterprise, urging careful attention to core educational elements and learning objectives—one set for the master's degree and another for the Ph.D.—that are common across all STEM fields. However, many of the recommendations in this report are also intended to stimulate review and revision of incentive and reward policies, teaching and mentoring practices, and curricular offerings. They may also lead to the expansion of career exploration mechanisms and transparency about trainee outcomes that can inform career paths for students.

Importantly, this report also calls for a shift from the current system that focuses primarily on the needs of institutions of higher education and those of the research enterprise itself to one that is *student centered*, placing greater emphasis and focus on graduate students as individuals with diverse needs and challenges. An ideal, student-centered STEM graduate education system would include several attributes that are currently lacking in many academic institutions. In an ideal STEM graduate education system:

- Prospective graduate students would be able to select their graduate program aided by fully transparent, easily accessible data about costs incurred and viable career pathways and successes of previous students, at the level of the institution and its departments.
- Students would acquire broad technical literacy coupled with deep specialization in an area of interest. They would acquire the core competencies outlined in Chapters 3 and 4. As they acquire this knowledge base, students would have multiple opportunities to understand better and to learn to consider ethical issues associated with their work, as well as the broader implications of their work for society.
- Students from all backgrounds would fully participate and achieve their greatest potential during their educational experience through transparent institutional action to enhance diversity and promote inclusive and equitable learning environments.
- Students would encounter a variety of points of view about the nature, scope, and substance of the scientific enterprise and about the relationships between science, engineering, and society, and they would be encouraged to understand and grapple with differences of opinion, experiences, and ideas as part of their graduate education and training.
- Students would have opportunities to communicate the results of their work and to understand the broader impacts of their research. This includes the ability to present their work and have exposure to audiences outside of their department, ranging from peers in other departments to the broader scientific community and nontechnical audiences. Students would also understand and learn to consider ethical and cultural issues surrounding their work, as well as the broader needs of society.
- Students would be encouraged to create their own project-based learning opportunities—ideally as a member of a team—as a means of developing transferable professional skills such as communication, collaboration, management, and entrepreneurship. Experiences where students "learn by doing," rather than simply learn by lecturing and coursework, would be the norm.
- Students would be encouraged and given time, resources, and space to explore diverse career options, perhaps through courses, seminars, internships, and other kinds of real-life experiences. While some institutions have launched such programs, they should become universal, albeit sensitive to the specific contexts of individual institutions. For example, students clearly interested in future faculty positions might have the opportunity to teach undergraduates from a variety of institutions, from community colleges to research-based universities. Those students wishing to compete for research-intensive university positions would be advised about appropriate postdoctoral positions and the track records of those universities and/or specific faculty members in placing such individuals in faculty positions. Students with potential interests in nonacademic careers would be provided with opportunities to attend workshops and seminars about jobs in a wide range of industries, nonprofit organizations, and government, together with opportunities for placements in nonacademic job settings. Internships with corporations, government agencies, or nonprofit employers during summer months or the school year would become the norm rather than the exception for graduate students seeking careers outside of academia. Institutions would seek corporate and foundation funding to support such

learning experiences.

- Graduate programs and departments would develop more efficient channels for students to communicate with the administration and faculty regarding processes and decisions within the department and the graduate school that affect graduate student education. These channels would facilitate communication in both directions, offering students mechanisms to provide feedback and giving administrators and faculty a better understanding of the student perspectives on issues important to them.
- Graduate programs would develop course offerings and other tools to enable student career exploration and to expose students to career options. Faculty advisors would encourage students to explore career options broadly and would not stigmatize those who favor nonacademic careers.
- Institutions would help students identify advisors and mentors who can best support their academic and career development.
- Institutions would provide faculty with training, resources, and time both to improve their own skills as mentors and to provide for quality mentoring and advising to the graduate students they supervise directly, as well as other students in their departments or from across the institution, as appropriate. Training would provide strategies for navigating relationships in which goals and identities (cultural or demographic differences, career aspirations) may differ between mentor and mentee, and mentoring would center on the goals set jointly by the student and mentors and provide strategies for navigating relationships in which goals may differ between supervisor and student. This training would consider the various challenges faculty face at different stages of their own careers. For example, early-career faculty who are in the process of establishing themselves in a department with a research group or laboratory may require a primer on best practices for becoming a mentor and advisor. Long-tenured faculty might benefit from periodic refreshers to explore new skills or techniques in supporting student success. Institutions would provide opportunities for students to seek and develop multiple separate mentoring and advising relationships, including those that are interdisciplinary and cross departments. Institutions would also reward faculty for their accomplishments as mentors and advisors.

DRIVING CHANGE

Seeing this vision come to fruition will require firm and commensurate commitments at all levels and from all stakeholders in the nation's STEM graduate education system. Academic institutions must provide faculty time, resources, and incentives to focus more on the totality of graduate student learning through the adoption of evidence-based teaching practices and to support the broad range of educational and career goals that students hold. At the same time, educational institutions and the state and federal agencies and other funders that support and set policies for financial support of both research and graduate students will need to adjust the incentive systems so that they reward educational as well as research accomplishments. Such a change in incentive systems will reflect the conviction that producing well-educated students is a central element of their charge.

Achieving what the committee sees as the ideal, modern graduate STEM education will require substantial cultural change throughout the system. As discussed throughout this report,

the system must become more student-centric and must increase the value it places on best practices of mentorship and advising. The value placed on educating students at the master's level must be increased. The mind-set that seems to most heavily value preparing students at the Ph.D. level for academic research careers must readjust to recognize that some of the best students will not pursue academic research but will enter careers in other sectors, such as industry or government.

These cultural changes will only come about if there are changes in the incentive system that appears to drive so much of academia. The current system is heavily weighted toward rewarding faculty for research output in the form of publications and the number of future scientists produced. It must be realigned to increase the relative rewards for effective teaching, mentoring, and advising. Unless faculty behavior can be changed—and changing the incentive system is critical in that regard—the system will not change.

The committee recognizes that these cultural changes will inevitably have costs associated with them. The committee did not provide estimates for the financial costs, including the costs of creating, supporting, and maintaining new programs for students, data collection, and staff to provide support to students, because each institution will have different existing infrastructure, constraints, local context, and other considerations to manage in the implementation of these recommendations. Beyond shifts in the budget, many of the cultural changes also pose costs related to time and human capital resources, such as the increasing expectations on faculty and the effort expended by leadership and administration to support change. However, despite any costs, the changes advocated in this report must be achieved. Without such a unified commitment to continue the legacy of excellence in the system, the United States may not unlock the full potential of discovery to power its economy, protect its national interests, and lead the world in addressing the grand challenges of the 21st century.

Federal and state funding agencies have a particularly important role to play since their funding and support policies are often cited as being critical to the overall context and climate in which academic institutions are situated. Those policies are influential in shaping the incentive systems under which research institutions operate and researchers are rewarded. In fact, many of the recommendations in this report will be impossible to implement until federal and state policy makers are willing to reaffirm the value of graduate education to our nation's intellectual, social, and economic prosperity and to formulate policies that will enhance the quality of master's and doctoral education in the United States. Since so many STEM graduate students are supported through federal programs, the funding criteria for those programs present a unique opportunity to help shape the culture of graduate education throughout the country. Even in periods of extreme fiscal constraint, the federal government should recommit to making significant, coordinated investments in higher education and research, especially at the graduate level.

With these challenges in mind, we urge all relevant stakeholders—federal and state policy makers, colleges, universities, employers, faculty and administrators, students, national scientific and educational organizations, advocacy groups, and the public who supports and benefits from advances in STEM fields—to unite behind the recommendations in this report and, going forward, continuously assess whether STEM graduate education in the United States is meeting the needs of both a fully modern science and technology enterprise and the nation it serves. A renewed national commitment to modernizing STEM graduate education would surely benefit society for generations to come. Consistent with Vannevar Bush's recognition of science as the endless frontier, the nation will benefit fully from applying the power of science,

technology, engineering, and mathematics to the problems and opportunities of today and tomorrow.

RECOMMENDATIONS OF THE COMMITTEE ON REVITALIZING GRADUATE STEM EDUCATION FOR THE 21ST CENTURY

The committee's recommendations are summarized here and presented in the order in which the issues and goals are discussed in Chapters 3-5. Included as bullets are the actions the committee believes each stakeholder must take to resolve the issue or achieve the goal, particularly regarding the difficult topic of cultural change that the committee stresses is necessary to realize the vision it sets out for the ideal graduate education. The aggregated set of actions the committee recommends for each stakeholder is presented in Chapter 6. The intent of the listing in Chapter 6 is to lay out a systemwide action plan for achieving the goals outlined in this report, stipulating what each stakeholder must do to make the ideal graduate education system a reality.

Chapter 3

RECOMMENDATION 3.1—Rewarding Effective Teaching and Mentoring: Advancement procedures for faculty, including promotion and tenure policies and practices, should be restructured to strengthen recognition of contributions to graduate mentoring and education.

- Federal and state funding agencies should align their policies and award criteria to ensure that students in the programs they support experience the kind of graduate education outlined in this report and achieve the scientific and professional competencies articulated here, whether they are on training or research grant mechanisms.
- Institutions should increase priority and reward faculty for demonstrating high-quality teaching and inclusive mentoring practices for all graduate students, including the recognition of faculty teaching in master's degree programs, based on the results of restructured evaluations.
- Institutions should include teaching and mentoring performance as important considerations for reappointment, promotion, annual performance review, and tenure decisions. Institutions should also nominate faculty for external awards (such as those from technical societies) that reward teaching excellence.

RECOMMENDATION 3.2—Institutional Support for Teaching and Mentoring: To improve the quality and effectiveness of faculty teaching and mentoring, institutions of higher education should provide training for new faculty and should offer regular refresher courses in teaching and mentoring for established faculty.

- Institutions should require faculty and postdoctoral researchers who have extensive contact with graduate students to learn and demonstrate evidence-based and inclusive teaching and mentoring practices.
- Graduate programs should facilitate mentor relationships between the graduate student and the primary research advisors, as well as opportunities for students to develop

additional mentor or advisor relationships, including with professionals in industry, government laboratories, and technical societies.
- Graduate schools should provide extra-departmental mentoring and support programs.
- Graduate students should seek multiple mentors to meet their varied academic and career needs.

RECOMMENDATION 3.3—Comprehensive National and Institutional Data on Students and Graduates: Graduate programs should collect, update, and make freely and easily accessible to current and prospective students information about master's- and Ph.D.-level educational outcomes. In addition, to make appropriate future adjustments in the graduate education system, it is essential that comprehensive datasets about the system, its participants, and its outcomes be collected in a standard format, be fully transparent, and be easily accessible and transferable across multiple computer and statistical analysis platforms.

- Federal and state funding agencies should require institutions that receive support for graduate education to develop policies mandating that these data be collected and made widely available to qualify for traineeships, fellowships, and research assistantships.
- Institutions should develop a uniform, scalable, and sustainable model for data collection that can operate beyond the period of extramural funding. The data collection should follow standard definitions that correspond with national STEM education and workforce surveys to help inform benchmarking or higher education research.
- Departments and programs should review their own data from current students and alumni to inform curricula and professional development offerings, and they should provide these data to current and prospective students.
- Prospective students should use these data to inform graduate program selection, educational goal development, and career exploration.

RECOMMENDATION 3.4—Funding for Research on Graduate STEM Education: The National Science Foundation, other federal and state agencies, and private funders of graduate STEM education should issue calls for proposals to better understand the graduate education system and outcomes of various interventions and policies, including but not limited to the effect of different models of graduate education on knowledge, competencies, mind-sets, and career outcomes.

- Funders should support research on the effect of different funding mechanisms on outcomes for doctoral students, including traineeships, fellowships, teaching and research assistantships; the effects of policies and procedures on degree completion, disaggregated by gender, race and ethnicity, and citizenship; and the effect of expanding eligibility of international students to be supported on federal fellowships and training grants.

RECOMMENDATION 3.5—Ensuring Diverse, Equitable, and Inclusive Environments: The graduate STEM education enterprise should enable students of all backgrounds, including but not limited to racial and ethnic background, gender, stage of life, culture, socioeconomic

status, disability, sexual orientation, gender identity, and nationality to succeed, by implementing practices that create an equitable and inclusive institutional environment.

- Faculty and administrators involved in graduate education should develop, adopt, and regularly evaluate a suite of strategies to accelerate increasing diversity and improving equity and inclusion, including comprehensive recruitment, holistic review in admissions, and interventions to prevent attrition in the late stages of progress toward a degree.
- Faculty should cultivate their individual professional development skills to advance their abilities to improve educational culture and environments on behalf of students.
- Institutions, national laboratories, professional societies, and research organizations should develop comprehensive strategies that use evidence-based models and programs and include measures to evaluate outcomes to ensure a diverse, equitable, and inclusive environment.
- Institutions should develop comprehensive strategies for recruiting and retaining faculty and mentors from demographic groups historically underrepresented in academia.
- Federal and state agencies, universities, professional societies, and nongovernmental organizations that rate institutions should embed diversity and inclusion metrics in their criteria.
- Federal and state funding agencies and private funders that support graduate education and training should adjust their award policies and funding criteria to include policies that incentivize diversity, equity, and inclusion and include accountability measures through reporting mechanisms.

RECOMMENDATION 3.6—A Dynamic Graduate STEM Education System: The STEM education system should develop the capabilities to adjust dynamically to continuing changes in the nature of science and engineering activity and of STEM careers. This includes mechanisms to detect and anticipate such changes, experiment with innovative approaches, implement appropriate educational methods, and support institutional mechanisms on a larger scale.

- Faculty and graduate departments and programs should periodically review and modify curricula, dissertation requirements, and capstone projects to ensure timeliness and alignment with the ways relevant work is conducted, and to provide students with opportunities to work in teams that promote multidisciplinary learning.
- Professional societies and nonprofit organizations should convene and lead discussions with graduate programs, employers, and other stakeholders and disseminate innovative approaches.
- Federal and state funding agencies, professional societies, and private foundations that support or conduct education research should support studies on how different STEM disciplines can integrate the changing scientific enterprise into graduate education programs and curricula.
- Graduate students should learn how to apply their expertise in a variety of professional contexts and seek guidance from faculty, research mentors, advisors on strategies to gain work-related experience while enrolled in graduate school.
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RECOMMENDATION 3.7—Stronger Support for Graduate Student Mental Health Services: Institutions should provide resources to help students manage the stresses and pressures of graduate education and maximize their success. Institutions of higher education should work with their faculty to recognize and ameliorate behaviors that exacerbate existing power differentials and create unnecessary stress for graduate students. Toward that end:

- Institutions should administer periodic climate surveys of graduate students at the departmental level to assess their well-being in the aggregate and make adjustments when problems are identified.
- Institutions should take extra steps to provide and advertise accessible mental health services, such as those already available to veterans and most undergraduate students, at no cost to graduate students.
- Institutions should develop clear policies and reporting procedures for instances of sexual harassment and bullying.
- Graduate programs should fully incorporate awareness of mental health issues into the training experience for both students and faculty and should assess services to ensure that they are meeting the needs of graduate students.
- Faculty should be regularly informed on how to support and engage with students requiring or seeking mental health services.
- Graduate programs should encourage students to engage as a group in activities and experiences outside of traditional academic settings as a means of increasing feelings of inclusion and normalizing feelings associated with negative phenomena, such as imposter syndrome, that can reduce productivity and success in the training experience and extend time to degree.
- Graduate programs should allow students to have an active and collaborative voice to proactively engage in practices that support holistic research training and diverse career outcomes and that allow students to provide feedback on their experiences.

Chapter 4

RECOMMENDATION 4.1—Core Competencies for Master's Education: Every STEM master's student should achieve the core scientific and professional competencies and learning objectives described above:

- Institutions should verify that every graduate program they offer provides for the master's core competencies outlined in this report and that students demonstrate that they have achieved them before receiving their degrees.
- Graduate departments should publicly post how their programs reflect the core competencies for master's students, including the milestones and metrics they use in evaluation and assessment.
- Federal and state funding agencies should adapt funding criteria for institutions to ensure that all master's students they support—regardless of mechanism of support—are in programs that ensure that they develop, measure, and report student progress toward acquiring the scientific and professional competencies outlined in this report.
- Graduate students should create an individual development plan that includes the core competencies, as outlined in this report for master's or doctoral degrees, as a key

feature of their own learning and career goals and that utilizes the resources provided by their university and relevant professional societies.
- Students should provide feedback to graduate faculty and deans about how they could help students better develop these competencies.

RECOMMENDATION 4.2—Career Exploration for Master's Students: Master's students should be provided opportunities for career exploration during the course of their studies.

- Faculty, who serve as undergraduate advisors, should discuss with their students whether and how a master's degree will advance the students' long-term educational and career goals.
- Institutions should integrate professional development opportunities, including relevant course offerings and internships, into curriculum design.
- Master's students should seek information about potential career paths, talk to employers and mentors in areas of interest, and choose a master's program optimal for gaining the knowledge and competencies needed to pursue their career interests.
- Industry, nonprofit, government, and other employers should provide guidance and financial support for relevant course offerings at institutions and provide internships and other forms of professional experiences to students and recent graduates.
- Professional societies should collaborate with other sectors to create programs that help master's students make the transition into a variety of careers.

Chapter 5

RECOMMENDATION 5.1—Core Competencies for Ph.D. Education: Every STEM Ph.D. student should achieve the core scientific and professional Ph.D. competencies detailed in this report.

- Universities should verify that every graduate program that they offer provides for these competencies and that students demonstrate that they have achieved them before receiving their doctoral degrees.
- Universities should scrutinize their curricula and program requirements for features that lie outside of these core competencies and learning objectives and that may be adding time to degree without providing enough additional value to students, such as a first-author publication requirement, and eliminate those features or requirements.
- Graduate departments should publicly post how their programs reflect the core competencies for doctoral students, including the milestones and metrics the departments and individual faculty use in evaluation and assessment.
- Federal and state funding agencies should adapt funding criteria for institutions to ensure that all doctoral students they support—regardless of mechanism of support—are in programs that ensure that they develop, measure, and report these scientific and professional competencies.
- Students should create an independent development plan that includes these competencies as a core feature of their own learning and career goals and that utilizes the resources provided by their university and relevant professional societies.

- Students should provide feedback to the graduate faculty and deans about how they could help students better develop these competencies.

RECOMMENDATION 5.2—Career Exploration and Preparation for Ph.D. Students: Students should be provided an understanding of and opportunities to explore the variety of career opportunities and pathways afforded by STEM Ph.D. degrees.

- Faculty who serve as undergraduate and master's advisors should discuss with their students whether and how a Ph.D. degree will advance the students' long-term educational and career goals.
- Institutions should integrate professional development opportunities, including relevant course offerings and internships, into doctoral curriculum design.
- Institutions, through their career counselors and career centers, should assist students in gaining an understanding of and opportunities to explore career options afforded by STEM Ph.D. degrees.
- Students should seek information about potential career paths, talk to employers and mentors in areas of interest, and choose a doctoral program optimal for gaining the knowledge and competencies needed to pursue their career interests.
- Every student and his or her faculty advisor should prepare an individual development plan.
- Industry, nonprofit, government, and other employers should provide guidance and financial support for relevant course offerings at institutions and provide internships and other forms of professional experiences to students and recent graduates.
- Federal and state agencies and private foundations that support graduate education should require STEM graduate programs to include career exploration curricular offerings and require STEM doctoral students to create and to update annually individual development plans in consultation with faculty advisors to map educational goals, career exploration, and professional development.
- Professional societies should collaborate with leaders in various sectors to create programs that help Ph.D. recipients transition into a variety of careers.

RECOMMENDATION 5.3—Structure of Doctoral Research Activities: Curricula and research projects, team projects, and dissertations should be designed to reflect the state of the art in the ways STEM research and education are conducted.

- Universities, professional societies, and higher education associations should take the lead in establishing criteria and updating characteristics of the doctoral research project and dissertation preparation and format.
- Students should seek opportunities to work in cross-disciplinary and cross-sector teams during their graduate education and via extracurricular activities and be incentivized by their departments and faculty advisors to do so.
- Graduate programs and faculty should encourage and facilitate the development of student teams within and across disciplines.