Reform Efforts in STEM Doctoral Education: Strengthening Preparation for Scholarly Careers

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Doctoral education in the sciences, technology, engineering, and mathematics (STEM) disciplines is currently a major focus of interest, concern, and reform. Economic growth, national security, and the innovation and discoveries that enhance quality of life within the country and across the globe are closely related to the availability of a strong pool of well-educated individuals with excellent scientific talent and high-level preparation. As argued in a recent report issued by the National Science Board (2003), "Science and technology have been and will continue to be engines of US economic growth and national security" (p. 7). In a world context where complex challenges are numerous, including inadequate food supplies, global climate change, and daunting health issues, a system that ensures an effective pipeline for the preparation of individuals with scientific and technical talent is essential. A key stage of that pipeline involves doctoral education. At the doctoral stage, high-level talent is developed for conducting research in university and nonacademic settings and for teaching future generations. Government and private sector leaders, as well as academics, recognize the necessity and imperative to ensure the quality of doctoral study in the sciences, technology, engineering, and mathematics (Council of Graduate Schools, 2007; National Science Board, 2003, 2006; Walker, Golde, Jones, Bueschel, & Hutchings, 2008).

In recent years, contextual pressures and challenges, concerns about the quality of undergraduate education and the supply and talent of faculty who teach them, along with questions about the quality of students' experiences as they pursue advanced degrees, have motivated efforts to reform and strengthen doctoral education in STEM fields. The purpose of this chapter is to examine and discuss these efforts to improve STEM doctoral education. The chapter is organized in four parts. First, it begins with an exploration of the context in which STEM graduate education is situated and the recent events that have created a climate for reform. Second, it discusses in more detail particular issues toward which reform efforts in STEM doctoral education have been directed. Third, the chapter reviews the kinds of reform efforts being used to strengthen and improve STEM doctoral education, highlights

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J.C. Smart (ed.), *Higher Education: Handbook of Theory and Research* 25,
DOI 10.1007/978-90-481-8598-6_3,

several specific examples of initiatives and programs, and presents the available evidence concerning the impact and outcomes of those efforts. Fourth, the chapter concludes with an agenda for research and strategic action concerning reform in STEM doctoral education.

At the start, I note that post-doctoral work is also crucially important—to the individuals serving in post-doctoral roles, to the universities and research projects that employ them, and to the broader society benefiting from their research. The post-doctoral experience also has become the focus of concern and discussion in recent years, and a number of important issues and challenges pertaining to this aspect of STEM work deserve attention. However, the focus of this chapter includes only doctoral-level education in the STEM fields. A longer treatment would be required to consider the many issues relevant to post-doctoral work in STEM fields. I also note that a substantial part of the literature on doctoral work in STEM fields focuses specifically on its role in preparing future faculty. However, the critiques of STEM doctoral education, as discussed below, emphasize that STEM doctoral education can lead to a number of important careers, with academic work as one option. Thus, in this chapter, I focus on reform in STEM education with the recognition that STEM doctoral graduates may pursue academic as well as non-academic careers.

Context and Background

About 40,000 doctoral degrees are awarded each year in the United States. The number of Ph.D.s granted grew in the 1960s and early 1970s, leveled in the 1980s, and grew again from 1990 to 1998 to reach the level of 43,000 doctorates awarded annually. Much of the expansion occurred in the sciences and engineering. In particular, doctoral degrees granted in the life sciences increased from 18% of the doctorates awarded in 1973 to 48% in 2003. The increase in the proportion of doctoral degrees granted in engineering increased from 1% in 1973 to 17% in 2003, and in the physical sciences, during this period, the jump was from 7% to 27%. Of particular importance, however, is the fact that these increases were primarily due to expansions in international student enrollments, not from an increase in students from the United States (Nerad, 2008, p. 49).

By the mid-1990s, concerns were emerging in the United States about doctoral education overall, as well as specifically in STEM fields (Committee on Science, Engineering, and Public Policy, 1995; National Science Board, 1997; Rice, Sorcinelli, & Austin, 2000). In the tight labor market of the 1980s and 1990s, many doctoral graduates were not finding faculty positions, which fueled conversations about the state of graduate education. In the STEM fields, with the end of the Cold War, a shift occurred in federal funding, away from basic research toward more "strategic" research pertaining to such areas as the economy, education, and the environment (Carney, Chawla, Wiley, & Young, 2006, citing National Research Council, 1994). Many doctoral graduates were not finding employment in basic research, which contributed to concerns that graduates were insufficiently prepared for non-academic work or to address the many societal needs—including work in applied research and development, consulting, and other areas—requiring advanced knowledge in science and engineering (Carney et al., 2006).

Various reports were released which outlined issues and problems. The Committee on Science, Engineering, and Public Policy (1995), a committee of the National Academies, released a report entitled *Reshaping Graduate Education of Scientists and Engineers* (widely known as the "COSEPUP" report) which generated much attention. The National Science Board also released a report concerning science and engineering graduate and post-graduate education (1997), and the Association of American Universities published the report of the Committee on Graduate Education (1998). These publications raised questions about whether graduate education in the United States was meeting national needs and preparing graduate students for the changing context in which they would work. The COSEPUP report, for example, recommended that graduate programs in sciences and engineering should give students more opportunities and options to develop a wider array of skills appropriate for diverse work options, that programs should offer more career guidance and information, that attention should be directed to time required to complete degrees, and that efforts should be made to increase the participation of women and minorities. At the same time, employers were expressing concerns about the readiness of new doctoral graduates for the workplace, state governments were calling for more accountability from higher education institutions in regard to the learning outcomes, skills, and abilities of their graduates, and students themselves were creating unions, at some universities, in response to their own concerns about the experiences they were having as teaching and research assistants during the doctoral experience (Austin & Wulff, 2004; Nerad, 2008).

During this same time period, an array of individuals and groups were talking about the state of graduate education, the importance of research on doctoral education and the preparation of future scholars, the need for reform, and the kinds of strategies that would enhance the quality of doctoral preparation. For example, graduate deans, faculty developers involved in teaching assistant preparation, and researchers interested in doctoral education as the initial step in faculty careers were initiating studies and programmatic efforts to strengthen the doctoral experience (Anderson, 1998; LaPidus, 1997; Nyquist, Abbott, & Wulff, 1989; Nyquist & Sprague, 1992; Nyquist & Wulff, 1992; Nyquist, Wulff, & Sprague, 1991). Key research and scholarly publications also added to the discussion in the late 1990s and early 2000s, including Nerad and Cerny's *PhDs: Ten Years Later Study* (1999), Golde and Dore's *At Cross Purposes* (2001), and Wulff and Austin's *Paths to the Professoriate* (2004). Foundations such as the Pew Charitable Trusts and the Spencer Foundation, government organizations such as the National Science Foundation, and higher education associations such as the American Association of Colleges and Universities (AACU) and the then-existing American Association for Higher Education (AAHE), were becoming involved, offering support in the form of funding or programmatic initiatives—or both (Association of American Universities, 1998; Austin, 2002b; Gaff, Pruitt-Logan, & Weibl, 2000; Rice et al., 2000; Nyquist et al., 1999).

One response to the array of concerns about the preparation of doctoral students for their careers was the establishment, in 1993, of the Preparing Future Faculty (PFF) program, supported by a grant from the Pew Charitable Trusts to the Association of American Colleges and Universities (AAC&U) in collaboration with the Council of Graduate Schools (CGS). PFF was designed to give doctoral students aspiring to the professoriate an expanded professional development experience that prepared them to be effective teachers, researchers, and active citizens. Participants benefitted from mentoring, opportunities to learn about faculty life, including teaching responsibilities, and exposure to the array of institutional types in which they might work in academe (Gaff, Pruitt-Logan, Sims, & Denecke, 2003; Gaff et al., 2000; Pruitt-Logan & Gaff, 2004; Pruitt-Logan, Gaff, & Jentoft, 2002).

Key stakeholders concerned about doctoral education came together at a national conference sponsored by the Pew Charitable Trusts and facilitated by Jody Nyquist of the University of Washington in 2000. At this meeting, entitled "Re-envisioning the Ph.D.," the stakeholders outlined the problems they saw in doctoral education from their particular perspectives, discussed the extent to which doctoral education was meeting the needs of society, and called for a renewal of quality and focus in doctoral education (Nyquist & Woodford, 2000; Nyquist, Woodford, & Rogers, 2004). This meeting launched an active and extensive website clearinghouse that, for some time, provided an up-to-date listing of resources and information on programs, research, and initiatives pertaining to doctoral education. The meeting also became the launching pad for further projects, dialogues, and institutional and national projects and initiatives to strengthen doctoral education across disciplines, including STEM fields.

Other responses developed also. The Carnegie Foundation for the Advancement of Teaching began a major initiative entitled the Carnegie Initiative on the Doctorate (Walker, 2004; Walker et al., 2008). I discuss this initiative in more detail later in the chapter. Another significant effort to further the discussion and reform movement was the "Responsive PhD Initiative," sponsored by the Woodrow Wilson National Fellowship Foundation for 5 years beginning in 2000. This project involved 20 universities and focused on developing new paradigms, establishing new practices, exploring new partnerships, and involving new people in doctoral education (Weisbuch, 2004). Another significant, funded initiative that emerged in response to the national interest in strengthening doctoral education is the Center for Innovation in Research and Graduate Education, led by Maresi Nerad and located at the University of Washington, which is conducting research to guide continuing reform efforts (Center for Innovation in Research and Graduate Education, 2003).

While the national conversation has included the wide range of fields in which doctoral education is offered, interest in reform in STEM doctoral education has been particularly strong. As noted, the COSEPUP report (Committee on Science, Engineering, and Public Policy, 1995) and the National Science Board's report on science and engineering graduate and postgraduate education (1997) had fueled the national dialogue about the quality of STEM doctoral education. Then, in 2003, the National Science Board, which serves as the policy-making body of the National Science Foundation and provides advice to the President and the Congress concerning policy relevant to national science and engineering issues, published a report entitled *The Science and Engineering Workforce: Realizing America's Potential*. This report issued a warning and challenge: "The United States is in a long-distance race to retain its essential global advantage in science and engineering human resources and to sustain our world leadership in science and technology" (p. 41). The report continued its analysis by highlighting the importance of a coordinated effort to ensure the preparation of those with the needed skills in science and engineering: "The Federal Government has a primary responsibility to lead the Nation in developing and implementing a coordinated, effective response to our long-term needs for science and engineering skills. US global leadership and future national prosperity and security depend on meeting this challenge" (p. 42). The emphasis of the report was on the need for a well-educated workforce with high-level training to meet the needs of the country and the broader society for innovation and discovery in science and engineering.

The report provided an analysis of two major trends that affect the preparation of high-level talent in science and engineering. First, due to an increase in global competition for talent in science and engineering, the United States may not be able to fill gaps in its needs for scientific expertise with talent from the broader international labor market. Other industrialized countries are becoming more aggressive in their strategies to attract graduate students in science and engineering, thus competing with the efforts of American graduate schools to find excellent students. The competition for well-skilled professionals in science and engineering, both in the domestic and international markets, is keen, since such individuals have options for well-paying and interesting positions both in their fields and in other arenas. In considering graduate school choices, talented undergraduates in science and engineering consider such factors as their perceptions of career choices that are open to them, the opportunity costs of directions not taken, the quality of life they will experience in graduate school, and the debt they will accrue. Given these considerations, talented individuals from both the domestic and international settings may choose not to attend graduate school (National Science Board, 2003).

Second, the number of United States-born students interested in pursuing engineering, physical sciences, and mathematics is declining. More precisely, from 1999 to 2000, the enrollment of U.S. citizens and permanent residents in science, technology, and engineering declined by 3%. Between 1980 and 1999, the number of U.S.-born White males who received Ph.D.s in STEM fields declined from 9,362 to 8,138. Overall, the increase in enrollment in science and engineering fields can be accounted for by international students (National Science Board, 2003, p. 21). In fact, already from 1990 to 2000, the percentage of non-U.S. born scientists and engineers filling positions in the country increased from 14% to 22%. At the doctoral level, the percentage of international students enrolled increased from 24% in 1990 to 38% in 2000 (National Science Board, 2003, p. 9). In arguing for plans to attract more US-born individuals to study science and engineering at advanced levels, the report noted that the need for talented individuals in these areas cannot be met without finding ways to ensure that people from underrepresented groups succeed in their studies (National Science Board, 2003).

This downward trend in the involvement of US-born citizens (in particular, White males) is occurring at the same time that retirements in the science and engineering workforce are expected to increase rapidly in the next twenty or so years. Additionally, science and engineering occupations are increasing three times more quickly than positions in other areas of work. Furthermore, the challenges associated with the events of September 11, 2001 mean that the need for individuals with science and engineering skills is even greater than originally expected (National Science Board, 2003).

In response to the concern that the United States is lagging in its ability to produce a large enough, well-prepared pool of highly qualified scientists and engineers, the National Science Board (2003) called for action in several arenas. The recommendations focused on: (a) undergraduate education in science and engineering, (b) the knowledge base and research concerning the science and engineering workforce, and (c) initiatives to attract and retain excellent pre-college teachers in mathematics, science, and engineering. Of particular relevance to this chapter, the report emphasized reform in graduate and post-doctoral education in STEM fields. Recommendations focused on adjusting "advanced education of scientists and engineers to better align with national skills needs" (p. 25). Specific recommendations focused on: preparing students to work in disciplinary and cross-disciplinary areas in a range of careers in various sectors; developing research on the impacts of different approaches to supporting graduate education, including fellowships, research work, and traineeships; research on such topics as time-to-degree and the involvement of foreign students in US science, mathematics, and engineering endeavors; the role of the federal government in supporting science and mathematics graduate and postdoctoral education through recognizing programs that model good practice and encouraging collaboration between research and non-research institutions; promoting diversity and access to graduate programs, especially for those in underrepresented groups; addressing changes in grant procedures and encouraging adjustments in faculty reward systems to enable faculty members to have more time to mentor; and research on the science, engineering, and mathematics workforce.

The publication in 2007 of *Rising above the Gathering Storm: Energizing and Employing America for a Brighter Future,* produced by the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine, continued the call for urgent attention to the state of sciences and engineering in the United States. Recognizing that the country's prosperity relies heavily on research and development, the report reiterated concerns about global competition and challenges to U.S. leadership in scientific and technological innovation. Among its four key recommendations, the report called for "mak[ing] the United States the most attractive setting in which to study and perform research so that we can develop, recruit, and retain the best and brightest students, scientists, and engineers from within the United States and throughout the world" (p. 9).

As discussed in this section, a national dialogue about doctoral education gained momentum during the 1990s and into the new century through the efforts of foundations, researchers, and national organizations, such as the National Science Foundation, and through publications, conferences, and research. Doctoral students themselves have contributed to the dialogue about the strengths, issues, dilemmas, and challenges in graduate education through their responses to surveys and interviews, their articulation of issues through the graduate teachers' unions in place at some institutions, and their contributions at scholarly and professional meetings. The next section discusses in more detail key issues that emerged in this dialogue that have fueled efforts to reform and improve doctoral education overall and STEM doctoral education in particular.

Major Concerns About Stem Doctoral Education

The liveliness of the discussions over the last 15 years have produced a number of suggestions for reform in doctoral education overall and STEM doctoral education in particular. The consensus around the challenges and the issues to be addressed is evident in the similarity of the conclusions and recommendations offered in the various reports and conferences. Here I discuss these recommendations for reform by organizing them into two primary areas of focus: (1) preparation for diverse employment options; and (2) the structure, quality, and nature of the doctoral experience.

Strengthening Preparation for Diverse Employment Options

A prevalent concern, appearing in national studies and reports as well as in student discussions, pertains to the extent to which doctoral education prepares students for the diverse career options available to them (Golde & Dore, 2001; National Science Board, 2003; Nerad, 2008; Nyquist, Austin, Sprague, & Wulff, 2001). Doctoral students in STEM fields may expect careers either within academe or in other sectors, so preparation must take into account both career routes. However, preparation has been criticized for not fully meeting expectations and needs. Golde and Dore (2001), based on their quantitative study of how graduate students in a number of fields perceived their experiences, asserted (in an oft-quoted comment) that the preparation of doctoral students does not match what they want to learn nor the needs and expectations in the positions they enter. Similarly, based on qualitative research, Nyquist et al. (2001) concluded: "Graduate education does not match the needs and demands of the changing academy and broader society" (p. 5). As discussed below, the discussions and recommendations have pertained to both preparation for academic careers as well as careers outside academe—and in fact, a major theme in recommendations for reform is that doctoral education, and particularly STEM doctoral education, should be sufficiently flexible to prepare students for a range of employment options.

Concerns About Preparation for Academic Work

In regard to the role of doctoral education in preparing students for academic work, a frequently mentioned conclusion has been that aspiring faculty members are not fully prepared for the responsibilities of academic careers (Austin 2002a, 2002b; Carney et al., 2006; Golde & Dore, 2001; Nerad, Aanerud, & Cerny, 2004; Nyquist et al., 1999; Wulff, Austin, Nyquist, & Sprague, 2004). They often do not understand the full range of work that faculty members do, including what responsibilities they might have in regard to institutional governance, advising, and participating in outreach to the broader community. In a study reported in 1998 involving 187 doctoral students, Golde (1998) found that 90% felt prepared to conduct research and 63% felt they were ready to teach undergraduates; however, only 33% felt prepared to teach graduate students, 30% to advise undergraduates, 26% to advise graduate students, and 19% to participate in service and governance responsibilities. Doctoral students also often do not understand the various kinds of institutions that comprise the American higher education landscape and the missions and history characterizing each type (Austin & McDaniels, 2006a; Nerad, 2008). Thus, prospective faculty members may not understand the employment options open to them. More specifically, scientists and engineers may not perceive the ways in which they can contribute to the preparation of a citizenry informed about critically important scientific issues through work in teaching-oriented universities and colleges. In fact, in Golde and Dore's (2001) research involving more than 4,000 graduate students (in a number of fields), 54% had a "strong preference" to assume positions in large research-oriented universities, while only small percentages indicated preferences for liberal arts institutions, community colleges, or comprehensive institutions. Since available positions in research universities are far less than the doctoral students expressing preference to work in them, and since there is great need for preparing all future citizens to be knowledgeable about scientific issues relevant to their lives and the well-being of the planet and the society, greater attention in doctoral education to cultivating interest in and preparing future faculty for work in the range of institutional types in academe would be desirable.

Concerns About Preparation for Careers Outside Academe

Preparation for industry and non-academic workplaces is also essential and has been a central call in the reform discussions (Carney et al., 2006). The National Science Board report on *Realizing America's Potential* (2003) explained that, when higher education was expanding in earlier decades, graduates from science and engineering programs could anticipate the availability of positions in academe. Currently, however, industry is the largest employer of science and engineering graduates, and demand for individuals with Ph.D.s to fill academic positions has decreased. In 1999, for example, 48% of scientists and engineers with doctorates were employed in academic positions and more than half were employed outside academe (National Science Board, 2003). Thus, in making recommendations about meeting America's workforce needs, the National Science Board recommended more attention in STEM graduate education to new areas in science and engineering (such as nanoscale science and engineering), more preparation for future scientists and engineers in interdisciplinary skills, more attention to preparing talented individuals for traditional fields that are currently related to infrastructure needs in the country (such as computer science), and more attention to preparing future professionals for areas of federal focus where a mismatch occurs between enrollments and need (such as nuclear physics and engineering) (National Science Board, 2003). Those who will enter the workforce also need to understand the global economy (Carney et al., 2006). Overall, the reform reports and the research on various stakeholders' concerns have raised questions and urged greater attention to explicit preparation of doctoral students for non-academic employment options.

Competencies to Develop in Doctoral Education

The publication of literature conceptualizing doctoral education as a period of socialization for academic work has paralleled the discussion of the adequacy of doctoral education for preparing students for future careers—academic and non-academic (Anderson & Seashore Louis, 1991; Austin, 2002a, 2002b; Austin & McDaniels, 2006a, 2006b; Bess, 1978; Golde & Dore, 2001; Tierney & Rhoads, 1994; Weidman, Twale, & Stein, 2001). Building on the literature on socialization, the research on the graduate experience and on faculty work, and the recommendations calling for reform in doctoral education, Austin and McDaniels (2006a) outlined key areas that doctoral education should address in order to prepare future faculty members for the work they will do. They recommended that doctoral students in all fields—including STEM fields—should develop competencies in four areas: (1) conceptual understandings of scholarly work; (2) knowledge and skills relevant to the major aspects of faculty members' work; (3) interpersonal skills; and (4) professional attitudes and habits. The work of a scholar is marked by certain characteristics, whether conducted within academe or in other settings. Thus, the recommendations that emerged from discussions in the national dialogue about the preparation of future faculty have considerable relevance for preparing students for a range of career options. Furthermore, doctoral students may not know in which arena they will ultimately work, and their career paths may, over time, weave across sectors.

In terms of the first area of competencies to be developed in doctoral education (conceptual understandings), Austin and McDaniels (2006a) suggested that future faculty should understand the "essential purposes and core values" of higher education (Levine, 2000), the responsibilities of institutions of higher education to the broader society, the history of American higher education, the types of institutions within the higher education landscape, and the traditions of teaching, research, and service that have shaped the roles of faculty members in American higher education institutions. The importance of preparing doctoral students to understand their responsibility to make contributions to the public good also was encouraged by Austin and Barnes (2005). Austin and McDaniels (2006a, 2006b) also asserted that adequate preparation for "conceptual understandings" must include thorough knowledge of one's discipline, which would involve understanding the culture of the discipline; the paradigms, theories, and philosophical traditions that guide its work; the research methods and modes of scholarly communication commonly used; the major debates and cutting-edge questions challenging those working in the field; and the ways in which one's field intersects with others. Additionally, doctoral preparation should help students develop a sense of professional identity in which they come to see themselves as scholars, who understand the norms, values, and responsibilities associated with this role (Austin & McDaniels, 2006a, 2006b).

The second major competency area encompasses knowledge and skills in key areas of faculty work. Future faculty must understand teaching and learning processes, including the processes through which learning occurs, ways to respond to individuals' learning differences, and strategies to foster learning (Wulff & Austin, 2004). Future faculty also should have deep knowledge of how learning occurs and the challenges related to learning in their disciplines (Hutchings & Shulman, 1999), as well as ways to use technology to enhance learning. Well-honed research skills are at the heart of preparation for a faculty role—or for any other professional role as a scholar in a discipline. Austin and McDaniels (2006a) argued that all scholars should understand how to frame questions within their fields, how to design scholarly projects, how to collect and analyze data, how to present results for a variety of audiences, and how to give and receive feedback about their work. Appreciation and knowledge of the forms that service and engagement with the broader society takes within their fields is another key ability relevant to faculty work—and work in other sectors, as well. Specifically, how to link theory and research with application and practice and how to communicate with diverse audiences are essential skills for scholars and faculty members.

The third area of competency pertains to interpersonal skills (Austin & McDaniels, 2006b; Stark, Lowther, & Hagerty, 1986). Those who will serve as faculty members—or as scholars and professionals in other areas of work—should be able to communicate effectively in various forms and to a broad array of people (Austin, 2002a, 2002b; Austin & Barnes, 2005; Terenzini, 1996). They also should be able to work effectively with people within the academy and beyond, and, as many issues require an interdisciplinary approach, with colleagues across a range of disciplines. Understanding the dynamics of group process, knowing how to collaborate and work in teams, and having the skills to resolve conflicts become important attributes to develop in doctoral study (Austin, 2002b; Austin & Barnes, 2005; Austin & McDaniels, 2006a; Klomparens & Beck, 2004).

Fourth, doctoral education should prepare future faculty—and future scholars in all areas of work—to value and express various professional attitudes and habits. Of utmost importance is the internalization of the code of ethics that is prized by the profession (Austin & McDaniels, 2006b; Braxton & Baird, 2001; Pescosolido & Hess, 1996; Stark et al., 1986). A consistent concern through a number of the reports addressing reform in STEM doctoral education pertained to ethics and responsible conduct of research (Carney et al., 2006; National Science Board, 2003). Scholars learn how ethical guidelines should guide their research, the importance of confidentiality, the appropriate ways to treat human or animal subjects, how to recognize and manage conflicts of interest, and how to enlist ethical guidelines in the processes of collaboration. They should know about laws and guidelines pertaining to intellectual property and how to balance the interests of all parties to research endeavors. Other professional attitudes to be cultivated include a sense of motivation to stay abreast of their fields and engage in continuous learning, the ability to cultivate and participate in professional networks, and a sense of how to find balance in regard to personal and professional responsibilities.

Lack of Attention to Developmental Career Preparation

The reports and studies analyzing doctoral education call for better preparation for both academic and non-academic careers, and more attention to preparing students with a full array of competencies. Additionally, extant literature questions the process through which graduate students learn. Whether doctoral students aspire to careers in academe or in other sectors, literature calling for reform expresses concern that doctoral education is not structured to develop the competencies graduates will need in a systematic, developmental way (Austin, 2002a, 2002b; Austin & McDaniels, 2006a; Nyquist et al., 1999; Wulff et al., 2004; Walker et al., 2008). Doctoral students typically have some opportunities to teach and conduct research under faculty guidance. However, these assignments are usually not designed to offer comprehensive preparation. For example, teaching assistants' assignments often address university needs for instructional coverage of undergraduate courses, not the needs of individual doctoral students to develop a set of teaching skills in a way that takes into account the doctoral students' development as teachers (Austin, 2002b; Nyquist et al., 2001). Assignments are not necessarily organized to ensure that any individual doctoral student has, across the graduate career, a range of different types of teaching opportunities. While teaching assistants usually have some training, STEM doctoral students often are discouraged by their advisors from spending much time on programs or training to deepen their knowledge of teaching (Austin, 2002b); time spent on developing as a teacher results in time away from the laboratory conducting research. While doctoral students in science and engineering often are working on research projects, they still may not have opportunities to develop, in a systematic way, the full array of research skills they may need in a career. Rather, they may get involved in projects that are in process, after grant proposals are written or before the final reports are prepared, thus enabling them to learn only about some stages of the full research process. In fact, in one study of doctoral students' perceptions of their experiences, interviewees reported a lack of competence in grant-seeking and proposal development (Austin, 2002b). Doctoral students also reported that they receive little preparation in other facets of scholarly work, including engaging in work in connection with the public, assessing ethical issues, and, for those interested in academic careers, participating in institutional governance or working on curriculum development (Austin, 2002a; Lovitts, 2004; Wulff et al., 2004).

In summary, the calls for reform coupled with the research and theoretical literature over the past decade and a half have focused considerable attention on shortcomings in the ways in which doctoral students—including those in STEM fields—are prepared for their careers. Those voices critiquing doctoral education point to the need to prepare students more fully and explicitly for both academic and non-academic career options, to ensure that career preparation includes the array of abilities and understandings that graduates will need in employment contexts, and to offer educational experiences that provide developmentally progressive learning opportunities.

The Structure and Nature of the Doctoral Experience

Critiques of doctoral education not only pertain to whether graduates are prepared for academe and for assuming other employment options. Additionally, observers, researchers, and policy makers point with concern to the nature of the doctoral experience itself. As discussed below, the length of time to complete a degree coupled with the rate at which attrition occurs is frequently mentioned (Klomparens & Beck, 2004; Nettles & Millett, 2006). In studies that gather student views, key issues are also relationships with faculty members, mixed messages about what is valued in scholarly work, disappointments around shortcomings in regard to community, and concerns about the quality of life in academic careers.

Time to Degree and Completion Rates

Two major concerns that are mentioned as motivating factors for various studies and programmatic efforts to strengthen doctoral education are the time it takes for students to attain their degrees and the attrition rate from doctoral education. Overall, the time that students take to complete degrees in science and engineering fields is less than in the humanities and social sciences. About a decade and a half ago, Bowen and Rudenstine (1992) reported elapsed time to degree (time from entering a program to completion) was 6.2 years in engineering, and 5.9 in the physical sciences, compared with 9.2 years for humanities students and 8.13 for social sciences students. More recently, Nettles and Millett (2006) reported that their research indicated a somewhat shorter time to degree—a median time of 5.75 years for students in sciences, mathematics, and social sciences, 4.75 for those in engineering, and 6.75 for those in humanities. Nevertheless, while STEM fields may have shorter times to degree than other fields, and while the mean age for completing doctorates in science and engineering areas (31.8 years) is the lowest across fields, students in these fields often must follow their doctoral work with post-doctoral experiences. Thus, a considerable period of time passes until a new scholar is actually in a full-time faculty position. In addition to the implications for the individual in terms of becoming established in a stable position, a lengthy period of preparation also slows the availability of scientific talent available to the labor market. Thus, time to degree has become a major interest of graduate deans concerned with the smooth flow of students through the graduate school pipeline.

The impact of teaching and research assistantships on the students' experiences and time to degree varies depending on their fields (Nettles & Millett, 2006). Overall, assistantships provide students opportunities to make connections in the academic and social community, develop greater understanding of graduate education and what is necessary to succeed, and some experience as teachers or researchers (Lovitts, 2001, 2004; Nettles & Millett, 2006). In regard to the impact of various forms of doctoral funding, Nettles and Millett (2006) reported: "None of the three major forms of student support—fellowships, teaching assistantships, or research assistantships—predicted time to degree. Only in the social sciences was debt incurred as a doctoral student a factor in lengthening time to degree" (p. 175)

Attrition rates are also a concern that motivates efforts to improve doctoral education (Lovitts, 2001, 2004; Walker et al., 2008). Nettles and Millett (2006) explained that pinning down exact rates of attrition is difficult, partly because the interpretation of any figure varies depending on the time in the program a student decides to stop. When students leave early in their doctoral experience, they may be making reasonable decisions about their interests and futures. However, when several years of tuition (either from the institution, other funders, or the student directly) and time (on the part of the faculty and the student) have been invested, attrition represents investments lost. For some decades, the overall attrition rate in doctoral education has been about 45–50% (Bowen & Rudenstine, 1992; Lovitts, 2001), a daunting figure that is motivating reform efforts in doctoral education. Again, though, it is important to note that a specific figure must be viewed with caution. In her study of attrition in doctoral education, Lovitts (2001, 2004) concluded that students often do not have the appropriate information about standards of quality, how to choose advisors, and the "cognitive maps" of the environments they are entering that are needed to negotiate successfully through the doctoral experience.

Advising and Mentoring

Both qualitative and quantitative studies of doctoral education have raised alarm bells about the guidance that students receive. Students have reported that they lack clear information about the steps involved in progressing toward their degrees and the expectations they are to meet regarding requirements (such as examinations, meetings with guidance committees, and dissertation proposals). According to research data, students report that they do not have regular conversations with their faculty advisors about such important issues as their career goals, their areas of focus, and the connections between their professional aspirations and the opportunities available in the labor market (Austin, 2002a, 2002b; Austin & McDaniels, 2006a). Anderson and Swazey's (1998) study of doctoral students led them to conclude that "only half [of the doctoral participants responding] agreed—very few strongly—that faculty members were explicit in their expectations" (p. 6).

In addition to receiving insufficient information, doctoral students often report receiving "mixed messages" as they strive to make sense of their experiences and decisions about their priorities and futures. Students learn a great deal by observing and working with faculty members in an apprenticeship fashion. They watch what faculty value and how they spend their time. They also observe that what is claimed to be important (such as teaching) is often not rewarded. In short, students report receiving conflicting signals about what work they should do and what work is valued (Austin, 2002b; Nyquist et al., 1999; Wulff et al., 2004).

Students typically report relatively few opportunities to talk in depth with faculty advisors about the life of a scholar, how they should prepare for their careers, and how they might make career decisions. They are sometimes surprised and even disillusioned to find that faculty members do not focus more time on their advisees, and, while cordial, may appear reluctant to forge personal connections with their doctoral students (Austin, 2002a, 2002b; Austin & McDaniels, 2006a; Nyquist et al., 1999; Wulff et al., 2004). Overall, a number of the studies of the doctoral experience point to short-comings in the nature and extent of mentoring and advising that students receive.

Insufficient Sense of Community

Closely related to issues about mentoring are concerns about the community within doctoral programs. Doctoral students tend to turn to peers for support and even guidance and information about the graduate experience (Austin, 2002b; Wulff et al., 2004). While peer relationships are useful, the limitations in relationships with advisors, mentioned above, are especially challenging for some students (Rice et al., 2000). In her research on doctoral attrition, Lovitts (2004) concluded that concerns about community are especially important to students who ultimately choose to drop out. For women and students of color, feelings of isolation, expectations to conform, and negative stereotyping can be strong factors undermining doctoral success (Antony & Taylor, 2001, 2004; Taylor & Antony, 2001; Lovitts, 2004). Lovitts (2004) has urged departments concerned with retaining students, especially those in under-represented groups, to be particularly attentive to the extent to which the culture is welcoming, creates a sense of community, and responds to students' needs.

Quality of Life

Research over the past decade also shows that doctoral students, across fields, are concerned about the quality of academic life. Watching their own advisors and faculty members, doctoral students express uncertainty about the pressures of the academic lifestyle and the extent to which a faculty career will enable them to live with a sense of "balance" in their personal and professional responsibilities, which many hope to have (Rice et al., 2000).

In their survey research, to which more than 8000 University of California doctoral students responded, Mason, Goulden, and Frasch (2009) found that many graduate students, both male (74%) and female (84%), are concerned about family issues in relation to their career goals. In particular, many doctoral students do not want the hectic lifestyles that they observe their faculty members lead and do not perceive the research-intensive university as a “family-friendly” work environment. The survey also showed that a majority of doctoral students feel concerned about having children while working on the Ph.D., due to the time that doctoral work requires, the stress of managing both doctoral work and children, and the extent to which affordable child care, insurance, and housing are available.

In their earlier, well-publicized, “Do Babies Matter?” study, Mason and Goulden (2002, 2004) focused specifically on how academic careers impact family formation. The research showed that, for women faculty, postponing pregnancy and childbirth until after the years of doctoral study, the years of post-doctoral research (which typically are part of the experience of scholars in the STEM fields), the early faculty career, and the receipt of tenure often means that women have fewer children than they would prefer. This postponement of family formation also leads to considerable stress for women academics. The implications of such research for doctoral education, especially in STEM fields, is that students assess their own career decisions about whether, where, and in what positions to work in academe partly in light of what they observe and experience as doctoral students and what they perceive about the quality of academic life.

Those interested in attracting talented young people to STEM academic careers should take note of the concerns that both men and women have about the nature of academic life and the personal challenges that women in particular are likely to encounter in academic careers. Mason et al. (2009) pointed out that women doctoral students in departments where there are few female faculty (as is often the case in STEM fields) are less likely to perceive research-intensive universities as “family friendly.” Thus, doctoral students’ experiences and perceptions pertaining to academic life as it relates to their personal aspirations relates to the pipeline of a diverse pool of academics for future faculty positions.

Reports, research studies, and observations about doctoral education are quite consistent in the concerns and criticisms that they mention. Reports assert that STEM doctoral students are typically prepared rather narrowly, without sufficient attention to the full range of knowledge, abilities, and skills that they will need in academic careers. Furthermore, they often receive little encouragement to explore career options beyond academe, nor specific attention to considering ways in which their skills and abilities can be directed to a wide array of career options. In terms of the structure and nature of doctoral education, key concerns are time required to complete the Ph.D., high attrition rates, inadequate advising and mentoring, limitations to the sense of community characterizing the doctoral experience, and students’ perceptions about the quality of life in academic careers. These various criticisms of doctoral education have been important considerations in the conceptualization of programmatic interventions designed to reform doctoral education in STEM fields.

Programmatic Interventions

The policy and research reports highlighting the shortcomings of doctoral education in the sciences, technology, engineering, and mathematics have led to an array of responses. Government bodies, foundations, graduate schools, departments, and individual faculty members have responded to the urgency of reforming doctoral education. In preparing this chapter, I faced the decision of how to discuss practical responses to the calls for reform. One choice was to offer short summaries of a number of programs. An alternative was to discuss several different types of programs in some depth, providing, where available, some evaluation data about impact. I chose to provide an overview of key characteristics on which programmatic responses to STEM doctoral education differ, and then to select several programs for discussion.

One key characteristic of programmatic efforts to reform and improve STEM doctoral education pertains to the sponsor, who is often also the funder. The nature of the sponsor has some influence on the degree to which a program has national attention. There are five types of sponsors: (1) national organizations and agencies, such as the National Science Foundation (NSF), the Council of Graduate Schools, and the Association of American Colleges and Universities; (2) private foundations and organizations, such as the Alfred Sloan Foundation, the Woodrow Wilson National Fellowship Foundation, and the Carnegie Foundation for the Advancement of Teaching; (3) disciplinary associations, such as the American Chemical Society; (4) individual universities; and (5) individual departments and faculty members. These various sponsors have supported an array of programs. For example, the National Science Foundation has funded a number of projects, including the GK12 Program to provide STEM doctoral students with opportunities to work with K-12 teachers and students. Another major NSF Program is the Alliances for Graduate Education and the Professoriate (AGEP), which has the purpose of encouraging more US citizens and permanent residents, especially from underrepresented groups, to enter STEM fields. NSF also funds various discipline-specific fellowship opportunities for graduate students.

A second characteristic around which initiatives might be characterized is the level of focus. Some initiatives, for example, are designed to provide opportunities for individual STEM students, while others focus on departmental or institutional interventions, and others create multi-institutional networks. Third, one might characterize programs on the basis of the topics or areas of graduate education that they target. For example, some programs are intended to develop doctoral students as teachers, while others focus on research development. Some programs provide opportunities for future scholars to learn about the array of higher education institutions in which they might work, and others link them with K-12 education. Some initiatives are designed to address a number of the concerns and criticisms that have been levied at doctoral education; others take a more focused, single-issue approach.

I have selected four programmatic initiatives which illustrate several of these characteristics, and discuss in detail the goals, programmatic elements, and change strategies of each. First, I discuss the National Science Foundation's Integrated Graduate Education and Research Traineeship (IGERT) Program, which is an example of a major national program, supported with federal funding, and designed to provide a comprehensive graduate experience that addresses a number of the recommendations for enhancing preparation of future scholars. Second, I present the Carnegie Initiative on the Doctorate, funded by a major private national organization. This program has a very different change strategy; it involves gathering departments in various fields for dialogues about the challenges in doctoral education and supports these departments in developing discipline-specific, and institutionally responsive, plans for strengthening doctoral education. Third, I discuss the Center for the Integration of Research, Teaching, and Learning (CIRTL). While this is NSF-supported, it takes a different change strategy than IGERT. CIRTL encourages institution-level program development, while also creating a network of institutions that are sharing ideas about reform in STEM doctoral education. CIRTL prepares graduate students to approach their teaching responsibilities with the same analytical skills that they bring to their research. Embedded within the description of CIRTL is also a discussion of two participating universities and their individual efforts to make institutionally-specific reforms (which are supported by CIRTL). Fourth, I discuss the efforts of Dr. Brian Coppola and his colleagues in the Chemistry Department at the University of Michigan. Their work is an example of a reform effort at the department-level, encouraged by the commitment, creativity, and enthusiasm of a faculty member.

Taken together, these four discussions provide an overview of the kinds of reform efforts occurring in STEM doctoral education. Following these examples, I discuss key theoretical and practical questions that must still be addressed concerning STEM doctoral reform. Efforts are underway; but conclusions about the relative effectiveness of different models remain open questions.

Integrative Graduate Education and Research Program (IGERT)

In response to concerns about the quality of doctoral education and the recruitment and preparation of a diverse and talented cohort of advanced scholars in sciences and technology, the National Science Foundation started the IGERT Program in 1997 with a specific focus on promoting interdisciplinary STEM graduate education. Awards are made to institutions, not to individual students, which encourages institutional impact and innovations in graduate training. By 2005, NSF had provided 125 grants, totaling more than $300 million dollars. Individual institutions are awarded 5-year grants of about $3 million dollars, with most of the funds used to provide traineeships to doctoral students who participate in interdisciplinary or multidisciplinary programs (Carney et al., 2006).

The IGERT Program has been designed to help Ph.D. programs in science and engineering offer their students "the technical, professional, and personal skills needed for the changing career options of the twenty-first century" (Carney et al., p. 4; citing Integrative Graduate Education and Research Training Program, Program Solicitation, NSF 95–517, 2005). The program specifically focuses on developing U.S. students in response to the concern about a diminishing pool of domestic talent in science and engineering. The solicitation highlighted the specific purposes of IGERT grants (cited in Carney et al., 2006, p. 4):

- Educating U.S. Ph.D. scientists and engineers who will pursue careers in research and education, with the interdisciplinary backgrounds, deep knowledge in chosen disciplines, and technical, professional, and personal skills to become, in their own careers, leaders and creative agents for change.
- Catalyzing a cultural change in graduate education, for students, faculty, and institutions, by establishing innovative models for graduate education and training in a fertile environment for collaborative research that transcends traditional disciplinary boundaries.
- Facilitating diversity in student participation and preparation, and contributing to the development of a diverse, globally-engaged, science and engineering workforce.

According to the Program Solicitation (IGERT, 2005), the NSF holds certain expectations for IGERT projects. The programs should, first, broaden the career possibilities for Ph.D. candidates by ensuring that they develop necessary personal and professional skills, including skills in teaching, mentoring, and leadership as well as communication and teamwork. Second, the institutional programs should encourage interdisciplinary work, which is expected to be the underlying theme of the traineeship activities. This goal is fostered through interactions among faculty and students across and within disciplines and the incorporation of interdisciplinary research into graduate education. Third, an IGERT grant is expected to ensure that students are exposed to a broad base of cutting-edge research and methodologies, opportunities to learn about ethics and responsible conduct of research, and encouragement to develop an international perspective. Fourth, expectations focus on the structure of doctoral programs. The award of an IGERT grant carries the expectation that a program will develop a strategy for recruitment, mentoring, and retention of U.S. students (including those from groups underrepresented in STEM fields), a strategy to assess the project both formatively and summatively, a strong plan for administering and managing the grant, and a commitment on the part of the university to provide an environment that supports integrative research and education. Overall, NSF seeks to encourage institutional innovation through the IGERT program.

While institutions have the leeway to organize their IGERT programs as appropriate for the specific context, the IGERT model emphasizes five components: (1) Each project is to have an interdisciplinary theme that involves a diverse array of faculty members. Project plans to integrate research and education and to encourage collaboration are organized around the theme; (2) Students are to develop a breadth of skills that will enable them to work in interdisciplinary environments, while at the same time gaining deep knowledge in their major area; (3) Students' experiences are to prepare them for both academic and nonacademic career options. Thus, they may have internships or mentoring experiences in academic, national laboratory, industrial, or other work settings; (4) Students are to gain an international perspective, which they may develop through institutional programs, fieldwork in international contexts, or through collaborative research experiences; (5) The program should help students develop both professionally and personally, so they can understand the complexities of challenging problems, including the scientific, political, ethical, business, social, and policy dimensions of these issues (Carney et al., 2006, citing IGERT, 2005). IGERT permits universities to interpret "interdisciplinary" in their own way. Among the strategies used to achieve this goal are the funding of trainees who come from diverse disciplines, involving faculty from different disciplines in team teaching and developing courses relating to multiple disciplines, and involving trainees in research projects with faculty from various disciplines. Some programs strive to develop students as experts in more than one field, others emphasize developing mastery in one field along with an ability to work with colleagues in other fields, and others encourage students to learn research techniques from various fields.

From the early years of IGERT, the National Science Foundation has collected some evaluative data. The evaluation plan included third-year site visits to projects started in 1998, 1999, and 2000 (including extensive interviews with administrators, grant Principal Investigators, IGERT trainees, and key faculty involved in the project). Additionally, the NSF used a web-based system to collect annual data from each institution with an IGERT grant beginning in 1997. Then, in 2003, in order to get comparative data with institutions that did not have IGERT grants, NSF contracted with Abt Associates to conduct an extensive and carefully conceptualized evaluation of the initial impacts of the IGERT Program on students, faculty, and institutions that had received awards (Carney et al., 2006).

Evaluation Findings

Impact on students. The Abt evaluation (Carney et al., 2006) reported that IGERT participants develop more interdisciplinary expertise as compared to students who do not participate, while maintaining equal levels of development in depth of knowledge in their own fields. They have more opportunities to work with faculty from other universities and with scientists in public and government laboratories. They are more likely to have multiple formal advisors and an advisor from a department other than their own, and they are more likely to have worked on research projects with students from other departments. Overall, participants develop more extensive teamwork skills and the ability to communicate with those in other areas. The data also indicated that IGERT participants are more fully prepared for an array of career possibilities. A greater percentage than the non-IGERT comparison group conducted research, worked, or studied off-campus. Sixty-three percent of IGERT students, compared with 44% of the comparison group, agree that they are being prepared for various career options. Both groups are similar, however, in their career goals; about one-third aspire to faculty positions in research universities, and another one-third want to find either an industry or an academic position. While not all IGERT programs have developed specific ways to foster international experience, some have provided opportunities for IGERT students to work with scientists from abroad who come to the U.S., to engage in internships abroad, or to travel to international conferences. In regard to the IGERT goal to ensure students have training for professional and personal development so that they can understand relevant issues in the world's complex problems, the data also show significant impact. IGERT participants are much more likely to have specific training in ethics and responsible conduct of research, as well as in research methods, statistics, and very current instrumentation. Furthermore, they are more likely to have had experience with multidisciplinary teams and to feel better prepared for such teamwork. The data also show they receive more training in communicating beyond their disciplines and feel more prepared in this area than their counterparts. Overall, based on their more extensive learning experiences, the doctoral students reported feeling more well-prepared for their careers than do those without IGERT training.

Impact on faculty involved in IGERT programs. The National Science Foundation also planned for the IGERT Program to impact the faculty involved as well as the doctoral students. Thus, the Abt evaluation also studied impact on faculty (with a matched comparison group) and concluded that the program has enriched the interdisciplinary experiences of the faculty members involved. The evaluation report noted that the faculty members studied (those working with IGERT and not) get involved to some degree in interdisciplinary work. However, the IGERT faculty have a heightened interdisciplinary dimension to their work. They team-teach more with others outside their discipline, and are more likely to mentor students in other disciplines. IGERT faculty report that their participation has helped them to develop a larger repertoire of teaching strategies and to bring a more expansive array of topics into their courses. They also collaborate on research and co-author with colleagues outside their disciplines at a greater rate, and are more likely to publish journal articles and present at conferences outside their own disciplines. Additionally, they indicate they are better positioned to win grants because of IGERT and have learned new research techniques. The evaluation study also noted that IGERT faculty members indicate enthusiasm for their involvement and willingness to give considerable time to IGERT work without special compensation.

Impact on institutions. Beyond the impact on the students who receive IGERT traineeships and the faculty who work with the program, IGERT has had a broader impact on the universities where the programs are offered in terms of promoting interdisciplinary graduate education. According to the Principal Investigators whom the Abt evaluation project interviewed, institutional impacts include new degrees, certificates, and degree requirements, policy changes in regard to interdisciplinary teaching, and more general institutional interest and support for interdisciplinarity. While assessment of faculty involvement in interdisciplinarity remains an issue at some institutions in relation to tenure decisions, the Abt evaluators concluded that the IGERT program has made a demonstrable impact on advancing support for interdisciplinarity at participating universities.

Impact on recruitment. The Abt evaluation study (Carney et al., 2006) also reported that faculty members involved in IGERT believe the program has enabled them to recruit "more and better academically qualified individuals," and that IGERT programs will help increase the number of U.S. citizens who pursue doctoral education in STEM fields (2006, p. 70). The recruitment of women and minority individuals has equaled the national averages but the goal of showing increases in diversity has not yet been achieved.

Summary of impacts. Overall, the evaluation data show that IGERT has made a significant impact on supporting universities in developing innovative, interdisciplinary graduate programs. As compared with their counterparts, student participants are having more experiences working with faculty members and students across fields, learning teamwork and communication skills, participating in explicit training concerning ethics, and becoming aware and prepared for diverse career options. The evidence is solid that the IGERT program is addressing a number of the concerns and challenges outlined in the reports and studies calling for reform in STEM doctoral education.

Carnegie Initiative on the Doctorate

The Carnegie Initiative on the Doctorate (CID) is a recently completed 5-year program sponsored by the Carnegie Foundation for the Advancement of Teaching to address the challenges confronting doctoral education in the United States (Golde, Walker, & Associates, 2006; Walker, 2004; Walker et al., 2008). The project selected 84 Ph.D.-awarding departments in six fields: Chemistry, Mathematics, and Neuroscience in the STEM areas as well as Education, English, and History. Each department agreed to be part of an on-going process of examining the purposes of their doctoral programs and the extent to which they were effective or ineffective, developing and implementing changes in response to the findings, and monitoring the effects of the changes. The CID staff organized "convenings," which brought together teams from the participating departments, including graduate students themselves, for the purpose of discussing themes and issues emerging from the process of departmental self-examination. Additionally, the CID staff visited the departments periodically to interview departmental team members and institutional administrative leaders, and they conducted surveys of faculty and students which provided supplementary information to inform the discussions. The overall project plan was to help doctoral programs "hold a mirror up to themselves" to engage in "purposefulness, assessment, reflection, and transparency" (Walker et al., 2008, p. 13).

In essence, the CID project did not have a specific set of action strategies to encourage the participating departments to adopt or advance. Rather, it promoted change by encouraging those directly involved in doctoral education to engage with difficult questions and to identify the changes they believed appropriate within their disciplinary and institutional contexts. While they believed that no single model of change was appropriate, the leaders of the CID did believe that the project could set in motion some powerful processes. In their words:

> What *does* work in all settings, we argue, and what is distinctly absent from most doctoral programs, are processes, tools, and occasions through which both faculty and graduate students can apply their habits and skills as scholars—their commitment to hard questions and

robust evidence—to their purposes and practices as educators and learners (Walker et al., 2008, pp. 5–6).

While they did not advocate specific areas for reform, the CID did have a set of underlying assumptions about how reform in doctoral education could be fostered most effectively. First, the Carnegie leaders chose to focus the project at the department level, believing that disciplines have unique norms and cultures that influence the doctoral experience and that, since departments provide the home base for faculty members, they are likely to be the most effective locus for reform efforts. Working with departments also enabled the project to "go deep" into the influences of the disciplinary traditions on the doctoral experience. Second, the project involved a set of institutions that were diverse in terms of prestige and the ways in which they went about doctoral education. Involving a range of institutional types made the project of wide interest across the American higher education landscape. A third assumption about change pertained to the importance of working from the local level, enabling each participating department to decide what reforms it would undertake in the context of its particular circumstances. Fourth, the CID highlighted the importance of making innovations and experiments public. Participants were encouraged to present their deliberations on challenges characterizing doctoral education in their fields as well as their efforts at innovation not only to the other participants, but also to colleagues nationally (these contributions were called "reports to the field"). Fifth, the change process explicitly involved doctoral students on the institutional teams, seeking their input and ideas at each step of the process. In reflecting on lessons learned, the CID staff asserted that graduate students are key ingredients in the change process (Walker et al., 2008).

Certain philosophical assumptions and values about doctoral education also formed the foundation for this effort to bring change to the participating departments and to raise questions that would be relevant to the disciplines. The Carnegie Foundation has a long history of shaping conversations and directions in American higher education. The philosophical perspective guiding the project was that doctoral education is a "formation process" through which students are developing a sense of professional identity as scholars that includes both intellectual and character dimensions. The project became known especially for creating "stewards of the discipline"—individuals who see their responsibilities both to their own careers and to their disciplines. A steward of the discipline is committed to generating new knowledge through research and scholarship, "preserving the best of the past for those who will follow," and preparing the next generation of disciplinary stewards (Walker, 2004; Walker et al., 2008, p. 11).

Another assumption about doctoral education grounding the project was a commitment to finding ways to create greater scholarly integration that would link the teaching and research aspects of a scholar's work. This interest led to discussions about how to thoughtfully develop doctoral students for their teaching responsibilities as well as how to create "pedagogies of research" that would provide more systematic preparation for scholarly careers. The project also highlighted a commitment to intellectual community, and framed conversations among participants about the conditions that foster greater creativity and risk-taking in doctoral education.

These two philosophical values—doctoral education as a "formation" process and the importance of scholarly integration—led to specific interest in ways to encourage greater collaboration for graduate students with peers and faculty members throughout the doctoral experience around the various aspects of scholarly work, including research, teaching, outreach, and institutional citizenship.

The description provided here of the Carnegie Initiative on the Doctorate has emphasized the philosophical perspectives because those are central elements in terms of the nature of this reform initiative. CID did not advocate specific innovations, but rather called for participating departments to make "a commitment to the ongoing process of improvement: deliberating about purpose, asking questions about effectiveness, gathering evidence to shape improvements over time, and taking action" (Walker et al., 2008, p. 142). This focus on encouraging deep questioning, data gathering, and dialogue within departments as well as across disciplines is what made this project unique in the reform landscape. Yet, many specific initiatives have emerged within departments—in STEM disciplines as well as in other areas—as a result of this initiative. Departments identified aspects of their doctoral programs that were not effective, developed new approaches, and implemented and began to gather data about the changes. Cross-disciplinary conversations highlighted practices in particular disciplines that could be adapted in others.

Examples of projects that CID departments designed illustrate the array of ideas and strategies that emerged from the project (Walker et al., 2008). In response to concerns that the doctoral experience should help students understand and create integration between the various aspects of scholarly work, including teaching and research, the Department of Anatomy and Neurobiology at the Boston University School of Medicine requires all Ph.D. students to serve as teaching assistants. These students take a required course about teaching, receive on-going mentoring as they teach, and are guided to develop both as researchers and teachers through systematic scaffolding that takes a progressive, developmental approach. The Interdisciplinary Program in Neuroscience at Georgetown University has taken specific steps to create an inclusive intellectual community that involves both students and faculty members and helps students understand their relationship to the larger disciplinary community. Journal clubs, simulated grant reviews, student involvement in panels on ethical conduct of research, and informal monthly "Tea-Time" gatherings to discuss controversial topics at the intersections of science and society are all part of the array of elements purposefully included in the doctoral experience. Another example of the kinds of ideas that have developed from coupling departmental analysis of doctoral practices with cross-disciplinary conversations involves experiments with research rotations (modeled after medical school rotations) (Walker et al., 2008). By giving first-year students opportunities to work with several different faculty members on various projects for relatively short periods of time, students gain broader knowledge of issues in their fields, connect with more faculty members, and begin to function as researchers early in their doctoral experience.

A major topic within the CID has been the concept of apprenticeship. The discussions led to interest in enlarging the traditional apprenticeship model, based on a student working with a single faculty member, toward more multi-generational, coordinated, and multi-mentor learning communities. Each department grappled with the implications of a new concept of apprenticeship in the context of specific disciplines. Through the conversations, innovative ideas, grounded in respect for disciplinary traditions but seeded with ideas from cross-disciplinary dialogues, are emerging. While the CID has officially concluded, the ideas generated through the project are still informing departmental projects and influencing national discussions about reform in doctoral education in STEM and other fields.

Center for the Integration of Research, Teaching, and Learning (CIRTL)

The Center for the Integration of Research, Teaching, and Learning (CIRTL), one of the National Science Foundation centers, focuses on improving STEM education at the postsecondary level (http://www.cirtl.net/). CIRTL's mission is to contribute to the national pool of talent by developing STEM graduate students who have the knowledge and commitment to create successful careers that include effective teaching as well as excellent research (CIRTL, 2003). Since the majority of STEM doctoral students graduate from less than one hundred universities, CIRTL's mission includes contributing to the preparation of a well-qualified STEM faculty for the nation. The Center rests on the assumption that doctoral education heavily emphasizes research, typically providing little time and encouragement for graduate students to develop as teachers. The Center is also based on a recognition that teaching occurs through what is often called informal education (e.g., in such venues as museums and schools) as well as in formal higher education classrooms.

Funded by a large grant, CIRTL began in 2003 with three universities—the University of Wisconsin Madison, Michigan State University, and the Pennsylvania State University—which collaborated to develop and implement professional development strategies appropriate for STEM doctoral students. The University of Wisconsin Madison (UW) served as the incubator for the emerging strategies and, through the Delta Program (the UW version of CIRTL), became the prototype of the CIRTL approach. A second NSF grant, beginning in 2008, supported the creation and expansion of the national CIRTL Network to include six universities, adding Howard, Texas A&M, the University of Colorado-Boulder, and Vanderbilt to Michigan State University and the University of Wisconsin Madison (Penn State withdrew from the Network). The Network institutions are committed to collaborating to develop and share professional development strategies and models that provide professional growth opportunities for STEM graduate students (as well as for post-docs and faculty members). While the overall goals are consistent at each institution, the particular details of the professional development programs vary in response to institutional contexts, history, and background with professional development.

The signature of CIRTL is a set of three pillars whose principles guide program planning and which are reflected in each institution's CIRTL plan. The first pillar, Teaching-as-Research (TAR), refers to "the deliberate, systematic, and reflective use of research methods by science, technology, engineering, and mathematics instructors to develop and implement teaching practices that advance the learning experiences and outcomes of both students and teachers" (CIRTL, 2005, p. 1). TAR is similar to what is widely called the Scholarship of Teaching and Learning (SoTL) or action research, but the TAR name resonated well with scientists early in the project development. Essentially, graduate students participating in CIRTL learn to use the skills of research they develop as scientists to identify challenges and problems in their teaching and their students' learning, frame specific questions, gather and analyze data to address those questions, and develop findings that can inform improvements in their teaching (Austin et al., 2009).

The second pillar concerns "Learning Communities," defined as a process that "bring[s] together groups of people for shared learning, discovery, and generation of knowledge" (CIRTL, 2005, p. 1). A key aspect of the definition of a learning community is that it has a functional purpose as individuals work together to achieve a goal and accomplish a task (Austin et al., 2009).

The third pillar, called "Learning-through-Diversity," recognizes the relationship between excellence and diversity. This pillar "capitalizes on the rich array of experiences, backgrounds, and skills among STEM undergraduates, [graduate students, post-doctoral scholars, and faculty that can]... enhance the learning experience of all" (CIRTL, 2005, p. 1). The pillar also draws attention to the importance of approaches to teaching that create inclusive environments. CIRTL participants learn to recognize, honor, and build on diversity as a means to deepen everyone's learning (Austin et al., 2009).

In its early years, CIRTL focused on creating prototypes of courses, internship experiences, workshops, resources to help teachers understand and build on diversity, and a teaching certificate. CIRTL course designs include "The College Classroom," "Effective Teaching with Technology," "Instructional Materials Development," and "Diversity in the College Classroom" (Pawley, Pfund, Miller Lauffer, & Handelsman, 2006). The diversity resources developed by CIRTL, including a review of inclusive teaching practices, a collection of syllabi from STEM courses that encourage diversity awareness, and a case book of diversity-related teaching situations relevant to STEM instructors, are available through its portal, which can be accessed via the CIRTL website (http://www.cirtl.net). The website includes an array of resources to strengthen the preparation of STEM graduate students for professional careers that may include both formal and informal teaching within an array of higher education institutions or outside academe. As the Network has expanded, various cross-Network activities have been developed. These include online courses available to graduate students from Network institutions and opportunities for doctoral students to visit other Network campuses to present their Teaching-as-Research projects and discuss disciplinary research projects. A description of activities at two of the CIRTL institutions shows the variations within CIRTL's work and also highlights how individual institutions are striving to strengthen STEM doctoral education.

Delta Program

The University of Wisconsin Madison was the original lead institution for CIRTL and created a prototype professional development program, called Delta, during the early years of the project (Austin et al., 2009; Brower, Carlson-Dakes, & Barger, 2007; Connolly, Bouwma-Gearhart, & Clifford, 2007; Gillian-Daniel, 2008). Delta is "a vibrant, interdisciplinary intergenerational learning community of current and future faculty" (Gillian-Daniel, 2008, p. 3), designed to prepare future educators who can help improve undergraduate STEM education. The Delta Program offers STEM graduate students (as well as post-docs) various high- and low-involvement opportunities, including six course options taught by teams of STEM and social science instructors, options to engage in internships with STEM educators to develop Teaching-as-Research projects designed to address teaching and learning issues in undergraduate courses, and monthly roundtable dinners involving discussions on topical issues. Delta also offers workshops on specific topics, such as approaches to the National Science Foundation's requirement that all grant proposals address broader impact, and "expeditions" in which graduate students and faculty visit offices and locations on campus to become more familiar with the learning processes that students experience (Carlson-Dakes & Pawley, 2005).

The three CIRTL pillars have been woven explicitly into all aspects of the Delta Program. Graduate students learn to identify learning or teaching problems, read relevant literature, develop hypotheses, design and implement interventions or possible solutions, gather and analyze data about the impact of the intervention, develop findings, and then use the findings to inform adjustments to their teaching. The concepts associated with the Learning-through-Diversity pillar are presented through a course, but also are embedded into each experience (for example, the expeditions into the university highlight resources that are available to support diverse student learning styles). The commitment to using learning communities (the third pillar) guides the structure of the Delta Learning Community. In all activities offered through Delta, instructors strive to model the underlying values and precepts of the CIRTL pillars (Austin et al., 2009; Gillian-Daniel, 2008).

Evaluation is embedded into all Delta activities and designed to assess participation, satisfaction, learning, application, and impact (Gillian-Daniel, 2008). Participation has been note-worthy, especially since STEM faculty sometimes express concern over any obligations that would take students away from research and laboratory responsibilities (Wulff et al., 2004). Gillian-Daniel (2008) reported that more than 1400 graduate students, post-docs, academic staff, and faculty members have participated at some level in Delta activities over the first four and a half years of the project. These figures represent about 100 graduate students participating in courses and programs each semester, with another 150–250 students, post-docs, faculty, and academic staff attending dinners and workshops. Of these participants, 36% have been in the biological sciences, 25% in the physical and mathematical sciences, 16% in engineering, and 13% in the social, behavioral, and economic sciences. In regard to satisfaction, 95% of participants have indicated that they are satisfied or very satisfied and 44% have participated in 15 or more hours of program options. A longitudinal study was begun in 2005 to follow participants in Delta as they move into their careers. Interview data collected from this group in 2005–2006 showed that, through involvement in Delta programs, participants had gained new knowledge and skills regarding teaching, developed more positive attitudes about teaching responsibilities, and developed a broader sense of career options, including more awareness of and interest in the array of higher education institutions in which one might work (Gillian-Daniel, 2008). The small group who had completed their degrees and moved into teaching positions by 2007 reported their perception that the Delta experience had helped them with their teaching responsibilities (Bouwma-Gearhart, Millar, Barger, & Connolly, 2007). Delta participants also reported giving campus and national conference presentations about their research on teaching and learning, and incorporating the findings from TAR projects into courses where they or their faculty mentors were teaching.

Michigan State University's PREP and FAST Fellows Programs

As a member of the CIRTL Network, Michigan State University (MSU) has built on its already established professional development program for graduate students to provide additional focused opportunities for STEM doctoral students. MSU's approach to involvement in CIRTL illustrates the coupling of programming available to all graduate students with specific programming for STEM students. The overall professional development program offered through the Graduate School to students across disciplines is called PREP. The name itself calls attention to four professional skills that the program is designed to help doctoral students develop: planning throughout their graduate careers in order to identify and develop their career goals; resilience and tenacity to manage the personal and professional challenges that arise across the stages of the graduate experience; engagement in decision-making about one's professional development; and the professionalism to pursue high standards in research, teaching, and service (http://grad.msu.edu/prep/). The program is based on the assumption that doctoral students' needs and interests vary across the stages of the graduate school experience, including the early stage (involving course work, qualifying exams, and writing the dissertation prospectus), the middle stage (involving certifying exams, dissertation research, and the process of developing professional networks), and the late stage (dissertation writing and the job search). The program is represented by a matrix that crosses the three career stages with three levels of time commitment and engagement (low, medium, and high) required for participation in the professional development activities. At the intersection of career stages and levels of involvement, students can find descriptions of professional development options, including workshops and conferences, available to them (http://grad.msu.edu/lcpd.htm).

Recognizing that the literature on the doctoral experience has highlighted the shortcomings in American doctoral programs in regard to preparing students for the full array of higher education institutions in which they might work as faculty members, and the many employment options they might consider outside of academe, the PREP Program includes opportunities for students to explore a wide array of career options, including, for example, opportunities to participate in simulated interviews for faculty work in different types of colleges and universities, and workshops with non-academic employers about the skills and abilities they seek. The Graduate School evaluates students' satisfaction and assessment of learning after each professional development experience by immediately surveying participants.

The university's Graduate School also offers doctoral students the opportunity to pursue a teaching certificate. Completion of the certificate requires participation in a number of professional development opportunities, a mentored teaching experience in the discipline, and the creation of a portfolio that involves reflection on one's development as a college-level teacher. A formal review process of the portfolio is required. While only a small number of students each year opt to complete all requirements for the certificate, it provides an option for doctoral students to delve deeply into preparation for the teaching components of their careers.

STEM doctoral students have the opportunity to participate in the PREP workshops and professional development opportunities, as well as to pursue the teaching certificate. Additionally, as part of MSU's involvement in CIRTL, STEM doctoral students can apply to be FAST Fellows, a year-long mentoring program designed to help doctoral students get a "fast" start to an academic career and develop the skills to teach and assess the impact of their teaching on students' learning. The FAST Fellows teach under the guidance of a faculty mentor, convene regularly for meetings and workshops, and interact in learning communities that meet regularly to explore resources about teaching, learning, and assessment, and the broader array of research on higher education. Each Fellow also works on a scholarly project concerning a teaching topic (known in the CIRTL community as a Teaching-as-Research project), which involves framing a teaching-related question, collecting and analyzing data, and disseminating the findings in campus conferences and, sometimes, at national conferences and in publications. The FAST program also provides some funding to support Fellows' projects and to enable them to travel to conferences relevant to their projects. While the second year of the program has just ended, the facilitators are already collecting data from participants in order, over time, to develop a comprehensive evaluation of the impact and outcomes of the program (Bouwma-Gearhart et al., 2007).

Other Evaluation of CIRTL Impact

A comprehensive evaluation program is underway to examine the impact of the CIRTL Program (CIRTL, 2007). The plan has three levels of assessment: (1) impact on student participants; (2) the process and factors contributing to and challenging institution-wide plans for STEM doctoral student development; and (3) the process of building an inter-institutional network around issues of STEM doctoral student professional development and the impact of participation in the CIRTL Network on the institutions participating. Evaluation processes include a range of qualitative and quantitative data collection strategies focusing on individuals, institutions, and the network overall. A second National Science Foundation-funded project is supporting an on-going study of the long-term impacts of participation in CIRTL and other kinds of professional development opportunities on STEM doctoral students as they move into the first 5 years of their careers. Such studies on the long-term impact of doctoral student professional development are scarce, so the results, several years hence, will be important.

Departmental Reform Efforts

Departments and individual faculty members also are working to strengthen STEM doctoral education. One example is the work of Brian Coppola and his colleagues in the Chemistry Department at the University of Michigan. Scientific research has long been advanced through the use of research teams. Not only do research teams advance discovery of new knowledge; they also serve as the incubation site for young researchers, who learn how to be researchers by working in close proximity and under guidance from faculty members and senior colleagues. Coppola's approach models the research team strategy to prepare future scholars for responsibilities as teachers (Coppola, 2007; Coppola & Roush, 2004). The premise is that a department has the responsibility of preparing the next generation in all aspects of scholarly work. I quote Coppola's (2009) words here as they eloquently make a case for preparing future scholars in teaching as well as research:

> Research groups are the nuclear families of academia, and the obligation we have to replace ourselves in academia is profound. If academic scientists stopped doing research, discoveries would still be made. If academic scientists stopped filing patents, inventions would still be invented. But if academic scientists stopped educating the next generation of academics, the entire system of educating scientists comes to a swift and grinding halt.
>
> We owe it to the next generation to educate as well as possible, and my thesis is that integrating a scholarly development model in teaching and learning—for all of those who become the next generation of academics, based on what we know from research—is the necessary next step in the evolution of our profession (p. 35).

Modeling the research team approach, doctoral students join teaching groups to engage collaboratively with faculty members, post-doctoral fellows, and undergraduate students in working on teaching projects, such as curriculum or instructional development relevant to the department's mission (Gottfried, Sweeder, Bartolin, & Hessler, 2007; Varma-Nelson & Coppola, 2005). Sometimes colleagues from other fields may join the group to help, for example, with curriculum design projects, and to evaluate teaching materials produced by the group. The doctoral students involved receive financial support, as they would if they were participating as members of a research team. The University of Michigan Chemistry Department sometimes uses resources from the GANN Program (Graduate Assistantships in Areas of National Need, a program supported by the U.S. Department of Education) to support doctoral students who are including education-related projects as part of their graduate study (Coppola, 2009). Some of these students include chapters on the scholarship of teaching and learning as part of their dissertations. Another key ingredient for the success of the teaching groups, as with research teams, is that a department must have a few faculty members willing to take the lead with the groups.

Coppola has written about the standards to which the work of the teaching teams is held. In collaborating to do what is called the scholarship of teaching and learning, they must do work that is "informed," "intentional," recognized to be "impermanent," and "inheritable" (Coppola, 2009, p. 36). To elaborate, the teaching projects must be informed by an understanding of the nature of the problem and how it relates to the broader context of teaching and learning, as well as an appreciation for the appropriate approaches to studying and addressing the problem. The work must be "intentional," in the sense of having clear goals, with explicit links that align the project goals, the plans and methods to address the problem, and the evaluation of the strategies used to address the problem. Coppola also argues that team members must recognize that their efforts to address the problem must be subject to further research and questioning, as are research results, and thus, the work must be recognized as "impermanent." The process and results of the teaching-related work must be documented so others can evaluate its value; that is, the work must be "inheritable," just as research findings must be presented in sufficient detail to enable others to replicate a study. A key element in framing the work of the teaching teams is that everyone involved is a scientist, engaging in an aspect of the scholarly work of a chemist—that is, the work is explicitly framed as central to the work of being a chemist, not marginalized or second-class work (Coppola, 2009).

The approach taken by the Department of Chemistry at the University of Michigan has been evaluated by a colleague whose expertise is in the study of higher education (Coppola, 2009). Results of the evaluation indicated that the graduate students participating in the teams working on teaching projects were better prepared as educators and understood the array of dimensions of faculty work more fully as compared to those without such team experience. The evaluation also revealed that the approach was becoming imbedded into the core mission and work of the department. According to Coppola (2009), faculty attention is captured, and resistance is at least neutralized, when funds come into the department to support students involved in this work. The evidence that the program is of interest to prospective students, apparently adding a competitive edge to the department in its efforts to recruit excellent graduate students and faculty, also helps win faculty support (Coppola, 2009).

Future Research: Next Steps in Research and Action

A number of innovative efforts to strengthen doctoral education in the sciences, technology, engineering, and mathematics have been developed and implemented over the past decade or so. While the body of research about the doctoral experience has grown considerably in this time period, the body of research about the change efforts themselves is still modest. Some programs have been evaluated to examine short-term impact and to gather insights that can be used for improvement. However, more comprehensive research needs to be undertaken. A more expansive body of research on the nature and impact of change strategies to improve doctoral education would be very useful to institutions making programmatic decisions within environments of competing priorities and to funding agencies making decisions about the allocation of resources.

I suggest that a research agenda about reform in STEM doctoral education can be organized around a broad "theory of change" framework that seeks to learn more about the impact of various strategies in relationship to the change processes selected. There is little research at present that offers much guidance concerning which strategies are most likely to have what kinds of impact in terms of strengthening STEM doctoral education. A "theory of change" approach recognizes that different strategies to strengthen STEM doctoral education build on differing assumptions about such important issues as what the outcomes of a reform effort should be, what the target for change is, what factors contribute to the most impact on student learning, how much involvement in a reform initiative is necessary to produce certain kinds of outcomes, and how to maximize institutional investments in improving doctoral education. Here I suggest several categories of questions that deserve research, the answers to which would deepen understanding of change processes in STEM doctoral education:

- *Program Components and Organization*: What elements in professional development programs for STEM doctoral students (e.g., mentoring, internships, courses, short workshops) have what kinds of impacts and are most useful in preparing STEM doctoral students for their future careers? What is the relative benefit of different levels of "dosage?" That is, to what extent (how many hours) and in what kinds of ways do students need to be involved in professional development in order for significant impact to be gained? Are programs more effective in regard to student learning outcomes if they focus on single aspects of professional work (doing research or teaching) as compared to programs that strive to help students integrate the various dimensions of a scholar's work? What are the benefits of organizing programs around departmental strategies as compared to organizing institution-wide or network-wide strategies?
- *Impact on Participants*: What is the impact of various professional development programs on STEM doctoral students in regard to their attitudes and understandings about various facets of scholarly work? In what ways and to what extent do various programs have an impact on the career choices of developing scholars? What are the processes through which STEM doctoral students develop as teachers and researchers? Are there particularly important stages or experiences relevant to development in these areas of scholarly identity and ability? How do programs designed to better prepare doctoral students for their careers impact graduates as they assume their first professional positions? How do doctoral students who have been prepared systematically for teaching responsibilities handle first positions in departments whose cultures heavily value research over teaching? What is the long-term impact on career development of graduates who have participated extensively in programs such as IGERT or CIRTL?[1]

- *Role of Faculty/ Impact on Faculty and the Institution*: How does involvement in programs to strengthen doctoral students' preparation affect faculty members? For example, to what extent does working with doctoral students in a departmental "teaching team" affect faculty members' own teaching, research, or attitudes about their roles in doctoral preparation? What factors contribute to changes in faculty members' attitudes about the purposes of doctoral education or about the roles of faculty members in contributing to students' professional growth? In what ways and to what extent do departmental efforts to reform STEM doctoral education spill-over to have an impact on other departments within the institution?

In addition to organizing research studies to examine the change processes, design, and components of various reform efforts and their impact, I suggest several specific studies which would contribute important and useful insights to those working to improve STEM doctoral education. Some of the studies I mention have been included in recommendations offered in other reports. First, both the National Science Board (2003) and the leaders of the Carnegie Initiative on the Doctorate (Walker et al., 2008) call for more in-depth qualitative research concerning STEM doctoral education. Institutional leaders, including graduate deans trying to develop effective programs for STEM doctoral students, would benefit from well-designed and detailed case studies that highlight the characteristics and impact of specific programs (e.g., strategies for shortening time-to-degree or programs to deepen specific areas of professional knowledge, such as ethical behavior or awareness of employment options in diverse institutional types or outside academe). Understanding more about the specific experiences of students in particular disciplines, including, for example, the challenges they experience in learning about research and teaching in their disciplinary context and their processes of decision-making about career options, would be deepened by well-crafted, discipline-specific, ethnographic studies (Walker et al., 2008).

In a number of STEM fields, women and individuals of color are underrepresented. While there is some research concerning the experiences of these students as they progress through doctoral study, more research that focuses specifically on the STEM fields would be useful. The experiences and challenges confronted by part-time students also should be studied, with a focus on the kinds of strategies that would help students in non-traditional situations (e.g., women returning to graduate education after a period of child-raising) succeed in doctoral study.

Third, interdisciplinary scholarly work is increasing, and, as already discussed in this chapter, young scholars preparing for their careers should learn how to engage in this kind of scholarship. More needs to be known about how to help graduate students develop depth and breadth of knowledge (Walker et al., 2008). How can they best be supported in pursuing their disciplines in depth, while also learning how their fields intersect with other areas of study, the norms, values, and habits of thought in other disciplines, and the necessary skills for cross-disciplinary collaboration? One suggestion is the development of "general education for doctoral education," recommended by Catharine Stimpson (2002), who served as Dean of the Graduate School at New York University. Important research questions could focus on the challenges STEM students experience as they engage in interdisciplinary work, the processes through which they grapple with the balance between breadth and depth in their studies, and the impact on their understandings and values of courses and other curricular and programmatic efforts to help them develop skills related to engaging in interdisciplinary work.

A fourth area focuses on the sustainability over time of initiatives to reform STEM doctoral education. Considerable investment is being made by funding agencies and institutional leaders in developing and implementing innovative approaches to preparing STEM doctoral students for their careers. With all externally funded projects, there is always the looming question of whether and how the programs will be sustained after external funding concludes. Typically institutions are encouraged to commit funds at progressively higher levels across the years of external funding, in order to encourage and prepare universities for assuming the full burden of financial support. Maintaining financial support is only part of the concern. Reform initiatives can also flounder in the face of other priorities. One strategy to address this concern is to embed reform efforts in multi-institutional networks. After funding concludes, the network may be a strong factor to encourage individual institutions to continue their reform efforts, since institutions of similar reputations often strive to stay at par with their counterparts. An important area of research concerns the factors that contribute to sustainability of reform initiatives over time. A related question pertains to how initiative leaders ensure that programs balance fidelity to their missions with appropriate responsiveness to pressures and reasons to adapt or change. These questions have practical implications that could be very useful to funding agencies and institutional leaders seeking ways to ensure that investments of time and resources have long-term and substantial impact.

Finally, in addition to offering suggestions for further research, I emphasize that ongoing, thoughtful conversations are needed about STEM doctoral education. These conversations should address the strengths and concerns associated with the doctoral experience, including the preparation doctoral education provides for young scholars' future career paths, as well as ideas for continuing efforts to strengthen STEM doctoral education. Faculty members, institutional administrators, and members of external groups, including disciplinary associations, funding agencies, and accrediting groups, should be involved. And, of course, STEM doctoral students themselves must be key participants in reflecting on the quality of their graduate experience and ideas for improvement. Efforts to strengthen the preparation of the future scholarly talent in the sciences, technology, engineering, and mathematics will impact the quality of undergraduate education, the country's economic competitiveness, the extent of high-quality research addressing major problems, and, ultimately, the well-being of people throughout the world.

Notes

1. The National Science Foundation has recently funded a study, now underway, whose goal is to address the question of the impact of various kinds of graduate school professional development experiences on the early career development of STEM scholars.

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