

ADVANCING GRADUATE EDUCATION IN THE CHEMICAL SCIENCES

Full Report of an ACS Presidential Commission

As Submitted: December 6, 2012

EXECUTIVE SUMMARY

Over the past 100 years the chemical sciences¹ have contributed immensely to the security, health, and economic vitality of our nation. These practical benefits have been built on enormous advances in knowledge about molecules and their behavior. In turn, command of that knowledge has risen from sound chemical education in our nation's colleges and universities and research contributions made by university faculty members, by professional scientists, and by graduate students as part of their pursuit of advanced degrees. A vital program of graduate education in the chemical sciences is essential to assure the continued success of the enterprise and to sustain our nation in an ever more technical and globalized world.

This report is the result of a deep and thorough analysis of the current state of graduate education in the chemical sciences. Its authors are leading experts in academia, industry, and government. The report is built on extensive fact-finding by chemical scientists and engineers representing every aspect of the enterprise ranging from beginning students to members of the National Academy of Sciences.

The Commission was appointed and charged by American Chemical Society President Bassam Z. Shakhashiri to undertake a wholesale review over a year-long period. Appendix A identifies the members of the Commission, as well as its special advisors and many additional participants invited into its topical working groups. Appendix B provides President Shakhashiri's charge letter.

This document is a full rendition of the final report. A compact version conveying, in essence, only the overall conclusions and recommendations is available both in print and electronically at www.acs.org/gradcommission.

The Commission judges that the state of graduate education in the chemical sciences is productive and healthy in many respects, but has not kept pace with the significant changes in the world's economic, social, and political environment since the end of World War II, when the current system of graduate education was formed. Employment opportunities for chemical scientists and engineers have changed, too, and continue to do so. Collaboration among disciplines has become a hallmark of cutting-edge investigation, in which partners

¹ Throughout this report, the chemical sciences are understood to encompass chemistry, chemical engineering, biochemistry, molecular biology, materials science, polymer science, nanoscience, and other activities that focus on molecules, chemical reactions, and chemical properties.

may be located next door or around the globe. Thus, the ability to communicate clearly across disciplinary and cultural lines has emerged as a critical skill. As technology comes to dominate more of our economy and national security interests, we look more often to scientifically trained leaders to provide guidance and advice.

This report addresses the changed world and the role that graduate education in the chemical sciences must play in this century to assure the continuing success of the chemical enterprise and the vitality of our nation. Changes are recommended, not because the previous approaches were wrong, but because the technological leaders of this century must have skills crafted to meet its demands.

In this report, the Commission speaks most immediately to its individual faculty colleagues, who determine on a daily basis the content of graduate education and the requirements for completion of degrees. But there are other intended audiences, including departmental leaders, deans, provosts, and presidents in universities, leaders of funding agencies important to the chemical sciences, national policymakers, leaders of industries that employ chemical scientists and engineers, and leaders in the key professional societies, especially the American Chemical Society.

The report is organized around five major conclusions, each accompanied by specific recommendations and suggestions:

1. Current educational opportunities for graduate students, viewed on balance as a system, do not provide sufficient preparation for their careers after graduate school.

The Commission reaffirms the anchoring concept that a doctoral program in the chemical sciences must manifest traditional depth and must maintain a focus on mastery.

But the members also conclude that curricula need to be refreshed, and better-designed opportunities should exist for the development of critical professional skills. The Commission offers many and varied recommendations, which, briefly stated, are a) to encourage departments to undertake greater oversight over the progress of their graduate students, and b) to emphasize the need for programs to offer specific activities that would enhance students' ability to:

- Communicate complex topics to both technical and non-technical audiences and to effectively influence decisions,
- Learn new science and technology outside prior academic training,
- Collaborate on global teams and/or with global partners and clients,
- Effectively define, drive, and manage technical work toward a practical, significant result, and
- Clearly understand the ethical conduct of research.

Four years should be the target for completion of the PhD, with the departmental median time less than five years.

The Commission understands that there is inevitable tension between its recommendations that doctoral programs be shortened while also being retailored to include elements that are not generally addressed effectively in existing practice. For this reason, the members believe graduate education must become more efficient. Opportunities for improved efficiency exist in better program design, superior monitoring of student progress, use of the summer before the first year of graduate study, and fuller use of short courses and internet-based offerings.

2. The system for the financial support of graduate students, as currently operated by private, institutional, state, and federal funds, is no longer optimal for national needs.

The support system rests too heavily on individual research grants and involves serious conflicts between the education of graduate students and the needs for productivity and accountability in grant-supported research.

Federal and state funding agencies, private funders, and universities themselves, should take steps toward decoupling more student-support funds from specific research projects, in the interest of providing students the opportunity for better balance between training in research and training in other career skills, without significantly impacting the research productivity of faculty.

The goal, with perhaps a ten- to fifteen-year horizon, should be to decouple the preponderance of student support from specific research grants and contracts. In the near term, funders and graduate program leaders should engage in trial projects designed to prove out new mechanisms.

In particular, federal agencies and private funders should experiment with a new strategy for “graduate program grants” to support graduate students. Analogous to training grants, but with perhaps greater support for innovation in the educational program, graduate program grants should be made available to departments on a competitive basis.

Of course, the Commission would naturally welcome increased funding for graduate student stipends; however, its recommendations in this area are not mainly about more funding, but about improving the deployment of existing funding.

3. Academic chemical laboratories must adopt best safety practices. Such practices have led to a remarkably good record of safety in the chemical industry and should be leveraged.

Progress would afford better protection to students and other workers at all academic levels and would better prepare students to meet the natural expectations of their future colleagues and employers.

Specifically, the Commission urges that safety as a culture must be consistently led by example in all graduate programs in the chemical sciences.

Faculty members in the chemical sciences can and should take the lead toward best practices, and should advocate for support at the highest institutional levels.

In the end, leadership from the top of an institution is essential for a sound safety culture to take root and thrive. The hazards and issues in the chemical sciences also exist in departments and programs outside the chemical sciences all across college and university campuses. A strong safety culture must not vary across institutions, and mechanisms for managing the associated costs cannot be left to individual departments or research groups.

4. Departments should give thoughtful attention to maintaining a sustainable relationship between the availability of new graduates at all degree levels and genuine opportunities for them. Replication in excess is wasteful of resources and does injustice to the investment made by students and society.

Given what seems to be a permanently restructured employment market for PhDs, the Commission perceives a risk that the number of career opportunities in the chemical science professions may be insufficient to accommodate those qualified for and desiring entry. Left unaddressed, an imbalance will likely be highly damaging to the talent level and traditional academic strength in the chemical sciences. The Commission urges departments to adjust program sizes in the light of truly attractive opportunities for graduates. It further recommends that this consideration be paramount in determining the scale and balance of any program.

A large undergraduate teaching need is not a sufficient justification for a large graduate program. Teaching needs that remain uncovered by graduate students in a healthy program should be addressed by faculty or other professionals hired and supervised by the department.

Faculty members and other academic leaders in every graduate program, whether at the master's or doctoral level, are urged to reassess and to focus the program distinctively toward its competitive advantages. There is too much similarity among the nation's graduate programs. More variety, supported by a diversity of career opportunity, will yield a more innovative, adaptable landscape.

The ACS should collect and publish aggregated, privacy-protected data, organized by graduate program, on post-degree outcomes for all graduates, including time-

to-degree, types of job placements, salaries, and overall student satisfaction with the graduate experience and employment outcome. The notion is to provide prospective students with relevant information toward an informed decision in choosing a graduate school.

Programs should build the domestic fraction of their graduate enrollments as a high priority. The Commission fully recognizes and values the great contributions that have historically been made in our graduate programs and in our national technical enterprises by international citizens who were first attracted to the US as graduate students. However, the Commission also notes that the balance in graduate degree production has steadily shifted toward international students. A legitimate concern is whether the nation will continue to have a readily employable technical base large enough to sustain global leadership in innovation. International students should not continue to substitute for the domestic share; instead, a mix richer in domestic students should be targeted.

The Commission has detected concern that recent enrollment trends reflect, in part, a perception that domestic applicants are not as soundly prepared for graduate school as in the past. It is beyond the charge of this Commission to review undergraduate preparation in chemical sciences programs in the US, so we offer no conclusion on this point; however, we suggest that it is time for a serious inquiry to be made through a suitable mechanism.

To take advantage of the nation's whole talent pool, graduate programs must place an emphasis on attracting and empowering students from underrepresented groups.

- 5. Postdoctoral training and education is an extension of graduate education that is important for success in a variety of career paths, particularly for faculty appointments. Postdoctoral associates should be treated as the professional scientists and engineers they are. A postdoctoral appointment should be a period of accelerated professional growth that, by design, enhances scientific independence and future career opportunities.**

Ideally, the disadvantages of career delay and lower salary are offset by several advantages of postdoctoral training and education; however, many postdoctoral associates have inadequate career mentoring, and many take such positions for reasons that do not support their professional development.

The Commission recommends that a) institutions, departments, and faculty mentors take greater responsibility for ensuring that postdoctoral associates develop professionally, b) all funding agencies require general mentoring plans of applicants seeking support for postdoctoral associates, c) funding agencies become more receptive to requests for support of more senior research associates who are

regular employees of research institutions, and d) foundations and other funding agencies re-explore programs for “teaching postdoctoral associates.”

Early in its process, the Commission was charged specifically to address two central questions, with the intent that its conclusions underlie any actionable recommendations:

- What are the purposes of graduate education in the chemical sciences?
- What steps should be taken to ensure that they address important societal issues as well as the needs and aspirations of graduate students?

Charts I and II summarize the Commission’s answers to the central questions. Contained within them are many points defining the broad importance to the nation of graduate education in the chemical sciences.

The Commission’s charge certainly includes master’s level education. The members recognize the distinctive roles that it fulfills in our society and generally believe that there is room for fuller use of this degree level in developing the professional workforce. The master’s degree needs to be reconsidered as the diversity of opportunities in the chemical sciences increases.

With this report, the Commission genuinely hopes to free departments and programs from feeling the need to be practically identical. There is room for greater variation in program design than has been recently typical in American graduate education in the chemical sciences. We believe that our field would benefit from more venturesome design and greater experimentation.

For this reason alone, the Commission explicitly discourages any form of checklist for graduate programs or any analogue to the ACS Committee on Professional Training, which serves usefully to approve undergraduate chemistry programs.

The Commission understands that progress on several of the dimensions addressed among its conclusions and recommendations will require modifications to the reward structure for faculty members participating in doctoral programs. The community needs to engage seriously in exploration of alternatives.

In this respect, as in many others, the Commission is focusing on the goal, rather than the path. Our emphasis on experimentation is acknowledgement that many new paths will need to be explored as progress is sought along various dimensions of graduate education.

CHART I

PURPOSES OF GRADUATE EDUCATION IN THE CHEMICAL SCIENCES

The primary purpose of graduate education is education. The proper first focus is to educate students to solve problems in society, including the effective education of the succeeding generations.

Purposes transcending the individual:

- 1) At the doctoral level, to develop scientists and engineers who have demonstrated the ability to design and carry out independent research leading to new knowledge.
- 2) At the master's level, to develop scientists and engineers with augmented technical knowledge beyond the undergraduate level, sometimes toward specialized professional capabilities.
- 3) To prepare the technical workforce for industry and government in the chemical sciences.
- 4) To provide faculty for universities, colleges, and schools who can capably educate and inspire students interested in chemical sciences at high school, undergraduate, and graduate levels.
- 5) To involve students personally in the advancement of the chemical sciences through the processes of investigation and discovery leading to new knowledge.
- 6) To provide intellectual underpinnings for continued national leadership in science and technology.
- 7) To cultivate a professional culture and professional capabilities fostering innovation, which, in turn, leads to job creation and enhanced living standards.
- 8) To generate research and intellectual property that leads to economic development for a region and for the country.
- 9) To create solutions to societal needs, for example in energy, health, climate change, security, and defense.
- 10) To develop future business, cultural, and political leaders who can articulate scientific and technological issues and help the nation toward wise choices in an increasingly technology-dependent, globalized society.

Purposes focused on the individual:

- 11) To teach graduates how to enter a new field, how to pose worthwhile problems, how to be productive in generating valuable new knowledge, and how to evaluate critically their findings and those of others. This is the first purpose of doctoral education.
- 12) To prepare the student soundly, in a reasonable period of time (preferably five years or less for a doctoral degree after the baccalaureate), for effective, rewarding careers after graduate school, both with respect to technical knowledge and skills, and with respect to other aspects of professionalism, including high standards of integrity and effective communication.
- 13) To help the student to understand how chemical processes are applied to solving problems and creating products and how new scientific knowledge is translated into practice.
- 14) To foster fearlessness in approaching new technical areas and new operational challenges.
- 15) To cultivate and to preserve the student's curiosity, joy of discovery, openness to new ideas, and desire for lifelong learning.
- 16) To develop – experientially, to the greatest practical extent – personal and professional skills needed to compete in an evolving interdisciplinary and global environment.

CHART II

ADDRESSING SOCIETAL NEEDS AS WELL AS THE NEEDS AND ASPIRATIONS OF GRADUATE STUDENTS

- 1) A strategic imperative for the nation is to assure that excellent opportunities exist for the most able students, whose careers are likely to contribute extraordinarily to national technical advancement and productivity.
- 2) A principal national concern continues to be with the historically low participation rates in the chemical sciences of women and students from underrepresented populations. New, effective ways should be sought to increase the appeal of careers in the chemical sciences to all groups. This is not just an issue of fairness. Without better success along this line, the United States may not be able to generate a technical workforce that can sustain technical leadership.
- 3) Graduate students should be advised more fully and more competently about the diverse career options meriting consideration in a dramatically changing employment marketplace.
- 4) Standards of laboratory safety for graduate education and research should adhere to best practices found in industry.
- 5) Graduate education should provide opportunities for students to explicitly contemplate, discuss, and otherwise be exposed to how chemical sciences can contribute to meeting major challenges of the 21st century, such as sustainability, health, energy, security, and quality of life.
- 6) Students with aptitude and interest should have educational options, within the context of graduate school, to develop entrepreneurial knowledge and leadership skills.
- 7) Talented young scientists and engineers in the chemical sciences may be delayed too long in reaching a stage of independent or highly responsible professional practice. Ways should be sought to provide opportunities for young people to reach this stage by their late 20s, rather than their early to middle 30s.
- 8) Much better use should be made of master's level education, with a focus on new programs aimed at specific competencies that can form sound foundations for a healthy career.
- 9) More attention should be given to systematic development of educational opportunities offering substantive experiences efficiently connected with career goals, such as industrial internships, coupled enrollment in other degree programs (e.g., other sciences or engineering, public policy, law, entrepreneurship), and international experiences.

CHARGE AND PROCESS

In October 2011, ACS President-Elect Bassam Z. Shakhashiri appointed and charged a Presidential Commission on Advancing Graduate Education in the Chemical Sciences to undertake, through calendar year 2012, a wholesale review of educational practices at the graduate level. The project was completed as charged, and this document is the Commission's complete final report.

In parallel, a Summary Report, containing only the Commission's principal conclusions and recommendations, is also being published. This Full Report includes all of the information in the Summary Report together with a large amount of background information and analysis.

The roster of Commission members appointed by President Shakhashiri is provided in Appendix A, and his charge letter is reproduced in Appendix B.

The President's first request of the Commission was to address two central questions:

- What are the purposes of graduate education in the chemical sciences?
- What steps should be taken to ensure that they address important societal issues as well as the needs and aspirations of graduate students?

President Shakhashiri also asked the Commission to address five other questions in preparing its report and actionable recommendations:

1. Is the current structure of different types of departments in the chemical sciences (chemistry, chemical engineering, chemistry and biochemistry, chemistry and chemical biology, chemical and biomolecular engineering, materials science, etc.) a strength or a weakness with respect to graduate education?
2. What are the employment issues for graduate students in both industrial and academic settings? Are we providing the right educational opportunities?
3. What are the financial support mechanisms for graduate education in the chemical sciences? Is the current mix the best one?
4. Is the current profile of our graduates the correct one, not only in terms of domestic vs. international, but in terms of diversity along other axes as well? Do they have the proper background for the type of graduate education we want them to attain?
5. What are the expectations of graduate students; are our educational institutions meeting them; and what promises do they make to students, both explicitly and implicitly? In particular, what should be the lengths of the graduate student program and any subsequent postdoctoral training? And why is the attrition rate

for PhD students in the chemical sciences as high as it is (only 62% finish within ten years).

The Commission convened for the first time in January 2012 and also met on a plenary basis in June and November. In other periods, the Commission carried out its work through correspondence and numerous teleconferences.

Throughout the process, the Commission maintained an open door for observations and suggestions. A well-advertised presentation about the process was made at the ACS meeting in San Diego and at a workshop of the National Academies; listening sessions were held with graduate students and recent graduates at the ACS meetings in San Diego and Philadelphia; an article on the process and the issues was published by the Chair;² correspondence was received and circulated, and innumerable conversations were held among members of the Commission and colleagues across the nation.

At the earliest stage, there was a recognition that the Commission would need to break into topical groups to make efficient progress on the diverse aspects of graduate education. Seven working groups were organized, one to address the central questions in the President's charge, five to address his particular questions, and one to address postdoctoral education, which was later perceived as an important sphere of concern. To enlarge the pool of engaged expertise and to broaden the range of perspectives, the Commission recruited two special advisors to work on a plenary basis and 19 invited participants for the individual working groups. The special advisors and invited participants are listed in Appendix A.

The working groups proceeded mainly through teleconferences and email. They brought their initial thinking into the June plenary session of the Commission, then refined their ideas for discussion by the Commission in a series of teleconferences leading to the November plenary session, at which the Full Report and Summary Report were shaped.

In the United States, graduate education is a highly local responsibility, with important operational policies and practices determined at the departmental level or even at a divisional or program level. In this report, the Commission speaks most immediately to its individual faculty colleagues, who determine on a daily basis the content of graduate education and the requirements for completion of degrees. But there are other intended audiences, including departmental leaders, deans, provosts, and presidents in universities, leaders of funding agencies important to the chemical sciences, national policymakers, leaders of industries that employ chemical scientists and engineers, and leaders in the key professional societies, especially the American Chemical Society.

² Faulkner, L. R. The Future of Graduate Education in the Chemical Sciences: What is Really Best for Students? *Interface* **2012**, 21(1), 63-65.

BACKGROUND

This Commission's effort has been undertaken at a time of serious introspection in the chemical sciences and in the American academic enterprise at large. Times and circumstances have changed and are clearly changing further. Questions rise in many minds about the integrity and effectiveness of our system of graduate education. Are we doing the best things for the development of students? Are we attracting the talent that the nation needs into our part of science and technology? Are we preparing our graduates effectively for a substantially altered employment market?

Anxieties like these are not limited to the chemical sciences, as one can readily discern from the burst of recent major reports on graduate education in the United States, all having appeared in the last 24 months. In chronological order, they include:

- The Whitesides Report of the American Chemical Society,³ which addresses innovation in the chemical enterprise and includes recommendations for changes in culture in research universities and practice in graduate education.
- The summary of the 2012 National Research Council workshop on graduate education in chemistry,⁴ which was a one-day event covering a wide range of issues relevant to the work of this Commission.
- The Tilghman Report of the NIH Biomedical Research Workforce Working Group,⁵ which appeared publicly in draft form and has received considerable attention for its recommendations concerning the support and education of doctoral students and postdoctoral scholars.
- The Holliday Report of the National Research Council,⁶ which addresses many aspects of American research universities, but has one of its ten recommendations focused on changes in graduate education.
- The PCAST report⁷ on changes needed to revitalize the US research enterprise.

³ Whitesides, G. M., Chair; et al. *Innovation, Chemistry, and Jobs*, ACS Presidential Task Force on Innovation in the Chemical Enterprise, American Chemical Society, Washington, 2011.

<http://web.2.c2.audiovideoweb.com/va92web25028/InnovationChemistryJobsReport-PDFs/InnovationChemistryandJobs.pdf>

⁴ Francisco, J. S., Chair; et al. *Challenges in Chemistry Graduate Education: A Workshop Summary*, Committee on Challenges in Chemistry Graduate Education, Board of Chemical Sciences and Technology, National Research Council, Washington, 2012. http://www.nap.edu/openbook.php?record_id=13407&page=R1

⁵ Tilghman, S. M., Chair; et al. *Draft Report*, Biomedical Research Workforce Working Group, National Institutes of Health, Bethesda, MD, June 14, 2012. http://acd.od.nih.gov/bmw_report.pdf

⁶ Holliday, C., Chair; et al. *Research Universities and the Future of America: Ten Breakthrough Actions Vital to Our Nation's Prosperity and Security*, Committee on Research Universities, Board on Higher Education and Workforce, National Research Council, Washington, 2012.

http://www.nap.edu/openbook.php?record_id=13299&page=R1

This Commission's views are consistent with the most important conclusions in these contemporaneous publications. Significant changes in practice seem necessary to meet the best interests of our students, our nation, and our science. In the pages below, the Commission places the issues more precisely into the context of academic practice in the chemical sciences and offers specific recommendations.

Graduate education in the chemical sciences is a large and ancient topic. It involves deep traditions and has achieved enormous successes. Changes will not come simply or easily, but lack of adjustment to sclerosis and to new realities will inevitably enervate our enterprise and diminish American capabilities in science and industry. This report is a starting point -- a reconnoitering for a journey. It is not intended as a final guide. Progress in years ahead will be built on experiments that prove out new practices. It will also be built on the work of other commissions focusing sharply on topics that we have been able only to outline. The American Chemical Society can play a very constructive role in the long-term process of reform.

PURPOSES OF GRADUATE EDUCATION IN THE CHEMICAL SCIENCES

If we are to improve graduate education in the chemical sciences, we must first ask what the purposes are of such education. Since all graduate education in chemical sciences is offered in universities, it is impossible to address the purposes of graduate education without first considering the purposes of a university. Most would agree that the traditional purposes of a university are

- to create new knowledge,
- to transmit knowledge to others,
- to contribute to solutions of societal problems.

Graduate education is intricately entwined with all three of these missions. Graduate students in the chemical sciences are themselves the recipients of knowledge, but they also transmit knowledge by teaching undergraduates, and they perform much of the research that leads to new knowledge, which, in turn, supports progress toward solutions to societal problems.

Universities are accountable to society for their financial well-being as well as for their independence from political influence – they have a social contract with society. Sectors of society support universities because they find the missions of universities to be important. The support comes in many forms: private support from individuals and foundations, public

⁷ Holdren, J. P.; Lander, E. S., Co-Chairs. *Transformation and Opportunity: The Future of the US. Research Enterprise*; President's Council of Advisors on Science and Technology: Washington, DC, 2012.
http://www.whitehouse.gov/sites/default/files/microsites/ostp/pcast_future_research_enterprise_20121130.pdf

support from state and federal sources, industrial support for teaching and research, and tuition from students. Each of these sectors has its own version of the university's mission. Cole offers this list:⁸

- extending education to all citizens
- preparing the workforce and increasing the knowledge base for new jobs
- enhancing social welfare
- reducing social injustice
- improving economic development and well-being throughout the world
- supporting military readiness and national security

While the various versions of a university's mission are often congruent with the traditional missions, they are not always so. Nor do all of society's sectors contribute to the funding of the university in proportion to their expectations of it. For example, while total state support for public universities rose nationwide by 10.6% from 2002-2007, support per student actually fell 7.7%.⁹ The cost of providing education increased during this period, and tuition as a percent of the public higher education total revenue rose by 36.2%, shifting the burden from the state taxpayer to the students and their families. Research support from the federal government fell during the same period, and the rate of private contributions to higher education has fallen since 2007. Industrial in-house research efforts have fallen dramatically in the past 20 years, placing more responsibility on universities to be engines of innovation and economic development.

As financial support for universities has dwindled, the expectations of different sectors of society have occasionally led to conflicts of interest for the university. This potential for conflict is forcefully summarized by the Kalven Committee Report¹⁰ quoted in Cole:¹¹

The mission of the university is the discovery, improvement, and dissemination of knowledge. Its domain of inquiry and scrutiny includes all aspects and all values of society. A university faithful to its mission will provide enduring challenges to social values, policies, practices, and institutions. By design and by effect, it is the institution which creates discontent with the existing social arrangements and proposes new ones. In brief, a good university, like Socrates, will be unsettling.

Universities sometimes have a conflict between being unsettling and being funded. Can a university simultaneously be concerned for the welfare of those living near a polluted site while doing research with or for the companies that caused the pollution? The fact that

⁸ Cole, J. R. *The Great American University: Its Rise to Preeminence, Its Indispensable National Role, and Why It Must Be Protected*; Public Affairs (Perseus Books Group): New York, NY, 2009; p. 170.

⁹ State Higher Education Executive Officers (SHEEO). State Higher Education Finance 2007. http://www.sheeo.org/finance/shef_fy07.pdf

¹⁰ University of Chicago, Kalven Committee Report, November 1967.

¹¹ Cole, *ibid.*, p. 145.

those whose environment is being polluted are unlikely to support the university financially is not sufficient reason to ignore their plight as a subject of scholarly examination or humanitarian action. Similarly, societal pressures to provide economic stimulus can influence professors to work on commercial projects while diverting them and their students from broader problems with less commercial application.¹² When evaluating the purposes of graduate education in the chemical sciences, one must be mindful that pressures from some sectors of society might undermine the mission of both the university and the graduate education that it provides.

With this caveat, we can now examine why funders support graduate education in the chemical sciences, how it addresses societal issues, and whether it meets the expectations and aspirations of the graduate students. Fortunately, the educational and research needs of graduate students in the chemical sciences are usually aligned with the needs and expectations of the various sectors of society that provide university support.

With the help of a working group charged specifically to address President Shakhshiri's two central questions, the Commission came to define the purpose of graduate education compactly in Chart I, presented first with the Executive Summary. Some purposes are manifested in the individual student, whereas others relate to the benefit of society at large.

Advised by the same working group, the Commission also developed Chart II in response to President Shakhshiri's question about steps that should be taken to ensure that graduate education addresses important societal issues as well as the needs and aspirations of graduate students.

Charts I and II, taken together, provide a compact reminder of the many elements and intricate relationships defining the broad importance to the nation of graduate education in the chemical sciences.

There are currently about 22,000 graduate students enrolled in chemistry programs; another 8,000 are enrolled in those of chemical engineering. In the physical sciences, 35% of PhD recipients are employed in four-year educational institutions, 45% in the private sector, and 20% in governmental and non-profit organizations. In the biological sciences, 45% are in four-year educational institutions, 30% in the private sector, and 25% in governmental and non-profit organizations.¹³

Taking chemical scientists to be roughly evenly divided between physical and biological sciences, and setting aside those in governmental and non-profit organizations, we

¹² Cole, *ibid.*, p. 161.

¹³ Wendler, C.; Bridgeman, B.; Markle, R.; Cline, F.; Bell, N.; McAllister, P.; and Kent, J. *Pathways Through Graduate School and Into Careers*; Educational Testing Service: Princeton, NJ, 2012.
http://www.pathwaysreport.org/rsc/pdf/19089_PathwaysRept_Links.pdf

find that roughly half of PhD chemical scientists are employed in industry, while the other half are employed in academia. Consequently, preparing graduate students for industrial positions is of equal importance to preparing them for academic positions. Most students interviewed by the Commission felt that preparation for industry was underemphasized.

Through a Working Group on Education for Employment, the Commission focused on the preparation of students for life after graduate school, regardless of the domain in which they might be employed.

If education is to be provided to the diverse range of students interested in the chemical sciences at secondary, undergraduate, and graduate levels, the profile of graduate students going on to both educational and industrial careers ought to represent the same diversity. Through a Working Group on Sources and Preparation of Students, the Commission addressed the profile of graduate students, both in terms of domestic vs. international students, and in terms of other axes of diversity as well.

Generation of research and intellectual property for economic development, as well as addressing societal needs, are issues that require examination of both the funding models and organizational structure of research universities.

Should we continue to organize ourselves around departments of chemistry, biochemistry, chemical engineering, materials science, etc., or would we be better off to reorganize around societal needs such as health, energy, climate change, etc.? Taylor, in his recent *Nature* commentary,¹⁴ states, "...universities must tear down the walls that separate fields, and establish programmes that nourish cross-disciplinary investigation and communication. They must design curricula that focus on solving practical problems, such as providing clean water to a growing population." Whitesides and Deutch¹⁵ agree with the goal of research directed toward practical problems that address society's challenges, but they recommend a different means to this end: "Chemistry should cluster its teaching and research around the exciting and uncertain future rather than the ossified historical past. A first step is to merge chemistry and chemical-engineering departments."

Through a Working Group on Departmental Structure, the Commission considered whether the current organizational models are optimal.

The Commission also examined the financial basis for graduate education, through a Working Group on Student Support Mechanisms.

The most recent data show that research and development expenditures at all US. institutions of higher education total more than \$61B and are 61% Federal, 6% state and local

¹⁴ Taylor, M. Reform the PhD System or Close It Down. *Nature* **2011**, 472, 261.

¹⁵ Whitesides, G. M.; Deutch, J.; Let's Get Practical. *Nature* **2011**, 469, 22, 2011.

governmental, 5% industrial, 20% local institutional, and 8% from other sources (mainly foundations and NGOs).¹⁶ Institutional funds come mostly from private donations.

The current model for graduate education support is primarily through funding the research projects of principal investigators (PIs), who then support graduate research assistants. The support of students through individual PIs puts graduate students in a position where they are dependent on PIs for both intellectual mentoring and financial support, making progress doubly difficult when student-mentor controversies arise. Would it be better for funding agencies to support graduate students directly for one or more years before having them receive their tuition and stipend from research projects? A discussion of the direct fellowship model has recently been brought into focus by a commentary from Hoffmann¹⁷ and subsequent letters.^{18, 19}

No system for graduate education in the chemical sciences can function smoothly unless the expectations of graduate students are matched by the expectations of the institutions that they attend. What are these expectations? Are they reasonable, and how well do institutions meet them? A principal expectation is that of future employment. What are the supply and demand issues for PhD chemists? Other expectations involve time to degree completion. There has been some lowering of this time since the mid-1990s, but averages over various disciplines are in the 6-8 year range, with chemistry at about 6 years.²⁰ Almost 50% of PhD graduates in engineering and the sciences move on to postdoctoral positions, where most stay for more than two years, especially in biologically related fields. Finally, since only 62% of those starting a PhD in the chemical sciences finish within ten years,²¹ the attrition is fairly high. What are the implications of this attrition rate? Through a Working Group on Institutional Expectations of Students, the Commission examined such questions.

The five working groups named in the preceding paragraphs were organized to address the issues just discussed, which in turn had been framed earlier by President Shakhashiri through the five particular questions in his charge. As the Commission moved

¹⁶ National Center for Science and Engineering Statistics. *Higher Education Research and Development: Fiscal Year 2010. Detailed Statistical Tables*, NSF 12-330; National Science Foundation: Arlington, VA, 2012.

<http://www.nsf.gov/statistics/nsf12330/>

¹⁷ Hoffmann, R.; Cost Cuts Should Come from Research, Not Just Education. *Chron. Higher Educ.* **2009**, 55 (May 8), A26.

¹⁸ Mervis, J.; Reshuffling Graduate Training. *Science* **2009**, 325 (31 July), 528. This is an article discussing suggestions by Roald Hoffmann in *The Chronicle of Higher Education*.

¹⁹ Letters commenting on the Mervis article: a) Moosavi, S. C.; Restructure Conflicting Grant Incentives. *Science* **2009**, 326 (23 October), 521, 2009; b) Town, M.; Training Scientists to Manage. *Science* **2009** (20 November), 326, 1062; c) Castellano, M. J.; Mueller, K. E.; Increase Grants Too. *Science* **2009**, 326 (18 September), 1498; d) Butera, R. J.; Stable Funding Is Key. *Science*, **2009**, 326 (18 September), 1499, 2009.

²⁰ National Science Foundation. Science and Engineering Doctorates: 2010.

http://www.nsf.gov/statistics/sed/data_table.cfm

²¹ Sowell, R., Ed. *PhD Completion and Attrition: Analysis of Baseline Data*; Council on Graduate Schools: Washington, DC, 2008. http://www.phdcompletion.org/resources/CGSNSF2008_Sowell.pdf

through its work, it reached the conviction that it would also need to consider issues in postdoctoral education; therefore a working group was organized on that topic.

Although the Commission organized its investigations in working groups built mainly on the five particular questions in President Shakhashiri's charge, it has elected to organize its principal messages under a set of five main conclusions dealing with 1) the educational experience of graduate students, 2) financial support of graduate students, 3) safety as a culture, 4) sustainability and opportunity in graduate programs, and 5) postdoctoral education. The next five chapters cover these topics in sequence, each containing the Commission's overall conclusion and specific recommendations for that topic.

Contributions from the various working groups are spread across the following chapters. Footnotes identify linkages of text sections to the working groups; however we emphasize that all text in this report has been edited and reviewed by the Commission as a whole. Every section titled "Overall Conclusion and Specific Recommendations" received especially careful attention in plenary meetings and teleconferences.

THE EDUCATIONAL EXPERIENCE OF GRADUATE STUDENTS

Analysis

The experiences of graduate students leading to their development as professionals make up the largest sector of the Commission's scope, and the largest body of our recommendations has arisen in this domain. We examined the topic from distinct perspectives in three different working groups, and the discussion in this analytical section preserves those perspectives under separate headings covering a) education for employment, b) oversight of student progress, and c) the impact of academic organization. The working groups reached overlapping views on primary issues and recommendations; thus, the separate perspectives were merged at the Commission level. The Commission's synthesis of its overall conclusion and specific recommendations, which follows this analysis, reflects a unified perspective.

Education for Employment²²

Education for employment has two main targets, academic institutions and industry. A number of students also join government laboratories, which have many of the needs of both academic and industrial laboratories, but no teaching requirement. We will not specifically discuss education for employment in government laboratories, under the assumption that our discussions of education for academic institutions and industry will meet all the needs of

²² Material in this section was developed for the Commission by the Working Group on Education for Employment.

government laboratories. Also, we have broadened the definition of industrial employment to include start-ups and other entrepreneurial settings, which are becoming more common options for graduates. In addition, globalization is an important aspect of the modern workplace in both industry and academia that must be incorporated into the discussion. We will not specifically cover non-traditional careers outside science and technology, such as law, medicine, politics, and journalism; however, the changes we propose would strongly facilitate transition to many such non-traditional careers.

Creativity and analytical skills that enable excellence in scientific discovery and problem solving, coupled with deep subject matter knowledge, is a sure recipe for success in any employment venue. For many decades, the US graduate education system has been the best in the world at promoting these qualities, but as we look at the needs of today's modern companies, and at the academic institutions that feed them, there are gaps. They include the ability to work in interdisciplinary areas, communication skills, teaching skills (especially for academic employment), and safety culture. The good news is that these gaps are all readily addressable through a number of additions to the graduate education program. In this section, we describe the gaps in more detail and articulate the needed additions.

Gaps for Industrial Employment. Today's US-based businesses face an intense pace of innovation in a global marketplace from rapidly developing economies, such as China, that aim to overtake the US. economically over the coming decades. "Time to productivity" for new hires is important. And gone are the days of individual industrial technologists working in silos to develop the next big thing. Instead, most industrial scientists and engineers serve on teams whose members often have very different backgrounds and roles. Beyond the core academic competency in chemical science or engineering, the ability to work in these teams requires that professionals be able to:

- Communicate complex topics to both technical and non-technical audiences and to effectively influence decisions,
- Learn new science and technology outside prior academic training,
- Collaborate on global teams and/or with global partners and clients,
- Effectively define, drive, and manage technical work toward a practical, significant result, and
- Clearly understand the ethical conduct of research.

Moreover, today's companies demand safety performance from their employees that far exceeds what students are accustomed to in academic settings. There are many safety skills that are easily taught, such as doing hazard analyses, but the core issue is that students must be "grown" to value safety in a manner that is "bone deep" and can drive the highest level of performance, known as interdependent behavior. This culture of safety is often a surprise to newly hired students. It should not be.

Addressing the Gaps for Industrial Employment. With the exception of safety, all of the gaps listed above can be addressed by a number of means. The most all-encompassing approach is to significantly enhance interdisciplinary collaboration among the students. The following are what the Commission considers to be best practices:

- Encourage students toward projects that require collaboration and broaden the student's field of study. In particular, encourage collaboration across disciplines as much as possible.
- Require at least two original research proposals, one with a focus outside the student's immediate field of study.

For the PhD in chemistry, Caltech has long required the completion of five original research proposals critiqued by a faculty committee: two during candidacy for students in their second graduate year (one in-field, one out-of-field), and three more (two in-field, one out-of-field) before graduation. This extensive training has been found to be exceedingly valuable to students in their later academic and industrial positions, because they had mastered the tools of organizing research proposals.

For other professional skills and attributes, such as communication, teamwork, and business productivity mindset, there are a number of other best practices. In general, graduate programs should:

- Require all students to give a general lecture. The Commission encourages lectures outside of one's department or research group, for example, to other academic departments, local professional society meetings, or chemistry outreach programs to local schools. There should be some mechanism for providing the students with feedback on how well they performed.
- Require all PhD candidates to include a short summary of two or three pages in their PhD thesis communicating their research to non-specialists, including, in principle, family members, friends, potential employers or investors, civic groups, newspaper reporters, state legislators, and members of the US. Congress.
- Formalize a requirement for each student to prepare a draft of at least one publication.
- Strongly encourage students to take an ACS-developed or comparable course on "how to give a talk," provided either on campus through specifically trained faculty or online.
- Strongly encourage a course that exposes students to aspects of business relevant to their training, such as innovation, product development, or entrepreneurship.
- Strongly encourage students to attend the ACS Career Pathways workshops at the annual meetings.

- Strongly encourage students to attend ACS-organized webinars on how industrial research is done, and perhaps leverage the safety performance partnership described below to include aspects of this topic.

Gaps for Academic Employment. Addressing the gaps discussed above will also surely enhance a student's performance in many aspects of an academic job, but a critical remaining gap is in teaching skills. The existence of this gap weakens teaching effectiveness in academic institutions, and represents a major challenge. While graduate students are certainly exposed to teaching through teaching assistantships, their experiences generally are not drawn from carefully crafted programs designed to teach students how to teach. Requiring lectures and the "how to give a talk" course discussed above will certainly help, but it is not enough for most students.

Addressing the Gaps for Academic Employment. We propose that the ACS develop a formal course that students who intend to seek academic employment must take during their graduate program. To make this requirement work well, academic institutions should strongly encourage this course, or a credible analogue, of all its doctoral students who will seek teaching positions. The course should be focused on undergraduate curriculum development, teaching standards, and teaching methods. It should be provided on campus through specifically trained faculty or perhaps online, in part or in whole. Another option for the chemical sciences is to develop more broadly something similar to the summer school offered by the American Society for Engineering Education in chemical engineering.²³

Of course, there are other skills relevant to an academic career that are not now effectively developed in doctoral candidates. A course might be developed beyond the one discussed above to cover the mentoring of graduate students, grantsmanship, interactions with program officers, and other related topics.

Safety as a Gap for All Employment. The Commission concurs strongly that students' lack of familiarity with best practices in laboratory safety also represents a significant gap, regardless of the type of employment the student ultimately pursues. This matter underlies Conclusion 3 in this report and is covered separately below.

Keeping the Fundamentals of the Discipline Strong. In order for the ideas presented here to be successful, our field must avoid a "zero-sum" mentality, whereby these "additions" are allowed to reduce the rigor of the scientific and technical component of the PhD. To this end, it is important to rigorously define the requirements for a strong technical foundation and to determine how they are best assured through coursework and non-course testing such as cumulative examinations and faculty reviews of oral research presentations.

²³ American Society for Engineering Education, 2012 ASEE Chemical Engineering Faculty Summer School, <http://www2.cemr.wvu.edu/~wwwche/ASEE/>

*Oversight of Student Progress*²⁴

The particular expectations that our departments and faculty members have concerning students -- in terms of workload, time to degree, degree of independence, and other matters -- are intimately connected to the expectations that students have concerning our institutions and on what our institutions and students each expect of themselves. The desired situation is one in which all of the expectations are compatible, shared transparently, and meet the goals and needs of all participants.

The last part of that statement is the principal challenge to compatibility of expectations, since our faculties must optimize toward dual goals: to deliver leading research programs while educating and mentoring students to do the same, and to prepare students for a diverse variety of satisfying careers. At the same time, in order to provide financial support for research programs and the student participants in them, faculty members and departments must manage and be accountable for a wide variety of grant, contract, and donor relationships with government agencies, foundations, and corporations. These are realities of the graduate education enterprise in the chemical sciences that are not going to change soon; therefore, we must develop and manage expectations in a manner consistent with them. The optimum balance of student and faculty interests is what we seek to achieve.

Several issues particularly motivated the Commission's inquiry into expectations, namely, the long and growing times to obtain PhDs in chemistry and chemical engineering, the need to improve the safety environment in university chemical laboratories, and a desire to understand the root causes of attrition from PhD programs.

Student Preparation. Of course, the very first expectation in graduate school is that the admitted student is prepared for the work. The reality is that many are not. There is great variability in undergraduate preparation; therefore graduate schools need to be more aggressive about making clear to undergraduate institutions what is required for baccalaureates to be successful in graduate school. In addition, graduate schools should make remedial courses available to address deficiencies in undergraduate preparation.

Many graduate programs have done away with placement examinations for incoming students. In the past, these exams guided remediation, so that all students might strengthen and broaden their knowledge of chemistry. The need for remedial courses has not disappeared with the disappearance of placement examinations; if exams are not used, other methods for evaluating the preparedness of all incoming students should be employed. An on-line self-assessment tool for undergraduates to work with during their junior undergraduate year might be developed to guide them to courses or experiences that will become important for them when they enter graduate school.

²⁴ Material in this section was developed for the Commission by the Working Group on Sources and Preparation of Students and the Working Group on Institutional Expectations of Students.

Most graduate students do not arrive with good preparation for teaching undergraduates. Much data suggest that those who are better teachers are also better at many other aspects of the doctoral program, e.g., research or communication.^{25,26} Proper training of incoming graduate students, preferably in a program beginning in the summer before their first semester, is highly desirable. Incoming graduate students might serve, for example, as instructors in programs for high school or community college students. Of particular importance during the summer period is to evaluate which students have language problems and to have courses available to improve their command of English. It is also important that future teaching assistants receive proper training and orientation for teaching a diverse student population.

Financial Support and Advisor Selection. The next chapter is devoted to matters related to student support mechanisms; however, some of what is said later is reinforced here, since funding is such an important element of expectations and of relationships.

There is widespread agreement that early years of graduate study are optimally supported through mechanisms that do not tie a student immediately to a specific research advisor or program. Fellowships, training grants, and unrestricted support, often from industry, as well as support as teaching assistants (more prevalent and feasible in chemistry than in chemical engineering, owing to service teaching) are possible mechanisms to achieve the desirable situation, where students have some time and flexibility to settle on the best match of research advisor, group, and problem for themselves.

Rotation experiences where students actually work for a few months in several laboratories before choosing one, a relatively common procedure in biological chemistry and bioengineering programs, are generally viewed favorably by their participants, although they do require some type of funding mechanism not tied to a specific research group. Rotations and teaching assistantships, even early in a graduate degree program, may slow the pace toward a degree, but also have compensating effects that might make the student's experience more successful and more efficient.

Teaching Experience and Career Guidance. Involvement in teaching is a valuable experience in the development of all doctoral students, but doubly so for students who plan to be teachers after graduation. In general, doctoral programs need to help students more fully to build their approach to teaching, as well as their specific skills for it

Programs should also help students to explore realistic career options. The career path aimed specifically at teaching in environments other than Research I universities merits a

²⁵ Berrett, D. Want to Be a Good Researcher? Try Teaching. *Chron. Higher Educ.* **2011** (Aug. 18).

²⁶ Feldon, D. F.; Peugh, J.; Timmerman, B. E.; Maher, M. A.; Hurst, M.; Strickland, D.; Gilmore, J. A.; Stiegelmeyer, C. Graduate Students' Teaching Experiences Improve Their Methodological Research Skills. *Science*, **2011**, 333, 1037-1039

higher profile and more attention than it currently typically receives in our doctoral programs. Indeed, better and more encouraging advice should be available to students who may be interested in pursuing a wider range of career options than becoming a professor at a research university or a researcher at a major company. Students are open to, and with increasing frequency are seeking, new career paths, including but not limited to science policy, communications, law, and entrepreneurship. The entire graduate education enterprise will be enriched if this trend is embraced and incorporated into the operating procedures of graduate education.

Role of Doctoral Committee. Although one would like always to discuss faculty and student interests in doctoral degree programs in a framework of equanimity and balance, conflicts do arise between students and advisors. When they do, students are at a disadvantage in power and influence. Effective use of doctoral committees to review progress, to give advice from varying perspectives, and to help anticipate and mitigate negative effects of conflicts is a major element of best practice in graduate education in the chemical sciences and engineering. Current practice often limits meetings of such committees to major examinations (qualifying examinations, dissertation defenses, etc.). Doctoral committees should meet annually with each student to monitor progress, offer advice and suggestions, and, when appropriate, help with career counseling; private meetings of the committee with the student and advisor separately may be useful as a means of encouraging communication in the face of an imbalance of power.

Students put their educational experience and the launch of their careers in the hands of faculty members. They expect to be able to place their full trust in the faculty; we must create environments in which their trust is fully warranted.

Time-to-Degree and Other Matters. Understanding the expectations of the various players in graduate education is one issue; changing expectations is another matter altogether. There is a consensus feeling that the open-ended timescale of a doctoral degree in the chemical sciences does not encourage efficiency, productive use of time, or good professional habits. Indeed, paradoxically, time spent in the laboratory is sometimes used by advisors as a gauge of productivity. Deadlines for attainment of the degree, under penalty of cut-off of financial support, are blunt instruments to tackle this issue.

A more holistic approach is preferable, encompassing some of the directions and strategies mentioned above. Expectations can be set early and in an encouraging and enabling, rather than punitive, manner. This process can start from the premise that a doctoral degree in the chemical sciences and engineering should require no more than four to five years, with less than four years being possible in rare cases. Such a timetable can be achieved by thoughtful implementation of the role of doctoral committees described above. Annual, or more frequent, meetings with advisory committees can help train students to stay on a productive track, aimed more at producing results than putting in time. It can also protect

students, where needed, from advisors who want more time from students who have already accomplished sufficient work to be awarded a degree. This involvement of the doctoral committee can then extend into aspects of career counseling and networking needed for the best possible job placement. More formal and explicit elaboration of plans, and monitoring of progress toward those plans by advisor and committee, would not only reduce time-to-degree, but also instill good professional habits in students. Even though one cannot precisely schedule important progress in research, one can develop decisive experiments and anticipate alternative courses of action for different possible outcomes.²⁷

Attrition from Doctoral Programs. Just 62% of entering PhD students have been awarded the degree after ten years (presumably most of the 38% have dropped out of programs long before that point).²¹ There is a very definite need for more data, broken down by school, sub-field, age, gender, ethnicity and other factors, to comprehend the reasons for this fact.

Independent of the data, it is important for faculty in graduate programs to do a better job in earlier assessment of whether a student is truly well-suited to successful completion of a PhD. Some students who leave may not have been appropriately placed in PhD programs in the first place, which is not to say that they are necessarily weak students. A master's degree may be, and should be, a valid alternative for some students who are more motivated by narrower vocational goals, and not by basic research. Aspects of a sound early assessment process include building accurate expectations among undergraduate students bound for graduate school, better admissions processes, grades in early graduate courses, mentoring, and serious, early contact with a doctoral committee. There is a major need to establish understanding and best practices in this area and to share them broadly across academic departments.

Impact of Academic Organization²⁸

Contemporary problems in the sciences, including the chemical sciences, are ever more complex and challenging. Many occur at the interface of scientific disciplines and sub-disciplines. Therefore, their solutions generally require a multi-disciplinary, interdisciplinary, and team approach. Professionals must have depth and breadth in the chemical sciences, but also must command reasonable working knowledge of related fields.

Depth has been a hallmark of education in the chemical sciences, but there is growing concern that doctoral graduates are too narrow for the challenges they face immediately in

²⁷ Some of these recommendations apply equally well for postdocs, with the adjustment that the relevant timescale is 2-3 years, not 4-5 years.

²⁸ Material in this section was originally developed for the Commission by the Working Group on Departmental Organization.

their careers. A legitimate question is whether our current approach to depth has the cost of inhibiting essential multi-disciplinary interactions and experience in graduate research.¹⁴

Graduate education in the chemical sciences and the structure of departments should reflect and accommodate the real functional needs of our graduates and the changing reality in the scientific landscape. For departments in the chemical sciences this means setting up structures that emphasize interdisciplinary and multi-disciplinary collaborations and problem solving. There is likely to be more than one way or one model to accomplish this. Examples include:

1. Traditional Model. The traditional structure of departments in the chemical sciences is a consequence of long-standing traditions and the evolving nature of the chemical sciences. Unlike departments of chemical engineering, the vast majority of chemistry departments are organized and function along subdisciplinary lines and divisions (analytical, environmental, inorganic, material, organic, physical, theoretical, etc.). This is a result of several factors, among them: (a) tradition, (b) undergraduate teaching needs (in particular service teaching), (c) graduate recruiting, (d) faculty hiring needs and customs, and (e) logistics of managing large departments).
2. Chemical Engineering Example. Chemical engineering research is as diverse as chemistry, ranging from process control to biochemical engineering, yet there are no subdisciplines within chemical engineering departments. This arrangement reflects a philosophical stance common to all chemical engineering departments that all faculty and students have a stake of some kind in all aspects of the field. Since a very high proportion of chemical engineering graduates go to work in industry, rather than in universities, they have perhaps a bigger need and motivation to understand a broad range of the profession. They are aiming to be effective and influential in an industrial organization, probably in several different roles, over their careers. So, breadth is valued more than narrow expertise. To the extent that chemistry departments are sending a high proportion of their graduates to industry, less emphasis on divisional structure may prove valuable.
3. Industry Model. Much of industry uses a “matrix structure,” in which scientists have two homes, one within the discipline, and one within a particular project or program. R&D takes place at the interface. Industry values scientists who are adept at cross-disciplinary collaborations, and it is organized with great success in collaborative teams working on complex multi-disciplinary programs. An industrial organization operates as a community, where it is hard to think of anything of scale that can be accomplished by one individual. Industry generally assesses its work force every year and usually ranks all R&D people as one group, but also focuses on the key insights or contributions made by the individual

members of a team. This allows deconvolution of individual performance from that of the team.

4. Joint Appointments. A number of chemistry departments are making joint appointments between chemistry and related areas like biochemistry, materials, physics, or various fields of engineering. Such appointments are usually made post-tenure, but may also be made as part of the tenure-track arrangement for new hires. Such joint appointments have greatly fostered interdisciplinary activities, especially at the interfaces of the sciences and have broadened interdisciplinary perspectives.
5. Centers. Many academic institutions have established interdisciplinary research centers, generally formed around a broad current challenge, such as energy, nanotechnology, or cancer prevention. Many are also fostered by the federal funding programs like NSF's Materials Research Science and Engineering Centers (MRSEC) and NIH project grants, as well as large DOE projects. These centers involve faculty and graduate students from a large number of different traditional departments, and all have an interdisciplinary and multi-disciplinary focus. Typically, there is also a considerable emphasis on external partnerships with industry, government, foundations, or NGOs to bring solutions to local, national and international problems. Centers in many universities have helped faculty and students understand the power of creativity unleashed when broad cross-discipline and intra-discipline teams tackle problems.

It is generally recognized that the culture of collaboration and interdisciplinarity in academic institutions requires careful building, as well as encouragement and participation by many faculty over the years. These faculty and administrators not only help design, build, and manage centers and other collaborative efforts, but also provide inspiration and examples necessary to draw talented and productive faculty into the endeavor. Such faculty have promoted a wider view rather than more parochial interests. It is this kind of leadership that is necessary to foster an interdisciplinary and multi-disciplinary team approach to solving challenging, complex problems and to enable a well-functioning department in the chemical sciences. In the end, the exact organizational structure may not be so important as the attitudes, leadership, and management skills of the faculty.

Therefore, it is critical to capture the various experiences that universities have had with respect to the organizational structure of their programs in the chemical sciences. To this end, the Commission urges the ACS to engage, perhaps through a dedicated commission or task force, in a discourse with leading universities to determine the current, as well as the historical, structure of their chemistry-related programs and to evaluate the pros and cons of the various configurations. In particular, we are interested in ferreting out the novel, creative, replicable structures and how they have been implemented to maximize collaborative opportunities. The most useful data will come from universities that have tried a number of

organizational structures and have real-world evaluations of the relationship of the configuration to desirable outcomes. We appreciate the fact that many universities have grappled with and have experimented with a variety of options, and the commission desires to capture their observations and conclusions, leading eventually to recommendations on best practices based on actual experiences.

Overall Conclusion and Specific Recommendations

Conclusion 1: Current educational opportunities for graduate students, viewed on balance as a system, do not provide sufficient preparation for their careers after graduate school.

The Commission reaffirms the anchoring concept that a doctoral program in the chemical sciences must manifest traditional depth and must maintain a focus on mastery. But the members also conclude that curricula need to be refreshed, and better-designed opportunities should exist for the development of critical professional skills.

The Commission's specific points in this area are as follows:

- 1.1. In general, the Commission encourages departments to undertake greater oversight over the progress and opportunities of individual graduate students.
- 1.2. Graduate programs should be more active in diagnosing and remediating deficiencies in the preparation of first-year students.
- 1.3. Beyond core academic competency in chemical science or engineering, additional skills are critical for a student's future career. Faculty overseeing doctoral programs need to offer specific activities that would enhance students' ability to:
 - Communicate complex topics to both technical and non-technical audiences and to effectively influence decisions,
 - Learn new science and technology outside prior academic training,
 - Collaborate on global teams and/or with global partners and clients,
 - Effectively define, drive, and manage technical work toward a practical, significant result, and
 - Clearly understand the ethical conduct of research.

The most all-encompassing approach to these needs is to significantly enhance interdisciplinary collaboration among the students.

- 1.4. Four years should be the target for completion of the PhD, with the departmental median time less than five years. Degree times greater than five years should be strongly discouraged through enforced institutional policies.

The Commission understands that there is inevitable tension between its recommendations that doctoral programs be shortened while also being retailored to include elements that are not generally addressed effectively in existing practice. For this reason, the members believe graduate education must become more efficient. Opportunities for improved efficiency exist in better program design, superior monitoring of student progress, use of the summer before the first year of graduate study, and fuller use of short courses and internet-based offerings.

- 1.5. Every department should constitute a doctoral committee for each student composed of several faculty who will be intimately involved in the student's graduate education. Graduate programs should see that the doctoral committee is involved more closely and more frequently in graduate student mentoring than is currently the norm in PhD student advising. This should include, at a minimum, annual meetings, and opportunities for the student to address matters such as possible conflicts with the advisor.
- 1.6. Graduate programs should make an Individual Development Plan (IDP)²⁹ a standard part of every doctoral student experience. The structure and elements of the IDP should be developed in a tailored way at each institution, though some standardized versions are now available. These may be devised in their particulars by the student and advisor, and discussed initially and annually with the doctoral committee.
- 1.7. Faculty should encourage students to engage in projects requiring collaboration that broadens the student's field of study. In particular, faculty should encourage collaboration across disciplines as much as possible.
- 1.8. Departments should require at least two original research proposals, one with a focus outside the student's immediate field of study.
- 1.9. Departments in the chemical sciences are also encouraged to set up optimal structures that best enable and facilitate an interdisciplinary and multi-disciplinary team approach to complex problem solving.
- 1.10. Students interested in entrepreneurship should have access to a curricular option providing an introduction to relevant topics, including the protection and management of intellectual property, the basic economics of IP-based businesses, the financing of start-up enterprises, and selected legal concepts. This is an area in which the American Chemical Society might provide useful short courses for delivery on campuses or via the internet.
- 1.11. The ACS should develop one or more formal courses for the more explicit preparation of students who intend to seek academic employment. The first

²⁹ Austin, J.; Alberts, B. Planning Career Paths for PhDs. *Science* **2012**, *44*, 1149.

should be focused on undergraduate curriculum development, teaching standards, and teaching methods. It should be provided on campus through specifically trained faculty or perhaps online, in part or in whole. Academic institutions should strongly encourage all applicants for teaching positions to have resumes noting successful completion of this course or a suitable alternative.

An additional course might be developed to cover the mentoring of graduate students, grantsmanship, interactions with program officers, and other related topics.

- 1.12. The ACS is encouraged to undertake an extensive survey of representative graduate programs at selected major universities to ascertain requirements and expectations and organizational structure that best facilitate the educational goals of the Commission. Also, the ACS should assure that the Commission's recommendations on best educational practices are reflected in the work of the ACS Education Division, the ACS Graduate Education Advisory Board, and the ACS Committee on Economic and Professional Affairs.

Toward Implementation

The obvious concern about implementing these recommendations is time. The extra-learning agenda needed to improve the skills and versatility of students will require more time from both faculty and students. With the overwhelming desire to limit PhD programs to 4-5 years, the concern is that students will get less "real work" done during their graduate programs and that mastery will suffer. The Commission believes strongly that this need not and should not be the consequence.

In fact, all of the skill enhancements discussed here should make students more productive. If developed ideally, this increment of productivity, which could reasonably be expected by Year 3, should more than make up for any lost lab time in the earlier years.

If we take safety as one example, there is a demonstrated, strong correlation between occupational safety and operating performance of factories.³⁰ A great many industrial organizations have found safety to be powerfully coupled in a general way to productivity. They are not committed just because a safety culture reduces their exposure to liability, but in much greater degree because a bone-deep safety culture protects their people and because workers who consistently think carefully about what they are doing perform better.

³⁰ Veltri, A.; Pagell, M.; Behm, M.; Das, A. A Data-Based Evaluation of the Relationship between Occupational Safety and Operating Performance. *Jour. SH&E Res.* **2007** 4(1), 1-22.

The Commission believes that many of the concerns about the extra-learning agenda can be mitigated with a well-designed “boot camp” during the summer prior to the normal fall academic start, to be used for some of the evaluation and training described above. This is a period when students are naturally interested in building their preparation for success in the new environment of graduate school, which involves many challenges different from those of their undergraduate years.

Also, it is important to avoid entrapment in the idea that all of the skills advocated here for development need semester-long courses. Much of what we have discussed could be better developed in intensive sessions of one to several days. Internet-based delivery of some of the material is definitely practical. Some of the training suggested to be offered by the ACS might be accomplished as part of the national fall meetings, which are generally held in August just prior to the start of most fall academic semesters. Students could attend live when possible, but also remotely from their campuses.

Regarding funding, we believe that the costs for developing the proposed ACS courses should come from some reprioritization of current ACS spending, with the addition of some minimal funding from the academic institutions. Graduate program grants, to be proposed in the next chapter, might turn out to be good vehicles for development of other educational tools and experiences.

FINANCIAL SUPPORT OF GRADUATE STUDENTS³¹

Analysis

The system for support of graduate students in chemistry has served our society well for a long time. The large majority of graduate students is supported either on teaching assistantships from their departments or on research assistantships paid by their advisors out of research grants. In addition, some graduate students are supported on training grants from their departments or by fellowships (mainly from government, but sometimes from university endowments, industry, or foundations). In all cases, students receive a reasonable stipend and have some arrangement for avoiding heavy burdens from institutional tuition and fees.

However, the system for financial support of graduate students is no longer optimal in serving students and educational institutions, because the support mechanisms have evolved over recent decades, focusing students much more narrowly and restricting their ability to

³¹ Material in this chapter was developed for the Commission by the Working Group on Student Support Mechanisms.

develop needed breadth. Moreover, intrinsic conflicts of interest among the parties in the system have intensified and have become harder to manage.³²

There is room for improvement in the current mix and balance of funding mechanisms for graduate students, in order to better the overall graduate experience. While one size cannot fit all, there is a need to identify and establish best practices for graduate-student funding.

Current Situation

In their early years of graduate school, students are generally supported on teaching assistantships, involving instructing in laboratories and/or recitation sections. This arrangement works well for the department, but such teaching assignments are rarely structured to develop graduate students' skills in areas such as communication and teaching techniques.³³ Sometimes, especially at large campuses, teaching assignments can involve overbearing time commitments and responsibility for quite large numbers of undergraduates. Further, students are required in many situations to continue to support themselves as teaching assistants for the majority of their graduate career, thus slowing progress to the degree.³⁴

Research assistantships, normally funded out of a principal investigator's grant, support a large number of graduate students once they begin their thesis research. Funding in this way ties the graduate student to a very specific project, allowing the PI and the granting agency to maximize progress toward publication and grant renewal. However, research assistantships leave students dependent on their advisors for both financial support and intellectual guidance, diminishing students' intellectual independence and potentially making them hesitant to challenge their advisors. This arrangement can be especially difficult when student-mentor conflicts arise. Because a student on a research assistantship is tied to a specific project, little latitude is allowed for broadening activities that will enhance student skills. Federal policies regarding specific performance on grants have become much tighter in recent years³⁵ and reinforce these limitations on the student's ability to explore.

Funding by a department's training grant or by a government or private fellowship allows room for the types of student-skill development advocated elsewhere in this report.

³² Stephan, P. *How Economics Shapes Science*; Harvard University Press: Cambridge, MA, 2012. For a review, see Benderly, B. L. Academia's Crooked Money Trail. *Science Careers Magazine*, January 6, 2012,

http://sciencecareers.sciencemag.org/career_magazine/previous_issues/articles/2012_01_06/credit.a1200001

³³ Luft, J. A.; Kurdziel, J. P.; Roehrig, G. H.; Turner, J. Growing a Garden without Water: Graduate Teaching Assistants in Introductory Science Laboratories at a Doctoral/Research University. *J. Res. Sci. Teaching*. **2004**, *41*, 211-233.

³⁴ Bowen, W. G.; Rudenstine, N.L. *In Pursuit of the PhD*; Princeton University Press: Princeton, NJ, 1992.

³⁵ Kennedy, D. OMB Grants Reform Letter April 2012; Council on Governmental Relations: Washington, DC, 2012. <http://www.cogr.edu/viewDoc.cfm?DocID=151909>

International graduate students studying in the US. are generally supported by the department or PI with little or no support from their home country, even if the student intends to return home upon completion of the degree.

Addressing the Current Situation

Relatively unencumbered funding of student stipends, such as that from training grants or fellowships, provides graduate students with an optimal opportunity to make steady progress toward their degrees, while simultaneously having time to develop the professional skills that will allow them to succeed in their career. However, such funding is currently available only to a tiny minority of students. There is a general need to shift the mix of funding for student stipends.

The Commission urges that principal funders in the chemical sciences gradually decouple a much larger fraction of student-support funds from specific research projects. Indeed, we believe that the goal should be to transform the system of support by design over a ten- to fifteen-year period, so that a preponderance of student support becomes decoupled from research project grants. However, the Commission does not offer a recipe, because the members believe that new models of support need to be invented and tested through experiments sponsored by the principal funders of students in the chemical sciences.

Training grants represent a proven alternative to project-based support of graduate students. Currently, many life-science programs, particularly PhD programs at medical schools, are funded largely through NIH training grants.

The Commission advocates a new strategy, which we call “graduate program grants,” in which something like the training-grant concept might be coupled with support for departmentally designed improvements in graduate education. For example, graduate program grants might also provide funding for students to begin graduate work in the first summer after the baccalaureate, which the Commission sees as offering many potential benefits.

To provide an increased level of graduate support via graduate program grants, principal funders should redirect some of their research funding to such grants. Perhaps a portion of the funding for graduate program grants could also be provided by allocating a percentage of the money from each individual PI’s research grant directly to departments for graduate-student support. Awarding direct grants to faculty teams based on proposals that include mechanisms to develop professional skills in graduate students will guarantee that programs large and small can profit from graduate program grants.

Service by students as teaching assistants should continue to be viewed as an integral part of the graduate experience, but should be used with better forethought and design to

develop the student's professional skills.^{25, 26, 36} Teaching opportunities with increasing responsibility should be distributed across the graduate program. For graduate students planning a career in teaching, these opportunities should include instruction in teaching techniques and the responsibility to develop and deliver classroom lectures.

Overall Conclusion and Specific Recommendations

Conclusion 2: The system for the financial support of graduate students, as currently operated by private, institutional, state, and federal funds, is no longer optimal for national needs.

The support system rests too heavily on individual research grants and involves serious conflicts between the education of graduate students and the needs for productivity and accountability in grant-supported research.

Here are the Commission's specific recommendations and suggestions in this area:

- 2.1. Federal and state funding agencies, private funders, and universities themselves, should take steps toward decoupling more student-support funds from specific research projects, in the interest of providing students the opportunity for better balance between training in research and training in other career skills, without significantly impacting the research productivity of faculty.

The goal, with perhaps a ten- to fifteen-year horizon, should be to decouple the preponderance of student support from specific research grants and contracts. In the near term, funders and graduate program leaders should engage in trial projects designed to prove out new mechanisms.

- 2.2. In particular, federal agencies and private funders should experiment with a new strategy for "graduate program grants" to support graduate students. Analogous to training grants, but with perhaps greater support for innovation in the educational program, graduate program grants should be made available to departments on a competitive basis. They could be used
 - to provide students with semesters of support free of extensive service as teaching assistants, just as grant-funded research assistantships do now.
 - to provide funding for students to begin graduate work in the summer after the bachelor's degree, so they can get a start on exploring research opportunities and have the opportunity for initial training in critical skills

³⁶ Ethington, C. A.; Pisani, A. The RA and TA Experience: Impediments and Benefits to Graduate Study. *Res. in Higher Educ.*, **1993**, *34*, 343-354.

such as safety, communications, pedagogy, and responsible conduct of research; and

- to reward all programs at all levels for developing curricula to serve the overall education needs of students;

While the Commission would naturally welcome increased funding for graduate student stipends, this recommendation for reshaping student support is not mainly about more funding, but about improving the deployment of existing funding.

- 2.3. The US Department of Education should make the GAANN Program (Graduate Assistance in Areas of National Needs) more generally useful. The program currently provides grants to institutions of higher education for support of talented students from traditionally underrepresented backgrounds who must demonstrate financial need. If the Department of Education were to reformulate the GAANN program by making it generally applicable, it could go a long way toward supporting strong graduate students not only in the chemical sciences, but in other sciences as well.
- 2.4. Faculty members should view work by graduate students as teaching assistants much more strategically as an opportunity (and an obligation of the program) to enhance the professional development of the student. The experience should be deliberately complementary to research. However, teaching assistantships should not be the major basis of support throughout one's graduate career, because such a situation shifts the student's balance of time commitment too far away from essential research activities.
- 2.5. Government sources should rebalance fellowship programs to make more awards available to students in the second year of graduate school and beyond (i.e., application made after the student has begun graduate school), rather than primarily in the first year.
- 2.6. The governments of many nations sending graduate students to the US. have strengthened financially, so departments and programs should place increased emphasis on international students being supported by their home countries. The Commission is recommending many important changes in student support patterns, and greater ease in implementing them would arise naturally from fuller native support of international students.
- 2.7. With respect to timetable and student support, the Commission recommends the following structure for most students in most doctoral programs in chemistry departments. Graduate programs in the other chemical sciences are urged to strive toward implementing a similar pattern, modified as needed by departmental financing patterns:

- Summer before the start of courses. This is an optimal time for students to receive initial training in professional skills, including instructional skills, and to begin exploring research opportunities. Support for all students for two months should be provided by departmental funds, including graduate program grants.
- 1st year. Nearly all students should be supported on teaching assistantships or, where available, graduate program grants.
- 2nd year. Most students should be supported by the department on individual fellowships or graduate program grants. Federal fellowships would also be available to some students. Teaching assistantships should be used as needed, but should be at an advanced level (more responsibility, more training in pedagogy) compared to the first year.
- 3rd year. Research assistantships tied to the PI's specific project, graduate program grants, individual fellowships, or teaching assistantships.
- 4th and (if needed) 5th year. Research assistantships, individual fellowships. If teaching assistantships are used, they should include a major component of pedagogical training and should require a reduced time commitment compared to earlier years, to allow more rapid progress to degree.

Toward Implementation

Two constituencies must work in partnership to effect the Commission's proposals: funding agencies and graduate faculty. To assess the value and practicality of these recommendations regarding redeployed funding, a leading agency (optimally the National Science Foundation) should initiate a five-year pilot program whereby faculty teams would be funded based on proposals that would include plans to institute changes in their graduate-student support system, as well as to establish or improve mechanisms for developing critical professional skills among their graduate students. Included would be a formal first-summer program for all incoming graduate students. In addition, the lead agency might allocate a percentage of grants to PIs at pilot institutions, to support general departmental fellowships not tied to a specific project. In the pilot phase, university administrations would be encouraged to provide enhancement funding to participating departments, especially at programs beyond the "top-tier," since optimized funding for graduate students would be expected to make the program more attractive to highly qualified applicants.

Pilot funding might also be considered by private funders, such as major foundations. Again, supported programs would need a well-developed plan to develop professional skills in their students during their graduate career.

Expansion beyond the pilot funding programs would depend on metrics for success being met: positive feedback from graduate students and departments in formal surveys; students coming from involved programs judged by their future employers to be better prepared for their careers; and eventually increased quality of students who choose to undertake graduate work in chemistry.

In the longer run, funders would need to develop a policy on whether graduate program grants should continue to be based on faculty teams, in the manner of present-day training grants, or should, by definition, encompass an entire graduate degree program. This is a matter requiring more study than the Commission has been able to provide.

SAFETY AS A CULTURE³⁷

Analysis

Although students can be taught methods for doing work more safely, achieving a culture of safety is another matter. It must be led by example. When students join an organization that has a high-performance safety culture, they most often see leadership at the top that is fully engaged in safety and setting the overall tone. Safety is a part of each employee's daily routine, and unsafe behaviors are simply not tolerated.

Matters of safety are not only issues of physical security; they also provide important educational opportunities.

Because such a safety culture is very common in today's large corporations, we see a safety performance partnership (SPP) between industry and academic organizations as a natural step toward improved safety awareness and culture among students. An SPP is essentially a vehicle for corporations to share best practices with students and faculty on a regular, systematic basis. Such sharing of information is routine within and among corporations and is an important component of establishing a strong safety culture. The SPP should include site visits by students, faculty, and institutional safety professionals.

The Dow Chemical Company is now piloting an SPP with the University of Minnesota, Pennsylvania State University, and the University of California, Santa Barbara. Even if other companies were to join this initiative, it would be a challenge to scale the partnership to include all research universities.

Therefore, the Commission proposes that ACS play a lead role in facilitating training and sharing best practices. For example, a comprehensive safety curriculum based on best

³⁷ Material in this chapter was developed for the Commission by the Working Group on Education for Employment and the Working Group on Institutional Expectations of Students.

practices should be developed. It could then be disseminated using the web. The Khan Academy has already demonstrated the viability of structured knowledge maps and individual lessons taught via the internet. This model is easily scaled to all universities and could be augmented by industry participation.

Faculty leadership will be essential to improve university safety.

Most likely, a few pioneering institutions will drive broader adoption. With appropriate publicity by ACS, a strong safety culture can become a competitive advantage in attracting students. Further motivation can be driven by working with funding agencies and the government to encourage adoption. Finally, we also believe that the SPP can serve as a convenient way to show students how industrial research is done in general, and every opportunity should be taken toward that goal.

The ACS Committee on Chemical Safety (CCS) has the mission of promoting and facilitating safe practices in chemical activities. CCS provides advice and counsel to ensure safety by calling attention to potential hazards and stimulating education in safe chemical practices. The Committee also serves as a resource to other ACS units on matters related to chemical safety and health.

CCS has recently released the report, *Creating Safety Cultures in Academic Institutions: A Report of the Safety Culture Task Force of the ACS Committee on Chemical Safety*,³⁸ which provides invaluable help toward a strong safety culture in two- and four-year undergraduate, graduate, and postdoctoral programs. It identifies:

- The best elements and best practices of a good safety culture
- Specific guidance, suggestions, examples, and recommendations that could be used by universities and colleges
- Tools and resources that will help strengthen the safety culture

The report also makes specific recommendations about leadership and management, about teaching laboratory safety, about attitudes, awareness and ethics, and about institutional support needed for a safety culture.

Among the points made in the CCS report is the following:

Many of the suggestions made in this document can be made at little or no additional cost. Nevertheless, new and innovative approaches for building a strong safety culture may require funding.

³⁸ Committee on Chemical Safety, *Creating Safety Cultures in Academic Institutions: A Report of the Safety Culture Task Force of the ACS Committee on Chemical Safety*, American Chemical Society, Washington, 2012, http://portal.acs.org/portal/PublicWebSite/about/governance/committees/chemicalsafety/CNBP_029720

Indeed, funding is certainly required to bring most departmental practices to a desired level. This is a serious matter for university administrations to deal with. We have more to say about this topic in the section entitled “Toward Implementation” below.

Overall Conclusion and Specific Recommendations

Conclusion 3: Academic chemical laboratories must adopt best safety practices. Such practices have led to a remarkably good record of safety in the chemical industry and should be leveraged.

Progress would afford better protection to students and other workers at all academic levels and would better prepare students to meet the natural expectations of their future colleagues and employers.

Specifically, the Commission makes the following recommendations and suggestions:

- 3.1. Safety as a culture must be consistently led by example in all graduate programs in the chemical sciences.
- 3.2. A natural supporting step is to establish a safety performance partnership between industry and academic institutions, whereby corporations share best practices with students and faculty on a regular basis. ACS should play a lead role facilitating training and sharing of best practices and should sponsor the development of a comprehensive safety curriculum based on best practices.
- 3.3. Leadership from the top of an institution is essential for a sound safety culture to take root and thrive. The hazards and issues in the chemical sciences also exist in departments and programs outside the chemical sciences all across college and university campuses. A strong safety culture must not vary across institutions, and mechanisms for managing the associated costs cannot be left to individual departments or research groups.

All colleges and universities should see that widespread and in-depth attention is given to the report: *Creating Safety Cultures in Academic Institutions: A Report of the Safety Culture Task Force of the ACS Committee on Chemical Safety*. Specific programs to implement the recommendations of this report should be established in all academic chemical science and engineering departments.

Faculty members in the chemical sciences can and should take the lead toward best practices, and should advocate for support at the highest institutional levels.

Toward Implementation

The Commission reiterates for emphasis its point that there is no chance for a strong safety culture to succeed in a college or university without policy-level leadership from the very top. The members, of course, realize that the main readers of this report will be our colleagues on the faculties of programs in the chemical sciences. With rare exceptions, they will not be in a position to make decisions for the institution at the required level. However, they are able to grasp the importance of our recommendations on safety, and they have the power to bring the issue before the appropriate leadership of their institutions. We urge our colleagues to press the case aggressively toward a sound institutional policy on their own campuses, and to persist in the effort, as required. This report might be useful in some of the communication.

The institutional interest in safety standards is fundamental. Failures jeopardize the people of the institution and expose the institution to serious liability and disgrace.

The costs of safety practices for research should be built into the indirect costs charged by universities; they should be adequate to provide what is needed (including supplies, equipment, skilled personnel, training, and more). The direct-cost budgets of research grants do not seem to provide the appropriate mechanism for funding safety measures. The top down approach to handling the costs of safety is imperative to make certain there is uniform implementation of safety practices and hardware across all chemical laboratories of a university and to eliminate conflicts of interests among individual PIs making financial decisions regarding safety implementation in their own laboratories.

The costs of safety practices outside research laboratories, most notably in teaching facilities, are inevitably an institutional responsibility. Suitable standards should govern them, and appropriate mechanisms should fund them.

Including an inquiry about the safety culture in the post-degree survey could be useful as a way of tracking the perception of progress among recent graduates.

At present, there is no joint agreement or declaration among academic institutions concerning specifics of safety standards or the promotion of a safety culture. In this chapter, we have recommended the recent publication of the ACS Committee on Chemical Safety as a resource; however it seems as though the academic enterprise would benefit from more direct collaboration on these matters, extending, of course, well beyond the chemical sciences. One of the major national associations of research universities should consider taking up the subject.

SUSTAINABILITY AND OPPORTUNITY IN GRADUATE PROGRAMS

Analysis

This chapter is about the matching the nation's production of new degree-holders, especially at the PhD level, to the nation's needs. One part of that picture concerns opportunities for new graduates; a second part relates to the recruitment of new students into graduate programs; and a third concerns the strategic management of program size and balance. These components are addressed sequentially under separate subheads.

Opportunities for New Doctoral Graduates

The Commission's work has been undertaken at a time of significant insecurity over opportunities for new graduates. Not surprisingly, the Great Recession drove much higher unemployment rates among degree-holders in the chemical sciences, which have persisted through the slow recovery, just as in other fields.

In the period just before the economic collapse in 2008, less than 2.5% of chemists at all degree levels were unemployed and seeking employment, but that number had doubled by 2011 to 4.6%. It improved slightly in 2012 to 4.2%.³⁹

For new chemistry graduates at all degree levels, the picture is more daunting: The unemployment rate was about 6% in the time before 2008, but rose to 13.3% in 2011 (latest available data).⁴⁰

New PhDs in chemistry were unemployed, but seeking employment, at about a 4% rate before 2008, but that rate had reached 9% in 2011. Of those employed, about 40% were in postdoctoral appointments before 2008, but in 2011 the postdoctoral fraction accounted for 47%. About half of new PhDs reported that they were in full-time permanent employment in 2008, but in 2011 only a third so reported.⁴¹

Postdocs accounted for the employment of only 1.3% of all chemists (not just new graduates and not just PhDs) in 2008, but that fraction tripled to 4.2% in 2010, then fell back to 2.6% in 2012.³⁹ These particular numbers show the sharp difficulties encountered by new PhDs seeking employment in the post-crash years.

There is little doubt that the rate of producing new chemical sciences PhDs in the US is too high for the current employment market, but the current imbalance could not have been

³⁹ Rovner, S. L. Salary & Employment Survey for Chemists. *Chem. Engr. News*, 2012, 90 (39), 40-43. <http://cen.acs.org/articles/90/i39/Salary-Employment-Survey-Chemists.html>

⁴⁰ American Chemical Society, Department of Research and Member Insights. Employment Trends and Concerns Facing New Graduates in the Domestic Chemical Workforce, August 2012.

⁴¹ Morrissey, S. R. Starting Salaries. *Chem. Engr. News*, 2012, 90(23), 36-38. <http://cen.acs.org/articles/90/i23/Starting-Salaries.html>

avoided without years of forethought. Because the average time-to-degree is about six years in our fields and because many PhDs temporarily occupy postdoctoral appointments, the time constant for adjustments in new employment candidates at the doctoral level must be something like 7-9 years. It is simply not possible for the system to adjust to changes in demand taking place on shorter timescales, and certainly not to those with the suddenness and degree of the 2008 contraction.

The question of greatest relevance to the work of this Commission is whether the employment markets have undergone or will be proceeding through systematic changes that should lead PhD producers to alter the scale or the balance of their programs.

By the word “balance,” we mean the mix among distinct areas or capabilities fostered in the program. Among departments of chemistry, balance would relate to the number of new PhDs produced in traditional subfields, or the numbers produced, for example, with synthetic, computational, or measurement skills.

There is indeed evidence of recent systematic shifts and persistent imbalances in the employment market for PhDs in the chemical sciences. We cite three points:

- In the last decade, 300,000 jobs have been lost in the pharmaceutical industry worldwide.⁴² This total is larger than the entire US pharmaceutical employment base.⁴³ Large US research facilities have been closed⁴⁴ and sizable systematic reductions in domestic research capabilities have been implemented or announced, apparently driven in significant part by consolidation in the industry. Some of the reduced functions have been outsourced to other technologically strong nations.⁴⁵
- Over the last two or three decades, there has been significant growth in the number of postdocs, especially on the life-science side of the chemical sciences. Quite a few PhDs now work through two or three postdoctoral appointments, a phenomenon mainly about warehousing doctoral chemical scientists, rather than about career development. Its continuation reflects an imbalance in the production rate for PhDs relative to career employment options.

⁴² Harper, M. A Decade in Drug Industry Layoffs. *Forbes*,

<http://www.forbes.com/sites/matthewherper/2011/04/13/a-decade-in-drug-industry-layoffs/#comment-2923>

⁴³ Bureau of Labor Statistics. NAICS 325400 – Pharmaceutical and Medicine Manufacturing.

http://www.bls.gov/oes/current/naics4_325400.htm

⁴⁴ Edwards, A. Saddened Town Recalls History with Drug Giant. *New York Times*. 2012 (July 1).

<http://www.nytimes.com/2012/07/02/nyregion/saddened-town-recalls-history-with-drug-giant-roche.html>

⁴⁵ Arnold, C.; Phelan, V. Outsourcing in the Pharmaceutical Industry: 2011 and Beyond. Equaterra, KPMG Institutes, <http://www.kpmginstitutes.com/shared-services-outsourcing-institute/insights/2011/pdf/pharma-outsourcing-trends-2011-and-beyond-6173.pdf>

- The Commission has received anecdotal testimony that PhDs are now commonly available for industrial jobs in the biotechnology industry that historically were held by master's level technicians.

Through the recent work of Sauermann and Roach,⁴⁶ there is fresh insight into the way doctoral candidates themselves are thinking about career options and about how their views on this subject evolve during their experience as graduate students. A striking aspect is how broadly they view the options. Almost a third of the students indicate interest in start-up enterprises. In the experience of the Commission, this fact alone indicates a radical reconception of the post-PhD job market in the minds of today's doctoral candidates.

In the Commission's judgment, PhD programs owe students much fuller guidance on career options, as well as access to improved and more varied preparation for career paths.

More will be said below about managing the size and balance of a program. At this point, the Commission makes only the point that the nation has an essential interest in continuing to produce an adequate supply of new talent in the chemical sciences at the top competitive level, gauged in worldwide terms. That sort of talent will not continue to be attracted into our fields without good access to genuinely attractive career paths.

*Sources of Graduate Students*⁴⁷

The Commission considered questions concerning the graduate student profile in the chemical sciences: Is the current profile the ideal one, not only in terms of domestic vs. international students, but in terms of diversity along other axes as well? Do entering students have the proper background for the type of graduate education we want them to attain?

Before providing commentary on these questions, it is fruitful to examine Table I for the profile of PhD recipients in chemistry for 2010, the latest year for which we have extensive data.⁴⁸ Data for earlier years are also available.⁴⁹⁻⁵¹ Salient features are that 37.4%

⁴⁶ Sauermann, H.; Roach, M. Science PhD Career Preferences: Levels, Changes, and Advisor Encouragement. *PLoS ONE* **2012**, 7(5):e36307.

<http://www.plosone.org/article/info:doi/10.1371/journal.pone.0036307?imageURI=info:doi/10.1371/journal.pone.0036307.g001>

⁴⁷ Material in this section was developed for the Commission by the Working Group on Sources and Preparation of Students.

⁴⁸ National Science Foundation. Science and Engineering Doctorates: 2010.

http://www.nsf.gov/statistics/sed/data_table.cfm

⁴⁹ National Science Foundation. Doctoral Recipients from US. Universities, 2009.

http://www.nsf.gov/statistics/nsf11306/data_table.cfm

⁵⁰ National Science Foundation. Characteristics of Doctoral Scientists and Engineers in the United States: 2006.

<http://www.nsf.gov/statistics/nsf09317/pdf/nsf09317.pdf>

⁵¹ American Chemical Society, Committee on Professional Training. Survey of PhD Programs in Chemistry, 2008

http://portal.acs.org/portal/PublicWebSite/about/governance/committees/training/reports/cptreports/CNBP_021707

of degree recipients were women, that 42.6% were not US citizens or permanent residents, and that the average time to doctorate from the start of graduate school was 5.9 years. As shown in the table, the figures are slightly different for male vs. female students.

TABLE 1. CHARACTERISTICS OF 2010 CHEMISTRY DOCTORAL RECIPIENTS

	All PhDs	Males	Females
Total PhD	2,306	1433	863
Sex (%)			
Male	62.6		
Female	37.4		
Citizenship (%):			
US citizen or permanent resident	57.4	56.3	59.3
Temporary visa holder	36.8	38.7	33.5
Unknown	5.8	5.0	7.2
Marital status (%):			
Never married	34.6	34.8	34.2
Married	46.6	47.4	45.2
Marriage-like relationship	7.4	6.4	9.2
Separated, divorced, widowed	2.0	2.4	1.3
Unknown	9.5	9.0	10.2
Bachelor's in same field as doctorate (%)	71.8	71.4	72.3
Master's earned (%)	41.5	41.4	41.7
Age at doctorate (yrs)	29.4	29.6	29.0
Time to doctorate (yrs)			
From bachelor's	6.7	6.8	6.4
From graduate school start	5.9	6.0	5.7

Of course, not all chemical sciences PhD recipients are from departments of chemistry. The data vary among different sub-fields, but not all are tabulated. In 2010, the percentage of female PhD recipients was 46.0 in biochemistry, 37.4 in chemistry, 30.1 in chemical engineering, and 26.1 in materials science and engineering.

Distributions of underrepresented minorities (URMs) as percentages also varied with sub-discipline, as shown in Table 2 below.

TABLE 2. UNDERREPRESENTED MINORITY PERCENTAGES^a

	AI	As	Black	Hisp	White	≥2	Other
Biochemistry	0.1	11.8	3.5	4.2	76.4	2.2	1.5
Chemistry	0.4	10.9	4.1	4.8	76.1	2.0	1.7
Chemical Engineering	0.0	9.2	1.4	5.0	79.4	2.1	2.8
Materials Science Eng.	0.0	16.6	5.1	6.4	67.7	2.2	1.9

a) AI = American Indian/Alaska Native, As = Asian, Hisp = Hispanic, ≥2 = two or more.

Among all 2010 doctorates in all fields, 3.1% have one or more disabilities, whereas in the physical sciences, the percentage is 2.7%.

Domestic and International Students. The balance between domestic and international students was considered; for 2010 chemistry doctoral recipients, only 57.4% were US citizens or permanent residents.⁴⁸ The desired ratio will depend on the institution and its ability to recruit students, but should probably be kept within a range such that the best international students are encouraged to enroll, while at the same time there is an active recruiting for qualified domestic students.

The Commission agrees fully with the strongly held view in the community that participation in US graduate programs by international graduate students is highly desirable. Including them demonstrates to both domestic and international students that the scope of scientific discovery spans all countries, serves the desire that these groups should learn from one another, addresses the need for programs to have enough students to teach undergraduates and perform research, and supports the desire to develop closer ties with the science and technology enterprise in other countries.

Efforts should be made to ensure that international students have adequate language skills for teaching and that they do not express biases that affect their teaching roles or the climate within the department in ways that are inconsistent with institutional values. In addition, there should be diversity among international students; they should not overwhelmingly come from one nation or continent.

At some institutions, the fraction of international students has exceeded a tipping point, such that succeeding classes become increasingly international. More efforts must then be made to recruit domestic students. These efforts will succeed only if undergraduate programs in the chemical sciences are proactive in recruitment and retention of chemistry students and are providing them ample opportunities for research. We should recognize and applaud those undergraduate programs and faculty that have high retention rates for chemistry students, have good efforts to eliminate gender and racial biases, and have high-quality first- and second-year introductory courses. Perhaps a new award for this purpose could be established by the ACS.

Diversity Along Other Axes. The Commission agrees that a desired recruiting outcome would be a graduate student population that reflects the diversity of the US population, so that we have the best chance of tapping the creative talents of all citizens who are interested in obtaining graduate education in the chemical sciences. The data above show that we are far from this goal in terms of underrepresented minorities and those with disabilities. As well, our graduate profile likely draws from specific economic classes; not all students interested in chemistry have the opportunity to attend college, let alone pursue an advanced degree. Many undergraduate students do not know that graduate education is supported by teaching or research assistantships that cover not only the cost of the tuition, but provide a stipend as well. Dissemination of these facts to students in the first two years of chemistry courses may help to attract a more diverse set of chemistry majors and, eventually, graduate students. Early identification of undergraduates interested in chemistry, followed by summer research opportunities and mentorship would help recruit both underrepresented minorities and those of limited economic means.

In a recent survey on these issues,⁵² almost all department chairs surveyed agreed that increasing the number of women and underrepresented minority students in both STEM education and the country's STEM workforce is an important national need. More than nine in ten believe a diverse STEM student population is beneficial to their institution's academic success and the country's long-term economic competitiveness. However, only one-third report that their institutions have in place a comprehensive STEM diversity plan. Interestingly, female STEM undergraduates are viewed as most likely to be poised for STEM degree completion, while URM students are viewed as least likely. Institutions might seek targeted fellowships, and they might work with minority undergraduate chemistry associations to increase recruiting.

Departments have opportunities to work more closely with community colleges to improve the numbers of female and URM graduate school recruits. NSF reports indicate that almost half of science and engineering graduates with bachelor's degrees attended a community college.^{53, 54} In addition, increased attention to retention throughout the graduate career could make a large difference. Currently, only 62% of chemistry graduate students complete their PhD within 10 years.²¹ If graduate institutions do not already have a diversity

⁵² International Communications Research. Bayer Facts of Science Education XV: A View from the Gatekeepers – STEM Department Chairs at America's Top 200 Research Universities on Female and Underrepresented Minority Undergraduate STEM Students, 2011. <http://bayerus.online-pressroom.com/bayerus/?LinkServID=FABE4A9A-1372-5B6F-0B65BCC31979EA60>

⁵³ National Science Foundation. Science and Engineering Indicators 2012, Chapter 2. <http://www.nsf.gov/statistics/seind12/pdf/c02.pdf>

⁵⁴ Mooney, G. M.; Foley, D. J. *Community Colleges: Playing an Important Role in the Education of Science, Engineering, and Health Graduates*, NSF 11-317 (revised); National Science Foundation: Arlington, VA, 2011. <http://www.nsf.gov/statistics/infbrief/nsf11317/>

plan in place that helps with retention, departments in the chemical sciences should establish their own programs.

Size and Balance in Graduate Programs

In all institutions, graduate programs have evolved to their present size and balance⁵⁵ in response to a range of inputs and pressures, including the size of the faculty and their degree of engagement with research, the distribution of expertise and interests among the faculty, the service teaching load on the department, available support for graduate students beyond teaching assistantships, the scale and balance of applications from students deemed qualified for admission, and mean time-to-degree. On the institutional side, size and balance in a graduate program are only lightly influenced by opportunities and outcomes for students after they complete their degrees. Mainly, they are consequences of the other considerations listed above. Applications for admission are certainly influenced by students' perceptions of opportunities after graduation, but those perceptions are distanced from reality by five to ten years and are hampered by very limited knowledge.

The Commission believes that careful estimates of genuinely attractive opportunities for graduates should become the starting point, and the paramount consideration, for management of a graduate program in the chemical sciences. This is at least a matter of stewardship, but it is, in the end, a matter of institutional self-interest, for it will not be possible to sustain the flow of real talent into the program unless its graduates have reasonable access to good opportunities.

The Commission judges that graduate education, service teaching, and research volume must be separately managed. While it is certainly appropriate to take advantage of natural synergies, graduate education should not be subsidiary to either of the others.

The service teaching load is very large in some units of the chemical sciences, and graduate students represent a legitimate and necessary part of the teaching staff needed to meet the demand. However, a large teaching obligation in a department is not an appropriate basis for scaling a graduate program beyond what attractive opportunities for graduates can justify. If a well-sized graduate program is unable to fully meet teaching demand in concert with the faculty, the remainder of the teaching should be covered through other professional appointees. Many departments enlist professional staff members otherwise dedicated to technical service functions, such as managing instrumentation, or they hire qualified instructors on a full-time or part-time basis. It has also been common for many years to engage top senior undergraduates to teach in first-year laboratories.

⁵⁵ By the word "balance," we mean the mix among distinct areas or capabilities fostered in the program. Among departments of chemistry, balance would relate to the number of new PhDs produced in traditional subfields, or the numbers produced, for example, with synthetic, computational, or measurement skills.

The faculty-based research program in an academic unit is, of course, the foundation for graduate education at the doctoral level. In the chemical sciences, there is a deep integration of doctoral students in this work. However, as research volumes grow in a department, or even in a given research group, it can become unrealistic and undesirable to depend in the same degree on graduate students to staff the work. If a well-sized graduate program is unable to fully address the research volume anywhere in a department, the remainder should be met by other professional appointees. Often in the present world, that need is filled by postdocs, but permanent professional staff probably should become more common.

The Commission believes that graduate education would be strengthened powerfully by much greater transparency concerning graduate programs and their outcomes. We recommend below that the ACS undertake a new effort to collect, and to make broadly available, annually updated information on the essential characteristics of a graduate program, and especially on the placement of its graduates. More details on this proposal can be found in the section entitled “Toward Implementation” below.

In discussing the employment scene earlier in this chapter, the Commission was frank in its assessment that the current rate of PhD production is too large. While some portion of the excess reflects the current stage of the business cycle, there is evidence, in the growth of postdoctoral employment and in stagnant salaries over a long term, that the nation is producing a systematic excess of PhDs. This view naturally led the Commission to the question of whether there are too many PhD programs and what to do about them, if there are.

While a majority of members would agree that too many doctoral programs exist, the Commission did not believe that it would be productive to place an emphasis in this report on shrinking the total. There are few, if any, general mechanisms for accomplishing such a task, and any such recommendation would distract the community from more important things that can be done everywhere.

Even so, we are urging every program to assess itself in the light of the paramount consideration, viz., the availability of truly attractive opportunities for its graduates. Moreover, we are recommending a measure toward transparency that can become a powerful driver for better decision-making by applicants, as well as more realistic, more effective planning among the leadership of a graduate program.

The Commission is confident that there are too many graduate programs in this country trying to do the same thing in practically identical ways. We urge every department to determine its competitive advantages and to build upon them toward the goal of affording the best possible post-graduate opportunities for students. The Commission’s recommendation concerning transparency should boost more varied development of graduate programs. We see the potential for a livelier, more innovative, more competitive landscape in American chemical sciences.

Overall Conclusion and Specific Recommendations

Conclusion 4: Departments should give thoughtful attention to maintaining a sustainable relationship between the availability of new graduates at all degree levels and genuine opportunities for them. Replication in excess is wasteful of resources and does injustice to the investment made by students and society.

Here are the Commission's specific points:

- 4.1. Given what seems to be a permanently restructured employment market for PhDs, the Commission perceives a risk that the number of career opportunities in the chemical science professions may be insufficient to accommodate those qualified for and desiring entry. Left unaddressed, an imbalance will likely be highly damaging to the talent level and traditional academic strength in the chemical sciences. The Commission urges departments to adjust program sizes in the light of truly attractive opportunities for graduates. It further recommends that this consideration be paramount in determining the scale and balance of any program.

A large undergraduate teaching need is not a sufficient justification for a large graduate program. Teaching needs that remain uncovered by graduate students in a healthy program should be addressed by faculty or other professionals hired and supervised by the department.

- 4.2. Faculty members and other academic leaders in every graduate program, whether at the master's or doctoral level, are urged to reassess and to focus the program distinctively toward its competitive advantages. There is too much similarity among the nation's graduate programs. More variety, supported by a diversity of career opportunity, will yield a more innovative, adaptable landscape.
- 4.3. To encourage and help guide needed changes, the commission recommends that the ACS collect and publish aggregated, privacy-protected data, organized by graduate program, on post-degree outcomes for all graduates, including time-to-degree, types of job placements, salaries, and overall student satisfaction with the graduate experience and employment outcome.

The notion is to provide prospective students with relevant information toward an informed decision in choosing a graduate school. Other information, not identified here, might also be included. The establishment of such a resource is a large, important undertaking, meriting guidance from a dedicated task force.

- 4.4. Programs should build the domestic fraction of their graduate enrollments as a high priority. The Commission fully recognizes and values the great

contributions that have historically been made in our graduate programs and in our national technical enterprises by international citizens who were first attracted to the US. as graduate students. However, the Commission also notes that the balance in graduate degree production has steadily shifted toward international students. A legitimate concern is whether the nation will continue to have a readily employable technical base large enough to sustain global leadership in innovation. International students should not continue to substitute for the domestic share; instead, a mix richer in domestic students should be targeted.

Many colleagues report that the recent enrollment trends reflect a perception, and probably a reality, that international students are relatively more competitive for admission than in past decades, at least partly because domestic applicants are not as soundly prepared for graduate school as in the past. If so, an important step toward increasing domestic enrollments and success rates in graduate school is to achieve better preparation at the undergraduate level. It is beyond the charge of this Commission to review undergraduate preparation in chemical sciences programs in the US, so we offer no conclusion on this point, but we suggest that it is time for a serious inquiry to be made through a suitable mechanism.

- 4.5. To take advantage of the nation's whole talent pool, graduate programs must place an emphasis on attracting and empowering students from underrepresented groups.
- 4.6. Communications to undergraduates should point out that not only is graduate education in the chemical sciences free to them, but that they will receive a stipend as well.

Toward Implementation

This chapter contains a recommendation for a major new effort to be undertaken by the ACS. The Commission's goal is that a new, widely used resource would be established, through which prospective graduate students, faculty members in graduate programs, and other interested parties could obtain accurate information about the characteristics and professional outcomes of all graduate programs of like type in the chemical sciences.

Under Recommendation 4.3, we outline some of the information that we see as essential; however a fuller list might be appropriate. Disaggregation will be needed to determine the extent to which outcomes are similarly experienced by different populations.

The Commission wishes to reinforce the importance of this project. Transparency is a powerful driver of progress in the contemporary world.

Because the project is so important, we urge the ACS leadership to proceed with the greatest care. It is essential that integrity be assured through suitable mechanisms at every stage and that the design and operation of the data collection effort be advised continuously by a high-profile, fully qualified board, as the ACS does with its journals, for example.

In this chapter, the Commission has laid great emphasis on the concept that departments must shape graduate programs on the availability of truly attractive opportunities for students after graduation. We realize fully that this is much easier said than done; however we believe that departments can, by practical means, make useful assessments and reach a healthier future.

Faculties could be significantly aided in the effort if an appropriate association, possibly the ACS, were to undertake and make available periodic assessments, perhaps biennially, of the outlook for employment markets relevant to doctoral programs in the chemical sciences. This kind of work would differ from that published regularly, for example, in *Chemical and Engineering News*, because it would need a horizon of 5-10 years. Of course, such activity is subject to the uncertainty of the future, but it seems likely to be valuable if done well.

POSTDOCTORAL EDUCATION

Analysis

According to the National Postdoctoral Association,⁵⁶

...a postdoctoral scholar ("postdoc") is an individual holding a doctoral degree who is engaged in a temporary period of mentored research and/or scholarly training for the purpose of acquiring the professional skills needed to pursue a career path of his or her choosing.

Postdoctoral training in the chemical sciences is primarily funded by research grants and contracts, and is widespread and arguably important.

Postdoctoral positions, which typically provide two years of in-depth research experience, have become a virtual requirement for most faculty positions, particularly those in research universities. Indeed, candidates with postdoctoral experience are expected to be more successful in academia because they have had the benefit of a broader exposure to science, the experience of helping to lead a group, and the opportunity to work with an additional close mentor. When they start a faculty position, those with postdoctoral experience have better developed communication skills, are usually more scientifically mature, and have typically had exposure to how research funding is obtained.

⁵⁶ National Postdoctoral Association, <http://www.nationalpostdoc.org>

While these advantages might also help them in industry, most large chemical concerns are content to attract students directly following their PhD and to bring them into their own knowledge base and culture. Nonetheless, about half of all postdocs eventually work in industry.

Some statistics about postdoctoral associates are enlightening.^{57, 58} In 2009, the most recent year for which the NSF has published detailed data,⁵⁹ there were approximately 4200 postdocs in chemistry, 2350 in biochemistry, and 1100 in chemical engineering. The percentages of temporary visa holders in these groups were 64.7%, 60.7%, and 62.4%, respectively.

The expectation of those seeking a postdoctoral appointment is that the position will lead to a job better matched to their skills and interests. In addition, postdoctoral applicants seek to broaden their scientific knowledge, work with a new mentor, develop leadership skills, and start their professional careers. While these goals are usually met, there are several problem areas.

The first concerns incorporation of postdoctoral associates into the university fabric. Most postdoctoral appointments are made as an agreement between an individual faculty mentor and the appointee; universities usually have little direct involvement. Postdoctoral associates find themselves sometimes treated as employees, sometimes as students; often, they have the worst of both worlds. Few benefit from interaction with other postdoctoral associates; few are encouraged to develop contact with research groups outside the one where they are appointed; and few receive guidance from anyone in the department other than the faculty member who hired them.

Some “best-practice” postdoctoral programs exist. In these, postdocs are organized as a group, and each postdoc has several mentors in addition to the research supervisor. They receive training in areas such as job application and proposal writing. They give departmental seminars on their research. Each has an individual development plan that is discussed with the mentors. The “graduates” of such programs are often extremely successful in finding faculty positions in research universities or top industrial positions. However, the majority of such best-practice programs have been supported by non-governmental resources, such as endowed fellowships. Their success depends heavily on the flexibility of such support. When postdocs are supported solely on research funding, it is difficult to argue that they should spend time on issues not specifically related to the project being funded. The NSF has improved the situation

⁵⁷ Lichter, R. L.; Pearson, W., Jr.; Richmond, G. L., Organizers. *Postdoctoral Appointments: Roles and Opportunities, A Report on an NSF Workshop*; National Science Foundation: Arlington, Virginia, 2003. <http://www.merrimackllc.com/2003/postdoc-workshop.html>

⁵⁸ Sigma Xi, *Doctors without Orders: Highlights of the Sigma Xi Postdoc Survey*, 2005. <http://www.postdoc.sigmaxi.org>

⁵⁹ National Science Foundation, <http://www.nsf.gov/statistics/gradpostdoc/>

somewhat by requiring a mentoring plan from any applicant seeking funding for a postdoctoral associate.⁶⁰ While the NIH has similar requirements, not all funding agencies have adopted this practice.

Institutions and departments, as well as faculty mentors, should take greater responsibility for ensuring that postdoctoral associates develop effective careers. Important steps to this goal include the use of individual development plans, committees of multiple mentors, and the opportunity to present research at scientific meetings and departmental seminars. Institutions should appoint officers with responsibility for the well-being of postdoctoral associates and should treat them as professionals.

The Commission sees a significant future role for “teaching postdoctoral associates.” Effective programs matching a recent doctorate with a teaching mentor have been supported in the past, primarily by foundations, but few are available today. Arguments can be made that we should bring them back. Teaching postdoc programs have worked well in biomedical fields,⁶¹ and teaching postdocs are routine in the field of mathematics.⁶² Teaching postdocs could improve the quality of instruction at institutions that host them, and they would produce a cadre of faculty who would be attractive to other institutions. Trained professional instructors from teaching postdoc programs could become an alternative to the current reliance on doctoral candidates for so much of the teaching responsibility. Thus, foundations and other funding agencies should direct support to “teaching postdoctoral associates.”

Elsewhere in this document, the Commission has suggested that the number of traditional PhD granting programs with the same focus is too high. At some institutions, reducing the PhD program or redirecting its goals may well have the disadvantage that fewer graduate students would be available to teach undergraduate chemistry. This teaching cadre could perhaps be augmented by employing instructors who have had training in a teaching postdoc program. Furthermore, we are already seeing evidence that more effective teaching can occur when a classroom is “flipped,” that is, when the lecture is delivered asynchronously on-line and the classroom time is devoted to discussion. Those with teaching postdoctoral experience might be ideal discussion leaders.

A significant problem in the current employment pipeline for chemists is a bulge at the postdoctoral level. Particularly in more biological areas of chemistry, many current postdocs have previously been postdocs for one or even two appointments. For these individuals, the second, or later, postdoctoral appointment serves largely as a buffer zone in the ebb and flow of the job market; it is not a position that significantly improves one’s job chances. A better

⁶⁰ National Science Foundation. *NSF Proposal and Award Policies and Procedures Guide*, NSF 13-1; National Science Foundation: Washington, DC, 2012; pp II-19, II-20.

http://www.nsf.gov/pubs/policydocs/pappguide/nsf11001/nsf11_1.pdf

⁶¹ Price, M. Teaching Postdocs to be Professors. *Science Career Magazine*, October 26, 2012

⁶² American Mathematical Society, <http://www.ams.org/profession/leaders/culture/CultureStatement07.pdf>

solution to market fluctuations would be to control the entrance of students into PhD programs. From the university point of view there is little incentive to respond to the job market. The increase in PhD students is driven partly by the desire for more research dollars, and, except in chemical engineering and perhaps other chemical sciences, having fewer PhD students leads to difficulties in staffing the teaching of undergraduate classes. More availability of instructors with teaching postdoctoral experience might help the second problem, but a solution to the first problem is not obvious. Some feedback mechanism is needed to limit the size of the PhD programs when the job market contracts. A second helpful change would be for funding agencies to be more receptive to requests for support of more senior research associates who are regular employees of research institutions. Such positions would help to provide a professional path forward for postdoctoral associates.

Overall Conclusion and Specific Recommendations

Conclusion 5. Postdoctoral training and education is an extension of graduate education that is important for success in a variety of career paths, particularly for faculty appointments. Postdoctoral associates should be treated as the professional scientists and engineers they are. A postdoctoral appointment should be a period of accelerated professional growth that, by design, enhances scientific independence and future career opportunities.

Ideally, the disadvantages of career delay and lower salary are offset by the advantages of postdoctoral training and education, including the opportunity to broaden one's research experience, the growth that comes from helping to lead a research group, and the desirability of working with a gifted mentor. However, many postdoctoral associates have inadequate career mentoring, and many take such positions for reasons that do not support their professional development, e.g., to extend their residence in the United States or to engage in a holding action because of inability to obtain a more permanent position at their skill level.

The Commission makes the following recommendations:

- 5.1. Institutions and departments as well as faculty mentors should take greater responsibility for ensuring that postdoctoral associates develop professionally. Important steps toward achieving this goal include the use of individual development plans, regular access to multiple mentors, and the opportunity to present research at scientific meetings and departmental seminars. Institutions should appoint officers with responsibility for the well-being of postdoctoral associates.
- 5.2. All funding agencies should require general mentoring plans of applicants seeking support for postdoctoral associates. To help provide a professional path

forward for postdoctoral associates, funding agencies should also be more receptive to requests for support of more senior research associates who are regular employees of research institutions.

- 5.3. Foundations and other funding agencies should re-explore programs for “teaching postdoctoral associates,” so that trained professional instructors become an alternative to the current reliance on doctoral students for so much of the teaching responsibility.
- 5.4. A feedback mechanism linking the size of PhD programs to job availability is needed to minimize bulges in the career pipeline at the postdoctoral level. The Commission urges integrated thinking at the program level regarding numbers of postdocs and doctoral graduates emerging together into employment markets.

Toward Implementation

The recommendations above are aimed at funding agencies, foundations, institutions, departments, and individual postdoctoral mentors; each has a role to play. Previous reports, including those commissioned by the NSF and undertaken by various societies, have pointed to concerns similar to those expressed here. These concerns and our recommendations are also consistent with the views of the National Postdoctoral Association. What is needed is a shift in the reward system for funded faculty, so that they are motivated to be better mentors. This starts at the funding agencies and will be helped by pressure on institutions and departments to make the postdoctoral experience more uniformly beneficial. Perhaps major funding agencies should go a step further by requiring that institutions receiving funding have an institutional program in place to ensure success. Foundations likewise should work with institutions to find the most effective methods for preparing postdocs to be teachers. Finally, non-tenure track appointment ladders should be in place at most universities, so that postdocs ultimately have a career path that includes more options.

ADDITIONAL COMMENTS

Overall, the Commission hopes to free departments and programs from feeling the need to be practically identical. There is room for greater variation in program design than has been recently typical in American graduate education in the chemical sciences. We believe that our field would benefit from more venturesome design and greater experimentation.

For this reason alone, the Commission explicitly discourages any form of checklist for graduate programs or any analogue to the ACS Committee on Professional Training, which serves usefully to approve undergraduate chemistry programs.

The Commission’s charge certainly includes master’s level education. The members recognize the distinctive roles that it fulfills in our society and generally believe that there is

room for fuller use of this degree level in developing the professional workforce. The master's degree needs to be reconsidered as the diversity of opportunities in the chemical sciences increases.

The Commission understands that progress on several of the dimensions addressed among its conclusions and recommendations will require modifications to the reward structure for faculty members participating in doctoral programs. We do not have detailed proposals, but we acknowledge the importance of creative innovation in this area. The community needs to engage seriously in exploration of alternatives.

In this respect, as in many others, the Commission is focusing on the goal, rather than the path. Our emphasis on experimentation is acknowledgement that many new paths will need to be explored as progress is sought along various dimensions of graduate education.

In the one year available for this project, it has not been possible for the Commission to address even all important facets of graduate education, so one must view this work as an early step in a long-term process. This report is a starting point -- a reconnoitering for a journey. It is not intended as a final recipe.

In the effort to improve and reform, we expect that there will be successes and successive stages. Pioneering departments and practices will emerge and become exemplars. Subsequent commissions and task forces will be needed to address topics in greater depth or broader imagination than has been possible for us, or to revisit strategies in the light of results from actual trials. Our most earnest hope is that our field will brilliantly renew its vigor and intellectual strength.

ACKNOWLEDGEMENTS

The work of the Commission has been generously supported by National Science Foundation grant CHE-1158709 and the American Chemical Society, mainly through the ACS Presidential Discretionary Fund. Mary M. Kirchhoff served ably as ACS staff liaison to the Commission. Frank Walworth and Alicia Harris provided valuable support. ACS Executive Director and CEO Madeleine Jacobs was strongly supportive of the Commission's mission and process, and personally participated in the formative meetings. Gary B. Schuster and President Bassam Z. Shakhshiri advised the process throughout at the Commission's invitation. Many colleagues identified in the next section graciously assisted as members of topical working groups. Still other colleagues, including students, provided help as participants in the listening sessions, as sources of ideas and information, or as outside readers of review drafts of the report. To all who supported this work, the Commission expresses thanks.

APPENDIX A. MEMBERS AND ASSOCIATES OF THE COMMISSION

Commission Membership Appointed by President Shakhashiri

William F. Banholzer, Dow Chemical Company
Jacqueline K. Barton, California Institute of Technology
Stacey F. Bent, Stanford University
Ronald Breslow, Columbia University
Gary Calabrese, Corning, Inc.
Pat N. Confalone, E. I. du Pont de Nemours and Company
Michael P. Doyle, University of Maryland, College Park
Larry R. Faulkner, University of Texas at Austin, Commission Chair
Marye Anne Fox, University of California, San Diego
Joseph S. Francisco, Purdue University
Paul Houston, Georgia Institute of Technology, Commission Executive Director
Chad A. Mirkin, Northwestern University
Larry E. Overman, University of California, Irvine
Hunter Ripley Rawlings III, Association of American Universities
Geraldine Richmond, University of Oregon
Richard H. Scheller, Genentech, Inc.
Joel I. Shulman, University of Cincinnati
Peter J. Stang, University of Utah
Matthew Tirrell, University of Chicago
George M. Whitesides, Harvard University
Mark S. Wrighton, Washington University in St. Louis
Mary M. Kirchoff, American Chemical Society, ACS Staff Liaison

Special Advisors

Gary B. Schuster, Georgia Institute of Technology
Bassam Z. Shakhashiri, University of Wisconsin – Madison, ACS President

Invited Participants in the Working Groups

Hector D. Abruña, Cornell University
Richard Cavanagh, National Institute of Standards and Technology
Francis J. DiSalvo, Cornell University
James J. Duderstadt, University of Michigan
Jeffrey D. Evanseck, Duquesne University

David F. Feldon, University of Virginia
Carlos Gutierrez, California State University, Los Angeles
Rigoberto Hernandez, Georgia Institute of Technology
Anne Myers Kelley, University of California, Merced
David S. Kliger, University of California, Santa Cruz
Shirley Malcom, American Association for the Advancement of Science
Anne McCoy, The Ohio State University
Diep Nguyen, Illinois Institute of Technology
Susan Olesik, The Ohio State University
Peppi Prasit, Inception Sciences, Inc.
Melanie Sanford, University of Michigan
Ian Tebbett, University of Florida
Charles M. Vest, National Academy of Engineering
Isiah M. Warner, Louisiana State University

APPENDIX B. CHARGE LETTER FROM PRESIDENT SHAKHASHIRI



American Chemical Society

OFFICE OF THE PRESIDENT

Bassam Z. Shakhashiri
President-Elect, 2011
President, 2012
Immediate Past President, 2013

1155 SIXTEENTH STREET, N.W.
WASHINGTON, D.C. 20036
Phone 202-872-4461
Fax 202-872-6338

October 17, 2011

ACS Mission: To advance the broader chemistry enterprise and its practitioners for the benefit of Earth and its people.

ACS Vision: Improving people's lives through the transforming power of chemistry.

Advancing Graduate Education in the Chemical Sciences

A mission of the American Chemical Society is to promote excellence in post-secondary chemistry education and leadership in the professional training of chemists. As 2011 ACS President-elect I have appointed a Presidential Commission of influential leaders to examine the purposes of graduate education in the chemical sciences, to make recommendations for improvements, and to suggest strategies for implementing those recommendations. This examination is important in order to make efficient use of our university, government, and industrial resources, to provide exciting and meaningful careers to those in the chemical sciences, and to provide society with trained and inspired leaders who can improve the human condition.

One major task of the ACS Presidential Commission is to consider fundamental, comprehensive, and systemic changes suitable for graduate education in the chemical sciences. A second major task is to suggest actionable approaches for enhancing the quality of graduate research and education at all institutions.

The outcome of the Commission's deliberations will be the recommendation of a coherent strategy for improving graduate education in the chemical sciences by providing choices among viable models that can be adopted by a variety of institutions. For any particular institution, some models will be more appropriate than others. The choice among them and the distribution of these choices will affect research universities, comprehensive universities, graduate students, industry, and funding agencies, such as NSF, NIH, DOD, DOE, and NIST, as well as private foundations. The educational issues the Commission will discuss are common to other fields in both the sciences and engineering, and the Commission's work will not only influence graduate education in the chemical sciences, but other disciplines as well.

The Commission Charge

The main charge to the Commission is to address two major questions:

- What are the purposes of graduate education in the chemical sciences?
- What steps should be taken to ensure that they address important societal issues as well as the needs and aspirations of graduate students?

In preparing its report and actionable recommendations, the Commission will address additional questions including but not limited to the following:

1. Is the current structure of different types of departments in the chemical sciences (chemistry, chemical engineering, chemistry and biochemistry, chemistry and chemical biology, chemical and biomolecular engineering, materials science, etc.) a strength or a weakness with respect to graduate education?
2. What are the employment issues for graduate students in both industrial and academic settings? Are we providing the right educational opportunities?
3. What are the financial support mechanisms for graduate education in the chemical sciences? Is the current mix the best one?
4. Is the current profile of our graduates the correct one, not only in terms of domestic vs. international, but in terms of diversity along other axes as well? Do they have the proper background for the type of graduate education we want them to attain?
5. What are the expectations of graduate students, are our educational institutions meeting them, and what promises do they make to students, both explicitly and implicitly? In particular, what should be the lengths of the graduate student program and any subsequent postdoctoral training? And why is the attrition rate for Ph.D. students in the chemical sciences as high as it is (only 62% finish within ten years.)

Commission Members

Dr. William F. Banholzer, CTO, Dow Chemical
 Dr. Jacqueline K. Barton, Professor of Chemistry, Cal Tech
 Dr. Stacey F. Bent, Professor of Chemical Engineering, Stanford University
 Dr. Ronald Breslow, Professor of Chemistry, Columbia University
 Dr. Gary Calabrese, Vice President, Science & Technology, Corning Inc.
 Dr. Pat N. Confalone, Vice President, Global R&D, DuPont, ACS Board of Directors
 Dr. Michael P. Doyle, Professor of Chemistry, University of Maryland
 Dr. Larry R. Faulkner, President, Houston Endowment (**Commission Chair**)
 Dr. Marye Anne Fox, Chancellor, UC San Diego
 Dr. Joseph S. "Joe" Francisco, Professor of Chemistry, Purdue University, ACS Board of Directors
 Dr. Paul Houston, Dean, College of Sciences, Georgia Institute of Technology (**Commission Executive Director**)
 Dr. Chad A. Mirkin, Professor of Chemistry, Northwestern University
 Dr. Larry E. Overman, Distinguished Professor of Chemistry, UC Irvine
 Dr. Hunter Ripley Rawlings III, President, Association of American Universities
 Dr. Geraldine Richmond, Professor of Chemistry, University of Oregon
 Dr. Richard H. Scheller, Executive Vice President, Genentech Research & Early Development
 Dr. Joel I. Shulman, Professor of Chemistry, University of Cincinnati - formerly at Procter & Gamble
 Dr. Peter J. Stang, Distinguished Professor of Chemistry, University of Utah
 Dr. Matthew Tirrell, Pritzker Director, University of Chicago Institute for Molecular Engineering
 Dr. George M. Whitesides, Woodford L. and Ann A. Flowers University Professor, Harvard University
 Dr. Mark S. Wrighton, Chancellor and Professor of Chemistry, Washington University, St. Louis
 Dr. Mary Kirchhoff, Director, ACS Education Division (**ACS Staff Liaison**)

The Commission will establish its own timetable for its deliberations and should aim to complete its final report and actionable recommendations no later than **December 1, 2012**.

Members of the Presidential Commission will participate in three in-person meetings. Other documentation and subcommittee work will be carried out via electronic communication. Commission subcommittees will report on specific issues and/or hold focus-group discussions with all stakeholders such as students, postdocs, faculty, academic administrators, and private sector and government leaders at national and regional ACS meetings and elsewhere as well as via other means of communication.

I look forward with high expectations to the outcome of your important work. I am committed to supporting your efforts by all means available to me.

Thank you and best wishes.

A handwritten signature in black ink, reading "Bossam Z. Shakkhuni". The signature is written in a cursive style with a prominent flourish at the end.