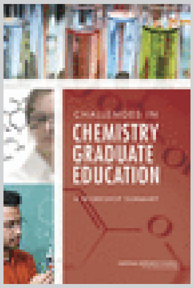

Challenges in Chemistry Graduate Education: A Workshop Summary

ISBN
978-0-309-25708-4

96 pages
6 x 9
PAPERBACK (2012)

Committee on Challenges in Chemistry Graduate Education; Board on Chemical Sciences and Technology; Division on Earth and Life Studies; National Research Council

CHALLENGES IN CHEMISTRY GRADUATE EDUCATION

A WORKSHOP SUMMARY

Committee on Challenges in Chemistry Graduate Education

Board on Chemical Sciences and Technology

Division on Earth and Life Studies

NATIONAL RESEARCH COUNCIL
OF THE NATIONAL ACADEMIES

THE NATIONAL ACADEMIES PRESS
Washington, D.C.
www.nap.edu

THE NATIONAL ACADEMIES PRESS 500 Fifth Street, NW Washington, DC 20001

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This material is based upon work supported by the National Science Foundation under award number CHE-1147410, and by the National Institutes of Health under award number N01-OD-4-2139, TO#273.

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International Standard Book Number-13: 978-0-309-25708-4
International Standard Book Number-10: 0-309-25708-5

Additional copies of this report are available for sale from the National Academies Press, 500 Fifth Street, NW, Keck 360, Washington, DC 20001; (800) 624-6242 or (202) 334-3313; http://www.nap.edu/.

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Acknowledgment of Reviewers

This workshop report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the National Research Council's Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the institution in making its published report as sound as possible and to ensure that the report meets institutional standards for clarity, objectivity, and responsiveness to the charge. The review comments and draft manuscript remain confidential to protect the integrity of the process. We wish to thank the following individuals for their review of this workshop report:

Ryan Dirkx, Arkema Inc.
Michael Doyle, University of Maryland
Robert Grubbs, California Institute of Technology
William Lee Olbricht, Cornell University
George Whitesides, Harvard University

Although the reviewers listed above have provided many constructive comments and suggestions, they did not see the final draft of the workshop report before its release. The review of this report was overseen by **Thomas H. Dunning, Jr.**, University of Illinois**.** Appointed by the National Research Council, he was responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authors and the institution.

Contents

1

Introduction

Chemistry graduate education is under considerable pressure. Pharmaceutical companies, long a major employer of synthetic organic chemists, are drastically paring back their research divisions to reduce costs. Chemical companies are opening new R&D facilities in Asia rather than in the United States to take advantage of growing markets and trained workforces there. Universities, especially public universities, are under significant fiscal constraints that threaten their ability to hire new faculty members. Future federal funding of chemical research may be limited as the federal budget tightens. All of these trends have major consequences for the education of chemistry graduate students in U.S. universities.

To explore and respond to these intensifying pressures, the Board on Chemical Sciences and Technology held a workshop in Washington, D.C., on January 23-24, 2012, entitled "Graduate Education in Chemistry in the Context of a Changing Environment." The workshop brought together representatives from across the chemical enterprise, representing leaders and future leaders of academia, industry, and government. The goal of the workshop was not to come to conclusions but to have an open and frank discussion about critical issues affecting chemistry graduate education, such as the attraction and retainment of the most able students to graduate education, financial stressors on the current support model and their implications for the future model, competencies needed in the changing job market for PhD chemists, and competencies needed to address societal problems such as energy and sustainability. The ultimate objective was to capture ideas and opinions as input to the National Science Foundation

(NSF), the National Institutes of Health (NIH), and other organizations in shaping current and future programs. The report summarizes the views expressed by workshop participants, and while the committee is responsible for the overall quality and accuracy of the report as a record of what transpired at the workshop, the views contained in the report are not necessarily those of the committee.

ORGANIZATION OF THE REPORT

This report of the workshop is organized into six chapters. Chapter 2 summarizes several presentations that focused on the challenges facing graduate chemistry education. Chapter 3 examines what the goals of chemistry education have been and how those goals might change in the future. Chapter 4 looks at the skills chemistry students acquire in graduate school. Chapter 5 explores how the structure of graduate education could change to meet future goals and impart necessary skills. Each of these chapters contains both summaries of the presentations made during the workshop and points raised during the discussion sessions held throughout the workshop. Finally, Chapter 6 compiles the suggestions for changes in and comments on graduate education described in earlier chapters as a way of summarizing the many ideas raised during the workshop.

Although not comprehensive, this report provides readers with an overview of several topics discussed at the workshop: (1) the challenges facing graduate chemistry education, (2) goals of chemistry education, (3) skills students acquire and would benefit from acquiring in graduate school, (4) how the structure of graduate education could change to meet future goals, and finally, (5) suggestions for change raised by individual workshop participants. This report does not contain any findings or recommendations related to these topics, as this was not part of the statement of task. This report summarizes presentations given at the workshop and the views expressed by workshop participants.

QUESTIONS TO BE ANSWERED

In his introductory remarks at the workshop, Joe Francisco, William E. Moore Distinguished Professor of Chemistry at Purdue University, who was chair of the committee for the workshop, said that U.S. graduate education has served as a global model for developing the best-prepared and most innovative chemists in the world. U.S. graduate programs continue to attract the best talents from around the globe. They provide employees for companies, universities, government laboratories, and other institutions in the United States and abroad.

However, he noted that the context for graduate education in chemistry is changing. The chemical enterprise has become more global. Chemistry graduate programs in other countries are becoming more competitive in attracting students and producing research results. These changes have profound implications for U.S. graduate programs.

Francisco listed a number of questions that could be addressed at the workshop.

- Do U.S. graduate programs need to do more to prepare students to be more competitive in a global chemical enterprise?
- Do educators know what industry is looking for in the new doctoral recipients that it recruits?
- What are the perspectives of students coming into these programs?
- Is the depth of training of graduate students more important than broader preparation? For example, do graduate students need more training in being able to communicate with people who do not have science backgrounds and with people from other cultures who speak languages other than English?
- If graduate training becomes broader, what will be given up, and will this compromise the quality of training?
- Do present-day graduate students need to be prepared for non-traditional jobs, especially given that many are interested in becoming entrepreneurs and others have been unable to find traditional jobs?
- Are graduate programs in chemistry contributing to societal needs on a local, regional, national, and global level?
- How can the diversity of chemistry graduate students be increased?

2

The Nature of the Challenge

> "Change has already come. We can view this as an opportunity for our community and for the United States, or we can passively react to change and have it imposed on us."
>
> – Matthew Platz, National Science Foundation

Two speakers at the workshop—Matthew Platz, Director of the Division of Chemistry at NSF, and George Whitesides, Woodford L. and Ann A. Flowers University Professor at Harvard University—focused specifically on the challenges facing chemistry graduate education. In addition, several other presenters and workshop attendees elaborated on these challenges later in the workshop. This chapter summarizes these comments to lay the groundwork for the potential solutions explored in Chapters 3-5.

WORRISOME TRENDS

Platz presented a number of "worrisome or alarming facts and provocative questions" that involve chemistry graduate education either directly or indirectly.

- From a high of more than 20 million people in the 1970s, employment in manufacturing in the United States decreased in the early 2000s, and then continued to decrease in the recession triggered by the 2008 financial crisis. (BLS 2011).Though the number has recovered somewhat in the last few years, "it remains to be seen how persistent that is and how strong that recovery will be," Platz said.

- Employment in the chemical industry also has dropped—from more than 1,035,000 in 1990 to 985,000 in 2000 to 789,000 in 2010, according to the Council for Chemical Research.
- Unemployment among American Chemical Society (ACS) chemists remained between 3 percent and 1 percent for the last quarter of the 20th century. But in 2002 it rose above 3 percent, and by 2010 was nearly 4 percent (Rovner 2011) (Figure 2-1). This is lower than the unemployment rate for all U.S. workers but higher than it has been since this data began to be collected.
- Meanwhile, the unemployment rate for new chemistry graduates rose from about 4 percent in 2000 to more than 10 percent in 2009 and 2010 (Rovner 2011, ACS 2012b).
- "Between 2000 and 2009, multinational corporations cut 2.9 million jobs in the United States and added 2.4 million jobs overseas," according to an August 21 2011, *Washington Post* article citing data from the Bureau of Labor Statistics (Yang 2011).
- The United States shed 28 percent, or 687,000, high-technology manufacturing jobs since reaching its peak of 2.5 million in

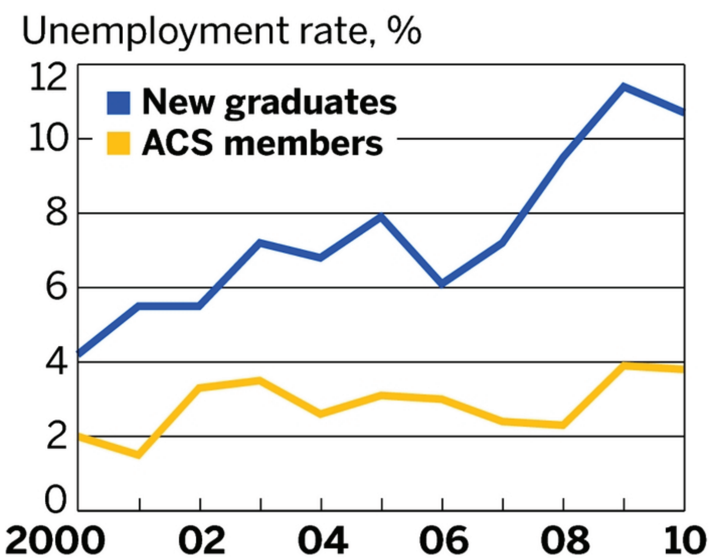

FIGURE 2-1 The unemployment rates remain high for chemists and chemical engineers.
SOURCE: Rovner, 2011.

2000, according to a January 18 2012, *Chicago Tribune* article citing data from the National Science Board (NSB 2012, Shropshire 2012). The global "middle class," defined as people with incomes between $6,000 and $30,000, rose from 1 billion to more than 1.5 billion since the mid-1980s and could climb to 4 billion people by 2040, according to an analysis by Goldman Sachs (Wilson and Dragusanu, 2008). When the executives of multinational corporations look at these data, said Platz, "they see where future demand is, and they redeploy their workforce accordingly."

- Young people who are graduating from college with an undergraduate chemistry degree face stark choices. They can go to graduate school in chemistry, in which case, if they aspire to be a professor at a research university, they will enter the workplace between ages 28 and 32, have an unknown likelihood of getting a job, command a salary of between $75,000 and $92,000 (though with little debt from graduate school), have little control over where they work, and face intense work demands. Or they can go to graduate school in dentistry or pharmacy, begin working at age 25, earn between $150,000 and $300,000 a year (though they may emerge from graduate school with $150,000 to $200,000 in debt), have control over where they work, and work four or five eight-hour days.
- In 2011, student debt exceeded $1 trillion dollars and Americans now owe more student loans than credit cards (Cauchon 2011).
- Future employment in industry of chemistry PhDs will increasingly be in small companies and start-up companies, and preparing people for these careers cannot be done by lengthening the time they spend in graduate school or as postdoctoral fellows.
- Today, 45 percent of children younger than age 5 are minorities (Center for Public Education 2011). Yet less than 8 percent of ACS chemists are Hispanic, black, American Indian, or some other race or ethnicity (ACS 2010, 2012a) (Figure 2-2).
- The costs of public undergraduate education per student are rising faster than the revenue that can be generated per student. Short-term fixes have been to teach more students with fewer faculty and staff and admit more overseas students, who pay out-of-state tuition.
- As students with liberal arts degrees continue to find it difficult to secure jobs, and as more international students enter U.S. colleges, enrollments in chemistry will likely continue to increase. This will generate wait lists for courses unless the laboratory experience can be radically changed. Alternately, university administrators could see chemistry as a "cash cow" to generate money for other parts of the institution.

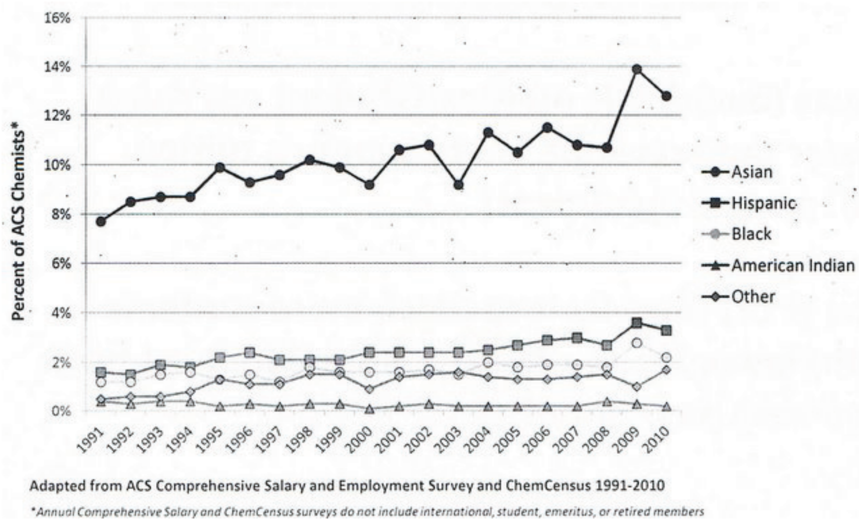

FIGURE 2-2 The numbers of Hispanic, black, and American Indian chemists have risen slowly over the past two decades.
SOURCE: Figure courtesy of Matt Platz, National Science Foundation, based on data from ACS 2010 and 2012a.

Signs of Promise

Despite the uncertainty that surrounds the future of the chemical sciences in the United States (see Box 2-1), Platz noted that graduate enrollment in chemistry and chemical engineering has been increasing in recent years (Figure 2-3). Also, the percentage of ACS chemists who are women has risen from less than 20 percent in 1991 to almost 30 percent two decades later. Similarly, the number of minorities has risen from about 11 percent to 20 percent, though most of this increase has come from Asian and Asian-American chemists.

Meeting the needs of 4 billion people living a middle class life is "at its heart, a problem of discovering new chemistry," said Platz. Many idealistic young people want to help solve the problems facing the global community. A major question is whether they will see research in many graduate chemistry departments as organized to deal with these challenges. "If they don't see it in chemistry departments, they will go elsewhere."

WHAT NEEDS TO CHANGE?

Since the 1800s, chemistry has been an extraordinarily successful science, noted George Whitesides. Just since World War II, it has made

Box 2-1
The ACS Commission on Graduate Education

Shortly before the workshop was held, the ACS established a blue ribbon commission to examine the purposes of graduate education in the chemical sciences. The commission, which is chaired by Larry Faulkner, President of the Houston Endowment, has been asked to address two main questions, ACS President Bassam Shakhashiri told the workshop attendees:

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

To answer these questions, the ACS commission was charged with considering fundamental, comprehensive, and systemic changes suitable for graduate education in the chemical sciences. It also was charged with suggesting actionable approaches for enhancing the quality of graduate research and education at all institutions.

Five working groups were formed to examine the structure of departments in the chemical sciences, employment issues, financial support mechanisms for graduate students, the backgrounds of chemistry graduate students, and the expectations of graduate students, including what they expect from a program and what the length of their training should be. In particular, Shakhashiri noted with regard to the final working group, why do only 62 percent of PhD students in the chemical sciences finish within ten years?

Target audiences for the commission's report include faculty and academic leaders at research universities and comprehensive institutions, graduate students, postdoctoral fellows, faculty and students at undergraduate institutions, federal and state policy makers, funding agencies, employers, industry leaders, national laboratories, private foundations, and others in the public sector.

The basic idea behind the commission, said Shakhashiri, was to provide a forum for thoughtful exchanges and the development of possible alternatives to current practices and structures in chemistry graduate education.

tremendous advances in such far-flung areas as catalysis, pharmaceuticals, spectroscopy, and the synthesis of complex natural products. Furthermore, chemistry now confronts an unprecedented array of exciting opportunities. The discovery and use of sources of energy pose many interesting chemical problems, from what is the nature of combustion to what is the ultimate future of solar energy, from the effects of nuclear radiation on chemical compounds to how to conserve energy and protect the environment. A cell is a collection of chemical reactions, none of which is alive by itself but all of which combine to constitute life. Under-

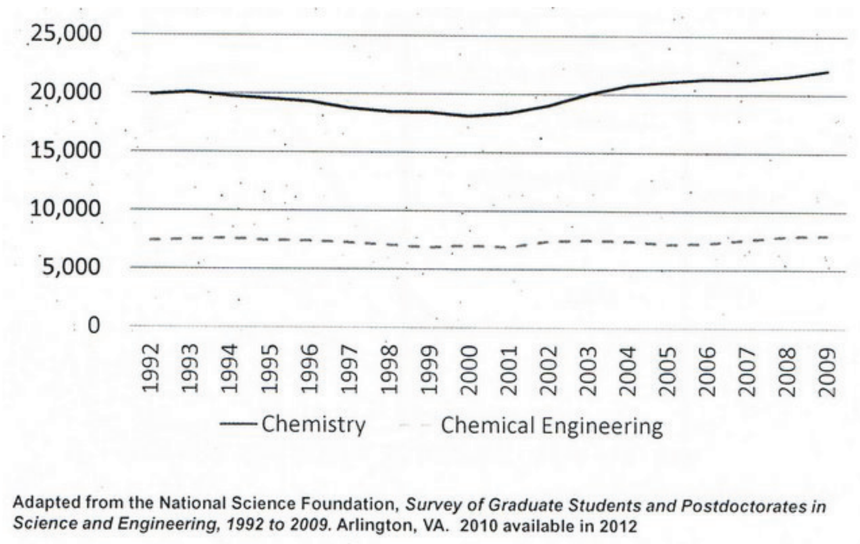

FIGURE 2-3 Graduate enrollments in chemistry and chemical engineering have risen slowly over the past decade.
SOURCE: Figure courtesy of Matt Platz, National Science Foundation, based on data from NSF/NIH 2012.

standing how living cells function is "entirely a chemical problem," said Whitesides. "I can't imagine a more interesting problem scientifically to work on than that." The chemical flows into, out of, and within megacities offer a wealth of fascinating chemical problems. Even major societal issues like environmental sustainability, the rising costs of health care, and enhancing national security have major chemical underpinnings.

Despite the current potential of the chemical sciences, the profession has been shrinking, has become less innovative, and is attracting less attention, said Whitesides. Over the past 20 years, the United States has lost 300,000 jobs in chemistry (ACS 2011). The pharmaceutical industry is contracting as the return on invested capital becomes less than the cost of capital. China and India are doing some kinds of chemical research not just less expensively than it is done in the United States but more effectively, according to Whitesides. And when popular science magazines list their 100 biggest discoveries of the year, very few if any are likely to be chemical discoveries. "We are not working for that purpose, but it says something about the way society is viewing the field. It is not connecting us to the solution of big problems."

In the past, chemistry in the United States has been structured around three players: universities, government, and industry. Furthermore, in chemistry, industry and universities have been closely coupled. For example, ring opening metathesis polymerization (ROMP), asymmetric epoxidation, and superacids, all of which resulted in Nobel Prizes, were essentially invented in industry, observed Whitesides. "That is not to say that the universities did not do fantastic work in making these into something new, but the interplay between invention in industry . . . and then the process of development, analysis, and invention in both has been very productive." However, the pressures of globalization and financial transparency have made it very difficult for big companies to involve themselves in longer term research, which is putting increasing responsibility on universities.

Only universities have the opportunity to lead change, Whitesides insisted. Industry is now largely occupied with exploiting knowledge and has a difficult time justifying the creation of new knowledge without having a product in mind. Government is characterized by competing interests and agents and responds primarily to political necessity. Universities have the greatest flexibility and are most able to choose their future course. Universities also have the ability to pursue what Thomas Kuhn called problems rather than puzzles, where the solutions can fundamentally change the game. "We have the ability to train and educate students to do things that are completely different from what we do so that they can live in a world that's completely different from the world that we live in."

The Changing Roles of Graduate School

The structure of academic research groups in chemistry remains focused around single investigators working one-on-one with graduate students. That model is not well suited for the kinds of complex systems-level problems now confronting chemistry, Whitesides said.

The current system of graduate education, however, focuses more on research than on learning. "Most of the emphasis goes into, in my opinion, research productivity, as opposed to thinking about the students." Professors work endlessly to secure grants, which is quite different than focusing on the training of graduate students.

The Liebig model, after the German chemist Justus von Liebig (1803-1873), who pioneered many of the features of chemistry laboratories still common today, is an apprenticeship model in which students are trained though repetition to do what the master does. Students learn to be good at what their professors are good at, whether synthetic chemistry or laser spectroscopy.

"We have had a good run with the Liebig model, but it may be time to abandon it and think of something else," Whitesides said. "I don't think it's good for the teachers, and I don't think it will build a future for the profession of chemistry that is recognizable to society. We should teach students rather than using them."

Whitesides expressed the idea that the tacit contract between society and academic chemical research is likely to change. Since World War II, the public has paid taxes and the government has spent part of those taxes on fundamental research at universities under the presupposition that fundamental research will serve as the basis for the solution of societal problems. In the future, said Whitesides, society will want to have a much better idea of the problems research is solving. If researchers are devoted to solving those problems, perhaps they can use 20 percent of the money invested to do fundamental research. In this way, universities will be much more accountable to the public. "We need to think about our obligations to those who are paying the bills," said Whitesides. "Money is not an entitlement."

Whitesides also described the current science and engineering system, saying that we have a system right now in which we tend to use the phrase "science and engineering." He argued, however, that there are actually three really important activities, science; engineering; and invention and discovery. Science understands things; engineering, solves problems; and chemistry, in Whitesides view, can work in the area of invention and discovery. Whitesides said, "Scientists can work on things that they don't understand but that exist, and engineers do a fantastic job of making things really work. But there has to be more of the activity of going from something where there wasn't a scientific or technical activity to one where there was." According to Whitesides, U.S. universities do not create inventions and discoveries well, but he does think we do it better than other countries.

Whitesides briefly listed a number of difficult issues that a change in this current social contract would raise, many of which are discussed in future chapters of this report:

- Research institutions and individual researchers would need to achieve a new balance between curiosity-driven research and problem-solving research, which would require careful consideration of many tradeoffs.
- Academic research is a "fundamentally elitist activity" and may need to become more so. Not many people are needed to do it, and they need to do it well to create new jobs and solve difficult problems.
- With graduate education, more can be less. As students take longer to earn their PhDs, five to six years spent learning the same technique may not do a student much good.

- Student outcomes need to be tracked to gain a better understanding of the kinds of jobs they are getting and how well they are doing.
- Whitesides believes that the question should be asked whether PhD theses are narrow technical presentations for jobs that no longer exist. Should U.S. graduate students be doing organic synthesis if most organic synthesis is being done in China? "That's not to say that these aren't really important activities, but we need to connect our investment in graduate school with what's actually needed to give jobs to students."
- Does everyone need a PhD for a technical job? A good master's program may be enough to teach technical skills.
- Traditional groupings such as organic, physical, inorganic, and so on will not work well for integrative ideas and problems. The proper way to combine these fields is not yet clear—it may differ for different institutions. Interdisciplinary groupings could bring in fields outside of the natural sciences such as economics, management, and finance where appropriate.
- Can a single academic group make more headway on a big problem than a consortium?
- In an interdisciplinary future, graduate school will need to be—and should be—harder. Organic chemists, for instance, will need to know biology and immunology. Students will need to work in a global culture, not just a U.S. culture, which will require that they have experience with those cultures.
- Postdoctoral fellows are the future of the academic world, yet academia is still uncertain whether they should be treated as students, as junior colleagues, or as employees paid to do a job. "Unless we get that straightened out, . . . we're going to waste some of the best people in science."

THE PERSPECTIVE FROM UNIVERSITY ADMINISTRATORS

Several university administrators at the workshop provided their views on the problems facing chemistry graduate education. Holden Thorp, Chancellor of the University of North Carolina, Chapel Hill, noted that public universities are under great strain. The financial crisis has stabilized, but financial doldrums have replaced the crisis. The public mood regarding higher education and funding government is challenging for public universities. Many people think that public universities are too big or are spending too much. College costs have become a major issue as tuition has risen much faster than the cost of living in many institutions.

As a result of these financial constraints, universities are under pressure to teach undergraduates more inexpensively.

Today, faculty members in chemistry departments typically are paid by the university for nine months and pay themselves during the summer from their grants, Holden noted. Pressure will increase to do what medical school faculty have done for some time, which is to pay more of their salaries off their grants. That could make research groups smaller as less money is available for graduate students. Meanwhile, universities will probably be asking graduate students to teach more.

The net result will probably be fewer graduate students in all fields over the next decade, said Thorp, unless the economy were to undergo rapid growth. There also will be more pressure on universities to ensure that graduate students develop the right kinds of skills to meet national needs.

Chemistry does a better job of preparing students for careers beyond academia than most other disciplines, said Thorp. Chemists have been working in groups for a long time, enabling them to learn about the teamwork required in the modern job market. "Chemists are well prepared to do lots of different things besides work in universities," he said. Compared with other disciplines, he said, "I would put chemistry close to the top of the ones that we probably need to worry about the least."

The Situation in California

Marye Anne Fox, Chancellor of the University of California, San Diego, observed that the University of California system has very serious financial problems. Her budget has been cut by 38 percent over the last three years. Attrition has covered part of these cuts, but an additional temporary hiring freeze proved traumatic for departments that were attempting to recruit new faculty. The transfer of money among campuses of the University of California system through a process known as "rebenching," along with the distribution of tuition raises, have not eased the crunch. Pressure on existing revenue streams is intense, and university employees have had to be laid off. Also, some departmental graduate student courses are being cut back, which has a negative effect on the curricular offerings of the university. The difficulties of being chancellor during such a period have contributed to her decision to retire in 2012, Fox said.

The University of California system currently has fewer graduate students than projected, given the size of the undergraduate population, and is seeking to identify funds to support graduate students. The state of California cannot provide these funds, so the universities are looking for other options. Efforts to build an endowment for the San Diego campus by appealing to industries in the area have not been as successful as hoped, said Fox, with only one-third of the $500 million goal being achieved two-thirds of the way through the campaign.

University personnel continue to be high spirited and do an effective job, but with a smaller cadre of people than in the past. The university system is trying to use innovative, interdisciplinary, and collaborative projects to build faculty morale. For example, faculty members have built innovative curricula and have experimented with classes taught partly through distance learning from national laboratories.

"There's nothing wrong with the University of California that couldn't be assisted or solved by a good donation of $1 billion," Fox concluded. "Lacking, however, this $1 billion, we have all sorts of problems with postdocs, with graduate students, with undergraduates who join research groups, and with how they are educated."

The Numbers of Chemistry Graduate Students

Paul Houston, Dean of the College of Sciences at the Georgia Institute of Technology, said that the chemistry community still has not grappled with the question of whether too many graduate students are in the pipeline in chemistry. The attrition rate in chemistry is high (as described below), and some graduates are doing multiple postdoctoral fellowships before they get jobs. Both trends suggest that the pipeline is too heavily loaded. On the other hand, society has many problems that it needs chemists to solve. "I don't know the answer," said Houston. "There are indications that, at least in this economic climate, we're putting too many students in the pipeline. But I think that's something that we will have to decide."

Houston also pointed to an issue raised by several other presenters. Though enrollment in graduate chemistry programs has increased over time, the percentage of students from outside the United States has risen rapidly. Many of these students will remain in the United States and make important contributions to the U.S. economy, but others will return to their home countries and build the infrastructure of chemical research there.

The Quality of Programs and Students

Finally, Michael Doyle, professor and Chair of the Department of Chemistry and Biochemistry at the University of Maryland, observed that the United States should no longer necessarily be considered the future leader of the chemical research enterprise. China, for example, is quickly creating a very large infrastructure for higher education and research.

In addition, graduate students from the United States are commonly considered to be less motivated and, in many cases, less capable than international students, Doyle noted. For example, the GRE scores of international students on average are well above those of U.S. students.

One way to enhance the talent of U.S. students headed to chemistry graduate education might be to segment students interested in medical school and students interested in chemistry education during their undergraduate years, said Doyle, as is done in Europe. Today, medical schools tend to attract more talented students on average than have chemistry graduate programs. Devoting more attention to students interested in graduate school as undergraduates may retain a higher percentage of those students in a graduate school track.

THE PROBLEM OF ATTRITION

A final problem discussed throughout the workshop was that of the attrition of graduate students in chemistry. Attrition is a problem in all of graduate education (see Box 2-2), but it is also a problem in chemistry, particularly among women. For example, Julie Aaron, a recent University of Pennsylvania chemistry PhD who now teaches chemistry and biochemistry at DeSales University, said that almost half the women in her graduate program left within the first two years. She said that all of the women who left the program had different reasons for leaving. But one theme was that the only future career they had exposure to was that of the other women faculty in the department, and many had trouble picturing themselves in that role, especially if they wanted to have a family. "You are saying, 'I have to wait until I am 40 to have kids.' I think that that is honestly something that scared a lot of people off." In addition, some women left to go to professional school, thinking that it would be much easier to raise a family as a pharmacist than it would be as an assistant professor.

Another new faculty member, Jennifer Schomaker at the University of Wisconsin, agreed that the attrition of women is a problem. She had children when she was in graduate school and attributed her success to being "a fighter." But she is having trouble retaining women in her group at Wisconsin, "which really bothers me, because I would like to be thought of as a role model. But the truth is they look at me and they say, 'You are here all the time. Do you see your kids? Are you having a good time?' For me it is really important that I do continue to maintain that really enthusiastic attitude, and it is tough, there is no doubt about it. I am not sure what the solution is to be honest with you."

During a discussion period, Kristie Boering from the University of California, Berkeley, made the observation that the environment for women varies greatly from institution to institution, even among research universities. She noted that she had two children as an assistant professor at Berkeley before she received tenure because Berkley has family-friendly policies and supportive people in the department.

Yu Ye Tong from Georgetown University provided a contrasting point of view by observing that if the purpose of graduate education is to produce "the cream of the cream," then attrition will be higher than it would be otherwise. If the goal of U.S. graduate education becomes to create a better prepared workforce, then the goals of graduate education may need to change.

Robert Bergman, Gerald E.K. Branch Distinguished Professor at the University of California, Berkeley, who was a member of the steering committee for the workshop, pointed in a discussion session to what he called "the elephant in the room": though many chemistry graduate students are well served by their research advisors, some are not being educated properly or even treated appropriately. In proposals for change, ways of curbing abuses of graduate students should be a major consideration, he said.

EXPERIMENTS IN CHEMISTRY GRADUATE EDUCATION

At the end of his presentation, Platz observed that the role of NSF is to fund successful experiments. In chemistry graduate education, a successful experiment could be a university, a chemistry department, or perhaps other departments that reimagine the graduate experience in a compelling way. This experiment could attract a diverse group of talented students who would meet with outstanding success upon earning their degrees. Such a program would generate national attention, be seen to have a competitive advantage, and spur imitators. In contrast, institutions that ignore the changes going on risk extinction. "The national leaders in this century will be those institutions that see this as a moment in time to create a new paradigm."

The Obama Administration has been very interested in science, Platz observed, and has clear ideas about what it wants to support. As a result, presidential priorities have been increasing as a proportion of the budget (Figure 2-4). Chemistry has not played a large role in these presidential priorities, though NSF's Division of Chemistry has been able to keep its core funding relatively stable, largely by reducing instrumentation costs. However, if the chemical sciences community wants federal funding for chemistry to increase, it must demonstrate how its proposals contribute to the administration's priorities. How can it help to create a workforce that is equipped to take on the challenges of the new century? How can it help create the skills in U.S. workers that will lead companies to locate their jobs here rather than in another country?

The most important goal of the workshop, Platz said, must be how

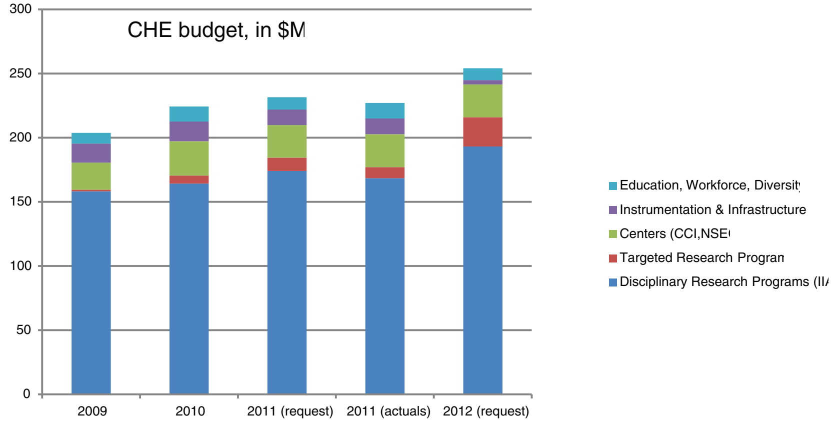

FIGURE 2-4 Administration priorities represent an increasing percentage of the Division of Chemistry (CHE) budget in recent years.
SOURCE: Figure courtesy of Matt Platz, National Science Foundation.

the chemical sciences can preserve and enhance quality with less money. "If we can come up with some strategies to do that, this workshop, in my opinion, will be a great success." He challenged the workshop participants to devise experiments in chemistry graduate education that can inspire the field and attract support. In particular, the goal should not be to play a zero-sum game but to find new money to fund experiments at five to ten universities in addition to the core funding for chemistry.

"Change has already come," Platz concluded. "We can view this as an opportunity for our community and for the United States, or we can passively react to change and have it imposed on us."

Box 2-2
The Future of Graduate Education in the United States

Patricia McAllister, Vice President of Government Relations and External Affairs at the Council of Graduate Schools, presented an overview of *The Path Forward: The Future of Graduate Education in the United States* (Wendler et al., 2010), which was produced by a joint commission of the Council of Graduate Schools and the Educational Testing Service. The report examines trends, strengths, and vulnerabilities in graduate education and makes a series of recommendations for policymakers, universities themselves, and employers. Though the report covered graduate education as a whole, many of its conclusions apply to chemistry in particular.

The Value of Graduate Education

Several lines of evidence point to the continuing value of graduate education in the United States. Enrollments at the master's and doctoral levels have increased at a 2 percent to 3 percent rate across all fields of graduate education over the past decade. Also, the workplace continues to reward people with graduate degrees, and these financial rewards have increased substantially since the mid-1980s compared with other levels of education (Figure 2-5). In addition, the unemployment rate is lower for people with graduate degrees than for people with lesser degrees of education.

Furthermore, the need for well-trained students is projected to increase. The Bureau of Labor Statistics has estimated that 2.5 million available jobs will require an advanced degree by 2018. Meeting this demand will require an 18 percent increase in people with master's degrees and a 17 percent increase in people with doctoral degrees (BLS 2009).

Minorities in Graduate Education

Minorities underrepresented in science and engineering fields go to graduate school at only about half the rate of white students, yet these groups are becoming a larger percentage of the U.S. population. According to the report, when high school sophomores were asked about their degree aspirations, one-third of African American and Hispanic students aspire to receive a graduate degree, compared with 41 percent of white students and half of Asian students (Bozick and Lauff 2007).

However, exposure to postsecondary education and completing an undergraduate degree correlate with students' aspirations. Among African American students who had completed an undergraduate degree, 85 percent said they aspire to achieve a graduate or advanced degree, compared with 79 percent of Hispanics and 70 percent of white students (Bozick and Lauff 2007). Thus, helping students get through undergraduate education is likely to increase the number and diversity of future graduate students.

continued

Box 2-2 Continued

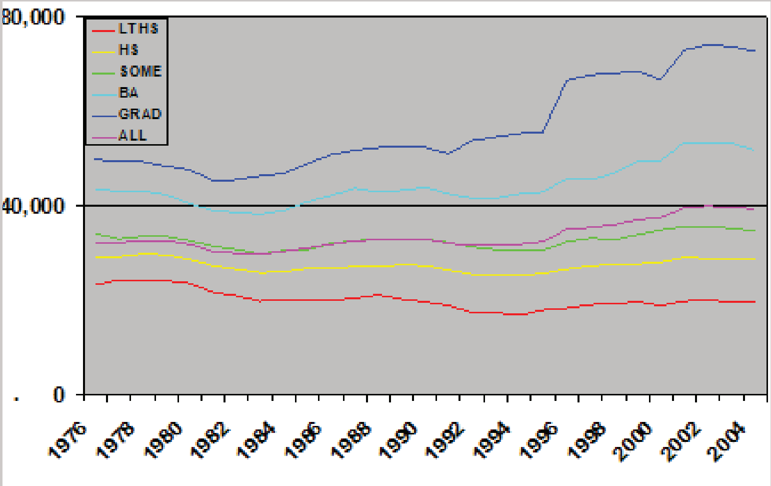

FIGURE 2-5 The market is rewarding graduate education.
SOURCE: Carnevale, T. (2009). Graduate Education in the Knowledge Economy. In Council of Graduate Schools (Ed.), Graduate Education in 2020: What Does the Future Hold (pp. 26-59). Washington, DC: CGS.

Vulnerabilities of Graduate Education

One clear vulnerability of U.S. graduate education is low completion rates, said McAllister. The estimated attrition rate in doctoral education across all programs is between 30 and 50 percent. Except in the field of engineering, fewer than one-quarter of students who enroll in graduate programs complete PhD degrees within five years (Figure 2-6). Within seven years, about half of the students enrolled in mathematics and in the physical and life sciences completed their degrees. But this level of completion is not reached for students enrolled in humanities and social sciences until nearly year ten. Also, domestic students complete their degrees at lower rates than international students, underrepresented minorities at lower rates than majority students, and women at lower rates than men.

Another vulnerability for students considering graduate degrees is debt. Students who graduate with a master's degree have on average a cumulative debt incurred during their undergraduate and graduate years of $50,000, while students with a PhD have an average cumulative debt of $77,000.

Recommendations

The Path Forward (Wendler et al. 2010) made a number of recommendations for universities. One is to graduate more of the students they admit. The PhD Completion Project of the Council of Graduate Schools has uncovered strat-

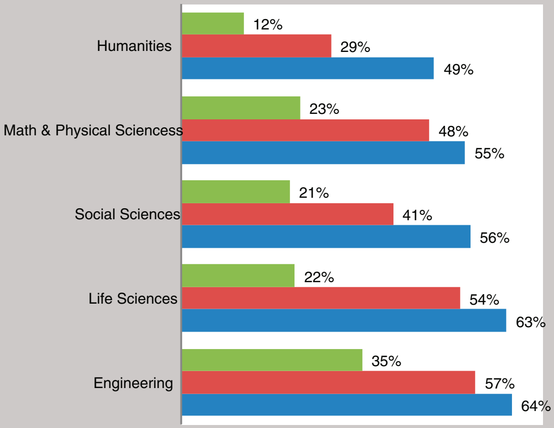

FIGURE 2-6 PhD completion rates in mathematics and the physical sciences are below 50 percent after seven years.
SOURCE: Adapted from Council of Graduate Schools. (2012). Analysis of Baseline Program Data from the Ph.D. Completion Project. Washington, DC: CGS. URL: http://www.phdcompletion.org/quantitative/book1_quant.asp.

egies that help (CGS 2008). These include improving the fit between the students who are admitted to graduate school and graduate school programs, better mentoring and a better fit between students and mentors, different financial packages to support students during their course of study, and the identification of sticking points in graduate education and the provision of help to get past those points.

For employers, the report recommends sponsoring graduate fellowship programs that reflect career pathways into various industries, creating lifelong learning accounts for professional employees that would encourage people already in a career to pursue advanced study, clarifying entry points into careers, and communicating the skills needed for 21st-century jobs beginning even at the high school level.

For policy makers, the report recommends the creation of the COMPETES Doctoral Traineeship Program, which would provide five years of support for doctoral students to help prepare the future talent needed in critical areas of national need such as health care, energy, the financial sector, and cybersecurity. It also proposes a program to support innovative master's programs such as the professional science master's. It recommends expanding existing programs that support graduate students across the federal agencies. It also urges reducing barriers for international students—for example, by modifying visa policies to make the United States more welcoming to international students and making it easier for international students to stay in the United States after graduation to contribute to the U.S. economy.

continued

Box 2-2 Continued

Follow-Up Initiatives

The Commission on Pathways Through Graduate School and into Careers (Wendler et al. 2012) is following up on *The Path Forward* report (Wendler et al. 2010) by looking at the factors that motivate or deter students from pursuing graduate studies in critical areas, particularly science and engineering but also others that align with careers in areas of national priority. It is examining what graduate students know about career paths, their aspirations, how they learn about occupational opportunities, the role of faculty and universities in this process, and the kinds of careers and occupations that people with graduate degrees follow. As part of the study, a survey of students who took the GRE between 2002 and 2011 generated 6,000 responses from students who are planning or currently engaged in graduate education. Surveys and interviews of deans and employers have revealed new information about their roles and expectations.

3

Goals of Chemistry Graduate Education

"Depth, breadth, and communication could be three anchors around which graduate education could be transformed."

—Wilfredo Colon, Renesselaer Polytechnic Institute

The broad goals of chemistry graduate education were a prominent topic at the workshop. As research becomes more interdisciplinary, international, and socially relevant, should graduate students receive a different kind of education? If so, how would the projects they undertake and their relationships with faculty members change?

This chapter begins by summarizing the presentation of Gary Schuster, Vasser Woolley Professor in the Department of Chemistry and Biochemistry at the Georgia Institute of Technology, who spoke about the changing roles of universities over the course of U.S. history. It also looks at the topics of breadth versus depth in graduate education and at the expectations of students and faculty. The specific skills that could be imparted by graduate school and the structure of graduate programs are discussed in the next two chapters.

THE CHANGING ROLES OF UNIVERSITIES

What is the work that the world wants universities to do?

The answer to that question, said Schuster, has varied over time. During what he called the first epoch, from the founding of Harvard University in 1636 to roughly the Civil War, the major objective of colleges was to educate members of the elite. Attended almost exclusively by white males, they produced ministers, physicians, and lawyers and were primarily teaching institutions.

With the passage of the Morrill Act in 1862, the focus of many universities became educating people to lead the United States through the Industrial Revolution. During this second epoch in the history of higher education, the federal government, for the first time, had a role in higher education, though the great land grant universities created by the Morrill Act focused largely on local economic development. Nevertheless, this economic development helped fuel the Industrial Revolution in the United States and raised the living standards of large masses of ordinary people.

The third epoch began in 1941 when the federal government created the Office of Scientific Research and Development to coordinate scientific research for military purposes during World War II. The tremendous success of scientific research during the war in developing innovations like radar, nuclear weapons, and penicillin led to a great expansion of science both during and after the war. Sponsored largely by the federal government and centered largely at universities, this expansion of science led to the creation of a massive infrastructure of facilities, people, and procedures serving the purposes of both research and education.

The third epoch came to an end, in Schuster's analysis, in 1993, after the collapse of the Soviet Union. Suddenly the government's rationale for supporting science was greatly diminished, which was symbolized by the cancellation of the superconducting supercollider project that year after $2 billion had already been invested in the project. During this fourth epoch, which continues today, many of the large corporations that hired chemists in the past have faded from the scene or are shells of what they once were. Other companies, such as many pharmaceutical companies, are moving many research jobs overseas to be nearer to growing markets and to take advantage of lower labor costs.

As a result, students today face a very different work environment than in the past. More students are going into small start-up companies, but the skills required for these jobs are different than those in large corporations. These companies need people with the experience and skill to solve problems immediately, because the company may need that problem solved to survive.

Given these changes, what should be the objectives of graduate education in chemistry? Schuster listed several:

- Students need discipline-specific knowledge and enhanced critical thinking skills.
- Employers need a skilled workforce.
- New discoveries are needed to enrich science.
- Companies need new ideas from which they can develop intellectual property.

- Local economies need jobs created by technologies based on research results.

Schuster argued that graduate education in chemistry should meet all of these objectives. But not all departments need to pursue all goals. Different departments and universities can specialize in different aspects of the work that needs to be done.

The important thing for universities to recognize is that epoch three is over, Schuster said. Today, academic chemistry continues to have a massive infrastructure focused on doing research and publishing papers. But the infrastructure built in epoch three is no longer sustainable. Other universities will not be far behind the University of California system in dealing with severe budgetary constraints, he predicted. The single objective of doing fundamental research, writing papers, and getting grants is no longer enough.

The new epoch will need to have new objectives. For example, the current PhD education is narrowly focused. This model has worked well to advance science, but it may be less effective in achieving the other objectives. Instead of a student working on one project for five years, perhaps a student could work for three different mentors over those five years on three different but related problems. "You sacrifice a bit of the depth, but increase the breadth considerably." (This subject is discussed later in this chapter, while the structure of graduate education in chemistry is discussed in Chapter 5.)

Another option to consider, and one discussed throughout the symposium, is the professional master's degree (which is also discussed in Chapter 5). Georgia Tech has master's degrees in a variety of areas like computational biology and human-computer interaction, Schuster noted, though not in chemistry or physics, because in those fields the master's degree is seen more as a consolation prize than as a desired credential. A reinvigorated master's degree program could provide students with breadth without the great depth of a PhD program. The problem for faculty is that these options would not generate as many papers, which would be a detriment for them in the current system.

Universities are in an evolutionary period, Schuster concluded. Some will devise new structures and procedures and will succeed, while others will fail. He quoted A. Lawrence Lowell, president of Harvard University from 1909 to 1933, who said in his inaugural address, "Institutions are rarely murdered. They meet their end by suicide. . . . They die because they have outlived their usefulness or fail to do the work that the world wants done" (Lowell, 1909).

During the discussion period following Schuster's presentation, Bergman pointed out that universities cannot do everything society wants, such as not teaching evolution. Nor should universities shut down departments like art history or sociology that do not produce useful products. "The university is more than that, and I would hope that . . . the ideas that come out of this meeting view the university as part of a larger context." The university needs to show society where it should be going rather than just responding to what the world wants, Bergman said.

Schuster responded that political forces can be very powerful in shaping what will and will not happen in academia. If universities keep doing exactly the same things that they have been doing, they will fail, he said. "We need to move into this new era and decide what it's going to look like."

BREADTH VERSUS DEPTH

A topic raised by Schuster—breadth versus depth in chemistry graduate education—was revisited throughout the workshop.

Wilfredo Colon from Renesselaer Polytechnic Institute said that the one nonnegotiable requirement of graduate education is deep fundamental knowledge in chemistry. Even if people are working together to solve an interdisciplinary problem, they need deep knowledge in their respective areas to make a contribution. At the same time, workshop discussions noted the need for breadth, both in other disciplines and in areas outside science, along with accomplished communication skills, Colon said. "Depth, breadth, and communication could be three anchors around which graduate education could be transformed."

The problem with many discussions of depth versus breadth, said Paul Houston from the Georgia Institute of Technology, is that everybody wants everything. Industry wants PhD recipients who have engaged in a deep research project, but they also want students with communication skills, the ability to cooperate with other people, familiarity with concepts throughout chemistry, safety training, and entrepreneurship, management, and intellectual property skills. "How do you design a PhD program that takes five years or less [that] includes all of these things? I think that's going to be a real challenge for us, to figure out how to keep focused on a deep research problem, which is the crux of a PhD in any field, and still have room for all these other areas that are desirable to our customers."

Several workshop participants questioned whether the current structure of graduate education distorts the principles on which graduate programs are based. Warren Jones from the National Institute of General Medical Sciences (NIGMS) recounted his experiences in stakeholder meetings in four cities for the training programs that NIGMS supports. He said that too often the graduate student experience was dominated by data gathering and the pursuit of the next paper. It was not sufficiently underpinned and driven by producing a creative problem-solving scientist. The technical demand was stressed rather than the intellectual.

Robert Bergman from the University of California, Berkeley, agreed that this is a critical point. Part of the problem is the pressure put not only on graduate students but on junior faculty to generate papers and earn tenure, as well as senior faculty to achieve other kinds of recognition.

Michael Rogers of NIGMS said that the institute is planning to strongly encourage, though not require, that graduate students and postdocs supported by NIGMS on either research grants or training grants have written individual development plans. He asked whether such encouragement or a requirement would be a good thing or would add too much to the workload of faculty members. Julie Aaron of DeSales University responded that the best approach would be for faculty members to sit with students informally and talk with them about where they want to go and how they plan to get there. "You don't want it to be just more paperwork for everyone to do."

She added that "in graduate school, we all had weeks where you got a lot accomplished and a week where you didn't do a whole lot. It was easy to fly under the radar once in a while. . . . Students [need] to define their goals: 'I want to present a paper or I want to go to a meeting this year so what do I need to get done by this date and how am I going to assess that.' It is definitely good to encourage that without making it just more paperwork."

THE EXPECTATIONS OF STUDENTS AND FACULTY MEMBERS

Another prominent theme during the workshop was the need for students and their faculty advisors to have consistent expectations. For example, Peter Dorhout of Kansas State University said that differing expectations between students and faculty members were the single largest source of conflict at his institution. Communicating expectations from faculty to student and from student to faculty would go a long way toward improving the student and faculty experience in graduate education.

John Schwab, formerly from NIGMS, noted that most graduate trainees are supported through research dollars, which generally do not include expectations regarding the breadth and depth of the graduate experience.

One possibility discussed at the workshop is a manual for graduate students that would be available to all students and faculty members. Such a manual could outline how many hours of work are expected, when to come to advisors with a question, and how to report a mistake correctly.

4

Skills Taught in Chemistry Graduate Education

"We don't want folks who are very focused and narrow. We want folks who are broad-thinking, looking to contribute not only to their work, but to support their colleagues."

—David Kronenthal, Bristol-Myers Squibb

Closely related to the goals of graduate education are the skills imparted through that education. This chapter takes a much more hands-on look at graduate education. It asks what skills have served chemists well in their positions and what additional skills would have been useful. It also considers the skills that will be in greater demand as the jobs in the chemistry field diversify and evolve.

This chapter divides the speakers who offered perspectives on skills into five broad groupings: new faculty members, industry representatives, new industrial chemists, chemists in nontraditional careers, and a venture capitalist. While some of the useful skills they cite overlap, others differ from person to person and sector to sector. Chapter 6 compiles these ideas, along with those in chapters 3 and 5, into a single list.

THE PERSPECTIVE FROM NEW FACULTY MEMBERS

Teaching as a Career

Julie Aaron, a second-year professor from DeSales University, teaches at a purely undergraduate institution and works with undergraduates rather than graduate students. She received her PhD from the University of Pennsylvania in May 2010 and her undergraduate degree at McMaster University in Canada. She was a chemistry major, taking the majority of her classes in chemistry and not writing a single essay as an undergraduate. She regrets that now, but "you want to do what is easy because you feel successful at it. We have to force ourselves to do things that aren't easy."

Her advisor at University of Pennsylvania was not supportive of her decision to go to DeSales and instead urged her to do a postdoc. However, many of the other people she knew who were doing postdocs had been doing them for three or more years. She took a chance on pursuing a teaching career and says that she is glad she did. "Teaching is truly what I believe I was meant to do, and I really enjoy it." She teaches between four and five courses a semester and is the only biochemist on the faculty. She is in charge of putting together the curriculum and laboratories and preparing for accreditation. She also is heavily involved in recruiting students into the major. She mentors a student doing undergraduate research and advises 25 or so students who are health-related and science majors.

Her experience as a teaching assistant was "tremendously important" in laying the foundation for these skills. During two of her years as an undergraduate, she was a teaching assistant for an undergraduate freshman chemistry laboratory course as well as a calculus course. In particular, as preparation to teach calculus, she took a course in which a faculty member taught teaching assistants how to teach math. A similar course in teaching chemistry would be an extremely valuable addition to graduate school, she said. It should be designed for students who are in their later years of graduate school and are planning to go into teaching.

Despite her experiences with teaching at University of Pennsylvania, Aaron had to develop several critical skills at DeSales. She was not prepared to design curricula and was challenged to put together two semesters of a biochemistry lab despite never having taken a biochemistry laboratory as a student. She had to learn in her teaching how to break down concepts and explain them in terms that diverse groups of students could understand. She also needed to be able to mentor and advise students, prepare proposals, manage her time, and prepare assessments.

She was supported by an NIH fellowship at University of Pennsylvania, which had both pros and cons. It enabled her to develop and pursue interests outside her research area of crystallography, in part by taking classes in the medical school. She also had monthly meetings with other people receiving the fellowship and organized symposia funded partly by the grant. But it created tension with her advisor who "wasn't exactly thrilled that I was doing all this other stuff on the side, but he kind of let it go. I didn't talk to him about it too much, and we had this great relationship where I think in the end he was really glad I did it, but as long as it didn't interfere too much with the lab." Her advisor encouraged her to attend meetings, present posters, and give talks, which helped her learn to speak in public. He also encouraged his students to write their own papers, which he then edited with them in an iterative process.

Also as a graduate student, she traveled to other universities and to several synchrotron facilities to work with other groups and collect data. And she mentored an undergraduate student while completing her PhD.

She regretted having only cumulative exams and not a qualifying exam. She also missed out on forcing herself through the challenging process of putting together a research proposal. "I would have benefited from that."

Though her relationship with her advisor was good, Aaron noted that many graduate students she knew had challenges with their advisors. These students usually had nowhere to go to talk about their problems. "We need to work on having a better way for students to deal with potential conflicts."

Returning to Graduate School from Industry

Jennifer Schomaker, an assistant professor in the chemistry department at the University of Wisconsin, worked at Dow Chemical for almost eight years before going back to graduate school, which gave her a somewhat different perspective on graduate school. Schomaker was good at multitasking, both because of her industry experience and because she went through graduate school with children. Many graduate students would benefit from a more disciplined approach, she said. "I am not saying we need to push them to ridiculous levels and say you must work *x* number of hours. But I think it is fair to say you are preparing for a professional career. This means you don't read Facebook whenever you feel like it. You treat your colleagues professionally. There is a certain standard of behavior that you should be exhibiting even in graduate school."

Her advisor in graduate school gave her a lot of independence, which is important in becoming an independent scientist. "As an advisor, you . . . need to let people find their own path. You need to let them come up with their own ideas even if you don't think they are good ideas. They need to work through this process."

As a graduate student, she learned how to distill her ideas into a single central theme. Some people are already good at that, but graduate school does not necessarily teach people to do that. She, too, did not write a research proposal in graduate school, but she now sees it as crucial. "You need to be able to generate an independent idea. You need to be able to communicate that to a broad audience. You need to be able to defend that." Graduate students also need feedback from faculty members on how to make their proposals better.

She had cumulative exams in graduate school and considered them a positive experience. However, as education becomes more interdisciplinary, it is hard to know what constitutes base knowledge. She also said it was important to mentor undergraduates. To have complete mastery of a subject and to communicate with a wider audience, graduate students need experience mentoring someone for whom science or chemistry is a completely new language.

As a professor, Schomaker tries to set goals with her students. What do they want to accomplish in six months? How are they going to do it? Students need to know that they are doing something important and should take their science seriously.

To counter the balkanization of graduate school, she encourages her students to explore other fields. Going to a seminar in a different field is not a waste of time, she said. She encourages her students to learn things that she does not know herself. "I don't want them to be clones of myself." Rotating through several different laboratories as a first year graduate student can help students select an appropriate research advisor and allows them to explore different areas. Professors are eager for new graduate students to choose a research topic and get started, especially when they see an especially talented student, but this is a disadvantage for many students, who have a tendency to keep working in an area where they worked as an undergraduate. In addition, rotations build relationships that can be helpful throughout a career.

Students should be encouraged to give talks and should get feedback about what they did well and areas where they could improve. Students also need exposure to different careers. Schomaker said that she works very hard, and some of her students are put off by that. But a graduate degree does not mean that people need to be like their advisors.

Mock interviews and student-run seminars can give students skills they will need in any career. Training in managing people also will prove useful no matter what students do, especially in unanticipated situations.

Finally, as did several other speakers, Schomaker emphasized the critical importance of safety. Students need to realize that safety will be part of their life, especially as safety provisions become more prominent in academia. Thinking about safety also can help them think about the best experiment to do. "You can panic in grad school and just run lots and lots of reactions. . . . You need to pick the best experiments to do. You need to take the time to think."

Strengths and Weaknesses of Graduate School

Samuel Thomas, an assistant professor in the chemistry department at Tufts University since 2009, was a graduate student at MIT and did a postdoc from 2006 until 2009. Graduate education and his postdoc were superb technical training, said Thomas. The experience also provided excellent training in public speaking, working in groups, and publishing scientific papers.

He felt less well prepared for mentoring students. As a graduate student, he felt compelled to focus on his own research rather than taking the time to mentor an undergraduate. That would have been a useful experience, he said, because the students he has now need information in a wide variety of areas, including safety, responsible conduct, and data recording.

He also could have used more exposure to managing people, including managing personalities, distributing credit, and inspiring students to do their best. Running multiple research projects at the same time also was something he did not do in graduate school.

In graduate school, he did a lot of proposal writing, which was important, since he learned as a postdoc that not every good idea equals funding. "Everybody has good ideas." But additional training in how to write for reviewers and for other audiences, along with more experience in grantsmanship in general, would have been useful.

Financial management would be useful to teach to graduate students, such as budgeting and indirect costs. "I am not saying that graduate students should be involved in constructing five-year budgets, but [they should have] an idea of what some of the challenges and constraints are when it comes to federal funding." Also, as a graduate student he knew virtually nothing about the organizational structure of funding agencies. "How to interact with those funding agencies would be great lessons that wouldn't take a huge amount of intellectual capital or time from departments and faculty and would be a useful endeavor."

Mentoring Workshop

Later in the workshop, Robert Lees, a program director at NIGMS, described a mentoring workshop for new faculty supported by the institute. Universities and funding agencies make a large investment in new researchers, Lees observed. The Mentoring Workshop for New Faculty in Organic and Biological Chemistry is designed to help increase the proposal success rate for new faculty to that of establish faculty members, even in the face of intense funding competition.

The annual three-day workshop brings together six to eight experienced academic scientists as mentors, approximately 30 assistant professors, and three to six NIH staff. Assistant professors receive instruction in proposal writing, the building of unique and productive research programs, and the development of skills for success in other academic and professional activities. The workshop is highly interactive throughout, featuring mock study sections with real NIH applications and research presentations by attendees followed by constructive critiques. Participants also discuss case studies submitted by attendees involving managing and motivating research groups, collaborations, professional ethics, publishing and reviewing, navigating departmental politics, teaching challenges, project selection, and mentoring. In addition, the program emphasizes the diversity of participants and safety issues.

Eight workshops have occurred to date, with approximately 250 participants altogether, and the response from both mentors and attendees has been highly enthusiastic, Lees said.

THE PERSPECTIVE FROM INDUSTRY REPRESENTATIVES

ExxonMobil

ExxonMobil recruits about 35 PhDs per year, said Thomas Degnan, manager of Breakthrough and New Leads Technology at the company's research and engineering arm. Out of 83,000 total employees, 2,000 are PhDs, and about half of those come from the chemical sciences. ExxonMobil has a central research laboratory and spends $800 million to $1 billion annually on research.

Degnan said that ExxonMobil believes that universities are doing a very good job of preparing PhDs to solve problems outside an academic setting. However, Degnan added that the company has adjusted its recruiting policies, focusing on 20 to 25 schools with strengths that match what the company needs. The schools have been chosen based on a past history of recruiting and relationships with particular professors or programs that tend to produce students with interests well aligned to those of the company. "We do provide other routes for PhDs," Degnan said, "But the highest likelihood for success in hiring is to come in through those universities or through an intern program."

The PhD experience teaches people to analyze problems deeply, understand the basic scientific context, and thrive in an industrial environment, according to Degnan. The company looks for graduates with broad knowledge, the ability to work as part of a team, and the drive to help that team reach a higher level. New hires generally do not have just one area of focus during their tenure at the company, so the ability to adapt and learn new skills is important.

The interview process at the company focuses on critical thinking, creativity, communication skills, and work ethic—the qualities that go above and beyond technical proficiency and mark a standout candidate. "Identifying the best of the best requires that companies spend a lot of time working with the universities," he pointed out. "Often when we see individuals come in from larger groups working on focused programs, a key question is, what part did you actually do? What part of the creative work that came out of that is attributable to the individual? Without the company's intimate understanding of those programs, it's very difficult to parse that out."

Chevron Phillips Chemical

Bill Beaulieu, manager of polyolefin catalyst and product development at Chevron Phillips Chemical Company, briefly described the company, which was formed from the chemical assets of Chevron and Phillips but exists independently. A lack of government funding for polyolefin production and catalysis has led to a dearth of students in that area. However, the production of shale gas will likely drive petrochemical development in the next one to two decades, which could rejuvenate the U.S. petrochemical business.

In the last five years, Beaulieu has hired ten PhD chemists. "For me, that's a lot." Most new hires come through advertisements on the ACS website, which drew 140 applicants for a recent position. The company typically hires U.S. citizens or those with green cards.

All the candidates the company wants to hire have strong chemistry skills, but the soft skills—such as communication ability and teamwork—differentiate between a successful applicant and ones who will not make it past the first round. "You have to be able to work with the engineers, with the administrative assistant, with the manufacturing guys, with the marketing and sales guys. We all have to see the objective the same way at the end of the day."

Beaulieu said that the partnership between academia and the chemical industry could be much stronger. "There are a lot of things that the academic community offers that industry doesn't have or won't invest in," he pointed out. "With a view of how we can do things across broader functions, we could be more successful than we have been."

If a new hire comes from a great university, that person is not necessarily going to be a great contributor in an industrial environment, said Beaulieu. Some PhDs spend their time working on a project their professor devised rather than developing their own ideas.

Finally, Beaulieu pointed out that academia has recently placed more of an emphasis on safety regulations, which are a major area of focus in the chemical industry. Many employees spend time writing safety documentation, which is important to the company but may be an unfamiliar area for academics.

Merck, Sharp and Dohme

Sander Mills, vice president in discovery and preclinical sciences at Merck, Sharp and Dohme Corporation, said that chemists in leadership positions at the company agree across the board that new hires need rigorous training in chemistry, strong problem-solving and critical thinking skills, and the ability to innovate. "Assessing people's collaboration skills is really a challenge when they have worked mostly on their own in academia," he said. "We always really like it when we can see evidence that they are comfortable and productive in a team-based environment." Leadership is another desirable trait, along with enthusiasm for translating academic training to industry. In medicinal chemistry, new hires are expected to learn about many disciplines—such as biology and physical chemistry—and much of that training happens on the job.

The company looks for versatility in the way that potential hires address problems, he said. It also looks for evidence that their scientific training and chemical judgment have matured during their training. In addition, the ability to adapt will benefit their work in drug discovery.

Merck looks for new hires with the ability to grasp all the various areas of drug design so they can more quickly contribute their own ideas. In this vein, he said, the company often looks for candidates who have demonstrated creativity during their PhD work or are working on a project that lines up with the company's interests.

As the other industry representatives pointed out, communication and collaboration are crucial. Merck prioritizes problem-solving and experience, but soft skills will always give candidates an advantage in the industrial environment.

Bristol-Myers Squibb

David Kronenthal, vice president of chemical development at Bristol-Myers Squibb, echoed many of the previous panelists in listing desirable characteristics for new hires. The company looks for people who are highly trained, with a strong understanding of fundamentals but also the ability to go beyond that training. "We have a very selective process for recruiting and hiring," said Kronenthal, who is responsible for a department of 95 people, mostly chemists. Recruiters try to measure curiosity and leadership potential in candidates as well as their ability to multitask. Employees may not work on multiple projects, but they need to be able to consider what is happening in other departments.

"We don't want folks who are very focused and narrow," Kronenthal said. "We want folks who are broad-thinking, looking to contribute not only to their work, but to support their colleagues in the department."

The company bases career advancement on both achievements and behavior, he said, in an attempt to emphasize a positive culture. "Our feeling is that once you have these attributes, you can teach the rest." Chemists participate in interdisciplinary projects, branching out over the course of their career. The company also places great emphasis, as people become more senior, on mentorship, so that it continually brings along the next generation.

During the discussion period, Robert Bergman from the University of California, Berkeley, asked about the advantages and disadvantages of a tight job market. "I know it's good for [industry] to have 100 people applying for one job," he said. "It's not so good for us." In response, Kronenthal said that a broader set of skills helps give students the resources they need to be creative when fewer positions are available.

Corning

Joydeep Lahiri, division vice president and senior research director of organic and biochemical technologies at Corning, commented on the importance of teaching students how to choose where to direct their focus. People are generally hired with a project in mind, he said, but at Corning, a 160-year-old company with a centralized research approach, those who advance are the ones who spend time considering new angles and ideas.

Lahiri also talked about emerging skills for chemistry graduates, touching on the role of "value networks," a concept introduced by Clayton Christensen. In the corporate world, a free market helps balance redundant value networks, which occur when innovation slows and there is a performance oversupply, but there is no equivalent mechanism for academia. "What we find is that, for certain disciplines, we have an oversupply, and in certain disciplines we have an undersupply," he said. More dialogue between industry and academia could help balance supply and demand.

Lahiri added that soft skills can be taught without sacrificing depth, potentially by letting scientists work together on proposals and practice submitting proposals to business colleagues. "There are things you can do in the basic infrastructure of chemistry education," he said. "You don't have the luxury of many more years of education. But there are small, very significant changes that one can make that would be very impactful for a sustainable chemistry education in industry."

In responding to a question about transitioning between jobs, Lahiri pointed to the importance of working on interdisciplinary teams. Being able to explain chemistry to people who do not have a background in science provides adaptability in the job market. He also commented on the role of technology within companies. "One of the things we should do as a community—and this extends beyond chemistry—is to make sure that there is greater education of the value of technology among non-technologists, because it influences the financing of science and technology in the organizations. It's a heck of a lot easier to convince a CEO who is technically savvy about the value of science than a person who has no technical background."

DuPont Central Research and Development

DuPont technology, said talent acquisition manager Rajiv Dhawan, has three major platforms: advanced materials, agriculture and nutrition, and industrial biotechnology. Scientists at the company focus on increasing food production, decreasing fossil fuel dependence, protecting lives and the environment and growth in emerging markets.

New hires need strong technical skills as well as other assets, and those other assets—creativity, communication skills, and a willingness to collaborate—are the ones that differentiate standout candidates. This is especially important, Dhawan said, given that innovation is happening more and more at the intersection of disciplines rather than in distinct areas.

All principal investigators in central research are expected to come up with proposals every year, and those proposals involve working with business colleagues, marketing professionals, and managers, all of whom have different communication styles. Fluent communication is therefore a crucial skill, as is familiarity with a wide range of different areas. "It's about these chemists actually being scientists," Dhawan said. "You need to have that deep knowledge in one area. But to be able to be conversant in others is very important." Reading an array of journals, he suggested, contributes greatly to this diversity of knowledge.

DuPont expects its new hires to be able to think independently and originate research ideas. "Part of being a PhD is being able to come up with your own ideas and not just simple extensions of what your advisor told you to do." In addition, the company has recently emphasized hiring people with the entrepreneurship skills necessary to transform ideas into business.

THE PERSPECTIVES OF YOUNG INDUSTRIAL CHEMISTS

Thriving in Industry

David Tellers, a senior research fellow in the department of medicinal chemistry at Merck, Sharp and Dohme, agreed that problem solving skills are essential for an industrial position. In addition, he discussed three other skills: the ability to work in a team environment, the ability to communicate, and the combination of flexibility and resiliency.

Teamwork he defined as the ability to recognize your role within an overall program. That means working with both the upstream parts of a program and the downstream parts.

Communication skills include the ability to recommend actions in a succinct manner. The more quickly a conclusion is made, the more quickly the program moves along. Newer researchers also need to be ready to recognize and acknowledge better ideas, while later in a career it becomes more important to sell your ideas to people who are not chemists.

Resilience and flexibility connote changing as a task or project changes. "You can't come into it thinking, this is what I did in graduate school and this is what I signed up for. That will change definitely, and it will probably change a lot sooner than you think it will."

Graduate school helped Tellers to communicate by providing him with opportunities to present his results to the entire research group and to his advisor and other professors. Honest feedback from his advisor on what he was doing well and not doing well and on his career decisions was also important. He appreciated being told that an idea was bad or that he should do a postdoc in a particular place to get an industrial job in a particular area.

Having a broad exposure to chemistry and other fields does not necessarily make a person a problem solver, Tellers emphasized. For example, he would not have wanted to work in three different areas during his graduate years—that would have felt like a survey of different areas. "I personally found my most rewarding time in graduate school to be my last three years. I struggled my first two years to understand the science, and my last three years were the most fun because I felt like I had control of my discipline. That was where I made the most contributions to the science, not just the learning of the science, but the execution of the science."

Nevertheless, he now wishes he had more exposure to work outside his own discipline. Though he went to presentations outside his field, it was not required or highly recommended, and he wishes that this exposure would have been more formal. Interacting more with the nonchemist on his thesis committee, and having an attorney on that committee, also would have been useful.

In addition, he wishes he had interacted more with the surrounding community while in graduate school. "That might be my responsibility, but at the same time I think the department owes it to itself, in the epoch four that we are in today, to force students to go out and meet not just high school students but people in retirement homes, and justify why we need chemistry."

Finally, he wishes he had access to more descriptions of career opportunities in graduate school. What skill sets do you need if you want to go into the petrochemical industry, into pharmaceuticals, into academics? Videoconferences with former students who had gone into each of these areas, talking about their jobs without faculty members present, would have been extremely useful.

Developing Contextual Understanding

Siddhartha Shenoy, a senior research chemist at DuPont Central Research and Development, said that PhD students need to understand where their area of expertise is and how it fits into the broader context of science. This contextual understanding is vital during collaborative exercises. Otherwise, graduate students can think of only one way to solve a problem, which leads to self-selection of ideas and concepts and stifles innovation. People need to know how to work within a team that transcends a single field.

This becomes especially important during brainstorming sessions, when a group of people with different backgrounds break a problem down into first principles. Because of their different backgrounds, the people in the group break the problem down in different ways. “When you reconstruct that problem as a collective, you end up coming up with a very unique solution.” Similarly, understanding where one fits on a team helps in writing proposals involving people in different departments, which is “where the problems of tomorrow lie.”

Shenoy reminded the participants that the term “doctor” in Latin means teacher, and graduate students need to learn how to teach. Many graduate students look at teaching as a burden, but this mentality should be abandoned. Teaching builds invaluable skills, such as deconstructing a problem and teaching someone the same concept in different ways. “I do this on a day-to-day basis in DuPont when I propose my own research. The way I engage people in hitching their wagon onto my ideas is by teaching them what I think is the way to do it.” Also, teaching a subject in front of 300 people forces a graduate student to really understand that idea. Graduate students should know how valuable those skills will be later in their careers, no matter what they do.

THE PERSPECTIVE FROM OTHER SECTORS

Regulatory Science

Heather Gennadios, a chemist in the Division of Manufacturing Technologies at the Center for Veterinary Medicine, U.S. Food and Drug Administration, said that one of the most valuable things she learned in graduate school was how to learn a new skill or technology quickly. This is a great skill to have in her current job, where she looks at a wide variety of products using different types of science and technology.

Time management was another valuable skill to learn. In graduate school, she had to prioritize to accomplish everything that needed to be done in the time available, which is also very applicable to her current job.

Interpreting data was emphasized in her graduate education. Is this a valid experiment? Were the correct controls utilized? Do the data look real? She uses the same skills in reviewing applications from industry at FDA.

Being comfortable speaking in front of an audience is another important skill to learn in graduate school, Gennadios said. It would have been even more valuable to learn to speak in front of a broad audience and write for nonspecialists, since she often does both at FDA but did not have an opportunity to do that in graduate school.

Like Tellers, she emphasized the importance of learning about career options in graduate school. "When I was in grad school, I really wanted to go into industry, . . . but I ended up working for the government. At the time I didn't know that was even an option. Communicate with the students and tell them, if you don't get your first choice, what alternatives or what other fields are out there that are applicable to their degree. I think that would be very helpful."

Scientific Publishing

Jake Yeston said that graduate school was excellent preparation for his job as senior editor at *Science* magazine, though he ended up in publishing through an "accident." One day, when he was finishing a postdoc, he was looking at the classified job ads in *C&E News* and saw that *Science* was looking for a chemistry editor. "That really wasn't a job that had been on my radar at all. In the back of my mind, I understood that there were people who were editors. Some of them were professors who did it part-time. Some of them were people for whom that was a full career. But I hadn't really played out that idea. . . . But when I looked at the ad, I thought, actually, I would be pretty good at that."

At Berkeley he had two advisors in different fields of chemistry, so he had learned two very different research paradigms. Exposure to multiple fields turned out to be valuable at *Science*, which publishes papers from different fields as well as interdisciplinary papers. Learning to communicate across disciplines in graduate school, as well as doing a postdoc in Germany and helping other chemists express themselves in English, helped him edit at the magazine.

Unfortunately, he said, there are relatively few jobs in scientific publishing. Many graduate students are interested in the career, but not many jobs become available at any given time. Also, the profession is currently in a state of flux, as are all areas of publishing. But "the science publishing world as a whole is certainly not going to go away." Graduate students should know more about the field: Who does it? What is the right publishing model? Is it good to have professor-edited journals? Is it good to have independent career people editing journals?

Yeston added that one thing that could use improvement in graduate education is safety expectations. Safety needs to be a constant consideration, much more cultural, and much less pro forma.

THE PERSPECTIVE FROM A VENTURE CAPITALIST

Graduate education is not preparing students sufficiently for the entrepreneurial workplace, said David Berry, a venture capitalist from Flagship Ventures, which is based in Cambridge, Massachusetts. Flagship Ventures, which invests mainly in life sciences and sustainability companies and currently has about 70 companies in its portfolio, runs its own laboratories in which it can develop technologies to address big problems, such as energy security, food security, and a cure for cancer. The Flagship team iterates the ideation, innovation, intellectual property generation, and implementation phases until a protocompany is ready to launch. The process has resulted in about 24 companies over the past decade. Berry himself has started companies valued at about $2 billion that have created about 1,000 jobs, 300 of which he has hired himself.

People who have come right out of PhD programs are incredibly deep experts in a very narrow subject area, said Berry. They work independently and are driven by credit in the form of papers and patents. They tend to dislike experimental risks and know what experiments they should do. They are functionally smart people but individual contributors.

But in an entrepreneurial ecosystem, the status of a technology or a company six months into the future is uncertain. The companies Berry founds are based on ideas no one else is pursuing, which means that subject matter experts do not exist. "If I find someone who is a deep subject-matter expert, it tells me that I should shut down the company because I don't have anything that is actually innovative."

In such a situation, deep experts tend not to have the broad skills that are needed. Instead, Berry looks for what he called "athletes"—people who are smart, team contributors, willing to go beyond their comfort zones, eager to tackle any sort of problem, goal focused, and incredibly creative.

Flagship Ventures tries to build the culture in its companies that being wrong and admitting mistakes is as important as being right. In unexplored scientific or engineering spaces, the *no* answers are often more important than the *yes* answers. The company, rather than any specific project, needs to succeed.

Berry said that new hires from traditional PhD programs in the sciences take about six months to unlearn their graduate school behaviors and become a highly functional member of a company. "As a result, we have very significantly reduced the number of people who have that attribute from our hiring pool." For example, a company Berry is running with 20 employees has changed its business plan two times in the eight months of its existence. "I can't afford to spend six months training people to break old habits when companies are growing that fast."

Master's Degrees

Along the continuum from bachelor's degrees to PhDs, Flagship Ventures has hired the most people from the master's level. These students have spent more time learning broad subject matter. They may have dropped out of a PhD program for some reason, and as a result they tend to have a "chip on their shoulder," said Berry, which they can channel into entrepreneurial activities. They want to do so something profound rather than deep, and they want to prove themselves. "We love bringing these people in. They haven't had the time to develop some of the bad habits of individualized behavior. They sit there and they are inspired. They work very closely with the team. They love direction. They love to learn."

Berry has also noticed what he called "profound differences" among people who get a three-year PhD, a four-year PhD, and a five-year PhD. Many people who have gotten their PhDs in three years are absolutely stellar performers. Their subject mastery is not necessarily the key. Rather, they are able to use the laboratory environment efficiently and productively. They form collaborations and inspire creativity in others. They know something about marketing and salesmanship. They tend to function more like postdoctoral fellows, said Berry, because they draw on the talents of other PhD students. They view relying on others not as a failure but as a means of achieving success. Their skills are more important than the fact that they completed their PhDs in three years. "I don't know that we can engineer everyone to be the greatest student in a lab."

Entrepreneuring

Berry distinguished between science as discovering, engineering as problem solving, and "entrepreneuring" as building companies. It is not a common word, but he prefers an active word rather than the more static "entrepreneurship." It involves bringing a discovery to the market in the context of a company. Successful entrepreneurs tend to use a multidimensional form of systems thinking that is coupled with selling a product and protecting market advantages. People who do very efficient PhDs tend to have these skills and are very desirable for small-scale companies.

Graduate school laboratories that encourage their students to do more engineering and innovation force those students to think about the relevance and potential uses of a discovery. Rather than a single solution, students tend to devise a set of potential solutions and figure out which solution can solve the problem. Also, thinking about the protection of intellectual property trains students to look for opportunity spaces, where science creates business opportunities and jobs.

Many new companies take insights from multiple disciplines to meet a challenge. For example, a Flagship Ventures company working on global nutrition challenges combines mechanical engineering, chemical engineering, biology, physics, chemistry, and other disciplines. "We don't actually have a single chemist on our team, but we have a lot of chemical expertise in various ways by people who have proven in their graduate education to be athletes, typically much more from the chemical engineering and biological engineering sides of things."

Opportunities

Multidisciplinary PhDs are intriguing from an entrepreneurial perspective, said Berry. In this case, doctoral students would not be siloed to a particular area like inorganic chemistry but would know something about all of chemistry.

Many recent PhD students who Berry decides to interview are interested in selling and marketing, but they may not have learned much about these subjects in school. Taking classes in business schools is not necessary, but there are many lessons to be learned from professors who have succeeded as entrepreneurs.

Students should also have opportunities to interact with technology transfer offices and learn about intellectual property and other legal aspects of entrepreneuring.

The boundaries in traditional graduate education have led to a series of systemic problems, said Berry. "If we can start to eliminate those boundaries and let the sciences and engineering become much more fluid places, we'll see a lot of these opportunities for expanding knowledge bases."

Being able to work in teams is critical. Flagship Ventures has a fellowship program for entrepreneurs that is oriented toward team-oriented problem solving. Groups of 20 or so people are divided into small groups and are given a problem to solve in eight weeks. Most people fail in this task, but the 5 percent who succeed "engage very actively in team behavior and are very active in knowing what they are good at and what they are not good at. . . . More often than not, they will come back with a solution, not to the problem that we proposed, but to something that's adjacent or to something that's bigger. In my mind, that's a behavior that we should all encourage."

In response to a question about online courses, Berry said that the more entrepreneurial people will quickly find the courses and subject matter that they need to learn. They also are quick to suggest to company leaders that the company should invest in these resources. But not many people are trying to supplant traditional education with online courses.

Bergman pointed out that requiring a lot of courses tends to let students relax, learn the material, and take the exams, after which much of the material is quickly forgotten. Putting students to work on problems, even if broadly based, could help them learn to find out things for themselves. Having students write their own research proposals also helps them learn to think independently, he said.

Berry responded that much of education, from kindergarten on, involves listening to a talking head instructor rather than problem solving. "It's the way that we have learned to learn." In contrast, educational programs that challenge students to solve problems can engage at least some portion of students much more actively, and the percentage could increase if this approach were more widely used.

5

Structure of Chemistry Graduate Education

"Each university has to look at the environment that it is in, look at its history, look at its objectives, look at its resources, and set goals. If that goal is the same for every university, we have failed in leadership. But if we can provide different paths for success for universities that meet societal needs, . . . we will have been successful."

—Gary Schuster, Georgia Institute of Technology

The structure of graduate education reflects both the broad goals of that education and the specific skills graduate training is meant to impart to students. This chapter summarizes comments from the workshop participants on four structural aspects of chemistry graduate education: the degrees earned, the funding of graduate students, engaging in interdisciplinary research, and partnerships with industry. It concludes with a brief discussion of how chemistry graduate education might change as it responds to current pressures and trends.

MASTER'S DEGREES AND DOCTORAL DEGREES

The time it takes to earn a PhD and the activities undertaken during that time were major topics of discussion at the workshop. During his presentation, George Whitesides suggested several alternatives to current structures. Students could earn a two-year master's degree that has independent value in the workforce and then a three-year PhD. Alternately, students could do a three-year PhD and a two-year postdoc. Graduate students could take one year out of graduate school to do public service or work in a foreign country. Another possibility is reinstating a serious vocational master's program such as those that have been so successful in Germany, where high-wage manufacturing workers can compete on a global stage because of their high-quality technical training.

Regarding three-year PhD programs, Kristie Boering noted that such programs are required in Europe. But there the requirement tends to result in low-risk projects. "If graduate students have to have their PhD in hand in three years, you can't have them do interesting, innovative research."

The time to the PhD was shorter many years ago, noted Robert Bergman. Though some of the more complicated problems undertaken in graduate school today require more time, "the issue of doing imaginative or unimaginative research is more a question of the mindset of the supervisor than it is the opportunities in the science," he said. "Lots of really interesting stuff can be done in three years."

Bergman suggested that if students take more than three years to become well-trained investigators, they could do research with multiple groups and advisors. The resulting diversity of approaches could be "very helpful to the students in recognizing that there are multiple ways of thinking about problems."

Bergman also suggested that having multiple advisors could help graduate students from being mistreated by a single advisor. Also, students should have some recourse if they are in a research group where they are not being treated well.

Boering pointed out that graduate students could have a single faculty advisor but still engage in extensive collaborative work. Students could spend time either in other universities or in industry; for example, she sends her students all around the world to participate in research collaborations. Matthew Platz added that researchers are free at any point to ask NSF for a supplemental award for such purposes.

Siddhartha Shenoy observed that not every graduate student needs to get a PhD. Many people could leave with a master's degree and have a great career doing something they enjoy, which is focusing on one problem in the lab. "Forcing them to write an independent proposal that was completely different from their research—it was pushing them into an area that they didn't want to be in. It was outside their comfort zone." One possibility would be to have all graduate students earn master's degrees and then have them demonstrate why they want to go on to get a PhD.

Similarly, Michael Doyle pointed to chemistry graduate education in Japan, which is focused largely on producing technically trained master's degree recipients to work in industry. In Japan, PhD degrees are often preparation for leadership positions, and a comparable shift could occur in the United States.

Several workshop participants described the strengths and weaknesses of existing master's degree programs. For example, Cornell University has a master's of engineering program organized around issues like energy and industrial biotechnology. Some of these students go on to get a PhD, but most go to work in industry.

The masters's program at Georgia Institute of Technology is also interdisciplinary. For example, the master's in quantitative finance is shared among the computer science department, the psychology department, and the business school. Most are coursework master's programs with a research component during the summer, which is usually done through an internship.

Several participants also pointed to some of the drawbacks of existing master's degree programs. They have the potential to be focused more on making money for universities than giving students useful workforce skills. Several of the industry representatives said that they do not look toward students with master's degrees to fill important openings in their research divisions. Joe Francisco pointed out that universities that produce many master's degrees tend to be ranked lower than those that produce large numbers of PhDs, which may act as a disincentive to such approaches given current ranking systems.

Barbara Gerratana from NIGMS pointed to another position that tends to be overlooked in universities: that of a lecturer who does not conduct research. At universities, lecturers are often treated as second-class citizens. However, lecturers can make valuable contributions to teaching, and these can be good careers for students with PhDs. She also observed that in Finland, which leads the world in measures of student performance, it is harder to get into a master's program for teaching than to get into medical school. Skilled teachers in U.S. schools could have a tremendously positive influence on how students are educated and prepared for the workforce, she said.

FUNDING OF GRADUATE STUDENTS

Graduate students currently draw on four major sources of support: research assistantships, teaching assistantships, fellowships, and traineeships. All have pros and cons.

Research assistantships make students very dependent on faculty members for both research guidance and financial support. If a faculty member loses financial support, a student is unlikely to get through a PhD program quickly. However, research assistantships also can create strong and enduring bonds between a student and a researcher that can pay many dividends to both parties.

The type of teaching undertaken as part of a teaching assistantship makes a difference in the skills a student acquires. For example, teaching a large undergraduate freshman lab is not necessarily a valuable experience for a graduate student, Aaron pointed out. But learning how to teach lecture classes is very important. "My advisor allowed me to guest lecture for him when he was traveling for meetings, and the experience of putting together an hour lecture was really valuable." Similarly, Samuel Thomas said that outreach activities are most fulfilling when they are something students or faculty members are passionate about. For instance, he has been working with community colleges more than other educational institutions because he is more interested in community colleges.

Several workshop participants said that students with fellowships often enroll at a small number of elite universities, which tends to undermine broad political and policy support for these programs. Such fellowships also may deprive graduate students of useful experiences, such as teaching assignments. For example, Jennifer Schomaker agreed that she would have been well served by more experience as a teaching assistant, which she did not do because of her fellowship. "I was able to get it in other ways, but I think it is very important to get up there in front of a class and take a group of students who understand basically nothing and try to make the material accessible to them." Students with fellowships also may not have as strong a relationship with their faculty advisors as other students because they are not dependent on that advisor for support.

Bergman raised the issue of encountering objections from NSF about students with fellowships teaching because it amounts to using NSF funding to benefit the department rather than the student. Platz responded that the fellowship office at NSF felt that departments were using the fellowship program to help solve financial problems, which was not the intent of the program.

Traineeship programs in which particular institutions are funded to provide training for students avoid some of the problems associated with assistantships and fellowships. Students would not be dependent on faculty research funds, while departments would still have autonomy in deciding how to distribute support. As a provocative proposal, Platz asked how the funding situation would change if NSF devoted only 30 percent of its funding to individual investigators and gave much of the rest to institutions to distribute to faculty members as they chose.

A combination of support mechanisms for any given student is an intriguing option. For example, Paul Houston proposed supporting a student for one year as a teaching assistant, for two years on fellowships, and for two years doing research in a particular faculty member's laboratory. "It would be nice if we had some flexibility in the funding to allow that to happen."

ENGAGING IN INTERDISCIPLINARY RESEARCH

Many workshop participants noted that as the research carried out in universities becomes more collaborative and interdisciplinary, the structural divisions among departments are likely to diminish. Funding agencies could promote this process by funding interdisciplinary projects and centers. Joint appointments also help to break down barriers, so long as structures are in place to deal with such issues as promotion and tenure. Colocating people also reduces barriers, though then department members may not be found near each other. They may be scattered across multiple buildings.

Such changes are likely to have significant effects on graduate education. For example, students could have different interactions with faculty advisors when working on interdisciplinary projects. This need not be a problem, several presenters said, so long as faculty members are not exclusively focused on their own interests and to the exclusion of students' interests. The most important aspect of these interactions, said David Tellers, is quality rather than quantity. Students need honest feedback about how they are doing so they can make good decisions about their futures. Heather Gennadios added that advisors should not micromanage, but allow students to explore and make their own. "It's a careful line to tread for the advisor. You don't want to tell the student how to do everything. You want them to learn for themselves." Shenoy said he has worked on projects where he saw the faculty advisor too frequently, mostly because the advisor was more interested in that research area than others in the lab.

Some students may not be well served by working on more broadly based projects. Jake Yeston, for example, said that he particularly liked graduate school because it is an all-consuming endeavor. "You live, eat, and breathe chemistry," he said. "When I was in graduate school, the world outside of the Berkeley campus could have fallen apart and I barely would have noticed." Making graduate school less focused would be good for some people and worse for others. "It's possible that . . . you would lose something among the people who really do want to spend all of their waking hours doing that [working in a laboratory]."

A complication of a more interdisciplinary research environment is how students and young faculty members will be evaluated for jobs and promotion, many workshop participants noted. One possibility is to use interdisciplinary review panels such as those convened to evaluate interdisciplinary research proposals. Such panels could evaluate a person's contributions to solving a problem rather than to a specific discipline. Quantitative metrics will still exist, such as publications and the success of individual students, but somewhat different perspectives may be required.

PARTNERSHIPS WITH INDUSTRY

Bill Beaulieu said that the potential for universities to work with companies has barely been addressed. "A lot of businesses would enjoy the opportunity to leverage off the talent in universities to augment what we can do internally." Both partners can learn from the other, producing more rapid progress in both discovery research and development.

In his presentation, Whitesides said that university research programs should not be built around technology. When a research project is finished in the academic lab, it can be moved out to a spinoff company or an established firm. These technologies can create jobs for the future and should not be ignored, he said. In particular, ideas that originate in the United States should benefit this country, not other countries that pick up the ideas and develop them into products.

Rajiv Dhawan emphasized the role of internships in providing a breadth of experience in graduate education. Finding opportunities for large numbers of PhD students may be difficult, the internships would need to be funded, and there may be issues of liability or safety. But industry has experience with internships and could overcome these barriers.

Warren Jones from NIGMS noted that the 20 or so biotechnology training grant programs across the United States supported by the institute have a required industrial internship component. "The experience has been almost uniformly positive," he said. "The student wins, the industry wins, and the home host laboratory wins." Students learn what it is like to do research in a different environment, pick up new skills, and bring those skills back to their home lab. However, when universities initially encounter the requirement, they tend to be opposed to it, because faculty advisors do not like losing their students for several months to another setting. Not until they see how well it works do they agree to its value.

Internships are also a pathway to future employment. Degnan said that ExxonMobil hires 50 to 60 percent of its new employees via internships, which are offered to both undergraduates and graduates. Internships are available both over the summer and during the school year, and some offer students a chance to work in industrial labs while conducting their PhD research.

Many workshop participants said that intellectual property issues can be a complication in partnerships between companies and industry. Encouraging university faculty to patent more of their ideas could ease these complications while also making academic chemistry more valuable and relevant to industrial partners. On the other hand, Degnan observed that patenting ideas and maintaining those patents can be expensive. "You have to be prepared for that expenditure on an ongoing basis if you are really going to go do that."

Finally, Joe Francisco pointed to the value of online training to prepare students before they go to a new setting, whether that setting is in another laboratory, in industry, or in another country. For example, Purdue is developing online training for international students to help them transition easily into the laboratory.

INSTITUTIONAL CHANGE

In the final discussion session of the workshop, Platz noted that some institutions may have the resources to avoid change. But effective leaders will see the current time of change as an opportunity to improve graduate education.

Schuster suggested that the key is going to be diversification among universities. Not every one of the 3,000 universities that receive some sort of federal support can or should do the same things. The missions of these universities and departments will need to be further segmented. That was the situation before World War II, when universities received much more money proportionately from the states and were more responsive to their local environments.

Universities need to graduate PhD students trained for top-level academic, corporate, and government jobs, Schuster said. But other jobs need to be filled, too. How can those students be given the experiences and skills they will need? "Each university has to look at the environment that it is in, look at its history, look at its objectives, look at its resources, and set goals. If that goal is the same for every university, we have failed in leadership. But if we can provide different paths for success for universities that meet societal needs, . . . we will have been successful." Merit-based scholarships and fellowship programs could support this diversification, according to Schuster. Even if some of the funds flow to a few universities, other institutions could be funded through other mechanisms.

Wilfredo Colon pointed out that the top 10 or 20 percent of graduate students will always be fine, because they will get the best industrial and academic jobs. But what about the other 80 percent of students? One challenge for chemistry graduate education is how it can serve the entire population of graduate students.

Several workshop participants observed that a relatively small number of graduate programs have always produced the majority of PhDs in chemistry. The question then becomes what role other institutions can play and whether their programs are sustainable. Graduate education is an inherently elitist undertaking, since chemistry departments always want to attract the best students. However, times of rapid change are also when graduate programs can rapidly improve, especially among small schools and departments that have more dexterity than large institutions.

One suggested option is to look at graduate education in other countries to find how those nations are responding to similar pressures. In addition, Joydeep Lahiri from Corning urged that universities think about how they are unique. The leading universities have the resources to be strong in all disciplines of chemistry, but not every university does. Uniqueness should be considered a strength and a source of competitive advantage rather than a weakness.

BUILDING ON STRENGTHS

At the end of his presentation, Schuster recalled a phrase attributed to ancient China: "no one is as smart as everyone." Though the workshop participants were very broadly based, they did not represent all of chemistry. He and other speakers urged the participants to continue the conversations started at the workshop among themselves and with other chemists after the workshop ended.

Schuster also pointed out that the chemistry graduate education "over the last 60 or 70 years has been remarkably successful in doing what it has been asked to do. The science and the technology and the innovation and the job creation that have come out of graduate research in this country are the envy of the world." As such, it will be important for universities to build on their strengths as they change and not lose sight of what they have done and continue to do right.

It can be hard for people within the system to realize that the world is changing around them, Schuster said, but a failure to change can guarantee obsolescence. "You have to be able to step out of what you are doing and find a new that works in the current environment."

He suggested that the graduate chemistry community continue to think about how to devise experiments that will attract creative and committed people. "The risk of failure of one of these solutions is going to be high, but of several of them, maybe one is going to be successful, and that can be a paradigm-shifting approach."

6

Suggested Ideas to Change Chemistry Graduate Education and Skills to Benefit Students

This final chapter compiles ideas mentioned in previous chapters into a single list, with the person suggesting that idea identified in parentheses. The ideas have been divided into those focused primarily on students and faculty members and on department chairs, deans, and other research administrators, though many of the ideas apply across categories and have different implications for different groups. This chapter also lists skills discussed by individual presenters that could benefit students if taught during chemistry graduate school.

The suggestions should not be seen as recommendations of the workshop, the Board on Chemical Sciences and Technology, or the National Research Council. However, together with the list of skills cited in Box 6-1, they point to the tremendous potential of chemistry graduate education as it adapts to current challenges.

IDEAS FOR CHANGE FOCUSED ON STUDENTS AND FACULTY MEMBERS

- Greater clarity regarding the expectations of both graduate students and faculty advisors would reduce conflicts and confusion. (Dorhout)
- Encouragement from advisors to learn about areas outside a graduate student's research area can produce greater breadth in graduate education. (Aaron)
- Exposure to information about different careers in graduate

Box 6-1
Skills Discussed by Individual Presenters that Could Benefit Students if Taught During Chemistry Graduate School

The speakers at the workshop described many skills that chemistry graduate schools could teach to prepare students for the challenges they will face in the workplace. The following list is drawn from the summaries of their talks in this chapter. While all students could not be expected to learn all of these skills during graduate school, many workshop participants noted that mastering a subset of them could help them in their future careers.

Education

Constructing chemistry curricula and laboratories for undergraduates
Teaching undergraduate chemistry
Explaining concepts in different ways for diverse groups of students
Mentoring undergraduates

Research

Generating scientific research ideas independently
Preparing research proposals
Recording, interpreting, and storing data responsibly
Writing and publishing scientific papers
Acquiring a thorough familiarity with safety procedures and disseminating those procedures
Working in groups, including interdisciplinary groups
Interacting with funding agencies and managing the finances of a research team
Reviewing proposals and articles

Entrepreneurial

Transforming scientific ideas into business plans
Understanding how to sell products and protect market advantages
Interacting with technology transfer offices and intellectual property lawyers

Personal

Managing time effectively
Communicating orally and in writing with nonscientists
Interacting with the community outside research institutions
Learning to manage other people
Learning to be adaptable and acquire new skills
Thinking creatively and critically
Exhibiting leadership
Approaching a problem from a broad-based perspective

school, including opportunities to meet with chemistry PhDs who have entered those careers, can provide graduate students with information they need to make career decisions. (Schomaker)
- Graduate education can be excellent preparation for a teaching career either in higher education or K-12 education. (Gerratana)
- Teaching skills are important in industry as well as in academia to explain ideas and urge particular actions. (Shenoy)
- Opportunities to teach and mentor undergraduates and other students improves communication skills and understanding of the material being taught. (Schomaker)
- The opportunity to write and revise research proposals in graduate school, with feedback from advisors, can provide experience useful in many future careers. (Shomaker)
- Research done in interdisciplinary groups with multiple advisors could broaden graduate education and expose students to a diversity of approaches, as well as helping to prevent mistreatment of graduate students. (Bergman)
- Alternately, research projects under single advisors but with extensive collaborations could provide both breadth and depth in graduate education. (Boering)
- Exposure to "entrepreneuring" during graduate school can help students think about the relevance and potential uses of a discovery. (Berry)
- Letting graduate students work together and practice submitting proposals to business colleagues could help them thrive in the private sector. (Lahiri)
- Enhanced partnerships between universities and companies could provide valuable experiences for chemistry graduate students. (Beaulieu)
- Internships could greatly broaden the experiences of graduate students in chemistry while also benefiting university research. (Dhawan)
- Education programs at any level that challenge students to solve problems can engage students more actively. (Berry)
- Efforts to coordinate proposals for chemistry research and graduate education with federal priorities could increase funding for chemistry. (Platz)

IDEAS FOR CHANGE FOCUSED ON DEPARMTENT CHAIRS, DEANS, AND OTHER RESEARCH ADMINISTRATORS

- Depth, breadth, and communication could be themes for transforming graduate chemistry education. (Colon)

- Rotations in graduate school before beginning a research project can broaden exposure to topics in chemistry and forge important relationships. (Schomaker)
- Reducing the barriers between traditional fields of chemistry and involving other disciplines in research projects may enable faster progress on integrative problems. (Whitesides)
- Support from funding agencies, joint appointments, and the co-location of investigators from different disciplines all can help promote interdisciplinary research. (Houston)
- Innovative, interdisciplinary, and collaborative projects can build faculty morale even when resources are constrained. (Fox)
- Written individual development plans for all graduate students and postdocs supported by research grants or traineeships could help students set goals and adhere to them. (Rogers)
- A course for graduate students on teaching chemistry could build essential teaching skills. (Aaron)
- A progression of different support mechanisms for graduate students could help meet their changing needs as they move through graduate school. (Houston)
- New structures for graduate education—such as a separate master's degree with value in the workplace, time spent doing public service or work in a foreign country, or degrees that take less time to achieve—could have advantages for students and employers alike. (Whitesides)
- Master's degrees could focus on technical skills while PhDs focus on leadership skills, as is the case in Japan. (Doyle)
- Family-friendly policies and supportive colleagues can reduce the attrition of women in graduate chemistry education. (Boering)
- Chemistry departments that reimagine the graduate experience in a compelling way could generate national attention, be seen to have a competitive advantage, and spur imitators. (Platz)
- Greater emphasis on safety in graduate school is important both in graduate school and during careers. (Yeston)
- Enhancing partnerships between universities and companies could provide valuable experiences for chemistry graduate students. (Beaulieu)

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A

Committee on Chemistry Graduate Education Statement of Task

An ad hoc committee will plan and conduct a public workshop to discuss the graduate education in chemistry in the context of a changing environment for the practice of chemistry. The workshop will focus on the goals of graduate education in chemistry, and whether current programs align with goals appropriate for the current era. The workshop will include invited presentations and discussions of the following topics:

—Attracting and retaining the most able students to graduate education

—Financial stressors on the current support model and their implications for the future graduate education model

—Competencies needed in the changing job market for Ph.D. chemists. This includes nontraditional opportunities such as entrepreneurship, and employment in start-ups or other small businesses. It also includes changes in traditional opportunities such as the increasing off-shoring of basic chemistry research by major firms, and the evolving drug-discovery model and its impact on employment in the pharmaceutical sector.

—Competencies needed to address societal problems such as energy and sustainability

A summary of the workshop discussions will be produced and disseminated.

B

Workshop Agenda

Challenges in Graduate Education
January 23-24, 2012
National Academies Keck Center, Room 100
500 5th Street NW
Washington, DC

Monday, January 23

8:30 a.m. Welcome, Objectives, and Introductions; Joe Francisco, Purdue University; Chair, Workshop Organizing Committee

Overview—Drivers for this Workshop

8:45 a.m. Introductory remarks; Matthew Platz, Director, Division of Chemistry, NSF

9:15 a.m. ACS Presidential Commission on Graduate Education; Bassam Shakhashiri, President-Elect, American Chemical Society

9:30 a.m. The Path Forward: The Future of Graduate Education in the US; Patricia McAllister Vice President for Government Relations and External Affairs, Council of Graduate Schools

10:00 a.m. Break

10:15 a.m. "Graduate School. What is it supposed to do?" George Whitesides, Woodford L. and Ann A. Flowers University Professor, Harvard University (via web)

10:45 a.m. Chemistry Education: Fulfillment of Professional and Societal Goals; Gary Schuster, Vasser Woolley Professor, Georgia Institute of Technology

The Social Compact—Addressing Societal Challenges

11:15 a.m. David Berry, Flagship Ventures

11:45 a.m. Lunch

Stressors on the current model for chemistry graduate education

1:00 p.m. Panel Discussion: What challenges may force changes in the way departments currently recruit, fund, and train graduate students in chemistry?

Holden Thorp, Chancellor, University of North Carolina (via web)
Marye Anne Fox, Chancellor, University of California at San Diego
Paul Houston, Dean, College of Sciences, Georgia Institute of Technology
Mike Doyle, Chair, Department of Chemistry, University of Maryland at College Park

2:15 p.m. Break

Chemists in Non-Academic Settings: How well is graduate training preparing PhDs to solve problems outside the academic setting?

2:30 p.m. Panel Discussion: What are the skills industry managers need in PhD chemists, and how is employment of chemists and the skills they need evolving?

Thomas Degnan, ExxonMobil Research and Engineering
Bill Beaulieu, Chevron Phillips Chemical
Sandy Mills, Vice President, Discovery and Preclinical Sciences, Merck Sharp & Dohme
David Kronenthal, Vice President of Chemical Development, Bristol-Myers Squibb
Joydeep Lahiri, Division Vice President and Director of Bio and Organic Research, Corning, Inc.
Rajiv Dhawan, Talent Acquisition Manager, Du Pont Technology, E.I. Du Pont de Nemours, Inc.

4:00 p.m. Panel Discussion: What skills have served recent graduates well in their positions, and what additional skills would have been useful as they began their careers?

David Tellers, Merck Sharp & Dohme
Sid Shenoy, E.I. Du Pont de Nemours, Inc.
Heather Gennadios, US Food and Drug Administration
Jake Yeston, Senior Editor, *Science*, American Association for the Advancement of Science

5:00 p.m. Adjourn

Tuesday, January 24

Preparing the next generation of faculty

8:00 a.m. Panel Discussion: How well does graduate training prepare PhDs to become faculty?

Jennifer Schomaker, Assistant Professor of Chemistry, University of Wisconsin at Madison
Samuel Thomas, Assistant Professor of Chemistry, Tufts University
Julie Aaron, Assistant Professor of Chemistry, DeSales University

9:30 a.m. Agency efforts: NIGMS program to mentor junior faculty; Bob Lees, National Institute of General Medical Sciences

10:00 a.m. Break

10:15 a.m. Open Discussion: Are graduate chemistry programs serving our students well?

- Where are innovations needed to improve or enhance the training our students receive, and their preparedness to address the next generation of research challenges?
- What are the barriers to achieving innovation in graduate chem. programs?
- What should the graduate program of the future look like?

11:30 a.m. Wrap up; Closing remarks, Joe Francisco

12 noon Adjourn

C

Biographical Information

COMMITTEE MEMBERS

Dr. Robert Bergman received his Ph.D. at the University of Wisconsin in l966 under the direction of Jerome A. Berson. He spent 1966-1967 as a postdoctoral fellow in Ronald Breslow's laboratories at Columbia, and following that joined the faculty of the California Institute of Technology. After ten years at Caltech he accepted a Professorship at the University of California, Berkeley, and a joint appointment at the Lawrence Berkeley National Laboratory; in 2002 he was appointed Gerald E.K. Branch Distinguished Professor at Berkeley. Among his honors are a Sloan Foundation Fellowship, a Dreyfus Foundation Teacher-Scholar Award, the American Chemical Society Award in Organometallic Chemistry, election to membership in the U.S. National Academy of Sciences and American Academy of Arts and Sciences, the U. S. Department of Energy E.O. Lawrence Award in Chemistry and the American Chemical Society Arthur C. Cope Award, and the Royal Society of Chemistry Sir Edward Frankland Prize Lectureship. Bergman has long been interested in exploratory and mechanistic studies in organic and organotransition metal chemistry. He is probably best known for his discovery of the thermal cyclization of cis-1,5-hexadiyne-3-enes to l,4-dehydrobenzene diradicals, a transformation that has been identified as a crucial DNA-cleaving reaction in several antibiotics that bind to nucleic acids, his discovery of the first soluble organometallic complexes that undergo intermolecular insertion of transition metals into the carbon-hydrogen bonds of alkanes, and his work on the synthesis and cycloaddition reactions of complexes with metal-heteroatom multiple bonds. His research has recently expanded to include application of carbon-hydrogen bond activation to problems in synthetic organic chemistry, nanovessel catalysis, and methods for the conversion of biomass to fuels and commodity chemicals.

Dr. Joe Francisco is currently a William E. Moore Distinguished professor of Chemistry at Purdue University within the Departments of Chemistry and Earth and Atmospheric Sciences. Dr. Francisco received his B.S. from the University of Texas at Austin (1977), and his Ph.D. from the Massachusetts Institute of Technology (1983). Upon completion of his Ph.D., Dr. Francisco was a Postdoctoral Research Fellow at Cambridge University in England (1983-1985). He was also a Provost Postdoctoral Fellow at the Massachusetts Institute of Technolgy (1985). Dr. Francisco's many achievements and recognitions include President of the National Organization of Black Chemists and Chemical Engineers, 2006-2008; Alexandar von Humboldt Research Award for Senior U.S. Scientists, 2001; Fellow of the American Association for the Advancement of Science, 2001; Fellow of the American Physical Society, 1998; Guggenheim Fellowship, 1993; Research Associate, California Institute of Technology, 1991; Dreyfus Teacher-Scholar, 1990-95; Alfred P. Sloan Research Fellow, 1990-1992; National Science Foundation Presidential Young Investigator, 1988-1993; Provost Postdoctoral Fellow, Massachusetts Institute of Technology, 1985.

Dr. Charles T. Kresge is the Global R&D Director for Research and Engineering Sciences, Core Research & Development, of The Dow Chemical Company. His career with Dow began in 1999 when Kresge joined Corporate R&D in Midland as Global R&D Director. Before joining Dow, Kresge was a senior member of the technical leadership for the Strategic Research Center, Mobil Technology Company, Mobil Corporation. He joined Mobil in 1979 as a research chemist in the Catalyst Synthesis & Development Group in Paulsboro, New Jersey. Kresge then went on to hold various research positions dealing with the discovery, development, and commercialization of catalytic materials and processes. In 1985, Kresge joined W. R. Grace & Company as Group Head, Fluid Catalytic Cracking Research. He returned to Mobil in 1987 to become head of the Exploratory Synthesis & Characterization Group at Mobil's Paulsboro, New Jersey, Laboratory. In 1993, Kresge became head of Mobil's activities for catalyst synthesis, characterization, and applications at Mobil's Princeton and Paulsboro, New Jersey, Research Laboratories. This role was expanded in 1995 to include membranes, separations media, and inorganic materials science. Kresge became the technology leader and chief scientist for exploratory materials chemistry research at Mobil in 1997. In April 1999, Kresge joined Dow to assume his current position. Kresge is the corecipient of The Donald W. Breck Award in Molecular Sieve Science; recipient of an R&D 100 Award for Innovation and The Robert A. Welch Foundation Invited Lectureship in Nanochemistry; Chair, Gordon Research Conferences on Zeolitic and Layered Materials; Guest Editor, *Current Chemistry: Current Opinion in Colloid and Interface Science*; Editorial Board, *Journal of Solid State Chemistry* and *Advanced Functional Materials*; member of the Boards for the International Zeolite Association, Mesoporous Materials Association, and the International Congress on Catalysis; member, Council of the Gordon Research Conferences; member, Chemical Sciences Roundtable of the National Research Council; a member of the American Chemical Society, and a member of the University of California, Santa Barbara, Chemical Engineering Advisory Board. Kresge holds over 100 patents dealing with novel catalysts and their applications. He has presented over 50 invited talks and plenary lectures to the materials and catalysis communities and is the author of over 50 articles in scientific literature dealing with catalytic materials. Kresge is listed as one of the 100 most cited authors of the last ten years. His work was cited as one of the most important discoveries in chemistry in the last 75 years by the American Chemical Society. Kresge holds a bachelor's degree in chemistry from Swarthmore College and a doctorate in physical chemistry from the University of California, Santa Barbara.

Dr. Douglas Ray is the Associate Laboratory Director for the Fundamental & Computational Sciences Directorate at the Pacific Northwest National Laboratory (PNNL). Dr. Ray is responsible for PNNL's research programs conducted for the Department of Energy's Office of Science and for the National Institutes of Health. He directs more than 500 staff members in four research divisions: Atmospheric Sciences & Global Change, Biological Sciences, Chemical and Materials Science, and Computational Sciences & Mathematics. Dr. Ray joined PNNL in 1990. A laser spectroscopist, Dr. Ray's research interests include the effects of weak intermolecular interactions on chemical phenomena in condensed phases, at interfaces, in clusters and in supramolecular complexes. He earned a B.S. degree in Physics from Kalamazoo College and a PhD in Chemistry at the University of California at Berkeley. Dr. Ray is a member of the American Chemical Society, American Physical Society, American Geophysical Union, and American Association for the Advancement of Science.

SPEAKERS

Dr. David Berry is a Partner at Flagship Ventures, where he focuses on investing in and founding early-stage life science and sustainability ventures. He is a founder of Flagship portfolio companies LS9, Joule Unlimited, Theracrine, Eleven Biotherapeutics, Essentient, among others. David currently serves as founding CEO at Essentient, and previously served as founding CEO of Joule and Theracrine. David received a PhD from MIT and an MD from Harvard.

Dr. Robert (Bob) Lees, Ph.D., is a program director in the Division of Pharmacology, Physiology, and Biological Chemistry at the National Institute of General Medical Sciences, where he manages grants in synthetic organic chemistry. Prior to joining the National Institute of General Medical Sciences (NIGMS), he was a program director in the Developmental Therapeutics Program in the Division of Cancer Treatment and Diagnosis at the National Cancer Institute. Lees earned a B.S. in chemistry from Duke University and a Ph.D. in organic chemistry from Stanford University. He conducted postdoctoral research at the Massachusetts Institute of Technology.

Patty McAllister serves as Vice President of Government Relations and External Affairs at the Council of Graduate Schools in Washington, DC. She represents the interests of graduate education with federal policy makers, opinion leaders and other stakeholders. She is an experienced executive, having previously served as Executive Director of Public Affairs in the Communications and Public Affairs Division of Educational Testing Service (ETS), where she was responsible for directing a corporate-wide initiative on teacher quality. Previously at ETS, she served as Executive Director of State and Federal Relations for eight years. Ms. McAllister is a contributing author of *The Path Forward: The Future of Graduate Education in the United States (2010).* She has provided overall direction for the production of numerous reports including *Broadening Participation in Graduate Education (2009); Graduate Education and the Public Good (2008); Graduate Education: The Backbone of American Competitiveness and Innovation (2007); Where We Stand on Teacher Quality (2004);* and *the No Child Left Behind Act: A Special Report (2002).* She holds a BA in political science and a master's degree in Public Administration (MPA).

Dr. Matthew Platz is the Division Director for the National Science Foundation Division of Chemistry. Dr. Platz was born in Bronx, New York and obtained B.Sc. degrees in chemistry and mathematics from the State University of New York at Albany in 1973, and a Ph.D. in chemistry from Yale University in 1977. Following a post doctoral year at the University of Chicago, he joined the faculty of The Ohio State University as an Assistant Professor of Chemistry in 1978. Dr. Platz was promoted to Associate Professor in 1984, to full Professor in 1990 and served as Department Chair from 1994-1999. He has won university awards for distinguished teaching and research and in 2001 he was named Distinguished University Professor of Chemistry. Dr. Platz maintains an active research laboratory, which is funded by the National Science Foundation and the National Institutes of Health. A common theme is the use of photochemical techniques to generate and study highly reactive intermediates such as carbenes and nitrenes. His research has been recognized by the Cope Scholar award of the American Chemical Society and the Remsen Award.

Dr. Gary Schuster is currently the Vasser Woolley Professor within the Department of Chemistry and Biochemistry at the Georgia Institute of Technology. Dr. Schuster received his B.S. from Clarkson College of Technology (1968), and his Ph.D. from the University of Rochester (1971). Dr. Schuster was the recipient of the Chancellor's Award, University System of Georgia–1998; the American Chemical Society A C. Cope Scholar Award, Paul Flory-IBM Fellowship, and the ACS Herty Medal. Dr. Schuster's research interests include oxidative damage to DNA. The loss of an electron (oxidation) of duplex DNA results in the formation of a nucleobase radical cation (electron "hole") that is subsequently consumed in chemical reactions that often lead to mutations. We have found that nucleobase damage need not occur at the site of the initial oxidation. Radical cations in DNA can migrate long distances (hundreds of Å) by a reversible hopping process before being trapped irreversibly by reaction with H_2O and O_2. A defining characteristic of this process is the preferential reaction at guanine. We showed that the reactions of nucleobase radical cations in DNA are determined by the specific sequence of bases that comprise the oligonucleotides. In particular, Dr. Schuster's team observes that under certain circumstances oxidative reactions occurs at thymines despite the fact that it has a high oxidation potential. The consequences and mechanism of this reaction are under active investigation.

Dr. Bassam Shakhashiri is the first holder of the William T. Evjue Distinguished Chair for the Wisconsin Idea at UW-Madison. He is well known internationally for his effective leadership in promoting excellence in science education at all levels, and for his development and use of demonstrations in the teaching of chemistry in classrooms as well as in less formal settings, such as museums, convention centers, shopping malls, and retirement homes. The *Encyclopedia Britannica* sites him as the "dean of lecture demonstrators in America." His scholarly publications, including the multi-volume series, *Chemical Demonstrations: A Handbook for Teachers of Chemistry*, are models of learning and instruction that have been translated into several languages. He is an advocate for policies to advance knowledge and to use science and technology to serve society. He promotes the exploration and establishment of links between science, the arts and the humanities, and the elevation of discourse on significant societal issues related to science, religion, politics, the economy, and ethics. Professor Shakhashiri is the 2011 President-Elect of the American Chemical Society, and will serve one-year terms as president in 2012 and immediate past president in 2013. He completed undergraduate work at Boston University (Class of '60) with an A. B. degree in chemistry, served as a teaching fellow at Bowdoin College for one academic year and then earned M.Sc. and Ph.D. degrees in chemistry at the University of Maryland (1964 and 1968, respectively). After a year of postdoctoral research and two years as a junior member of the chemistry faculty at the University of Illinois-Urbana, Professor Shakhashiri joined the faculty of the UW-Madison in 1970, a position he still holds. In 1977 he became the founding chair of the UW System Undergraduate Teaching Improvement Council, now called the Office of Professional and Instructional Development. In 1983 he founded the Institute for Chemical Education (ICE) and served as its first director. His work with ICE inspired the establishment of the Center for Biology Education, the Merck Institute for Science Education, the Miami University (of Ohio) Center for Chemical Education, the Sacred Heart University SMART Center, and others. In 2002 he founded the Wisconsin Initiative for Science Literacy (WISL) and continues to serve as its director. From 1984 to 1990 Professor Shakhashiri served as Assistant Director of the National Science Foundation (NSF) for Science and Engineering Education. As the NSF chief education officer he presided over the rebuilding of all the NSF efforts in science and engineering education after they had been essentially eliminated in the early 1980s. His leadership and effectiveness in developing and implementing national programs in science and engineering education have helped set the annual NSF education budget at its current level of over $900 million. His NSF strategic plan launched the systemic initiatives and most of the other NSF education programs of the last two decades. Professor Shakhashiri is an elected fellow of the South Carolina Academy of Science, the Alabama Academy of Science, the New York Academy of Science, and the Wisconsin Academy of Sciences, Arts and Letters. He is the recipient of honorary doctoral degrees from George Washington University, Illinois State University, Ripon College, University of Colorado, Grand Valley State University, University of South Carolina and Lebanese American University. He is a national and international consultant to government agencies, academic institutions, industry, and private foundations on policy and practice matters related to science and to education at all levels. Professor Shakhashiri and his wife June live in Madison.

Dr. George M. Whitesides was born August 3, 1939 in Louisville, KY. He received an A.B. degree from Harvard University in 1960 and a Ph.D. from the California Institute of Technology (with J.D. Roberts) in 1964. He was a member of the faculty of the Massachusetts Institute of Technology from 1963 to 1982. He joined the Department of Chemistry of Harvard University in 1982, and was Department Chairman 1986-1989, and Mallinckrodt Professor of Chemistry from 1982-2004. He is now the Woodford L. and Ann A. Flowers University Professor.

PANEL MEMBERS

Dr. Julie Aaron joined the DSU faculty in 2010, and teaches biochemistry and general chemistry. She received her undergraduate degree in Chemistry from McMaster University and her Ph.D. in Chemistry from the University of Pennsylvania. Her dissertation focused on the structure and function of the metalloenzymes human carbonic anhydrase and epi-isozizane synthase from Streptomyces coelicolor. Her research interests include metalloenzymes, protein X-ray crystallography, and evolutionary relationships among proteins. Dr. Aaron lives in Bucks County, where she enjoys baking, reading, gardening, and generally being outdoors. She is an avid Phillies fan, loves to travel, and is an aspiring cyclist.

Dr. Bill Beaulieu is currently the Manager of Polyolefin Catalyst and Product Development at Chevron Phillips Chemical Company LLC. Dr. Beaulieu is the senior executive and part of the R&T leadership team with technical expertise, operational know-how, and business acumen. His industry background spans chemicals, plastics, petroleum, manufacturing, engineering, and technology with Chevron Phillips Chemical Company and Phillips Petroleum. Dr. Beaulieu has significant experience managing the development of new products, creating new market opportunities, increasing sales, and generating profits.

Dr. Beaulieu is currently responsible for the discovery, development, and commercialization of new proprietary catalyst systems for olefin polymerizations including ethylene, propylene, and other alpha olefins. In addition, he is responsible for development of research programs and strategies which lead to new products and their timely commercialization.

Dr. Thomas Degnan, manager of Breakthrough and New Leads Technology at ExxonMobil Research and Engineering Co. received his doctoral degree in chemical engineering from the University of Delaware in 1977. He and six members of his team won the recognition of “Hero of Chemistry” by the American Chemical Society for developing a novel, cost-effective and environmentally friendly polyester production catalyst and process. Dr. Degnan went to graduate school at UD after receiving his bachelor’s degree in chemical engineering from the University of Notre

Dame in 1973. He also earned a master's degree in business administration from the University of Minnesota in 1980.

Dr. Degnan joined 3M's Central Research Division in 1976 and then moved to Mobil's Central Research Laboratory (CRL) in Princeton, N.J., in 1980. In 1989 he transferred to Mobil's Paulsboro Research Laboratory as group leader for hydroprocessing catalyst development. He was promoted to scientist in 1993, and, later the same year, he was appointed as manager of the Catalyst Technology Group in Mobil's Research, Engineering and Environmental Affairs organization. In February 2000, Dr. Degnan was appointed laboratory director in ExxonMobil's Research and Engineering's Corporate Strategic Research Laboratory in Annandale, N.J., and in August 2004 he was appointed catalyst technology director for the Process Research Laboratories in ExxonMobil Refining and Supply Company. He was promoted to his present position in August 2006. Degnan is a member of the Catalyst Club of New York and the North American Catalyst Society and is vice-chairman of the Research & Development Council of New Jersey. He also is a member of the advisory council of UD's Center for Catalytic Science and Technology, the Engineering Advisory Council at the University of Notre Dame, the New Directions Council of Purdue University's Chemical Engineering Department and the advisory council for the Department of Chemical and Biomolecular Engineering at Johns Hopkins University. Dr. Degnan is the named inventor or coinventor on approximately 100 U.S. patents and has authored or coauthored more than 35 articles and outside presentations including one book and one monograph.

Dr. Rajiv Dhawan was born in Vancouver, British Columbia, Canada in 1975 and received his Bachelor of Science degree from Simon Fraser University in Burnaby, British Columbia. He received his Ph.D. from McGill University in Montreal, Quebec in 2004 in the area of metal catalyzed multicomponent coupling chemistry with Professor Bruce Arndtsen. This was followed by a postdoctoral appointment at Stanford University, with Professor Barry M. Trost as an NSERC (National Science and Engineering Research Council of Canada) Postdoctoral Fellow, where he worked on method development and on the total synthesis of a natural product. Dr. Dhawan started his career at DuPont Central Research & Development as a Research Chemist and worked on a range of programs including development of high strength fibers and new routes for pesticide intermediates. In October 2011, he was promoted to DuPont Science & Technology Talent Acquisition Manager.

Dr. Michael Doyle received his B.S. in Chemistry from the College of St. Thomas; his Ph.D. in Organic Chemistry from Iowa State University;

and completed a Postdoctoral at the University of Illinois, Chicago. Dr. Doyle is currently Professor and Chair of the University of Maryland's Department of Chemistry and Biochemistry. Dr. Doyle's research interests include asymmetric catalysis with metal carbenes and Lewis acids; structural design and chemistry of dirhodium carboxamidates; catalytic chemical oxidations; bioinorganic chemistry of nitrogen oxides and nitrosyls; reductions by organosilanes. Dr. Doyle belongs to a number of professional organizations, including the American Chemical Society (ACS), Fellow; American Association for the Advancement of Science (AAAS), Fellow; Royal Society of Chemistry, Fellow. Dr. Doyle has received many recognitions and honors, including NOBCChE Presidential Award for Outstanding Partner in Academia (2011); Fellow, American Chemical Society (2009); Edward Leete Award (2007), ACS Division of Organic Chemistry; Arthur C. Cope Senior Scholar Award (2006) from the American Chemical Society; Outstanding Chemistry Alumni Award, Iowa State University (2006); Harry and Carol Moser Award (2005), Santa Clara Valley Section of the ACS; Merit Award, National Institutes of Health (2003); ACS George C. Pimentel Award in Chemical Education (2002); Gilman Research Award (2001) from Iowa State University; Paul G. Gassman Distinguished Service Award (1998), ACS Division of Organic Chemistry; Japan Society for the Promotion of Science (JSPS) Invitation Fellowship (1996); James Flack Norris Award for Outstanding Achievements in the Teaching of Chemistry (1995), Northeastern Section of the ACS; Alexander von Humboldt Senior Research Award for U.S. Scientists (1995); Elected Fellow of AAAS (1995); D.Sc. Honoris Causa of the Russian Academy of Sciences (1994); ACS Award for Research at Undergraduate Institutions (1988); Chemical Manufacturers Association Catalyst Award (1982); Camille & Henry Dreyfus Foundation Teacher-Scholar Award (1973). To date, Dr. Doyle has mentored 145 undergraduate students who are coauthors of research publications, 60 of whom have received their Ph.D. in the chemical sciences; 45 Postdoctoral Associates; 6 students who received Ph.D. degrees and 2 students who received M.S. degrees (only since 2003).

Dr. Marye Anne Fox, a world-renowned chemist, is the seventh chancellor of the University of California, San Diego and distinguished professor of chemistry. Since her appointment as chancellor of UC San Diego, the university has established new research and partnership ventures to further innovation and increase international collaboration, achieved an ambitious $1 billion campaign goal, expanded academic and campus programs and facilities, received national and international recognition in prominent university rankings and assembled a strong, diverse leadership team to ensure the university's continued rise in excellence. Before her current appointment, Dr. Fox served as North Carolina State University's 12th chancellor, as distinguished university professor of chemistry at NC State (from 1998 to 2004) and as Waggoner Regents Chair in chemistry and Vice President for Research at the University of Texas at Austin. She joined the faculty of the University of Texas at Austin in 1976, after a postdoctoral appointment at the University of Maryland. Dr. Fox received her B.S. from Notre Dame College and her Ph.D. from Dartmouth College, both in chemistry. She has been elected to membership in the National Academy of Sciences and the American Philosophical Society, and to fellowships both in the American Academy of Arts and Sciences and the American Association of Advancement of Science. In October 2010, President Barack Obama named Dr. Fox to receive the National Medal of Science, the highest honor bestowed by the United States government on scientists, engineers and inventors. She has also received honorary degrees from 12 institutions in the U.S. and abroad. She was born in Canton, Ohio in 1947.

Dr. Heather A. Gennadios is a Chemist in the Division of Manufacturing Technologies at the Center for Veterinary Medicine, Food and Drug Administration. Her educational background includes a Bachelor of Science in Biochemistry from the University of North Carolina at Chapel Hill (1999) and a PhD in Biological Chemistry from the University of Pennsylvania (2008). Prior to her PhD, she also worked as an analytical chemist in the pharmaceutical industry for 3 years. Her current work focuses on the review of biotherapeutic drugs, including such technologies as recombinant proteins and stem cells. She has recently participated in writing a Guidance for Industry (GFI) document and is the leader for several technology teams as part of CVM's Innovation Initiative. She has also helped design and currently teaches a course for FDA investigators on Biological Therapeutics Manufacturing.

Dr. Paul L. Houston is Dean of the College of Sciences and Professor of Chemistry and Biochemistry at The Georgia Institute of Technology. He started his professorial career at Cornell University in 1975 following undergraduate study at Yale, doctoral work at MIT, and postdoctoral research at the University of California at Berkeley. He was formerly Chair of the Cornell Department of Chemistry and Chemical Biology (1997-2001), Senior Associate Dean of the College of Arts and Sciences (2002-2005), and the Peter J. W. Debye Professor of Chemistry. He was a member of the Cornell Center for Materials Research, the Kavli Institute at Cornell University for Nanoscale Science, and the Graduate Field of Applied Physics. Dr. Houston has been an Alfred P. Sloan Research Fellow (1979-1981), a Camille and Henry Dreyfus Teacher Scholar (1980), and a John Simon Guggenheim Fellow (1986-1987). He served as a Senior

Editor of the Journal of Physical Chemistry (1991-1997), as Chair of the American Physical Society Division of Laser Chemistry (1997-98), and as a member of the Science and Technology Steering Committee of Brookhaven National Laboratories (1998-2005). In 2001 he shared with David W. Chandler the Herbert P. Broida Prize of the American Physical Society for work on product imaging in chemical dynamics. He was elected a fellow of the American Academy of Arts and Sciences in 2005.

Dr. David Kronenthal is currently Vice President of Early Phase Chemical Development at Bristol-Myers Squibb. David Kronenthal attended Lehigh University and graduated in 1974 with a B.A. in Natural Sciences. He did his graduate work at the University of Connecticut studying Beckmann Fragmentation reactions and received a Ph.D. in 1978. From 1978-1980, Dave conducted postdoctoral research at Columbia University in the laboratories of Professor Gilbert Stork where he worked on the synthesis of histrionicotoxin. In 1980, Dave joined E.R. Squibb in the Department of Drug Discovery where he conducted research in the area of monocyclic, β-lactam antibiotics. In 1985, he moved to the department of Process Research and Development where he has spent the last 27 years identifying and developing synthetic routes to drug candidates including several commercial products. Dr. Kronenthal is currently Vice President, Early Phase Chemical Development. He is responsible for a department of 95 scientists at the BMS New Brunswick site comprising Chemistry Development from preclinical through Phase II as well as the Catalysis, Biocatalysis, Separations/Enabling Technologies, and Outsourcing functions. He has been cochair of the Bristol-Myers Squibb Unrestricted Chemistry Grant Committee since 2003.

Dr. Joydeep Lahiri is currently the Division Vice President and Senior Research Director of Organic and Biochemical Technologies at Corning, Inc. Dr. Lahiri and his group's research efforts at Corning are looking for new ways to provide better, more comprehensive drug screening information; identify and eliminate failures early in the drug discovery process; overcome previous technological limitations; and streamline the process of drug discovery. Dr. Lahiri leverages Corning's broad expertise to develop more efficient, accurate ways to capture valuable bioinformation early in the research process. He is also focusing on ways to eliminate extra steps in the research process such as end-user DNA labeling, which will not only save time but will minimize the chances of human error—two valuable advancements in drug discovery research. Dr. Lahiri's accomplishments, and those of his colleagues, have been cited in key industry journals, including Chemical and Engineering News, Nature-Science Online, BioArray News, Analytical Chemistry, and Nature Biotechnology.

Dr. Sander Mills is a vice president in discovery and preclinical sciences, and global head of chemistry. His areas of responsibility include discovery chemistry, process chemistry, analytical chemistry, structural chemistry, and chemistry modeling and informatics. After graduating from Drew University, he completed his Ph.D. in organic chemistry in Professor Peter Beak's laboratory at the University of Illinois at Urbana/Champaign. He then carried out postdoctoral studies in the laboratories of Professor Clayton H. Heathcock at the University of California, Berkeley as an NIH postdoctoral fellow. Dr. Mills joined Merck Research Laboratories in 1985 in the department of process research, and moved to the medicinal chemistry area in 1989. Dr. Mills' research at Merck has been wide-ranging, dealing with the design and synthesis of small molecules to treat asthma, pain, HIV infection, autoimmune diseases, and CNS disorders. In 1993 he was part of the team that discovered aprepitant (EMEND®), which in 2003 became the first substance P antagonist marketed for the prevention of chemotherapy-induced nausea and vomiting. He and his group went on to identify fosaprepitant (IVEMEND®), a water-soluble prodrug of aprepitant for parenteral administration, which gained regulatory approval in 2008. Dr. Mills has been an author or coauthor on more than 90 papers in professional journals on drug design, synthetic organic chemistry and the biology of medicinally active substances. He has been an inventor or coinventor on eighty U.S. patents covering an array of drug candidates and synthetic methods. He is a member of the Organic Chemistry and Medicinal Chemistry Sections of the American Chemical Society, AAAS and Sigma Xi.

Dr. Jennifer Schomaker is an Assistant Professor within the Chemistry Department at The University of Wisconsin. Research in the Schomaker group is driven by the need for more efficient methods to transform simple hydrocarbons into more complex building blocks for synthesis. Our program will encompass new catalyst development and optimization, elucidation of reaction mechanisms and applications of new methodologies to the synthesis of natural products and other useful molecules. Particular emphasis will be placed on the design of catalysts that can utilize inexpensive greenhouse gases for useful organic transformations. The potential applications of our new catalysts to industrially important transformations will also be explored. Projects in our group are designed to offer students the ability to gain skills that will serve them well throughout their scientific careers, whether in an academic, government or industrial setting. These include standard techniques for the synthesis of organic and organometallic compounds, the handling and manipulation of air-sensitive materials, mechanistic and kinetic studies, advanced NMR techniques, basic computational chemistry, total synthesis and training in scientific writing and presentation skills.

Dr. Siddhartha Shenoy is a Senior Research Chemist at DuPont Central Research and Development. He received his B.S. in Chemistry from the University of Virginia in 2001. He then moved to California to work on his Ph.D. under the direction of Professor Keith Woerpel at the University of California, Irvine. Dr. Shenoy's graduate work was focused in the areas of synthetic methodology development and physical organic chemistry, namely in the mechanistic study of chemo-, regio-, and stereoselectivity in the reactions of heteroatom-stabilized carbocations. Upon completion of his Ph.D. in 2006, Dr. Shenoy joined the laboratory of Professor Julius Rebek as a Skaggs Postdoctoral Associate at The Scripps Research Institute in La Jolla, California. During his time in the Rebek group, Dr. Shenoy developed a novel organocatalytic system that mimicked the function of terpene cyclase enzymes. Dr. Shenoy joined DuPont Central Research and Development in 2008.

Dr. David Tellers received his Ph.D. in Chemistry from Professor Robert G. Bergman at U.C. Berkeley in 2001 and subsequently joined Merck where he has had the opportunity to support programs across the pharmaceutical development paradigm, from initial discovery to commercial launch. He started at Merck in the Chemical Engineering Department and focused on the optimization of organic reactions through kinetic analysis. He then transitioned to Process Research where he assisted in the creation of a chemocatalysis group and worked on synthetic route development for clinical candidates. He is currently a Senior Research Fellow in the Department of Medicinal Chemistry where he is working on the development of oligonucleotide therapeutics.

Dr. Samuel Thomas is currently an Assistant Professor of Chemistry at Tufts University. He received his B.S. (2000) from the University of Rochester, and his PhD (2006) from MIT. Dr. Thomas was an American Cancer Society Postdoctoral Fellow (Harvard University) from 2006-2009. The Thomas lab takes an interdisciplinary approach to design and synthesis of organic materials. They combine synthesis, physical organic chemistry, photophysics, and electrostatics. Research includes (1) Electrostatically responsive materials that undergo a change in properties upon exposure to a stimulus such as changing the sign of charge upon contact electrification. Since a consistent theory that predicts how a material will charge upon contact with another material does not exist, they are developing rules to guide the design of materials for next-generation antistatic materials, label-free chemical detection, and chemically- or photochemicallytriggered electrostatic actuators. (2) Development of conjugated materials that are highly amplifying optical sensing materials where mobile excited states can transfer their energy (or be quenched) by electron, hole, or energy acceptors throughout the polymer backbone. The output for sensing applications of these materials is either fluorescence quenching or energy transfer, both of which have large background signal. The Thomas group is designing "materials amplification" from mobile excitons with dark-field sensing by using small amounts of reactive quenching traps and prequenched materials that radiate by coupling to plasmons upon binding. (3) Development of multifunctional polymers that bear ligands that bind specifically to targeted surfaces and thus serve as inhibitors with larger binding constants than their monomeric counterparts. Their research focuses on polymers that combine ligands for binding selectively to a surface with other useful functions and also take advantage of recent developments in controlled polymerization techniques to exert greater control over the distribution of functional moieties. Applications of such materials includes singlet oxygen photosensitizers for photodynamic therapy and thermally responsive materials for selective precipitation.

Dr. Holden Thorp has been an undergraduate student, a chemistry professor, a planetarium director, an inventor and entrepreneur, as well as a dean, at Carolina. He graduated with honors, won teaching awards, chaired a powerhouse chemistry department, developed technology for electronic DNA chips, founded spin-off companies, and succeeded as an administrator. As the 10th chancellor, Dr. Thorp draws from those experiences in leading Carolina, one of the world's great research universities. A North Carolina native, Dr. Thorp grew up in Fayetteville in a family steeped in UNC traditions dating to the 1800s. When he graduated from Terry Sanford High School, only one college was on his application list — Carolina, where he earned a Bachelor of Science degree with honors in 1986. Attending a world-class research university—where research and teaching are done by the same people—allowed him to work in chemistry labs with top faculty and inspired him to become a professor. He pursued that dream at the California Institute of Technology, where he earned a doctorate in chemistry in 1989, and at Yale University for postgraduate work. After teaching a year at NC State, he returned in 1993 to UNC, where he was dean of the College of Arts and Sciences and chair of the chemistry department before becoming chancellor in 2008. Dr. Thorp is a member of President Obama's National Advisory Council on Innovation and Entrepreneurship. As a result, the University hosted the council's first national forum in Chapel Hill. He coauthored "Engines of Innovation—The Entrepreneurial University in the 21st Century," a UNC Press book that makes the case for the pivotal role of research universities as agents of societal change. Royalties support innovation at UNC. Dr. Thorp serves on the U.S. Manufacturing Competitiveness Initiative for the Council on Competitiveness. He has published 130 scholarly articles on the electronic properties of DNA and RNA and cofounded Viamet Pharmaceutials in Morrisville, which is developing drugs for fungal infections and prostate cancer. The chancellor also is a member of a national Commission on Higher Education Attainment, which was created by the six presidentially based higher education associations to chart a course for greatly improving college retention and attainment and, in turn, restore the nation's higher education preeminence.

Dr. Jake Yeston joined the staff at *Science* in 2004, where he is now a senior editor, handling peer review for original research manuscripts submitted in chemistry and overlapping segments of applied physics and biochemistry. He earned an AB in chemistry from Harvard University in 1996 and a PhD in chemistry from the University of California-Berkeley in 2001, working jointly under Bob Bergman and Brad Moore on flash kinetics studies of transition metal carbonyl reactions, followed by postdoctoral research in ultrafast infrared spectroscopy at the Max Planck Institute for Quantum Optics (Garching, Germany) and the National Institute of Standards and Technology (Gaithersburg, MD).

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Workshop Attendees

Last Name	First Name	Affiliation	Title
Aaron	Julie	DeSales University	Assistant Professor of Chemistry
Arnaud	Celia	Chemical and Engineering News	Senior Editor
Beaulieu	Bill	Chevron Phillips Chemical	Manager of Polyolefin Catalyst and Product Development
Bergman	Robert	University of California Berkeley	Gerald E.K. Branch Distinguished Professor of Chemistry
Berry	David	Flagship Ventures	Partner
Bewley	Carole	The National Institute of Diabetes and Digestive and Kidney Diseases	Section Chief, Natural Products Chemistry Section, Laboratory of Bioorganic Chemistry
Boering	Kristie	University of California Berkeley	Lieselotte and David Templeton Professor of Chemistry
Booker	Squire	Pennsylvania State University	Associate Professor of Chemistry; Associate Professor of Biochemistry and Molecular Biology
Cardillo	Mark	The Camille and Henry Dreyfus Foundation, Inc.	Director

Cavanagh	Richard	National Institute of Standards and Technology	Acting Director, Materials Measurement Laboratory
Colon	Wilfredo	Rensselaer Polytechnic Institute	Associate Professor of Chemistry and Director of the Graduate Program
Cook	Kelsey	National Science Foundation	
Croft	Genevieve	National Research Council	Mirzayan Fellow
Degnan	Thomas	ExxonMobil Research and Engineering	Manager, Breakthrough and New Leads Technology
de Paula	Julio	National Science Foundation	Program Director
Dhawan	Rajiv	E.I. Du Pont de Nemours, Inc.	Talent Acquisition Manager, Du Pont Technology
Dirkx	Ryan	Arkema, Inc.	Vice President, Research and Development
Dorhout	Peter	Kansas State University	Professor
Doyle	Michael	University of Maryland	Professor and Chair, Department of Chemistry and Biochemistry
Dukovic	Gordana	University of Colorado	Assistant Professor of Chemistry
Fabian	Miles	National Institute of General Medical Sciences	Program Director, Division of Pharmacology
Faulkner	Larry	Houston Endowment; University of Texas, Austin	President
Ferguson	Andrew	Massachusetts Institute of Technology	Postdoctoral Researcher
Fox	Marye Anne	University of California at San Diego	Chancellor's Eminent Professor of Chemistry
Francisco	Joseph	Purdue University	William E. Moore Distinguished Professor of Chemistry
Gennadios	Heather	US Food and Drug Administration	Chemist, Division of Manufacturing Technologies
Gerratana	Barbara	National Institute of General Medical Sciences	Program Director in the Division of Pharmacology, Physiology, and Biological Chemistry
Henderson	Peter	National Research Council	Director, Board on International Scientific Organizations

Houston	Paul	Georgia Institute of Technology	Dean, College of Sciences
Jacobs	Madeleine	American Chemical Society	Executive Director & CEO
Jones	Warren	National Institute of General Medical Sciences	Chief of the Biochemistry and Biorelated Chemistry Branch in the Division of Pharmacology, Physiology, and Biological Chemistry
Kirchhoff	Mary	American Chemical Society	Director, Education Division
Kronenthal	David	Bristol-Myers Squibb	Vice President of Chemical Development
Labov	Jay	National Research Council	Senior Scientist/Program Director for Biology Education, Board on Life Sciences
Lahiri	Joydeep	Corning, Inc.	Deputy Vice President and Director of Bio and Organic Research
Lees	Bob	National Institute of General Medical Sciences	Program Director, Division of Pharmacology, Physiology, and Biological Chemistry
Lin	Eric	National Institute of Standards and Technology	Chief, Polymers Division, National Institute of Standards and Technology
Marino	Pamela	National Institute of General Medical Sciences	Program Director, Pharmacology, Physiology, and Biological Chemistry Division
McAllister	Patricia	Council of Graduate Schools	Vice President for Government Relations and External Affairs
Mills	Sander	Merck, Sharp and Dohme Corporation	Vice President, Discovery and Preclinical Sciences
Molinero	Valeria	University of Utah	Assistant Professor of Chemistry
Okita	Richard	National Institute of General Medical Sciences	Program Director, Division of Pharmacology, Physiology, and Biological Chemistry
Olbricht	William L.	Cornell University	Professor of Chemical and Biomolecular Engineering
Olson	Steve	Independent science writer	

Platz	Matthew	National Science Foundation	Director, Division of Chemistry
Ray	Douglas	Pacific Northwest National Laboratory	Associate Lab Director
Roberts	Robert	Institute for Defense Analysis	Chief Scientist
Rogers	Michael	National Institute of General Medical Sciences	Director, Pharmacology, Physiology, and Biological Chemistry Division
Schomaker	Jennifer	University of Wisconsin	Assistant Professor of Chemistry
Schuster	Gary	Georgia Institute of Technology	Vasser Woolley Professor
Schwab	John	Free agent	
Shakashiri	Bassam	University of Wisconsin	Professor of Chemistry
Shenoy	Sid	E. I. du Pont de Nemours, Inc.	Senior Research Chemist
Tam-Chang	Suk-Wah	National Science Foundation	Program Director
Tellers	David	Merck, Sharp and Dohme Corporation	Research Fellow
Theopold	Klaus	University of Delaware	Professor and Chair, Department of Chemistry and Biochemistry
Thomas	Samuel	Tufts University	Assistant Professor of Chemistry
Tong	YuYe	Georgetown University	Assistant Professor of Chemistry, Department of Chemistry
Wolczanski	Peter	Cornell University	Professor of Chemistry
Yeston	Jake	AAAS	Senior Editor, Science Magazine

BCST Staff

Zolandz	Dorothy	Board on Chemical Sciences and Technology	Director
Friedman	Douglas	Board on Chemical Sciences and Technology	Program Officer
Siddiqui	Sheena	Board on Chemical Sciences and Technology	Senior Program Associate
Yancey	Rachel	Board on Chemical Sciences and Technology	Senior Program Assistant
Gibbs	Courtney	Board on Earth Sciences and Resources	Program Associate