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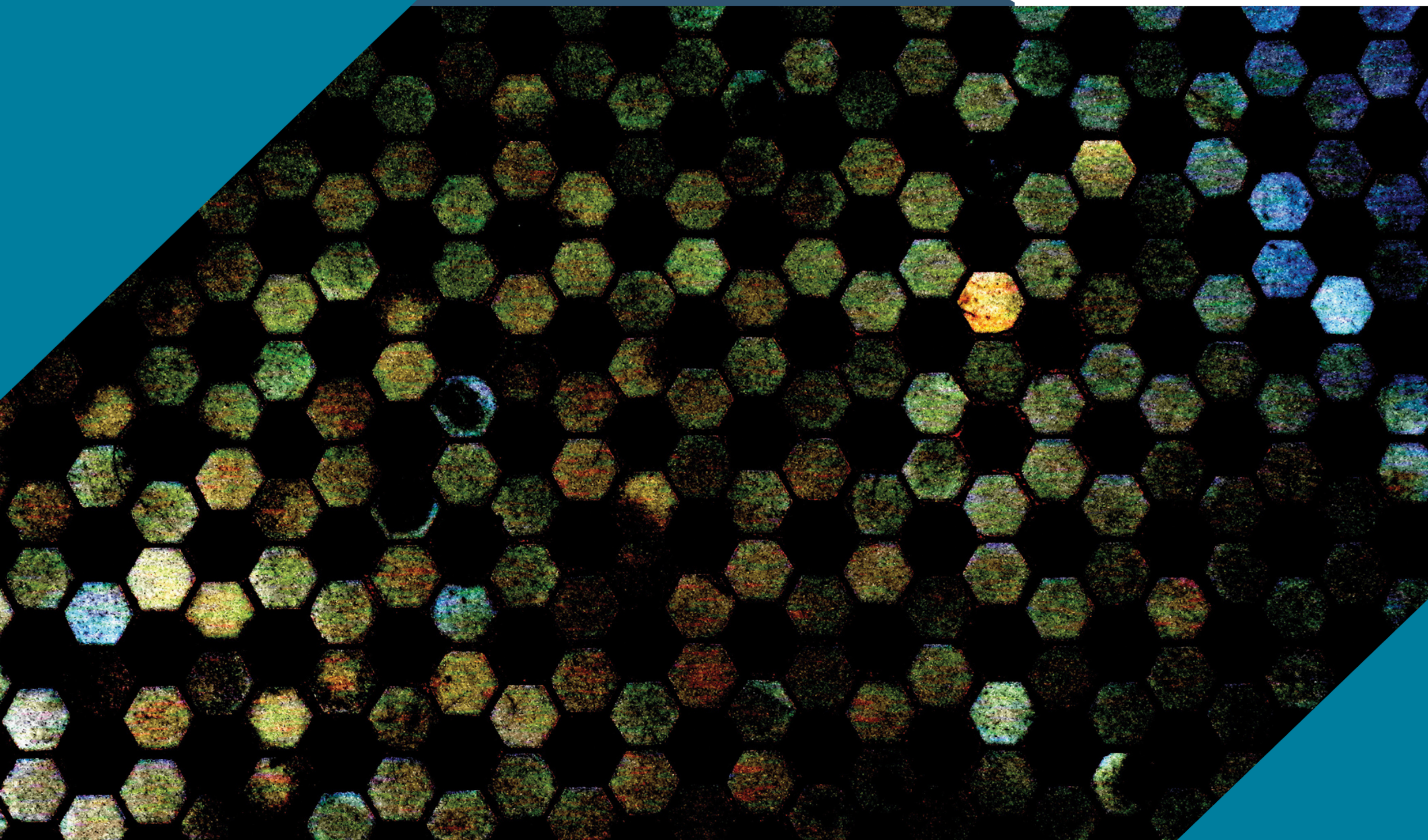

Preparing and Empowering The Next-Generation Chemical Workforce

A chapter from the consensus study report
The Importance of Chemical Research to the U.S. Economy

Contents

Introduction

Throughout the consensus study report, *The Importance of Chemical Research to the U.S. Economy*, there is an emphasis on the individuals who are responsible for chemical advances and those who are driving the chemical economy. While there are millions of workers that contribute to the chemical economy, the report focuses on the needs of the individuals who go through chemistry and chemical engineering training programs.

This document highlights the content presented in chapter 5, *Preparing and Empowering the Next-Generation Chemical Workforce*. Key themes include the need for a diverse workforce and equitable training practices, the need for well-developed mentorship and professional development programs, and an emphasis on educational training that is adaptable to the future needs of the chemical enterprise.

Key Takeaways

- Diversity in the chemical workforce is essential for the productivity of the chemical economy and is supported through inclusive and equitable practices in the classroom and workplace.
- Effective mentorship at all career levels is important for the success of individual members of the workforce.
- Minority-serving institutions excel at recruiting and retaining diverse chemistry cohorts.
- Flexibility in chemical sciences and engineering education is vital for the exposure of the workforce to new tools and emerging concepts and can be implemented through the support of basic education research.

A Diverse and Equitable Chemical Workforce

A talented chemical workforce is comprised of individuals whose intellectual curiosity in the chemical sciences was nurtured and reinforced through supportive pedagogy and opportunities to engage in impactful research. Cultivating interest in chemistry from grade school to graduate school and beyond ensures the continuation of a highly skilled workforce in the chemical sciences. It is critical that all community members are welcome in the exploration of chemistry. Thus diversity, equity, and inclusion (DEI) have become fundamental tenets of the sciences.

The U.S. Department of Housing and Urban Development defines diversity as encompassing "the range of similarities and differences each individual brings to the workplace, including but not limited to national origin, language, race, color, disability, ethnicity, gender, age, religion, sexual orientation, gender identity, socioeconomic status, veteran status, and family structures" (1). Although many definitions of equity and inclusion exist, the committee has chosen to adopt the following:

> Equity is about the fair treatment and equal opportunity for success and advancement for all people, irrespective of their identities. Inclusion refers to an organization's active efforts to invite and nurture the participation of its diverse members (2).

While efforts have been made to cultivate and maintain diverse, inclusive, and equitable work and educational spaces, there continue to be strong barriers that prevent talented individuals from entering or staying in the chemical sciences.

The Open Chemistry Collaborative in Diversity Equity (OXIDE) initiative has worked alongside Chemical & Engineering News since 2012 to collect data from Ph.D.-granting chemistry departments and publish demographic assessments of research-active, tenured or tenure-track faculty (3). From the 75 departments surveyed for the 2015–2016 academic year, only 19.4%of chemistry faculty were female, and only 5.9% of the faculty identified as underrepresented minorities (4). These numbers are reflective of the many significant barriers to entering and staying in the chemical workforce.

According to a 2011 National Academies' report, underrepresented minorities have lower retention rates as science, technology, engineering, mathematics, and medicine (STEMM) majors at undergraduate institutions because they face more barriers to persistence and completion (5). Beyond the better-known policy and structural barriers, there are also significant psychological barriers that marginalized populations face, such as discrimination and lack of social connections (6). As stated in a recent National Academies' report on mentorship in STEMM,

> Talent is equally distributed across all sociocultural groups; access and opportunity are not. . . . Individual STEMM professionals identifying as African American, Latinx, American Indian, first generation, or sexual or gender minority individuals and individuals with disabilities continue to be less likely to be successfully integrated in STEMM environments. These individuals may be questioned about their competence, challenged in their science, and simultaneously invisible as scientists, yet under the microscope as members of underrepresented groups in STEMM (7).

The chemical enterprise does not reflect the potentially available talent, as true diversity in the chemical workforce is lacking and not representative of our nation's demographics. According to Data Report 2021 (8), far fewer women and nonbinary individuals submitted manuscripts for publication to ACS journals compared to men, and men made up 73% of publication reviewers. Additionally, white- and East Asian–identifying authors comprise almost 70% of all ACS published authors and experience higher publication acceptance rates than those from other identifying groups. While publications are only one way to measure scientific contribution, these numbers show that the chemical workforce still disproportionally centers on white men to stimulate growth and innovation in the chemical sciences, leaving behind experts from marginalized communities.

Interventions and support mechanisms are crucial to improve the diversity of the chemical workforce, as they work to improve equity and inclusion while breaking down systemic barriers so that inclusive excellence can be achieved. Such mechanisms are varied in scope, design, and application. At the level of the individual, actions that chemists can take to support workforce diversity include professional advocacy, value-based leadership, meaningful mentorship, bias training, and bystander intervention (9). A 2020 Journal of Organic Chemistry editorial argues that "individual actions will not be sufficient. It follows, then, that combating institutional bias requires us to hold our departments, journals, and scientific societies accountable to the principles of diversity, equity and inclusion that they proclaim as central values" (10).

There are many programs sponsored by such institutions across the nation that aim to enhance DEI in the chemical sciences and STEMM more broadly. Other programs exist to support individuals from underrepresented communities who are pursuing an advanced degree. Table 5-1, found on page 138 in the full report and at the end of this booklet, presents an illustrative, rather than exhaustive, list of opportunities currently available at multiple career levels and sectors to support a diverse chemical workforce. For a more comprehensive list, the Institute for Broadening Participation (11) maintains a hub of opportunities for a range of education and career stages. Such programs were also highlighted at a recent National Academies' workshop hosted by the Chemical Sciences Roundtable and are summarized in a proceedings document (12).

While support mechanisms at every level of an individual's career are important, a diverse and equitable chemical workforce cannot exist without diverse and equitable recruitment and retention practices. In higher education, systemic issues exist broadly that prevent diversity, equity, inclusion, fairness, and justice, according to a National Academies' workshop proceedings (13). The proceedings notes that recruitment and retention processes in academia are "inequitable at every step," and a lack of diversity in these practices cannot be attributed in full to the lack of diverse Ph.D. candidates. Other resources, including a recent National Academies' consensus study, Promising Practices for Addressing the Underrepresentation of Women in Science, Engineering, and Medicine: Opening Doors, notes the inequities and major issues with hiring, recruitment, retention, tenure, and promotion structures within STEMM fields, especially those practices related to women of color (14).

The report lays out a comprehensive set of recommendations and action items that universities and departments can take to assess their own recruitment and retention practices and to determine solutions for improvement. These recommendations include extensive quantitative and qualitative analyses of an institution or department to "understand the nature of their unit's particular challenge with the recruitment, retention, and advancement" (15).

Another important facet of the strategy in that report is the emphasis on actions by leadership. One recommendation notes, "Leaders in academia and scientific societies should put policies and practices in place to prioritize, reward, recognize, and resource equity, diversity, and inclusion efforts appropriately" (16). Following this recommendation are several action items that include permanent positions in DEI, compensation for related efforts, and equitable promotion practices.

As chemistry departments strive to recruit and retain diverse talent, topical research and reports can be a helpful resource when used in coordination with the consulting of knowledgeable individuals at each institution who understand the culture and nuance of the individual program under consideration. Taking actions based on best-practice guidance and recommendations from relevant experts and community members can start to fix the inequities that are prevalent at every stage of recruitment and retention in STEMM and move toward a more diverse workforce in the chemical sciences.

Creating and maintaining equity-minded opportunities can ensure that the chemical workforce best reflects our nation's communities and talents, thus expanding the potential for discovery and innovation. Additionally, supporting diversity and inclusivity within educational and work environments lends support to the recruitment and retention of global talent, which are vital for the United States to maintain a competitive advantage in the chemical sciences.

Mentorship and Support for Success

Productive and supportive mentorship is essential to success throughout one's career, from recruitment and training to retention and advancement. Mentorship can be defined as "a professional, working alliance in which individuals work together over time to support the personal and professional growth, development, and success of the relational partners through the provision of career and psychosocial support" (17). Mentoring relationships can take several different forms, including formal or informal, dyadic or multiple-mentor structures, or group or peer mentorship (18). Mentorship is a critical aspect of an individual's personal and professional development that is not limited to periods of formal training and education.

In the chemical sciences, mentorship is historically associated with a dyadic or apprentice model, in which aspiring practitioners receive expert guidance to develop a particular technical skill set (19). Whether actively or passively, mentors serve as models for professional behaviors that are often emulated at later career stages once the apprentice has transitioned into the role of mentor. Today, it is widely accepted that the role of mentoring encompasses not just guidance on the acquisition of specialized scientific knowledge and understanding but also development of professional skills that help the protégé navigate the path toward securing their first post-training position and then operating effectively within it.

Challenges in Effective Mentorship

Students pursuing chemical sciences degrees can have vastly different educational, research, and professional growth experiences, depending on their access to, and relationships with, faculty mentors. Mentorship at the undergraduate level, while dependent upon strong dyadic interactions, often occurs at the departmental level and therefore naturally includes engagement with a broader range of instructors and advisors or counselors. Graduate-level trainees generally have far more localized interactions. One's doctoral advisor typically serves as the primary faculty mentor for a student. Thus, the quality of one's graduate school experience is highly dependent on the approach to mentorship taken by a single faculty member. Given that a student's graduate school success and professional outcomes are influenced strongly by faculty members and the quality of their mentorship, it is paramount that professors cultivate strong mentorship skills early in their careers.

While faculty jobs require mentorship, many academic institutions do not afford their faculty adequate mentorship training with appropriate levels of support and recognition. Traditional pre-faculty experiences focus nearly exclusively on the science and grant making related to research. Once hired, faculty often then resort to a "do-it-yourself" approach to mentorship, gleaning what they can from their own mentors, independently finding resources on best practices in mentorship in the form of reading materials and workshops, or learning from a senior faculty member who can share their personal experiences with mentorship. Placing the responsibility on the mentor to teach themselves the skills of effective mentorship is increasingly challenging for early-career professors who face enormous pressure to achieve certain research and publication metrics that will determine their own career success. The ability to secure grants to support their research, publish a sufficient quantity of papers on the path to tenure, and establish a robust and effective teaching program are priorities that strongly compete with the prioritization of student mentorship.

These realities highlight a potential conflict of interest between the simultaneous roles of research supervisor, mentor, and independent professional that are embodied in the personage of a single faculty member. Research advisors, in their roles as mentors, may at times need to act against their own professional interests in favor of those of their students. Career exploration is recognized and emphasized by several federal funding agencies, such as the NSF and NIH, as an important element of professional development for trainees. Experiences within companies and corporations are particularly valuable for students of the chemical sciences, as many will eventually take on one of the large number of industrial roles that make up the chemical workforce. However, many graduate students are supported by federally funded grants with strict timelines that could be affected by a student's temporary departure from the laboratory to pursue an external internship. Delays can affect the overall productivity of an advisor's lab, which in turn can affect subsequent grant applications or even consideration for promotion and tenure. If the grant involves milestones that determine future funding, students or trainees themselves could be affected as declined grants can equate to lower levels of funding support for students or trainees.

Faculty are faced with weighing their individual professional needs, the needs of their research program, and the needs of their students, which can be in direct conflict. It is no wonder then that some advisors are unwilling to support the decision of a student to take leave from the research group even if it is to the benefit of the individual student. The natural power imbalance that exists between students and advisors may lead some students to forgo requesting temporary leaves, even if doing so would result in significant personal and professional benefits.

Beyond these challenges, many faculty are unprepared to help students navigate nonacademic career options. A recent survey published in Nature found that the majority of students arrived at their career decisions by doing their own research; only 28% reported that an advisor's advice helped to guide their decisions (20). Some advisors are simply unable to assist students with an interest in these paths, but others may display outright hostility to such "nontraditional" careers. As a result, students at all levels often suffer from a lack of sufficient support and career guidance. The 2019 Nature survey also showed that nearly a quarter of graduate students would change their doctoral advisor if they could start over, with a fifth indicating outright dissatisfaction with their relationship with their supervisor. Additionally, the data revealed major difficulties in the ability of doctoral students to spend meaningful time with supervisors—nearly half report that they connect with advisors for less than 1 hour per week—contributing to a notable deficit in the ability to obtain important career guidance (21).

While students of all backgrounds are experiencing deficits in their mentoring relationships, the careers of women, nonbinary individuals, and other underrepresented students (Black, indigenous, people of color, LGBTQIA+, and others) are more likely to be affected by poor mentorship. Strong mentors are often more essential for the success of individuals from historically marginalized communities, as their other support systems via social, cultural, or family networks may not be sufficiently empowered to support their career development (22). A larger conversation about the importance of mentorship for underrepresented students in STEMM can be found in Chapter 3 of the National Academies' report The Science of Effective Mentorship in STEMM (23).

Beyond academia, mentorship in the workplace is also imperative for success. Workplace mentors can help to identify existing barriers encountered by underrepresented individuals as well as approaches to tearing them down within a given institution. Mentors provide guidance and sup- port to their mentees, which can be invaluable for someone early in their career or unfamiliar with the culture of the institution or company, particularly if their voice is less likely to be heard due to their identity. A positive mentorship experience can help an individual overcome challenges when faced with existing organizational hierarchy, power dynamics, and issues related to implicit bias, stereotypes, and outright discrimination. In large companies, there are typically multiple programs in place that provide opportunities for interoffice mentorship, including employee resource groups, human resources programs, functional organizations, and informal channels.

In contrast to other sectors in the chemical enterprise, mentorship is a familiar and expected action for employee development in many large industrial settings. Because industrial workers tend to have more experience with, and training in, productive mentorship, there is value for those working in the chemical industry to collaborate with academic institutions to provide mentorship to students. There are opportunities for these mentorship relationships to be formally built into programs that encourage cross-sector collaboration, such as NSF's Industry-University Cooperative Research Centers program (24).

Other reports have noted the opportunities to alleviate the various challenges of mentorship, and these recommendations could be implemented within the chemical workforce through alternative funding structures or alternative mentorship models that would allow both research advisors and trainees to flourish (25).

Another option that has been explored in other reports that might decrease the risk of a potential conflict of interest for faculty mentors and improve the overall institutional climate is the development of mechanisms to provide research funding directly to the trainee rather than provide the funding via a principal investigator (26). For the support and success of the individuals that comprise the chemical workforce, it is also worth considering a transition away from the traditional dyadic mentorship model toward a model that prioritizes a mentorship network (27). A more expansive mentorship model recognizes that mentees are multifaceted individuals with a variety of interests and needs, while a single mentor can only impart the views reflective of a single individual's lived experience. Such a mentorship network would enable the mentee to contact different individuals at different career and/or educational stages and more effectively access and utilize a diverse range of voices and views to benefit their own professional and personal development.

Creating a larger network of mentors also allows mentees to have more opportunities to learn from professionals that work in a variety of fields, both within and tangential to the chemical sciences. This cross-disciplinary exposure would better prepare students for a diverse range of careers and better support those already in their careers to be nimble in the ever-evolving landscape of the chemical sciences. Additionally, such a model would provide mentees who wish to pursue chemical research with greater knowledge and assistance in navigating challenging grant processes and funding structures.

Networks and Communities for Mentorship in Chemistry

Professional societies play a significant role in facilitating the creation and promotion of mentorship networks. Large professional organizations such as ACS and AIChE provide a variety of opportunities for interaction among students, academic faculty,and industrial chemists and chemical engineers. Some programs currently exist within these societies that work to seed mentoring pairs. One such example is MentorNet, promoted by ACS, which is a “mentoring platform that combines the technology of social networks with the social science of mentoring” to provide effective virtual mentoring relationships within the STEM community (28). AIChE’s Future Faculty Mentoring Program (29) formally pairs senior graduate students and postdoctoral scholars with senior faculty members for 1 year to cultivate lifelong relationships and broaden the mentees’ perspective of the chemical enterprise.

Programs also exist outside the professional society framework, such as the Chemistry Women Mentorship Network (ChemWMN), which aims to provide guidance to graduate and postdoctoral- level women by matching them to women faculty members (30). Another example is Empowering Women in Organic Chemistry, established as a forum to engage women in organic chemistry at multiple career stages, including graduate students, faculty,

and industrial practitioners, with the goal of providing an “environment for them to feel a true sense of belonging, develop powerful networks, and know the opportunities available to them" (31). Opportunities to partner with societies comprising a more targeted professional constituency, such as the National Organization for the Professional Advancement of Black Chemists and Chemical Engineers (32) or the Society for Advancement of Chicanos/Hispanics and Native Americans in Science (33), help to enable the successful formation of effective mentoring networks for underrepresented students and professionals. Such programs and mechanisms promote the concept of a broader mentorship network, as mentees are often matched with mentors outside of their home institutions.

Supporting Gender Equity

Several other ways exist to support individuals for successful careers beyond strong mentorship and unbiased funding mechanisms. While many will not be discussed in this report, it is important to highlight the importance of attracting and retaining members of the chemical workforce of all genders through equitable support and compensation. A study by Huang et al. (2020) (34) found that career-long publishing productivity in STEMM is significantly lower for women than for men, while the annual publishing productivity is essentially the same between the two studied genders.

The study concluded that while men and women are equally productive when actively publishing, men have 19.2% longer careers on average, amplifying their total impact on the fields in which they work. The Royal Society of Chemistry found that women are leaving their careers in the chemical sciences “before reaching their full potential” due to the current academic funding structures, academic culture, and lack of support for balancing personal and professional lives (35).

Not only does this diminish the available talent within the workforce, lower retention rates of women in chemistry have direct financial implications for the field. According to the findings from a workshop (36), it costs approximately $500,000 to produce a Ph.D. chemist, where most of the funds come directly or indirectly from federal grants. As women leave the chemical sciences post-Ph.D. attainment, the return on investment by the federal government decreases. Nonbinary and transgender individuals also exhibit lower retention rates in STEMM, as they frequently experience discrimination and hostility in the classroom and workplace (37). Women of color also face a “double bind” while navigating their STEMM careers, which is related to experiencing both racism and sexism (38).

Supporting underrepresented individuals in the chemical workforce is essential for the productivity of the chemical economy. An ACS Axial article (39) states that individuals can support women in chemistry by citing women-authored papers and supporting their work, nominating women for awards and leadership positions, and overall being an active bystander. Institutions can support all genders by implementing unconscious bias training, adopting climates and compensation structures to support those taking care of family members, and rethinking and redesigning their goals and management structures to be more inclusive and collaborative (40). Groups exist to support gender equity in the chemical sciences, such as the ACS Women Chemists Committee (41), which is committed to advocating for the promotion of women in chemistry-related fields.

Development Opportunities for Academic Institutions

The majority of those who currently or will comprise the chemical workforce are educated in chemistry, chemical engineering, or other closely related science or engineering fields. The preparation that individuals receive to enter the workforce is the direct product of the institutions that they attend. Formal academic preparation is vital for the successful integration of individuals into and their contributions to the chemical workforce. Without basic knowledge of the foundations of chemistry and/or chemical engineering, it would be difficult for the workforce to contribute to the solutions of our world's greatest problems. However,this formal academic preparation will look different depending on the school(s) one attends, their geographic location and socioeconomic status, and the development opportunities available and afforded to that individual. Note that this section will primarily focus on 2- and 4-year colleges and universities. Information on K–12 STEMM education is provided in a 2012 National Research Council report (42).

Regardless of one's academic path, it is important that students learn to apply the foundational knowledge of the chemical sciences to work in emerging fields, use new tools and methodologies as they are rapidly developed, learn new techniques, and be able to apply them creatively throughout their careers. Equally important is removing barriers to accessing quality education and research experiences so that all students who wish to pursue a career in the chemical sciences and support the chemical economy are given the opportunities, tools, and support they need to succeed.

Chemistry and chemical engineering degrees at all levels remain popular. There were 22,156 undergraduate chemistry degrees awarded in 2019 (43), and 14,406 undergraduate chemical engineering degrees were awarded (44) in the United States. However, while the current academic system is working for some, there are changes that can be made so that all students are supported. Furthermore, opportunities exist to introduce novel ways of teaching chemistry and chemical engineering and for evaluating the teaching institutions themselves.

Academic Institutions to Model and Support

To travel a better path, one that prepares all students to support the chemical economy, it is valuable to look at institutions and programs that are uniquely successful and innovative at producing chemistry and chemical engineering graduates. Chemistry and chemical engineering departments have historically underproduced a diverse group of graduates, with numbers still well below their potential. In chemical engineering, the number of degrees awarded to white women and individuals of color of all genders have remained essentially unchanged since 2008 and are well below the national average (45). For both chemistry and chemical engineering at all levels, students are overwhelmingly white.

Historically Black Colleges and Universities (HBCUs) and other minority-serving institutions (MSIs), such as Hispanic-Serving Institutions (HSIs), are unequivocally more successful at educating individuals who identify as persons of color, first-generation students, and/or students from low-income backgrounds for the chemical workforce. There are currently 101 HBCUs in the United States, and while 9% of Black undergraduate students attended an HBCU in 2018, these institutions were responsible for awarding 29% of the undergraduate degrees that Black students received. In 2018, 32% of the chemistry Ph.D.s awarded to Black students went to those who graduated from HBCUs (46). These data show that not only are HBCUs more successful at recruiting Black students, they are significantly more successful at supporting these students and nurturing their chemical careers.

Although HBCUs and other MSIs are better able to contribute diverse talent to the chemical workforce, the institutions themselves are not being supported adequately. For example, the number of Hispanic and Latinx students, as well as the number of HSIs, has grown significantly in the past 20 years. However,the federal funding to support these students and the institutions that support them has not changed, as the federal appropriations have remained stagnant for the past two decades (47). That report looked specifically at the return on investment in MSIs and concluded that MSIs contribute significantly to the STEM workforce; with greater investment, the positive impact that they impart would only increase (48).

Community colleges and other 2-year degree programs are also uniquely positioned to support diverse chemical sciences and engineering students, because they allow for greater flexibility in taking courses (full time, part time, and evenings), focus on educating their local population, and are significantly less expensive than 4-year degree programs.

These programs provide accessible education opportunities for students, and are more successful at attracting and retaining racially diverse students (49). Additionally, the majority of tribal colleges and universities in the United States are 2-year institutions (50). Although the success of these institutions is critical for supporting the populations of students that attend them,they are massively underfunded (51). STEMM programs at community colleges have strikingly limited resources, such as overloaded faculty who are undercompensated and overworked, limited to no professional development opportunities for faculty and staff, and a counselor-to-student ratio of1 to 1,000, at best (52).

Flexibility in Chemical Sciences Education

The many critical courses included in the undergraduate chemistry and chemical engineering curricula have remained unchanged for a long time. Both disciplines are held to the standards of an external body: the Accreditation Board for Engineering and Technology for chemical engineering programs and the ACS Approval Program for chemistry programs. The large number of core courses in each of the curricula can make it difficult to add new required or elective courses without adjusting current requirements. However, as technology evolves, weather events become more severe, and new global threats emerge, such as the COVID-19 pandemic and the climate crisis, flexibility in education is becoming more important than ever.

The potential for chemistry and chemical engineering foundations to be applied to innovative solutions is ever expanding. While foundational chemical knowledge is essential, and altogether remains the same, the methods and tools used to apply that knowledge and the ways in which we are able to access chemical information change over time (Chapter 4 of the full report discusses some of the most important emerging tools and technologies in the chemical sciences).

These changes are occurring more rapidly and more frequently, requiring those in the chemical workforce to innovate at warp speed. Operating at the boundaries of innovation requires that the chemical workforce be ever more flexible in their approaches and increasingly able to learn and use new skills and applications.

The flexibility required of the chemical workforce may not be mirrored by the education that the workforce receives. Ideally, chemistry and chemical engineering curricula would provide educators with ample opportunities to introduce new content, or simply adapt content, to match the current landscape of their respective fields. Providing education that is reflective of the state of the discipline engages and empowers students to obtain the degrees necessary for their desired careers in the chemical sciences and better enables those students to address the global challenges at hand once they enter the workforce. Such an education can only be provided if the courses and curricula remain nimble and are able to be adapted as fields evolve over time.

A key way that institutions can provide students with an education that is current with the state of the discipline is to provide opportunities for exposure to the new tools and technologies as they emerge. Some prevailing tools in the chemical sciences include computation and computer science, robotics, data science, and scholastic output. Impactful exposure to these tools does not necessarily require the present way that students are being taught chemistry and chemical engineering to be uprooted. Opportunities for introducing students to new tools and applications and reinforcing that knowledge can range from 1-hour laboratory modules or experiments to entire elective courses. Other opportunities for exposure can include research experiences and internships, student workshops and conferences, and online courses and tutorials.

However, current curricular models do not leave much room for the flexibility that is needed. At most institutions, if an educator wants to provide exposure to tools and methods that are not included in the set curriculum, their only option is to use their own incredibly limited time and resources to develop and incorporate such alterations. This places a heavy burden on the faculty, who are already stretched to provide meaningful mentorship and research experiences to their students, and requires them to do work for which they are not being adequately compensated or recognized. Additionally, this system of ad hoc injections of innovative content into courses does not promote the sharing of information among faculty and across institutions. When one professor takes the time to create new and innovative course content, there are limited methods of sharing that model with other faculty who are interested in making similar changes. Although such content can be published in the Journal of Chemical Education (53) or Chemistry Education Research and Practice (54), increased mechanisms for dissemination of these innovative ideas would enable greater collaboration and implementation.

Although there are many challenges with changing chemistry curricula, there are specific topical areas and teaching approaches where the chemistry education community has already made important progress. These areas are exciting for the future of chemistry education but still require extensive work before they can be universally implemented.

- **Computation and data analysis in chemistry education**: With the increased use of computational and data analysis tools in chemistry research, this topical area could benefit individuals entering the chemical workforce. Computational interfaces and programs are already being developed to help incorporate these skills into chemistry education (55; 56), but there are still many challenges to overcome in effectively and seamlessly implementing computation and data analysis into the curricula.
- **Sustainable chemistry and systems thinking in chemistry:** With the chemical enterprise continually increasing its focus on environmental sustainability, it will be helpful to introduce the concepts of green and sustainable chemistry, as well as systems-level thinking related to chemistry, in earlier stages of chemical education. Groups such as the Green Chemistry Institute of the ACS are developing green and sustainable chemistry modules that can be incorporated into the material that is normally covered in general and organic chemistry classes at the undergraduate level (57). Additionally, there are groups, such as Systems Thinking in Chemistry Education, who argue for the importance of systems thinking as a complementary approach to reductionist teaching styles that are typically used in chemistry classrooms (58). This group argues that a mix of approaches will produce members of the chemical workforce who are environmentally conscious and socially aware.

To fully explore the best ways to universally and equitably implement topics such as these into the chemistry curricula, it would be critical to convene a group of chemistry education experts who could assess the educational landscape of chemistry, decide what is important for the next- generation chemical workforce, and chart a pathtoward implementation. An in-depth discussion of reforming chemistry education goes beyond the scope of this report, but the study committee does note the importance of chemistry education being flexible and adaptable to changes in the chemistry enterprise. Introducing greater flexibility into chemistry and chemical engineering curricula without placing undue burden on faculty will require communication and collaboration among faculty, departmental leadership, university leadership, accreditation bodies, and funding entities. Conversations around how to best support excellence in chemical education are long overdue, and curricular development needs and opportunities must be considered by all parties. Discussions pertaining to continuous evaluation of the tools and applications utilized in the workforce would allow all educators to keep their courses current. The time needed to bring such parties together and have the conversations needed to enact change and create action could be substantial, and the agencies that support chemical research could consider financially supporting that time.

Furthermore, creating more equitable access to chemical education research and providing students with the tools and innovative spirit necessary to contribute to the future of the chemical workforce could be a substantially easier task if more advances were made in chemical education research. It is imperative to better understand the foundations of education and the optimal ways to impart knowledge with the current state of technological development. Basic chemical research can only flourish if chemical education research is also prioritized, because it is the key tool to develop the workforce.

Workforce Development

Professional development of individuals is vital for their success and fulfillment as well as their ability to contribute to the chemical economy. Professional development opportunities avail- able to students and professionals at all levels facilitate transitions during a person's career, provide beneficial knowledge, create valuable networks, and help increase retention in the field. Students studying chemistry and chemical engineering have a wide array of career paths available, including ones outside of the realm of the chemical economy (e.g., medicine, law, financial services, business consulting, government, and more). Those who do enter the chemical workforce can work in sectors and industries involving R&D, production, or business and focus on numerous fields, such as energy, chemicals, materials, consumer products, food, health, pharmaceuticals, or information. Regardless of a student's focus or the path of an individual's career, attaining hands-on experiences is key to beneficial professional development.

Undergraduate Student Development

Professional development at the undergraduate level helps students develop interest in and understanding of a field within their chosen major, as well as the role they might play in such a field. At the undergraduate level, students are tasked with determining whether to seek full-time employment after graduation and begin their professional career or pursue further education in a graduate program to eventually obtain a Ph.D., M.D., J.D., M.B.A., or other advanced degree.

Exploring career options is typically not an activity that is included in coursework requirements. Insights into available career paths can come from a variety of places: presentations by industry representatives, discussion in class about specific industries and jobs, participation in conferences (e.g., AIChE student conferences), and mentorship from someone in the field.

One of the most important ways to learn about the working world is through professional development experiences in which students can apply their scientific and technical knowledge to real-world problems. These experiences allow students to participate in defining an approach to a problem and generating knowledge toward solutions. Opportunities for development occur through a range of direct experiences, many of which are discussed in Box 5-2. Although these experiences are vital for the student, there are many barriers to securing an undergraduate professional development opportunity. These include identifying opportunities, successfully competing for them, and balancing financial needs and personal priorities with potential opportunities. Professional development experiences can be especially influential for the recruitment and retention of underrepresented undergraduate students. Several organizations have created programs to help increase diversity in the chemical sciences by providing scholarships, and mentorship, and assisting with placement in summer internships.

Guidance and mentorship are important to successfully navigate the process of obtaining professional development experiences. In many academic institutions, a centralized office of career advising and services is a primary source of help for students. However, there is a lot of variability among academic institutions on how useful these offices are for chemical sciences students, as the focus of a career services office may be primarily on managing the interface between employers and students for full-time employment or assisting students in programs with the largest enrollments.

Some companies take an active role in preparing students to work in industry through programs that engage students beyond internships. For example, company-organized activities and conferences allow students to get to know a company and perhaps attract those students as future employees. They can be particularly helpful at engaging groups traditionally underrepresented in the field.

Several universities, including the MIT ACCESS Program (59), have developed similar programs to expose students underrepresented in research to the opportunities afforded by pursuing advanced graduate degrees. Professional societies also have a role in helping students with career exploration. ACS provides resources on its website (60) for students to learn about different career options with a chemistry degree, and AIChE launched an Institute for Learning & Innovation with a pilot on career discovery to help students "gain clarity on optimal job choices and receive direction on how to acquire the necessary skills and training" for a job (61).

Graduate Student and Postdoctoral Development

Professional development at the graduate level serves to prepare students for their future careers after graduation. While some graduate students in chemistry and chemical engineering will become faculty members and continue to pursue research, many masters and Ph.D. graduates will enter the industrial or government workforce. Opportunities for employment also exist in science policy, nonprofits or nongovernmental organizations, professional societies, and more. But, the two main paths for graduate students in the chemical sciences include preparation to become an academic professor and preparation to enter either industry or government. Note that industry is defined broadly in this context and includes established companies, start-ups, and entrepreneurial opportunities to create new companies.

Graduate students interested in academic careers will overwhelmingly transition from a doctoral program to a postdoctoral position. Accordingly, many students who choose such a path often delay deeper exploration of academic careers until they are already in their postdoc position. For those who do seek earlier engagement in understanding academic careers and the process of securing a faculty position, opportunities such as AIChE's Future Faculty Mentoring Program as well as many of the NSF ADVANCE programs (62) provide the means to do so. These programs also help students to prepare for their roles as mentors and teachers, in addition to their research responsibilities, once they become faculty members. These programs are typically open to participants across educational institutions, though some universities also offer programs specifically tailored to their populations.

For graduate students preparing to enter the industrial workforce, they will first need to determine what industry to consider and what role to pursue, because their specific area of graduate research does not necessarily define the role that they could have within a company.

BOX 5-2

Undergraduate Professional Development Opportunities

Students in undergraduate chemistry and chemical engineering programs have a range of professional development opportunities afforded to them. This section outlines three of the most significant categories: internships, research experiences, and cooperative programs

Internships

Industrial internships expose students to a job role within a company, such as R&D, manufacturing operations, data analytics, and business processes. Students often first learn about internship opportunities when company representatives visit school career service offices or are at career fairs. Typically, company representatives that visit schools are from large Fortune 1000 companies. Any individual company only visits a finite number of schools based on proximity to company locations, majors at a school, number of open positions, and prestige and reputation of the institution. The opportunities at these companies, however, are only a subset of all the industrial internships available. Information about internship jobs at a company is often provided on the company's website through its careers portal, in theory making these internships available to all.

Many internship opportunities can also be found on the ACS platform, "Get Experience" (63). The onus is on the individual students to seek out interactions or initiate applications with companies who do not come to their school. An additional challenge is that the pool of potential candidates for an internship is often much larger than the number of openings, so they are competitive. Many U.S. national laboratories also offer internships. For example, the U.S. Department of Energy (DOE) offers summer and semester-long internships, including their Science Undergraduate Laboratory Internships (64), at its 17 national laboratories. The National Aeronautics and Space Administration hosts a similar set of internship programs at its research centers and other facilities (65).

Research Experiences

Undergraduate research experiences provide students with a valuable opportunity to learn about different areas of research within their field of study. They can occur at one's academic institution throughout a semester as an enrolled student or over the summer at a different institution. A primary source of funding for undergraduate research is the National Science Foundation Research Experience for Undergraduates (REU) programs (66). As of 2022, 75 universities offer REU programs in chemistry, and approximately 20% of the 141 Engineering REU programs are offered in chemical engineering or have projects in which chemical engineers would be able to participate (67). REU programs typically prioritize giving opportunities to early-stage students and students that are underrepresented in the chemical sciences and engineering. In addition to REUs, faculty members may have grant funding to support undergraduate research assistants. Some universities offer competitive grants to undergraduate students hoping to conduct research at their institution. In some cases, companies have partnered with universities to fund undergraduate summer research experiences. For example, the Amgen Scholars Program (80), which funds science and biotechnology research, has supported ~4,000 students since its inception in 2007. Additional opportunities are presented in the National Academies' report Undergraduate Research Experiences for STEM Students (69).

Cooperative Programs

Cooperative programs provide work experience at a company as part of the curricular sequence for degree completion. The academic institution assists in matching students to a company. The course offerings and scheduling are designed to allow students to have full-time work experience during one or two academic semesters. In schools with co-op programs, a bachelor's degree is typically completed in 5 years, with the additional year devoted to time spent in the co-op assignment. During a co-op assignment, students are paid at prevailing internship salaries, and tuition is not charged during the assignment. Cooperative programs for chemical engineering majors are more common than for chemistry majors; however, the number of schools that offer co-op programs is relatively small. A few schools (i.e., Northeastern University, Drexel University, and Kettering University) structure their undergraduate programs with co-op assignments for all majors and all students, and thus make them available for both chemical engineering and chemical science majors.

There is an expectation that many Ph.D. students will have an interest in R&D roles at a company, but other opportunities such as production, operations, consulting, data analytics, or business roles could be attractive. The Accelerate to Industry program (70) helps students explore opportunities in industry while developing the key skills needed to enter the workforce. Entrepreneurship is also a growing area of focus of universities and colleges to foster innovation from research conducted by students and faculty. Some schools have established programs in entrepreneurship to provide students with information and advice, workshops and courses, and alumni mentors and networks, including those in the chemistry departments at Case Western Reserve University (71) and Northwestern University (72).

While there are some opportunities for graduate students to explore industries through a summer internship, they are more limited than those for undergraduates. Additionally, working at an internship means time not working on dissertation research, which can extend the time a student spends in graduate school. However, direct industrial experience is often very impactful and useful for graduate students as they seek to define their industrial career interests. One avenue that graduate students can take to connect to the chemical industry is through graduate student symposiums. At these symposiums, hosted by a variety of institutions, graduate students present their work to industrial representatives and are provided a forum to interact with professionals and learn about different companies. Companies with strong R&D foci, who seek to hire Ph.D.s for roles in R&D, often engage students through these research symposiums.

Postdoctoral researchers occupy a unique role within the academic research system. As neither students nor faculty, the opportunities for postdocs are both more varied and more limited. A postdoc who is hired directly by a research group is classified as an employee of the university. Therefore, opportunities such as internships are typically not available because work above a full-time appointment at the university is not permissible. A postdoc whose appointment occurs through a fellowship is subject to the rules of the granting agency, which may defer to the guidelines in place for nonfellows at the university. The net result of the unique status of postdocs is that the vast majority of professional development opportunities available to them are offered through either the home institution or professional societies. However, most programs that target senior graduate students interested in academic careers are also open to postdocs. Opportunities for direct employment in industry are typically prohibited based on employment agreements; however, “fly-in” or other introductory programs offered by companies to senior graduate students may be available for postdocs as well.

Federal funding agencies have started to recognize that postdoctoral researchers need quality mentoring for the betterment of their personal and professional development. NSF now requires that a mentoring plan be part of any proposal that includes funding for postdocs, while other agencies, such as NIH and DOE, have emphasized the importance of mentoring for postdocs. As discussed in Section 5.2, better and more consistent mentoring practices for postdocs contribute toward their professional development and lead to a higher retention rate of those researchers within the chemical workforce.

Continuing Professional Development

Prioritizing professional development throughout the entirety of an individual’s career within the chemical workforce is essential for the health of the chemical economy. Supporting lifelong learning through professional development sets up the workforce for success, gives people the opportunity to learn new skills, and allows them to seek new opportunities, which together support the long-term health of the chemical economy. Too often people place professional development on the back burner as their lives becomes more demanding. But it is important that professional development opportunities for members of the chemical workforce be continuously prioritized, so that the workforce is prepared for and empowered by new challenges, tools, and opportunities.

Workforce professional development can be driven by workplace expectations set by the employer, whether it be a company, an academic institution, or the government. Professional development at this stage is varied, because the needs of early-career, mid-career, and experienced workers differ and expectations for continuing education vary across sectors. Broadly, development may consist of expanding an employee's technical and nontechnical knowledge and skills, preparing them for future roles in the organization or field, and developing their leadership and mentorship skills.

Individuals working in scientific and technical roles in industry learn on the job how apply their formal education to their profession. But new tools and techniques are always being developed, so continuing technical education is an important component of professional development in the workplace. This can occur through part-time study for advanced degrees, topic-specific short courses, and training sessions. Opportunities are offered at technical conferences, through the employer, or accessed online. Many companies cover the cost of these activities as an educational benefit provided directly to the employee or through an employer's training budget.

Nontechnical professional development tends to focus on the skills that can enhance an individual's ability to contribute to innovation. These include communication and presentation skills, working as a team, unconscious bias training, and continuous improvement methodologies. There appear to be fewer professional development opportunities for those working in academia and fewer requirements by schools for faculty to engage in professional development. Faculty who do so are generally driven by their own ambitions. In addition, professional development opportunities are sometimes not supported by universities, further increasing the barrier to access.

As was noted for the previous career stages, there are challenges for professionals in the chemical workforce to identify and access development opportunities. It is important that an institution's leadership set the expectations for, provide information about, and help people gain access to opportunities, training, and programs to further their education and understanding of their role within their field. Individuals can also access professional development through professional societies that focus on the chemical sciences and engineering. These professional societies organize conferences, offer courses and training, and provide networking opportunities.

Networking is a key skill that can be used to support one's professional development. For some, networking may suggest a social mixer to meet others who work in similar fields, and to cultivate relationships with people to help further one's career. However, networking can be viewed more broadly as interactions with colleagues (present, past, and future)in which ideas are exchanged and questions are asked with three goal sin mind: learning, generating ideas, and problem solving. Many technical environments, such as labs, naturally provide a venue for networking, as they promote collaboration and lead to productive interactions among colleagues. Networking beyond one's project team and organization is typically more beneficial for someone's professional development, since those interactions contribute to both institutional innovation and employee development through sharing knowledge and skills.

Conclusion and Recommendations

The U.S. chemical economy is best supported by a well-trained workforce. This chapter covered many different components of chemical training, including some that are subject-matter based, such as the need for nimble and flexible academic training programs, and some that are not specific to the chemical sciences, but equally important, such as the need for adequate mentorship and professional development. Based on the information gathered and presented, the committee came up with several conclusions related to building and maintaining the skilled and diverse chemical workforce that is foundational to support and enhance the U.S. chemical economy.

- **Conclusion 5-1:** A skilled science and engineering workforce paired with a diverse, inclusive, and equitable science and engineering research enterprise is central to a thriving, nimble chemical economy equipped to respond to emerging challenges and maintain U.S. competitiveness.

- **Conclusion 5-2:** The current structures and systems governing funding, promotion, retention, and professional development are in conflict and can stymie holistic career advancement for students, faculty, and research staff.

- **Conclusion 5-3:** MSIs, including HBCUs and HSIs, and community colleges excel at supporting the academic preparation of diverse populations of students that will enter the chemical workforce upon graduation.

- **Conclusion 5-4:** Effective mentorship is essential for the success of the chemical workforce at all levels and across sectors. Positive mentoring relationships can increase equity and inclusion in the classroom and the workplace, but mentors often have insufficient access to the resources and training needed to enable such relationships.

- **Conclusion 5-5:** Creating an equitable and inclusive learning environment that exposes trainees of the future chemical workforce to new and innovative chemical tools, technologies, and instrumentation, as well as interdisciplinary knowledge and critical collaboration skills, will require a serious and sustained investment from funding agencies, universities, industry partnerships, and accreditation programs. This investment is critical because the tools and practices that enable chemical research are constantly evolving, and training programs must be able to adapt to best facilitate the learning of basic-to- advanced chemical principles that will help students succeed.

- **Conclusion 5-6:** Professional development is a key factor for the success of undergraduate students studying the chemical sciences and can determine their future role in the chemical economy. While there are many opportunities for professional development for undergraduates in the chemical sciences, barriers exist that reduce the equity in competing for these opportunities.

- **Conclusion 5-7:** Professional development is vital for the chemical workforce at all career stages, but it can be difficult to prioritize and navigate. Institutions and professional societies can aid in promoting lifelong learning among those who contribute to the chemical economy.

To properly address these conclusions on a practical level, the committee recommends that steps be taken to fund research in chemical education, continually reassess chemistry curricula, and continue to provide opportunities for professional development. The following recommendations lay out these ideas in more detail.

- **Recommendation 7-1: Funding agencies that support chemical research should put a substantial investment toward education research to continue enabling the development of innovative ways of teaching students about new and emerging concepts, tools, technologies, and instrumentation in chemistry while creating an inclusive learning environment for all students.**

- **Recommendation 7-2: Universities, colleges, and accreditation programs should continually reassess their curriculum requirements and pedagogical practices to ensure that chemistry students in the chemical sciences are receiving state-of-the-art inclusive training and the most current chemical information and advances.**

- **Recommendation 7-3: Universities and agencies that fund and support education in the chemical sciences should provide professional development at all levels, allowing for opportunities that are specific to the needs of each educational or career stage, such as programs that connect students with internships or resources for career exploration and providing faculty with professional development opportunities aimed at advancing their scholarship and teaching.**

- **Recommendation 7-4: To continue progress in improving the diversity and equity of the chemical workforce, universities and chemical sciences departments should regularly assess their recruitment and retention practices related to trainees, faculty, and research staff. These assessments should be guided by relevant experts in research-informed equitable recruitment and retention practices of higher education institutions and units that also understand the nuances and details of the particular institution or entity. Institutions and units should continually take action and make meaningful investments based on their assessments. This work should be reported in a timely and transparent fashion to the institutional community.**

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Table 5-1 Programs and Initiatives That Support DEI and Diverse Individuals in the Chemical Sciences

Career level	Programs and Initiatives

Pre-College	• Upward Bound Math-Science Program
	  ◦ A U.S. federal TRIO program that aims to help pre-college students from low-income families, or who would be first-generation college students, to recognize and develop their potential to excel in math and science and encourage them to pursue postsecondary degrees in those fields.
	• American Chemical Society Project SEED Program
	  ◦ Provides opportunities for high school students with diverse identities and socioeconomic backgrounds to participate in summer research experiences at institutions of higher education across the United States.
	• Native American Science & Engineering Program (NASEP)
	  ◦ Offers Native American, Alaskan Native, and Hawaiian Native high school students experiences for 1 year aimed at developing their understanding of STEMM career opportunities.
	• Future of STEM Scholars Initiative (FOSSI)
	  ◦ Supports high school students who have an interest in pursuing careers in chemical manufacturing, engineering, environmental health and sustainability, or other related chemical-industry fields.

Undergraduate	• Ronald E. McNair Postbaccalaureate Achievement Program
	  ◦ A U.S. federal TRIO program that provides competitive funding to institutions of higher education to prepare students from underrepresented segments of society for later doctoral studies to increase the number of diverse Ph.D. holders.
	• Building Infrastructure Leading to Diversity (BUILD)
	  ◦ Housed by the National Institutes of Health, the initiative provides awards to undergraduate institutions to help them engage and retain students from diverse backgrounds while supporting institutional transformation.
	• Meyerhoff Scholars Program
	  ◦ Supports prospective undergraduate students who are interested in later pursuing graduate studies with the goal of increasing diversity of future leaders in STEMM fields.

Table 5-1 Programs and Initiatives That Support DEI and Diverse Individuals in the Chemical Sciences

Career level	Programs and Initiatives

Graduate	• University Centers of Exemplary Mentoring (UCEM)
	  ◦ Provides scholarships and other forms of support to help underrepresented minority students obtain a doctoral degree in engineering, the physical and natural sciences, or mathematics at a partner university.
	• GEM Scholars Program
	  ◦ Works to increase the participation of underrepresented groups at the master's and doctoral levels in applied engineering and science by matching the interests of individuals with the needs of GEM employer members.
	• WiscProf: Future Faculty in Engineering Workshop
	  ◦ A multiday event for Ph.D. students and postdoctoral scholars from underrepresented groups in STEM engineering fields to learn about academic career paths and the process of securing and succeeding within a faculty position.
	• American Chemical Society Bridge Program
	  ◦ Works to increase the number of chemical science Ph.D.s awarded to underrepresented students through the creation of transition (bridge) programs and a national network of doctoral-granting institutions.

Postdoctoral	• MLK Visiting Scholars Program
	  ◦ Hosted by the Massachusetts Institute of Technology (MIT), this program works to increase the presence of minority scholars at MIT. Scholars participate in research and academic programs.
	• Presidential Postdoctoral Fellowship
	  ◦ Hosted by Brown University, the fellowship supports Ph.D. graduates from underrepresented groups.

Multilevel and post-academia	• National Science Foundation (NSF) includes Planning Grants
	  ◦ Includes planning grants to support the development of infrastructure to increase the capacity for collaborative innovation to broaden participation in STEMM fields.
	• The Committee on the Advancement of Women Chemists (COACh)
	  ◦ Provides career-building and -development opportunities for women in chemistry and assists institutions in developing their diversity and inclusion efforts.
	• Inclusive STEMM Ecosystems for Equity & Diversity (ISEED)
	  ◦ Leads initiatives to support underrepresented individuals in STEMM by evolving and reconstructing systems and structures to increase inclusivity.

COMMITTEE ON ENHANCING THE U.S. CHEMICAL ECONOMY THROUGH INVESTMENTS IN FUNDAMENTAL RESEARCH IN THE CHEMICAL SCIENCES | **Mark S. Wrighton** (*Chair*), The George Washington University; **Cathy L. Tway** (*Vice Chair*), Johnson Matthey; **Ashish Arora**, Duke University; **Raychelle Burks**, American University; **Joseph M. Desimone** (*NAS*, *NAE*, *NAM*), Stanford University; **Shanti Gamper-Rabindran**, University of Pittsburgh; **Jeanette M. Garcia**, IBM; **Javier Guzman**, ExxonMobil; **Martha Head**, Amgen; **Russell Moy**, Southeastern University Research Association (through January 2022); **Kristala L. J. Prather**, Massachusetts Institute of Technology; **Jason Sello**, University of California, San Francisco; **Bala Subramaniam**, University of Kansas; **Jean W. Tom** (*NAE*), Bristol Myers Squibb

STAFF | **Steven Moss**, Study Director; **Liana Vaccari**, Program Officer; **Jessica Wolfman**, Research Associate; **Benjamin Ulrich**, Senior Program Assistant (through March 2022); **Charles Ferguson**, Board Director; **Brenna Albin**, Program Assistant; **Olivia Torbert**, Program Assistant (through February 2021); **Jeremy Mathis**, Board Director (through September 2021); **Maggie Walser**, Interim Board Director (through January 2022)

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