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CENTC's best practices for postdoctoral and graduate student education

The scientific workforce is changing rapidly and, for the most part, training of PhD students and postdocs has not kept pace. There has been a significant shift away from academia in the employment landscape, with an estimated 2/3 of PhD chemists and chemical engineers currently holding non-academic positions. Yet most doctoral students and postdocs don't learn about non-academic careers or have opportunities to meet chemistry PhDs who have followed these career paths.[1] Because traditional training has been narrowly focused on conducting research on a single project, many students lack the broad range of skills required for success in the 21st century including the ability to communicate effectively with both technical and non-technical audiences and experience with collaborations, especially across disciplines.[2]

In a report on graduate education from ACS in 2012[3] it is recommended that doctoral students have opportunities for leadership, be exposed to how chemical sciences can address the world's most significant challenges, understand how entrepreneurial processes are involved in bringing fundamental research findings to the marketplace and learn best practices for developing successful collaborations. More and more research is being conducted by interdisciplinary teams of investigators from multiple institutions in academic, industrial and government lab settings. The National Postdoctoral Association (NPA)[4] has similar recommendations for postdoc training, emphasizing the importance of receiving practical information about the wide array of professional opportunities outside of academia, including entrepreneurship, as well as cross-disciplinary training and learning the full range of skills required for their success as independent researchers. These include the ability to think critically and to identify and resolve problems in the process of their research. Trainees should also have access to professional development and career guidance including instruction and training in grant writing and in laboratory and project management.

CENTC

CENTC, the first NSF Center for Chemical Innovation (CCI), was widely distributed and ultimately comprised of 20 co-principal investigators at 14 universities and one national lab spread across the US and Canada. CENTC research addressed some of the grand challenges in chemistry, tackling issues related to energy, sustainability and national security. The aim of the Center was to discover and develop catalytic science to enable the implementation of new processes for efficient, environmentally responsible production of chemicals and fuels from common feedstocks. Fundamentally new technologies are needed to reduce dependency on foreign oil both for fuels and for commodity chemicals. CENTC collaborations were interdisciplinary and included researchers in organometallic chemistry, chemical engineering and computational chemistry.

We believed that our unique emphasis on interdisciplinary, collaborative research and our close ties with representatives from the chemical industry and at national labs created a rich environment in which participating graduate students and postdocs would learn about research careers outside of academia and acquire a diverse array of skills to succeed in an era of increasing complexity within the research enterprise.[4] The goal was to provide them with the skills, knowledge and experience to enable each one to excel in his/her chosen career path, be it in private industry, academia or national laboratories. Given the emerging paradigm of multi-investigator, multi-site, multi-disciplinary research in all of these arenas, the collaborative research conducted by CENTC postdocs and graduate students would provide excellent preparation for participation in this new dynamic.

In addition to traditional opportunities of training in a typical program consisting of single-investigators, CENTC students and postdocs also participated in activities unique to the collaborative nature of CENTC that included:

- Mentorship by multiple investigators through which CENTC postdocs and students could include in their employment applications letters of reference from CENTC investigators at different institutions.

- Frequent opportunities for presentations to other center members, a highly knowledgeable and engaged audience with a diverse portfolio of experiences. These included presentations at monthly project meetings, the CENTC annual meeting, and monthly center-wide videoconference meetings. Preparation for these presentations involved practice and feedback sessions with multiple faculty and center staff.

- Experience in brainstorming, project development and, for postdocs, proposal writing, through involvement in CENTC's annual internal project reviews.

- Encouragement and training to participate in, and take leadership roles, in CENTC high school outreach programs. Programs were student/postdoc driven, providing experience in forming a collaborative team, project planning and evaluation, and communicating science to the general public.

- Extensive networking opportunities with representatives from CENTC industrial affiliates, NSF program officers, and the distinguished group of CENTC senior investigators.

- Participation in, and planning of, workshops and other training opportunities in specific areas of career development at the CENTC annual meetings and throughout the year.

- Support for participating in lab visits to take advantage of specialized equipment and expertise.

- CENTC summer schools focusing on processes of translating fundamental research findings to innovations in the chemical industry provided instruction and workshops on NSF proposals, careers and patent applications. CENTC trainees had opportunities to network with prominent speakers and other participants from a wide variety of academic and employment sectors.

As part of their education programs, some centers have developed new curriculum or degree programs that impacted students participating in their centers as well as students from outside the centers. The highly collaborative aspect of CENTC research and wide distribution of research faculty made such programs impractical because with only one or two research faculty per institution, few CENTC students would benefit. Instead, much of CENTC's training was experiential and imbedded within the practice of collaborative research and project development, with most more focused educational and professional development programs provided specifically for CENTC trainees.

Professional Development

As mentioned above, a critical gap in graduate student training is the lack of information students receive about non-academic careers and development of skills important for success in careers outside of academia.[1,2] It was reported that even when resources on career options were available, students often didn't make use of the opportunities because they were hesitant to take time away from research. In creating professional development opportunities, we were mindful of the significant time commitment already required of our students and postdocs due to the frequent meetings and presentations and the necessary preparation time, so we provided mandatory professional development workshops at CENTC's annual meetings covering topics such as resume writing, communication, grant management, interviewing and outreach. By holding professional development activities during our annual meetings when all postdocs and students were present, we insured that everyone participated without having to take any additional time from their research.

Collaborative Research

Students and postdocs were full participants in CENTC's collaborative research and were involved in all of the research and planning aspects of the center. Every CENTC research project was collaborative and involved faculty mentors and other researchers from at least two sites. All project updates at Center-wide monthly videoconferences were presented by graduate students and postdocs, and they received input from other researchers who included inorganic chemists, chemical engineers and computational chemists. Additionally, individual project teams met for more frequent videoconferences to manage routine aspects of their specific projects. Through these frequent virtual meetings, as well as the annual in-person meetings, trainees gained valuable experience in communication across distances. By working in CENTC's highly

collaborative environment students and postdocs were exposed to a variety of research styles and interdisciplinary approaches to scientific problems. They developed mentoring relationships with faculty other than their own research advisors and many graduate students were able to include reference letters from more than one CENTC investigator in their applications for future positions. They learned the strengths and challenges of collaboration and how to foster successful research partnerships and postdocs. By reporting out on their research several times per year to the entire CENTC group, they were able to hone their communication skills.

Figure 1. Videoconference

Annual Meetings

While virtual meetings played a key role in facilitating ongoing research projects, face-to-face meetings were invaluable. Each year all CENTC investigators, including students and postdocs, met in person to discuss progress and future directions of research projects. These meetings were also attended by industrial affiliates and representatives from NSF. Again, graduate students and postdocs played a central role in presenting center research. All project updates were summarized through oral presentations by selected students and postdocs and every student and postdoc presented more detailed information on their projects at poster sessions where they received valuable feedback from experts in their research fields. Annual meetings also provided opportunities to interact with professionals from private industry, government labs and NSF and learn more about different career sectors. Access to industrial partners was especially valued by students and postdocs and several opportunities for those to occur were provided by design. A highlight of the meetings was the "Industrial Roundtable," where industrial affiliates provided feedback about the Center's research from a commercial perspective, suggesting new research targets and offering insights into CENTC technologies having potential for licensing, giving students and postdocs a view of how research discoveries can be translated into innovation and commercialization. Graduate students and postdocs were also full participants in discussions and brainstorming sessions exploring research directions for the coming year. As part of the actual planning process of the Center, our trainees developed skills for developing their own future independent research careers from initiation to ongoing review and evaluation. Opportunities for informal interactions with one another, senior investigators and partners from the chemical industry promoted a sense of community within the center and provided valuable networking experiences many of which led to long-term professional relationships and/or new professional positions within the represented organizations.

Figure 2. Annual Meeting Poster

Since all CENTC postdocs and graduate students attended the annual meetings we used the opportunity to provide more formal professional development workshops. Graduate students and postdocs arrived the day prior to the first day of the annual meeting to participate in these workshops and to rehearse their oral presentations.

Career development topics covered were:

- 2008 - Preparation of NSF "highlights" and development of "elevator speech" facilitated by NSF program officer, Kathy Covert

  The ability to communicate one's research in a way that can be understood by non-scientists is critical for contributing to the development of a science-literate society as well as informing legislators and policy-makers of the practical importance of investing in scientific research. Communicating effectively with scientists outside of one's specific area of research is also essential to developing productive interdisciplinary collaborations. Graduate students and postdocs created and presented one-minute speeches describing their individual projects and why they were important.

- 2009 - "Networking Strategies" and "Managing Your Relationship with Your Supervisor" facilitated by Brianna Blaser, PhD; Project Director, Outreach; Science Careers/AAAS

  Having professional relationships with a wide array of scientists is a tremendous advantage for career development, from getting feedback on research to establishing future collaborations and employment. CENTC graduate students and postdocs had opportunities to network both within the Center and at professional conferences and meetings. Dr. Blaser offered tips for making the most of networking opportunities and practical ideas for networking including proper etiquette, business cards, elevator pitches, and following up with contacts. A successful professional relationship with research supervisors is also essential for future success and suggestions were offered for establishing lines of communication and being proactive getting constructive feedback and developing a timeline for completion.

- 2010 - Grant-Writing and Management: Facilitators Nadine Gruhn, CENTC Managing Director and Kathy Covert, NSF program officer

  Grant-writing and management are skills that most PhD students and postdocs don't learn in traditional research settings and, in an ACS survey of chemistry PhD recipients, the one mentioned most as lacking in their training. Workshop focused on NSF proposals and awards, but also benefitted other scientists, such as those in private industry or government labs, who are also called upon to develop new projects and justify their importance towards accomplishing the goals of the funding organization, whether it be NSF, Department of Energy, or potential investors in one's company.

- 2011- Communicating Your Research to the Public – conducted by Dana Vukalovich and Stephanie Fitzwater, Pacific Science Center, Portal to the Public

  CENTC had a very successful ongoing partnership with Pacific Science Center in Seattle, which provided opportunities for us to engage in public outreach and also offered instruction in effective communication of complex scientific concepts to the general public. Graduate students and postdocs attending the annual meeting learned strategies for connecting with non-technical audiences and implemented them by creating introductory descriptions of their particular research projects – what problem is being addressed and why it is important – in lay terms.

- 2012 – Teambuilding – kayaking at Agua Verde Paddle Club

  The 2012 annual meeting was held shortly after CENTC received news that the Center award had been renewed by NSF for an additional five years, and also was a meeting attended by many new students and postdocs after the first cohorts had completed their time with CENTC. The training session at this annual meeting was more informal than previous sessions, to both allow the new participants more time to get to know each other in a casual setting, and to celebrate the news of renewal.

- 2013 - Tools for Collaboration – conducted by CENTC IT Manager, Imran Peerbhai, and Project Planning – led by Nadine Gruhn

  Graduate students and postdocs were fully engaged in collaborative research while with CENTC and through their participation they learned the advantages and obstacles inherent in collaboration across distance. However, they also benefitted from practical information about best practices for initiating and maintaining collaborations. In this workshop students and postdocs reviewed the progress of their CENTC projects, proposed short-term goals, identified additional collaborators and described how project members could work together

effectively. This session also provided training on some of the new IT-based collaboration tools that CENTC had recently upgraded/implemented.

- 2014 – Outreach demonstrations – Led by Nadine Gruhn and graduate students

  CENTC sought to involve students and postdocs in public outreach. This session involved demonstrations of several activities that could be used to engage public audiences. Activities included elephants toothpaste, liquid nitrogen ice cream, and hands-on practice with a variety of demos was provided as well as discussion on how to use them as an entry point to engage in conversation about the chemistry involved.

- 2015 - Panel Discussion: Job Search and Interview Skills

  A panel of representatives from the CENTC industrial affiliates and external advisory board (representing private industries, including pharma, energy and commodity chemicals, and national labs) talked about their companies or labs, what they look for in hiring scientists and fielded questions from graduate students and postdocs. Participants, who had prepared their resumes beforehand, met one-on-one with panelists to critique their resumes and conduct mock interviews.

Summer Schools

CENTC Summer Schools were week-long in-residence programs that provided pedagogical instruction focusing on processes by which basic research findings in chemistry can be translated to innovations in the marketplace. The semi-annual summer schools were open to the broader chemistry and chemical engineering communities and targeted senior graduate students, postdocs and early career researchers who were not a part of CENTC in addition to CENTC graduate students and postdocs. Presentations were given by leading chemists and chemical engineers from around the world who had been involved in recent discoveries and commercialization of processes related to more sustainable operations in industry. Speakers included researchers from academia and government labs, chemists from a broad spectrum of industrial applications as well as academics involved in entrepreneurship. Summer Schools emphasized the importance of collaborations across disciplines and between public and private institutions to move advances in basic chemistry to innovation in commercial processes. Workshops included grant proposal preparation and review, preparation of patent applications and interactive career panels that included researchers from an array of employment sectors. Integral to the summer school programs were multiple informal opportunities for networking with other attendees and speakers to share research and potential opportunities for collaboration. Participation in the summer schools provided CENTC students and postdocs a unique and rich educational and professional development experience through which they were exposed to a variety of careers and

employment sectors, learned about grantsmanship and had opportunities to network with prominent chemists and chemical engineers as well as peers. They learned about approaching grand challenges in chemistry through interdisciplinary collaborations, about the process of entrepreneurship and how basic research findings can be translated into new technologies in industry.

Lab visits

To learn about different types of catalysis and multiple approaches to research problems, students and postdocs were encouraged to visit other CENTC labs through which they could learn techniques not available at their home institutions and increase the breadth of their training. An international lab exchange program was also available, supported through a supplement from the NSF SAVI program. Lab visits were opportunities for graduate students and postdocs to get detailed feedback on their projects and mentorship from faculty other than their primary research advisor. In addition, some CENTC institutions offered special expertise and/or facilities. Students and postdocs whose projects could benefit from it had access to the high throughput facility at University of Ottawa. Professor Tom Cundari at University of North Texas offered a "Computational Boot Camp" for bench scientists to add understanding of computational analysis to their experimental skills.

Leadership Experience Through Outreach

It is becoming clear that researchers have a vital role to play in engaging with the public to educate them about the importance of science and research and to inspire the next generation of scientists. We wanted to instill in our students and postdocs an appreciation of the importance and rewards of conducting public outreach. CENTC's long-term research goals addressed problems of great social importance such as developing new technologies to allow generation of more efficient and sustainable energy and feedstocks. The urgency of finding potential solutions to society's dependence on fossil fuels is well-known and understood by most of the lay-public. We strongly encouraged our students to participate in local outreach activities at their home institutions or in their communities to share their excitement about chemistry and also to initiate conversations about how chemical research can solve some of society's greatest challenges. CENTC conducted high school outreach programs, one out of Rutgers University and the other from University of Washington. Each year teams of graduate students and postdocs would visit local high schools with a curriculum developed to fit in with educational standards and provide instruction and hands-on activities related to the broad interests of CENTC researchers. These programs were entirely student/postdoc-driven and provided excellent leadership opportunities. They gained experience in recruiting volunteers and building a working team, project planning, organization and evaluation, and communicating science to non-technical audiences. These two high school programs were developed by CENTC graduate students and postdocs.

Graduate students in the Goldman lab at Rutgers university developed an interactive high school-university program for outreach and education on greenhouse gases and global warming.

Students reached out to local public high school chemistry teachers in high minority-enrollment schools to offer the program and identify those who would be effective partners in implementing the program. The central goal of the initiative was to not only provide a didactic experience for high schoolers, but to also cultivate connections between high school and college level education. The plan was to give the younger students exposure to higher education that they might not otherwise get with the hope that the visits would generate an interest in science and pursuit of post-secondary education. A curriculum was developed that was integrated with two units in the high school chemistry curriculum: "Energy" and "Ideal Gases." The program included hands-on activities, discussions of scientific principles and opportunities for direct contact between high school students and the Rutgers team. Students were engaged with fun demonstrations and hands on activities that demonstrated the ability of CO_2 to raise atmospheric temperature. Discussion followed about careers in chemical sciences and the importance of research in chemistry to address critical societal problems such as global warming and development of more environmentally friendly fuels. Over time, and in response to feedback from high school students and teachers, the program evolved to one in which the high schoolers were presented with a problem (determine the molar volume of carbon dioxide gas or determine the density of air) and asked to design and carry out their own experiments to solve the problem. After several weeks of experimentation high school students presented their work in a poster session attended by the university volunteers, parents and teachers. The Rutgers team discussed students' results, procedures and the scientific method and shared their individual experiences in chemistry. This exercise provided a unique opportunity for students to apply their knowledge of science and creativity and ingenuity to address a laboratory problem without any instructions and generated a great deal of excitement for both students and teachers. The graduate student lead for the Rutgers program has moved on and continued conducting outreach as a major contributor to a CENTC partnership with Liberty Science Center in New Jersey that consisted of development of a multimedia game about chemical synthesis to be included in their "Energy Quest" exhibit.

At University of Washington (UW) two CENTC postdocs developed a high school activity with direct connections to their own Center research that included a modified version of a published small-scale biodiesel synthesis.[7] Their own research involved finding catalytic reactions with potential to convert glycerol, a by-product of biodiesel production, to a more useful feedstock chemical. The UW group developed a full curriculum around the activity and incorporated attention-grabbing demonstrations and opportunities for university students to share their personal experiences in chemistry and engage in discussions with high school students about chemistry education and research. The leaders purchased and organized necessary equipment and supplies. They recruited about 20 graduate student and postdoc volunteers, trained them and scheduled them for visiting local high schools. They were able to offer different modifications of the program according to the needs of the participating teachers – one that was three days in length and the other a single day. The program continued for the duration of CENTC and was coordinated by different graduate students or postdocs each year, partnering with two Seattle public schools, one of which was designated a STEM high school serving a diverse community. The program involved 4 teachers and about 450 students per year. The two who developed the program hold positions in industry and academia and continue to be involved in public outreach.

CENTC maintained a very productive ongoing relationship with Pacific Science Center (PSC) in Seattle. Home to the "Portal to the Public" program, PSC offered training to active researchers on effective techniques for communicating science to different types of public audiences. In addition to providing training to all of our trainees during an annual meeting as described above, some students and postdocs at UW participated in a course that provided more extensive and detailed instruction on communication and development of engaging activities relating to their specific research interests. Several UW students and postdocs were primary contributors of content during the development of CENTC's two exhibits at PSC. The took the lead on communicating with project planners from PSC, guiding them through the research labs and explaining their work in lay persons' terms and describing the nature of conducting research in chemistry.

Participation in outreach with CENTC while postdocs has had great impacts on their commitment to community outreach in their subsequent careers in academics

- "Thanks to my outstanding experience in CENTC, outreach and community engagement has been a priority in my research group from Day 1, helping to build a group of savvy communicators and forge a strong connection to local communities in North Carolina.
- "The outreach programs that I am involved with show the great impact CENTC has had beyond the group of researchers and PIs. I try to instill these core values in my teaching, research and outreach activities. These activities have significantly impacted my career and will do so for years to come."

Formative Evaluation

Ongoing evaluation is important for developing successful programs and assessing their effectiveness in meeting goals. From the early stages of the center, we sought feedback from our graduate students and postdocs about their CENTC experiences; what were the challenges and what improvements could be made to better serve their needs. We asked about which activities were useful – or not - what suggestions they had for professional development activities and how annual meetings could be more useful to them. In response to the earliest surveys, students and postdocs expressed a strong interest in having more access to researchers from the chemical industry. We set aside times during the annual meetings when students and postdocs could meet with CENTC's industrial affiliates to learn more about careers in industry. Periodic assessments allowed us to continue improving the opportunities for CENTC trainees to develop skills for success in whatever career paths they chose.

Alumni evaluation

As described above, we had some specific training goals for our postdocs and students – learning to work collaboratively and communicate effectively across distance, knowledge of a variety of types of catalysis and approaches to research problems, productive relationships with collaborators not at their home institutions, awareness of varied employment sectors for chemistry PhDs, excellent communication skills and opportunities for leadership. We believed that certain aspects of participating in CENTC would help in achieving those goals. At CENTC's conclusion we wished to determine whether our specific goals for training had been met and how our postdocs and graduates perceived their CENTC experiences after they had completed their participation in the program and continued on in their education and careers. We invited all graduate student and postdoc alumni to complete a survey on Survey Monkey. We were interested to learn which CENTC activities they felt had contributed most to their development as researchers, how CENTC had prepared them for specific activities or chemistry careers, and what attitudes or opinions they held about their participation in CENTC. Because time commitments were significant for CENTC trainees, it was also important to determine whether their CENTC experience had been worth the additional workload and also whether working with CENTC had prevented graduate students from earning their PhDs in a timely manner.

We collected demographic and quantitative information, and, using a 5-point Likert scale with 1 being strongly agree, 3 neutral and 5 strongly disagree, we collected qualitative information about the participants' experiences with CENTC. Thinking there may be differences between different groups of alumni such as those who were postdocs versus graduate students while with CENTC, those who were currently in industry positions versus academia, etc. we ran statistical analyses to control for 8 different variables. Of 137 individuals contacted, 62 completed the survey, for a 48% response rate.

Quantitative Information

At the time queried, of those who completed the survey, excluding those that were currently postdocs (18% of respondents), 43% of CENTC alumni were research scientists at a company, 37% faculty at 4-year colleges or universities, and 20% were working in other employment sectors including government labs and patent offices. 57% of respondents had been graduate students with CENTC and 47% postdocs (these add up to more than 100% because a few had been CENTC graduate students and then postdocs in another CENTC lab).

A significant concern, which was shared by several site visitors and NSF, was the potential impact of conducting high risk research on student and postdoc productivity and on the time taken for CENTC graduate students to earn their PhDs. Of those graduate students who completed the survey, all who had earned PhDs while at CENTC had done so within 6 years with an approximate average of 5.5 years. This is within the range of the mean times to earn a chemistry PhD in the US reported by ACS and NSF: 5.1 to 5.9 years,[3,5,6] respectively.

A good proportion of alumni had taken advantage of additional optional training opportunities offered by CENTC; 45% had attended a CENTC summer school and 29% had visited an outside laboratory. 56% had participated in outreach activities and, of those, 65% felt that it had contributed to their professional development.

Most (75%) had at least one publication from CENTC projects and 27% had co-authored IP disclosures or patent applications. Almost half (45%) had publications from non-CENTC projects carried out while they were also conducting research for CENTC.

Qualitative Information

Alumni were asked to indicate how strongly they agreed or disagreed with statements in three categories – which of 21 specific CENTC activities contributed to their development as researchers, how well CENTC had prepared them for each of 15 specific activities, and level of agreement with 15 different statements about their CENTC experiences. Use of the 5-point Likert scale method provided numerical scores for comparisons with lower scores indicating more positive responses. Because of the small sample size the threshold for statistical significance was high so we are mostly only able to report trends. The results reported here reflect only the opinions of 48% of CENTC participants and results are skewed due to the fact that those who completed the survey are a self-selected group. The weighted average scores ranged from 1.38 to 2.59. Out of 51 questions, 47 had net positive scores (<2.25), one negative (>2.5) and three neutral.

Activities judged most useful were working with multiple PIs, presentations at annual meetings, participation in project meetings and personal interactions at annual meetings. Those activities with lowest rankings were participating in outreach and training in communication to non-technical audiences.

Most alumni agreed that CENTC had prepared them well for working in collaborations (96%), conducting independent research (95%) and communicating to technical audiences (95%) with none disagreeing. There was less agreement that CENTC had prepared them for succeeding in an academic career, working with people from diverse backgrounds, and communicating with non-technical audiences (58%, 64% and 67% in agreement, respectively).

Nearly all respondents (>90%) agreed that collaborative research is important, that they would participate in CENTC again (only one would not and 3 were neutral) and that they had constructive relationships with their advisors. 81% agree that CENTC has prepared them to conduct independent research. The most negative scores had to do with access to career advice (59% agreed) or time for graduate students to complete their PhDs. Nearly one third (9 of 29) reported that it had taken them longer than their non-CENTC peers to earn their PhDs. This question had the most negative responses (9) and highest Likert score of all questions at 2.59. Published reports on graduate education indicate means to earn PhDs in chemical sciences of 5.1 years[5] and 5.9 years.[3] The published surveys included large numbers of PhD recipients in the

chemical sciences across the country and it may be that time to PhD is significantly lower in the specific departments in which CENTC students worked than in the national average.

Open-ended questions

Open ended questions were perhaps most revealing for determining what alumni identified as strengths and weaknesses of their CENTC experiences. Again, responses were overwhelmingly positive. When asked how they would describe their CENTC experiences to a peer, aspects of the program mentioned most frequently were collaboration, networking and professional connections. Collaboration, communication skills and other skills such as time-management, project planning, etc. were skills they have implemented or planned to implement in their post-CENTC careers.

Challenges most often reported were collaboration, learning multiple ways to approach problems and working on high-risk projects, the very features that characterized CENTC research. Excluding working on high risk projects, the challenges mentioned were also overwhelmingly viewed as positive and useful experiences. The time commitment required for participation in CENTC was not specifically mentioned as a challenge or a negative. Asked for suggested improvements, no one suggestion stood out from the others. Those mentioned more than once were getting off of dead-end projects earlier, having more contact with industrial affiliates and additional professional development.

Controlled Variables

We investigated how some different variables may have impacted alumni with respect to the qualitative data we collected and ran statistical analyses on 8 variables. While the usual threshold p value for significance is 0.05, because of the small size of our survey population, the more accurate threshold for significance for our data set is substantially lower: p=0.0024.

Project Size and Institutional Engagement

While all CENTC students and postdocs worked on collaborative projects, each project team was a different size, ranging from small projects with only two senior investigators and 1-2 co-workers, to large projects involving up to six senior investigators and over 10 co-workers. There was also a range from just a few to many people engaged in CENTC at each participating institution. We were interested to see whether our alumni who had worked on CENTC projects with fewer collaborators or who were located at institutions with smaller numbers of CENTC participants viewed their experiences differently than did those whose projects were larger or were located at institutions with many CENTC participants. For the most part, there were no differences in reported experiences when these parameters were taken into account. The one difference that did reach the level of significance (p=0.002) was having constructive

relationships with their faculty advisors. While most differences seen were not statistically significant, they were consistent with what would be expected from participants involved in more highly collaborative research. Those on larger projects did feel somewhat better prepared to work on multiple projects at one time and to use videoconference technology, and reported having constructive relationships with peers more often than did alumni who had worked on smaller projects. Respondents who had worked at high engagement institutions tended to feel better prepared to conduct independent research and to collaborate. Of note, the number of respondents who worked on larger or more highly collaborative projects was about 3 times those in the other groups.

Current position – faculty, industry or other

Positions were categorized into three groups: faculty at 4-yr colleges or universities, positions in chemical or chemical engineering industry and "other" which included scientists at national labs, patent reviewers, etc. Those currently in faculty positions felt somewhat better prepared for developing professional connections and networking than did the research scientists and were significantly more likely to seek out, or to have established collaborations ($p<0.0001$).

CENTC affiliation – graduate student or postdoc

There were few differences between survey responses from those who had been graduate students while at CENTC or postdocs. Those who had been postdocs with CENTC rated attending, and presenting at, monthly center-wide videoconferences slightly more highly in terms of contributing to their development than did those who were graduate students.

Site Visits

CENTC postdocs and graduate students played major roles in site visits and we looked at participation in site visits as an indicator of the level of their involvement with the idea that those who had been more involved might have reported more benefits from their CENTC experiences. Those who had participated in site visits felt somewhat better prepared to work in a collaborative environment. They also reported somewhat more constructive relationships with their faculty advisors and exposure to different approaches to research problems. We did find a significant difference between the two groups with respect to the extent to which lab visits had contributed to their development ($p=0.002$), with those who had participated in site visits agreeing more strongly that lab visits had contributed to their development.

Publications

Thinking that productivity during their time with CENTC might impact responses to the survey, we compared responses from those who had not yet published results of their CENTC projects

with those who had. Not surprisingly, those who had published reported feeling better prepared to write manuscripts than did those without publications, but this difference did not reach the threshold for significance. Interpreting the results between these two groups is confounded by the fact that the number of respondents with publications was about 3 times the number who had not published.

Comments

The following are comments about how CENTC alumni would describe their CENTC experiences:

"Understanding the needs of industry is critical to developing effective research proposals."

". . . connections to LANL via CENTC is largely the reason I was able to secure a position at LANL."

". . . input from multiple researchers often resulted in new ideas/resolutions to challenging problems."

"(I got) . . . exposure to different careers that I didn't think possible."

"(my CENTC experience) was productive from both the research and professional standpoints. It allowed me to develop a solid working relationship with a large number of leaders in our academic field and opened the door for future collaborative efforts."

"It was enlightening to watch project development from the ground level all the way up through publication and patent development."

". . . focus on high risk research presents a real challenge to graduate students and postdocs who need to have something to show . . ."

Summary of evaluation

Based on these results, CENTC's goals for training graduate students and postdocs were largely achieved. Due to the small sample size, finding differences that met the threshold for statistical significance was difficult, but we are able to report trends and get a sense of where we were most and least successful. In all, as far as student and postdoc training was concerned, responses were overwhelmingly positive with 92% agreeing that their CENTC experiences had contributed greatly to their development as researchers and that they would participate in CENTC if they had it to do over again. Collaboration, professional interactions with a wide array of PIs and researchers from industry and the emphasis on communication to technical audiences were the

greatest strengths of their CENTC experiences. Collaboration and working with multiple PIs were also reported as the greatest challenges of working with CENTC. While objective data collected showed that time to PhD for CENTC graduate students was close to the mean for US PhD recipients, many students reported subjectively that they did take longer to complete their PhDs than their non-CENTC peers. This an area that warrants close attention for CCIs.

Lessons learned

Nothing can replace face-to-face interactions. Annual meetings that included all CENTC researchers were essential to the success of the education of graduate students and postdocs. They were able to speak directly to representatives from industry and NSF and to build professional relationships with researchers outside of their home institutions. It was during these meetings that students and postdocs were able to participate in brainstorming and planning for the center, an experience that taught them about managing research projects and developing collaborations. For the Center as a whole the annual meetings, especially the informal interactions, served to reinforce the sense of community.

Be aware of professional development and enrichment opportunities provided by students' home institutions in order not to replicate.

Required exit interviews of departing postdocs and graduate students would be helpful in addition to a final survey of alumni. They would collect information from all participants rather than just those that choose to participate in a survey and would allow monitoring of program effectiveness in real time. It would be interesting to compare results between exit interviews and a final survey of program alumni.

High risk projects can have a negative impact on productivity and time to earn a PhD. It is critical that research mentors pay close attention to the progress of such projects – or lack thereof – and shift trainees to more productive projects when necessary.

There is strong interest in professional development and information about diverse career opportunities among postdocs and graduate students so it would be useful to offer webinars each year and post presentations on the center website.

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[3] "*Advancing Graduate Education in the Chemical Sciences*," Summary Report of an ACS Presidential Commission, **2012.** https://www.acs.org/content/dam/acsorg/about/governance/acs-presidential-graduate-education-commission-full-report.pdf

[4] http://www.nationalpostdoc.org/publications/mentoring-plans

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[7]Meyer, S. A. and Morgenstern, M. A., "Small Scale Biodiesel Production: A Laboratory Experience for General Chemistry and Environmental Science Students." *Chem Educator*, **2005**, 10, 1-3.