Orbiting a Nucleus as a Team

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In an atom, the densely packed nucleus contains protons and neutrons, while the diffuse electrons randomly occupy the surrounding space. Consider that a metaphor for undergraduate research. The nucleus is the problem, the question being pursued, while the electrons are the researchers who orbit the problem. For three semesters, we found a common orbit around various computational chemistry projects.

In the following sections, we present our perspective on the benefits and challenges of undergraduate research. We met in the fall semester of 2008 at Austin Peay State University when Ashley was a star student in Dr. Jones's general chemistry class. Our research collaboration began in January 2010 and although it did not yield groundbreaking results in our field, other more valuable outcomes were evident. As we worked together, we identified new definitions of success, significant challenges, and new motivations. Ashley's student perspective is denoted with the initials ASM, while Dr. Jones's faculty viewpoint is indicated with RMJ.

We hope that the story of our research relationship will encourage other faculty and students to persist in this difficult but rewarding endeavor. Involving undergraduates in research is one way to prepare the next generation of adults to successfully navigate life's abundant challenges.

Finding Motivation

ASM: There are many reasons for undergraduates to get involved with a research project. For a science major, the first (and most obvious) reason is to bolster one's resume – it's much easier to get a job or a position in graduate school with practical lab experience that accompanies the standard coursework for your degree. The primary reason I decided to seek out research, however, is that I like to solve puzzles. The great thing about academic research, particularly in the sciences, is that there is an ever-broadening frontier of the unknown. Even with the skills of an undergraduate, I wanted to explore those frontiers in search of deeper understanding, both for personal knowledge and for the scientific community as a whole. Undergraduate research is a great chance to get your feet wet with *real* science while still being guided by a mentor, which helps you learn and work without becoming too bogged down with things you do not yet understand.

Computational chemistry gave me the opportunity, not only to learn new ways to explore chemical systems, ways that don't necessarily involve a bench-top, but also the opportunity to apply chemical concepts taught

in class to the results the computer would generate. This fosters a much deeper understanding of the material, which is very useful for an individual who seeks to truly master the subject. Undergraduate research confirmed for me that my decision to continue on to graduate school was the path I truly wanted to pursue. I felt confident that, in pursuing a graduate degree, I would not be wasting a lot of time and money chasing a degree that, in the end, I do not really want or need.

RMJ: As Ashley noted, undergraduate research is a wonderful opportunity for students, but collaborating with undergraduate research students is extremely rewarding for me as a faculty member as well. When I taught general chemistry each semester, I regularly saw the glazed eyes of freshman and sophomore science majors while I lectured on entropy and electron configurations. But a few times each semester, I was able to connect the topic of the day with one of my research questions. In those moments, I would see a few expressions change and curious expressions appear. On more than one occasion, students have approached me after these class times and asked further questions. I love seeing the wheels begin to turn in students' minds! These simple conversations were the beginning of my work with undergraduate research students.

Ashley and I studied a series of nickel oxime radical compounds using density functional theory. Employing computational chemistry software (Gaussian and GaussView), Ashley developed theoretical models of the compounds, identified the most stable structures, and described the electronic structure of the compounds. In the different semesters we worked together, Ashley was enrolled in one of two independent study research courses, either CHEM 2940 (Introduction to Research, 1 credit hour, 3 research hours/week) or CHEM 4940 (Elements of Research, 1-3 credit hours, 3-9 research hours/week). Most of these research hours were completely independent. We met bimonthly for about 30 minutes to an hour (usually during my office hours) to discuss her progress and plan for the following weeks. Initially, she had many excellent questions and we spent more time talking through articles or books together in our meetings. By the end of our time working together, she was very capable of working on larger tasks and jobs without direct supervision. She worked in the lab directly adjacent to my office and would sometimes just ask questions from her desk. Watching Ashley grow in her independence and critical thinking skills was an outstanding benefit of our relationship.

In my eight-year tenure at Austin Peay State University, I mentored nine undergraduate chemistry majors, three of whom completed a senior thesis to earn an American Chemical Society certified degree. Watching these students graduate and move on to be successful was a highlight of my time in Tennessee. I found I really enjoyed orbiting together around the nucleus of a question and closing in on an answer. Now, in my new position at George Mason University, I work full-time to support undergraduate research on an institutional level.

Defining Success

RMJ: As faculty, we often describe success with standard metrics; e.g. he is competent at this lab technique or she can competently interpret a journal article; therefore, they are a success. Indeed, success can be measured by these traditional benchmarks, but is there a way to measure the deeper success of a valuable research experience? Can we understand the impact of a research experience on the determination of a student? On his ability to not give up in the face of adversity? On her willingness to pursue a problem that may not be successfully solved? Can we measure the significance of imagining possibilities? Not easily, yet it is these deeper concepts that best define success in an undergraduate research.

ASM: Before I got involved in it, I had a narrow view of successful research. It seemed that success was only defined by the number of papers you publish and which journals you

publish them in – this is certainly not what an undergraduate should be preoccupied with. While it is true that undergraduates can get research published, this should not be the overarching definition of success; it simply isn't likely for many undergraduate projects in chemistry. Many research projects for undergraduate students are short (one year, maybe two), and many fields of research require more time in order to have results that can be published. At first, this was a concept that I struggled with, and it made the process of getting involved with research daunting.

After becoming entrenched in my project, I naturally changed my idea of success. I understand now that simply gaining new knowledge is success. Taking advantage of opportunities that will give me an advantage in my career after graduation is success. Sharpening the skills introduced in coursework and applying those skills to solve new, complex problems is success. If, at the end of the project, a research student can confidently speak about what she did, but also why it was done and why it matters, then the student has completed successful research. I learned to recognize that the process and the journey are much more important than the results at the end.

Noteworthy Challenges

ASM: To a student who has only experienced chemistry in a classroom or a teaching lab, it can be difficult to know what sorts of questions research scientists are asking. As an undergraduate student, how you can possibly contribute anything worthwhile? The "I'm not good enough" complex can become a problem; as an individual without even a bachelor's degree, how can you possibly do work that other scientists, professional research scientists, or experts in their fields, will find enlightening and valuable? This can cause a student to hesitate before becoming involved in research since she approaches the problem already feeling completely overwhelmed. It is important to keep in mind that all scientists were once students, and that many of the techniques used in research labs around the world are completely accessible for a researcher at the undergraduate level. In fact, as the end of my undergraduate studies approached, I recognized that I understood the research much more deeply than first expected. I also had gained a more thorough understanding of the true value and consequences of my project. After all, it would be impossible to conduct unique research in which everything about the system is already known and understood!

One of the major challenges faced by an undergraduate at a small liberal arts college (SLAC) who desires to get engaged with research is simply finding opportunities. From my experience, it is largely the professors with pre-existing research interests who guide undergraduates into research. Until very recently, research for undergraduates was not something openly addressed or encouraged on my campus. Only through interactions with my professors did I learn about research opportunities that would allow me to explore a branch of chemistry that, until that time, I did not even know existed. With a limited experience and understanding of chemical systems, it can also be challenging for an undergraduate student to find a question that is answerable and also interesting to the scientific community.

Another major challenge is funding, especially for students at a SLAC, which is not a research-based institution. The sources of funding for research can be a mystery. Often, even projects that are already funded suffer from a lack of equipment or from equipment that is not at the level suited to modern research. Especially at a SLAC, the equipment available for student use may be dated and not up to the standard that most of the research in that field requires in order to claim and publish one's results with any certainty.

RMJ: In addition to addressing the challenges Ashley mentions, I believe it's also important to help student researchers understand that research is an arduous task that requires persistence. How do you inspire a student to be persistent? By modeling determination yourself. Research is also time-consuming for faculty, especially when teaching loads and service responsibilities are also increasing. Individual faculty must find a balance between their three primary roles in teaching, research, and service. This balance should be modeled by senior faculty who strive to be excellent teachers, have productive research, and demonstrate a commitment to service. While it is expected that this balance will be very individual, the standard for advancement within the academy should be universal. Expected benchmarks for retention, tenure and promotion should be clearly defined, and all faculty should be held to these standards.

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Abundant Benefits

ASM: The benefits of the relationship between research mentor and undergraduate student are innumerable. In the short term, the student gains an advisor and a resource – someone who can answer the questions the student will, inevitably, need to ask throughout the project and throughout her undergraduate career. In my experience, research really allowed me to expand my knowledge base into a specialized field that applied my learned skills from classes and allowed me to discover the extent of my own interests in the given field. In my case, the benefit of the mentor-undergraduate relationship is also a long-term friend and colleague who is a source of encouragement and advice even after the conclusion of the research project.

Undergraduate research begins to prepare the student for work after graduation, whether it will be done in graduate school or in the workforce, which will serve the individual as he/she continues on into his/her career. Thus, in the long-term, undergraduate research provides invaluable tools that may be used in any field that the student may choose to pursue. The skill set cultivated during research—creative problem solving, troubleshooting, and interpretation of data—is one that will be used every day of the student's life, both inside and outside of academia.

RMJ: I agree with Ashley that the relationship formed between student and mentor is a special one. Being a mentor of an undergraduate researcher also has unexpected benefits, not the least of which is advancing your own research projects. Research can be messy and carries no guarantees of success. However, and perhaps in spite of my perfectionist tendencies, I've certainly grown to enjoy the research process itself. The act of asking questions and pursuing answers is both engaging and stimulating, requiring creative and systematic problem solving. Perhaps the hackneyed phrase "thinking outside of the box" should be revised when often there is no box in the first place.

Ongoing Questions

RMJ: Sometime between the toddling years of early childhood and the college years, the flow of questions in most people has ebbed. Perhaps these young adults heard such phrases as "It's not polite to ask questions" or "That's just the way it is. Stop asking questions!" Is it any wonder why so many believe the facts in textbooks are written in stone? If asking questions is perceived to be disrespectful and perhaps even subversive, how can we encourage the process?

ASM: I learned through my work with Dr. Jones that conducting research and finding answers to one question really only leads to more questions. If success were defined by answering all the questions, no one would

have ever truly been successful in research. Einstein, Rutherford, Curie, and Newton all left unanswered questions and all work in science only reveals how much is left to be discovered. As a researcher, one really comes to appreciate the value in asking questions. It is impossible to know everything—even the things we believe we already know, such as "facts" printed in textbooks—and it is the responsibility of future scientists to constantly reevaluate those "facts" and force them to stand up to modern criticism. This is the way for progress to occur.

RMJ: Our research project in Spring 2011 yielded interesting results about the reaction of nickel oxime radical complexes. As we looked at the output from the calculations, more questions arose. Why is this dipole so large? Where is the electron density? Are these structures reaction intermediates? These are all good questions that show the persistent nature of research. There are always more questions to be answered. Learning this reality and finding comfort in the accompanying ambiguity are perhaps some of the most valuable skills resulting from undergraduate research.

Final Thoughts

We completely enjoyed working as a team while orbiting our problem. Out of our partnership has grown a valued friendship. Ashley has now departed from Austin Peay State University to pursue a Ph.D. from the University of Rhode Island. However, thanks to email and Facebook, our "electronic" connection will persist. Despite the challenges that undergraduate research presents, our relationship and research successes are a testimony to its incredible value.