PERSPECTIVE

UNDERGRADUATE RESEARCH IN THE SCIENCES AS A SERIES OF TRANSFORMATIVE OPPORTUNITIES

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EXPECTATIONS OF UNDERGRADUATES

Undergraduate students tend to find, from the moment of their arrival on campus until graduation, that they are held to a long series of ever-increasing professional expectations. Some are curricular standards set by the university, while others are evolving objectives the students decide for themselves. Students anticipate they should engage during lecture and laboratory courses, maintain high academic standings throughout their college career, and, potentially, pursue part-time employment. But perhaps one of the most pronounced expectations of an undergraduate is for the student to become socially and professionally involved on campus. The idea of campus "involvement" can be both vague and intimidating, especially to a new student.

Universities have numerous and varied organizations; these can be academic, social, faith-based, or service-oriented in nature, to name only a few. When a student is faced with many opportunities but has limited time, it can be a challenge to decide which of these commitments are worth pursuing with limited time. It is in an undergraduate student's best interest to choose activities that complement his or her area of study while promoting personal and professional growth. However, a student may be more interested in finding activities which build lasting, meaningful relationships with peers. This fundamental choice does not have to be a mutually exclusive one. None of the elements mentioned above are missing from undergraduate research experiences, which is why commitment to extended study outside of the classroom is one of the most valuable uses for an undergraduate's time. This is especially true of students majoring in biology. Research allows students to apply broad concepts learned in the classroom to original research problems in the field or laboratory setting, all of which enhances content comprehension, professional development, and peer interaction.

CONTENT COMPREHENSION AND TECHNICAL SKILL

The most immediate benefit of an undergraduate research experience is the ability to translate what is learned in the laboratory to one's understanding of scientific concepts learned in the classroom. A recent study by Hunter *et al.* indicated a common gain for students after an undergraduate research experience was perceiving "increased relevance of coursework" (2007). In a science lecture, broad and sometimes overgeneralized ideas are taught first, and eventually the finer details are covered. Research, however, begins by trying to answer a very specific question or solve a particular problem. For example, my first research experience involved determining the effects of different concentrations of carvacrol (a bactericidal extract from oil of oregano) on *Bacillus cereus*, a toxigenic bacterium associated with foodborne illness and ocular infections. Using a nematode model, *Caenorhabditis elegans*, I was able to quantify the effects of *Bacillus* toxins because the nematodes would ingest the bacteria and become infected. Although I had no background in cell biology or genetics at that point in my college career, my research advisor was able to build from my knowledge of basic biology and teach me about the organism I was studying.

Often, I encountered information while working in the lab before I had taken a course which covered those ideas—part of my *Bacillus* project involved transforming the bacterium with a specific plasmid vector that my advisor and I had designed. When I took genetics a few semesters later, I studied how bacteria are naturally competent. Research for me became a balance of relating concepts from the classroom to my project, and relating my research back to the classroom to realize the real-world implications of what I was learning. This learning style does not stress memorization as much as application, which is more valuable considering scientific "facts" may change with breakthroughs (AAAS, 2011). Translating knowledge between the lab and the classroom allowed me to appreciate the complexity and importance of what I was studying, while giving me a better, more complete understanding of some of the more challenging theories.

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As classroom content is applied to a real-world setting, students performing research also begin to increase their technical skill set in the lab. Some of the first aspects of my research experience were becoming oriented with the lab and learning proper execution of basic bench skills, such as using aseptic technique or performing polymerase chain reaction (PCR). Bench work and instrumentation revealed the reality of research: it can often be tedious. But the practical experience was worthwhile in learning what the process of designing, executing, and analyzing an experiment is like from start to finish. One of the most valuable skills learned in research is the ability to troubleshoot problems when they arise. In the early phases of my *Bacillus* study, one nematode was to be placed in an individual well with agar on a 96 well plate. Then, each individual nematode could be studied separately as the *Bacillus* toxins began to take effect. Isolating a microscopic animal, however, turned out to be extraordinarily difficult. It was hard to avoid picking up multiple nematodes at a time, so the methodology for the project had to be amended. While this may sound like it would have been a frustrating experience, it was actually exciting and eye-opening. The difference between a real undergraduate research experience and a "canned" lab experiment that a student encounters in a basic biology class is that no one knows the "right" way to execute a research project. This gives the student ownership of the entire experiment and the freedom to be creative when adjusting for problems encountered during the process, and the end results are that much more rewarding when the project is completed.

The three-hour labs designed for a classroom setting may give students some practice in bench techniques, but these skills are only applied to a piece of an overall research experiment. In an immunology lab, I read through a three-part protocol that stated parts one and two had been done for the students. This is not a criticism of the immunology course; it simply illustrates that students have a limited perspective of the goals in a research experiment and the process involved to acquire the end results in a short lab period. Furthermore, students may find it difficult to imagine application of methods they are using to solve real problems, even if they understand the concept being illustrated in a classroom lab. This is the advantage of undergraduate research: students are exposed to the scientific method from beginning to end, including the planning of the project and the presentation of results. After participating in undergraduate research, I no longer look at a graph and see only the data, but also have an appreciation for the months and years of work that producing only one figure required. I have a more realistic conception of what research is like, and I am more able to understand how other scientists arrived at their results and conclusions because I have a sense of what they may have done in their own processes. In fact, one study indicated students who perform research-based activities rather than lab-based activities gain confidence in interpreting data (Brownell, 2012). When I have questions about a concept in microbiology, I can imagine how a scientist may have approached discovering an answer because I have been exposed to a number of techniques and instruments used in my field. Research enables a student to think critically within his or her own field rather than simply accepting facts in a classroom without being able to put the "pieces" together in a broader understanding of the world.

Performing undergraduate research shifts a student's outlook on aspects of his or her own specific area of study. But the research process may also give students a new appreciation for other natural sciences as well, primarily because students will discover that subsets of science are not separated by as distinct of boundaries as course curricula may indicate. While I primarily use techniques I have learned in microbiology courses in the research lab, I also find myself referring to knowledge I acquired in chemistry or physics classes to execute my project. For example, purifying the plasmids necessary for transformation of *Bacillus* requires a number of reagents. I relied on general chemistry knowledge to make these solutions at appropriate concentrations. And while not a topic I studied directly, having knowledge of the laws that govern forces and energy because of my physics education also helps me to understand the living systems in which I was interested. Physics, chemistry, and biology all build upon each other, something that is not stressed in lecture. Therefore, it was difficult for me to see how necessary my understanding of all of these disciplines was until I had research experience.

Undergraduate research gives a student appreciation for all of the "core curricular" sciences, but for students studying microbiology, research also allows for a better understanding of the relationship between the various disciplines within biology. For example, my research in environmental microbiology involved taking measurements such as pH, dissolved oxygen, water table height, and temperature of the water in which the algae of interest was growing. These data were considered when studying nutrient effects on algae because they can influence algal metabolism, as well as the presence of other microbes, and interactions between these communities also impact algal biomass and metabolism. Evaluating the influence of the environment on microorganisms helped me appreciate that the toxigenic bacterium I was studying in the food microbiology lab also changed depending on the conditions in which the cells grew, even though my work was in the laboratory and not in the field. I appreciated more the ability to carefully control variables and I became a more conscientious scientist. While working with *Bacillus*, I learned the importance of handling samples with precise, sterile techniques, and this training prepared me to more efficiently process hundreds of water samples in the environmental microbiology lab. My involvement in two laboratory projects has exposed me to the details within a subdiscipline, but has also enabled me to think critically about the broader concepts and implications of the subjects I am studying, and the problems and diagnoses I will make in my future training and career.

"SOFT" SKILLS AND PROFESSIONAL DEVELOPMENT

Developing a deeper understanding of the biological sciences through research is a critical and valuable undergraduate experience, and a student undertaking a research project might expect this to be an outcome of the process. What students may find surprising is that they also grow interpersonal skills immensely while engaging in research. Communication of scientific concepts becomes more comfortable as a student has more practice both reading and writing scientific literature. Utilizing primary literature—peer-reviewed publication of original scientific findings—is helpful in learning background information for a project, but it also adjusts a student to thinking and speaking in scientific terminology. As scientific studies produce information much faster than editions of textbooks can be produced, relying on scientific articles for supplemental detail of a broader classroom concept can be a critical piece of an undergraduate science education (Hoskins, 2007). The first time I read a seven-page piece of primary literature about *Bacillus*, I spent several hours deciphering the dense writing. I found later that this was a valuable investment of my time; I became more confident in speaking about my research to professors and other students because I understood the "language." With enough practice, I could read a scientific article as fast as I could read anything else, and this gave me a sense of belonging to the scientific community.

The more a student reads primary literature, the better he or she will be able to compose a poster presentation, oral presentation, or manuscript in the future, and the more insightful their questions will become. Likewise, delivering an oral or poster presentation requires much practice to convey the essential information to an interdisciplinary audience. Successfully transferring the salient aspects of your work to a mixed audience involves not only a thorough understanding of your project on all levels, but a realization for how to "teach" and engage your audience as well. This concept is becoming more important with each passing year as new specialty areas develop within each subdiscipline of the life sciences. Without consideration of the audience at hand when rehearsing a presentation, the implications of a student's finding may be lost on those who are not familiar with the jargon of a subspecialty. It is critical that a student presents his or her findings in a way that allows the scientific community to learn from the results and build from them in future studies. With careful preparation, especially in the background content of a presentation, a student can successfully and confidently convey findings from a study without overestimating the audience's background, and without running overtime, two of the most common errors among students and experienced researchers alike. As a student gains more experience presenting, these presentations become less rehearsed and more of a conversation between the student and the audience. This is an exciting transformation, because students can begin to share ideas with peers about each other's projects, and they become more interested and engaged in each other's work as the conversation progresses. I encountered this at the 2014 Indiana Academy of Science conference, where a professor was presenting a poster on her study of the nervous system of the same nematode model which I used for my *Bacillus* project. As the conversation progressed, I was both learning from this professor and offering valuable information for her; it was a discussion that felt more collegial than instructional, which is atypical compared to most of my interactions with professors. Communicating and sharing ideas in this way builds a sense of fellowship between students and professors, so the student starts to feel less like a science major and more like a scientist through this process of contributing and collaborating.

Collaboration is, in fact, an important piece of the research process. Even if a student is working on an individual project, he or she will often rely on peers who have more research experience for advice and wisdom. This student-centered learning, with the advising professor assuming the role of a facilitator rather than an instructor, builds students' prowess in the lab and willingness to give input as to the direction of the research projects discussed. Teamwork in the lab makes the research projects more successful, but it also allows a students to form valuable friendships with others of their own discipline. Another research experience which I undertook relied heavily upon collaboration. During the summer of 2013, I studied in the Bonanza Creek Experimental Forest in Fairbanks, Alaska for three weeks with a professor and graduate student. We were assessing the effects of warming and nutrient addition on algal biomass and metabolism. This experiment had many components, and at times, it was difficult to keep the "big picture" in mind when I was focused on my comparatively small set of data. I was able to rely on the graduate assistant for help when I was trying to make sense of the results. She helped me have a better appreciation for the role of algae as primary producers, and I was able to keep the end goal of the experiment in mind because of her explanations. I began to see her as a mentor, but also as a friend, because we worked very closely over the course of those three weeks. But these friendships form regardless of the length or location of the project. I interact with students working in the same research labs as I on a more regular basis than many other students. Not only do we collaborate on our research together, but we have many of the same classes together as well, so some of the best connections I have had with peers during my college career have resulted from research experiences.

My relationships with my faculty advisors have also grown and become more valuable than I anticipated as I have become more involved with research. At the beginning, I was being told what to do and how to work at the bench. I was being taught in the traditional way I was used to in a classroom, although it was one-on-one interaction. As my skills grew and I relied on my professors less for technical instruction, I felt more confident in expressing my take on the data or my ideas for amending the methodology. My advisors respected what I had to offer; I felt trusted and accepted as a scientist, even while I was still their student. Beyond that, my advisors have been incredible resources to me in realms outside of the research laboratory. They have written recommendation letters for me and edited my research presentations and posters, but they've also given me advice throughout my undergraduate career, which has been what I value most about out interactions. I can share experiences I'm having in class or in the process of applying for medical school, and they encourage me and give me a sense of what to expect as I move forward in my college years. Having a faculty member support me as I work to accomplish my goals has increased my confidence and improved my work, and has been easily the best aspect of my undergraduate research experiences.

By mentoring undergraduate students, faculty engage in service to their profession by training future scientists. Of course, the student is helping further that research project, but there is a great deal of commitment to the training of that student and investment in that student's future given by the most dedicated faculty before those results emerge. "Service to the profession" has been heavily emphasized in my own

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research training; for example, I have been especially encouraged to be on a journal editorial board someday so that I can aid my peers in science by critiquing their manuscripts. As an undergraduate, students are prepared for this service through research training. Students will often read and discuss primary literature with each other or an advisor and learn how to critique an author's work thoroughly while still communicating the errors respectfully. Following an advisor's example, more advanced students can also facilitate the training of some of the novice students in bench technique and general concept comprehension. Commentary on each other's poster presentations and talks also models a professional conference, in which a scientist would field questions from colleagues and engage in dialogue about the study. In addition to professional service, students also serve their community through volunteerism. Our lab community, for example, organizes a fundraiser for Next Generation Nepal, which is a non-profit dedicated to returning trafficked children to their families. We use the "penny war" method of collecting donations and involve the science professors and students in the process. While not directly connected to our lab work, this collaboration for a greater cause on the part of a few research students has allowed us to contribute to society in both an academic and social capacity.

PERSONAL GROWTH AND IDENTITY

As students begin to build relationships with peers and faculty who are also involved in research, these students are engaging in a socialization process into the scientific community. Students in an undergraduate research experience are integrating the role "scientist" as part of their identity, and they are learning that a scientist is so much more than someone who executes an experiment. As I enter into my last year of undergraduate research, I find that I begin to take on the role of a peer mentor while still being guided by advisors and other students. Mentorship is so closely connected to research because science involves a great deal of collaboration to be successful. The characteristics that I have appreciated in my own advisors—patience, enthusiasm, and respect—I have attempted to implement in my own attitude when working with other students. For example, when consulting a lab partner on methodology for the *Bacillus* project, I noticed that she had difficulty recalling some of the math concepts from general chemistry. I was able to find a new way of explaining the calculations that she hadn't heard before which made sense to her. At the same time, my lab partner organized the methodology into a list and was able to walk me through what needed to be done. She saw the bigger picture of the project and how we needed to progress through each phase, whereas I was focused on the details of a particular step. We both assumed different roles in the partnership and were able to teach each other different aspects of the same research project, which was valuable leadership practice. In the future, my career as a physician will require a great deal of patience and commitment to mentorship of medical students and resident physicians. These partnerships are most successful when the members rely on each other's strengths, even though one is the "mentor" and one is the "mentee." It is difficult to be engaged and invested in one's own learning if one does not have an active hand in the learning process. As a physician, I would expect my mentees to offer input regarding the subject material and I, as a mentor, would be willing to let the students take ownership over solving the problem at hand with guidance from me. I know this method has worked for me while I have been a mentee, and I think it is important to deviate from the traditional lecture-based learning to some degree so the students feel like a valued member of the class or group. This is what research does, and I believe my peer mentorship experience from research will translate easily to the medical field.

Beyond mediating discussion and encouraging my peers in science, research has increased my interest in developing methods of communicating scientific findings to the general public. Through my involvement as an editor for *Fine Focus*, I collaborate regularly with a marketing team, while my role is primarily for handling manuscript submissions. The interdisciplinary project has revealed to me the importance of packaging content in a way that is appealing and understandable for a target audience. This is a new concept to me; I am familiar with marketing products, but the intricacies of marketing information have become a more immediate challenge to me as someone striving to publish in the sciences. The frustration that scientists can feel when their findings are lost on an under-informed audience is expressed by Volpes' The Shame of Science Education (1984):
Public understanding of science is appalling. The major contributor to society's stunning ignorance of science has been our educational system. The inability of students to appreciate the scope, meaning, and limitations of science reflects our conventional lecture-oriented curriculum with its emphasis on passive learning.

I would argue that while the public may have a limited view of some current scientific studies, scientists also have a minimal understanding of how to convey that information to a broad audience. Scientists write and talk for other scientists in the system of publication that currently exists. These are valuable data and analyses, but it is not for everyone. I would argue that undergraduate participation in research begins to encourage students to think about science from other perspectives so that the student can communicate to individuals of various educational backgrounds. For example, an ecology professor of mine once played an NPR interview of a paleontologist; this is a perfect example of an instance in which language had to be carefully tailored to speak to a particular audience, and this particular interviewee did so effectively. Undergraduates may, in their future careers, encounter situations in which they need to convey findings to the media or other public entities. Collaboration in research is a small step in developing these communication skills, because students are only working with other science majors. Nonetheless, students are bound to encounter diversity even within the sciences, and this student-centered, active learning process is excellent practice for conveying scientific content to a number of audiences.

To be certain, communicating scientific concepts is both exciting and challenging for any student new to research. A student is bound to encounter road blocks throughout the research process which will require critical thinking and problem solving, especially when the original methods fail to produce acceptable results. These frustrations are combatted by the desire to satiate one's own curiosity as to how living systems operate, which develops as one becomes more attached to the research project, and more empowered in knowing that research can allow these discoveries to be had. This desire for understanding motivates a student to be flexible as he or she copes with the challenges associated with running an experiment. I felt tested when attempting to run a successful polymerase chain reaction (PCR) for my *Bacillus* experiment. PCR, like other tools in the arsenal of a microbiologist, involves sensitive reactions and is time-sensitive as well. It was important for me to be precise when working with small volumes of DNA, primers, and reagents. Even though I knew I had handled the samples carefully, it still took several attempts to generate copies of the plasmid I needed, and I was embarrassed I might have had poor technique. My advisor reassured me I was doing well, and that successful PCR is determined by a variety of factors, some of which may have been outside my control. With this in mind, I was able to be more patient with myself as I made more attempts at PCR, and this shift in attitude has translated over to my classroom work as well. I am less likely to get frustrated if, for example, I am trying to solve a chemistry problem that I don't understand. Instead, I look for creative approaches to the question and persist until I find an explanation for the concept that makes sense to me. This patience and flexibility is crucial to the mindset of a college student, because balancing schoolwork can be difficult. Training in perseverance through the research process helps a student better face this obstacle.

Once I was able to solve problems on my own in the lab, I began to feel more ownership over the project which had been assigned to me. I was more comfortable working without supervision and I felt responsible for performing quality work, even though there would be no "grade" assigned to my research. This intrinsic motivation is harder to feel in a classroom setting. Classroom learning is passive, and students may not know how to integrate information that seems surface-level (Lopatto, 2009). The knowledge a student gains in a lecture doesn't feel as though it "belongs" to the student because it is so readily given. But new knowledge generated in research almost has an emotional attachment associated with it, because the student knows first-hand the work required to discover this information. In this way, research is its own reward, and it fosters a desire for understanding in other realms of a student's life.

The personal satisfaction and comprehension of scientific content are only gained, however, if the student is producing original results at the end of the research process. A research project which does not add new knowledge to the scientific community does injustice to both the student and fellow scientists. A typical classroom science lab, when the results are known at the process is designed to "work", is helpful in illustrating a concept but does little to prepare a student for the reality of research as a career, in which results are elusive and methodology often needs revision (Chmielewski, 2009). Furthermore, if a student is not striving to solve unanswered problems through research, the student does not have new information to publish, and the opportunity to grow scientific writing and presenting skills is lost. One way to ensure that a student is building on prior studies but is developing novel results is by reading primary literature. Consulting scientific journal articles, whether for a course or for research, begins to feel more like participating in a dialogue than tedious work. I became more interested in scientific discovery as my research progressed, making me more willing to ask questions of my teachers and advisors when I was confused. Throughout primary and even secondary education, there is this fear associated with "being wrong" which can prevent students from engaging in classroom conversation. This anxiety quickly becomes outweighed during undergraduate education by the desire to know more as a student becomes more involved with research.

This internal drive brought on by research has allowed me to overcome the fears associated with the risk of trying something unusual. Adapting the attitude that a new experience will enable me, even if it may seem intimidating at first, has been a direct lesson of my undergraduate research experiences. I have learned not to feel anxious when I don't know what to anticipate from a class or a job, because I have experience encountering "the unexpected" in the lab. For example, in the *Bacillus* experiment, the plasmids were designed with the addition of the *gfp* gene,

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so that once the bacteria transformed the vector, fluorescence would be an indicator of expression of products on the vector. We used a flow cytometer to measure fluorescence, and we expected stressed *Bacillus* to express a particular gene on the vector and therefore fluoresce. We also expected our control bacteria not to fluoresce because they did not have the vector with *gfp*. However, our control *Bacillus* did fluoresce. The experiment was repeated, because it was assumed that we mislabeled our samples or some other aspect of the methodology went wrong. But again, the control bacteria fluoresced. Making sense of the unexpected was challenging and exciting, and it was concluded that when stressed, *Bacillus* must produce a primary metabolite that fluoresces. An experience that could have been frustrating ended up being enlightening, and it has allowed me to readily embrace new challenges.

BROAD IMPACTS

Engaging in an undergraduate research experience is a large undertaking. Scientific discovery involves active learning and adapting to new findings, a process initially uncomfortable to students accustomed to lecture-style lessons and rigid syllabi. Yet these challenges enable a student to grow in ways that a standard course could not allow. Students learn the complexity of the scientific method, and are able to appreciate and understand published literature after going through the process themselves. Students collaborate with faculty and peers to better communicate their findings and learn from the experience of others. Students come to realize that they are more capable in understanding and performing science than they could have known. The contributions which undergraduate research students make to the body of scientific knowledge are rewarding and stimulate further interest and motivation in scientific work. In my own experience, research has allowed me to feel immersed in the process of doing science and has made me more invested and interested in my own education. My undergraduate career would have been incredibly different without research as a tool to enhance my core understanding of science and improve my confidence in professional settings. I highly encourage all students participate in an undergraduate research experience to realize their full potential as a scholar and scientist.

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