
Who's Washing the Dishes? Undergraduate Research Education

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When I was originally asked to give a talk at the DUE CCLI conference concerning undergraduate education, I agreed with some trepidation; to be candid, I didn't even know how to correctly pronounce "pedagogy" until a couple of years ago. I tried to talk a little about my history as a first-generation college student who, after earning a PhD, had a very unique educational outreach experience and found her niche in undergraduate research and teaching. Writing up this talk proved to be even more challenging than giving it. Nonetheless, I hope I've managed to provide some insight into my background and how, as a brand-new faculty member, I'm trying to integrate the "best practices" of my research career toward teaching science to undergraduate students.

A Brief Personal History

My science education has followed a seemingly normal path, with an undergraduate degree in Britain and acceptance into a graduate program in microbiology at the University of Colorado Health Sciences Center. Then an unusual thing happened to me not long after I received my PhD. I was in the lab one day and I got a strange phone call; the conversation essentially started out with, "We're making an IMAX movie about caves and were wondering if you were interested in being in it." I had absolutely no idea what an IMAX movie was or why they were interested in me. As I learned later, an IMAX movie is an immersive experience, where images are projected on a huge 60 by 80 foot screen only feet away from the audience. This image fills the viewers' field of vision, including the periphery, giving them a feeling of "being there," wherever "there" may be: from the summit

of Mount Everest to a submerged cave in the heart of the Yucatan jungle. To project a giant image, you need a giant negative. An IMAX film is the largest cinematic format, 70 mm wide and 15 perforations long—about 10 times the surface area of a regular 35-mm slide. To record a moving image, 24 of these frames, or six feet of film, must pass through the camera every second. A standard roll of IMAX film is 1,100 feet long, weighs 10 pounds, lasts a quick 3 minutes, and costs a whopping \$3,000. The producers were apparently looking for a cave scientist whom they could follow to produce a documentary. They were specifically looking for a scientist who was under 30; had a PhD; could kayak, ice-climb, and cave-dive; and looked like Sharon Stone! A cave explorer since the age of 14, I could certainly cave and pass as a kayaker and ice-climber, and at 26 I had a PhD, but Sharon Stone I was not.

It took four years to make the IMAX movie *Journey into Amazing Caves*. Once the movie was released, I had to go on "tour" to promote it. Before I was unleashed on an unsuspecting public, the producers insisting on hiring a professional speech coach to teach me how "to give a talk." As a PhD-trained scientist, I found the whole thing pretty entertaining. Upon reviewing my intended lecture, the speech trainer kept stopping me to say that there was "too much science" and that "people are going to be bored". Rather, she encouraged me to "tell people what it was like to ride in a helicopter." It became a battle of wills, and I would nod politely, say I understood her point, and then continue with the science.

While the producers wanted me to promote the IMAX movie itself, I wanted to promote the science of microbial ecology. Microscopic organisms were the first life to evolve

on our planet almost 4 billion years ago, shaping the environment in which we live today. Their metabolic activity changed the atmosphere from reducing to oxygenic and regulates the flow of carbon, nitrogen, and sulfur through the biosphere. Recent work by microbiologists has demonstrated that these microorganisms can be found in the harshest of conditions—from boiling waters in hydrothermal vents two miles below the surface of the Pacific Ocean to mine drainages in California where the pH of the water is lower than that of battery acid. Such work has led to a paradigm shift in our perception of biology, and biologists are starting to concede that the majority of life on our planet is microscopic, with an astonishing complexity elaborated through unique metabolic capabilities. This research also demonstrated that the harshest of environments on Earth are able to support life, lending credence to the idea that the conditions found on other planetary bodies in our Solar System, such as Mars, may also be capable of sustaining life. Despite this paradigm shift, the illustrious and significant history of microbes in the evolution of our planet, most people only pay a passing interest in “bugs” as things that make you sick. Through my promotional “tour,” I wanted to change this perception.

Despite the dire warnings of the speech coach, I think I was reasonably successful in changing some people’s perception of microbiology, with lots of people coming up to me after lectures and telling me they “had no idea that microbiology was so interesting”. However gratifying this was, one aspect of doing the lecture tour truly shocked me: the lack of common science literacy in the general public. Routinely, I would meet young women who didn’t know that girls were even “allowed” to be scientists. They believed that science was what boys did or that scientists are really boring, straight-laced people who always wear lab coats and funny glasses. I guess this picture of what scientists are is pretty pervasive throughout our culture; even during filming the IMAX movie, I’d start to do something adventurous and the director would stop me and say, “Oh no, you can’t do that! You’re the scientist!” I, of course, ignored him!

Until the IMAX tour, my perception had been that everyone knew that science was fun and interesting but had simply chosen not to pursue it as a career. As early as I can remember, I was fascinated with science and a need to know how things work. My mother claims that, in diapers, I used to walk behind her as she dug the garden, chewing on the

exposed earthworms to see what was on the inside. I was fortunate to have a remarkable grandfather who propagated that interest in science through books and home chemistry kits (we would gleefully blow things up at Christmas). When I took my first formal science class at the age of 11, my teacher somehow connected my young and enthusiastic, but somewhat distracted, mind to formal science. In one of these early classes, we were given a Petri dish and told to investigate the “microbial world.” When a yellow, stinky-slime grew out of something in my hairbrush, I was hooked and *knew* I would be a scientist. No one ever told me I couldn’t be a scientist, even though no member of my extended family had ever attended college. Before promoting the movie, I had been naive enough to think that everyone else had the same support and opportunities. They hadn’t, and that realization changed my perception of science and put me firmly on a path toward a career in science education.

Approaches to Undergraduate Research

Until I began my second post-doc, working with Dr. Norman Pace at the University of Colorado, Boulder, my post-baccalaureate science education had been exclusively graduate departments in Research I institutions, where I was trained to believe that the science was “everything.” The publish-or-perish ethos permeated every aspect of our work. Such a narrow vision of research limited my perspective, relegating science education to the position of a “distraction” from the real work. The only undergraduates that did work in these departments washed glassware, which was considered work experience! Norm, despite being a world-renowned research scientist, had a completely different approach; he actively included undergraduate students in his lab. He was also incredibly supportive of my role in the IMAX movie and encouraged me to see that promoting scientific literacy was as important as the research that we carried out in the lab.

After working with Norm, I took a post-doctoral position with Dr. John Roth, now at the University of California at Davis. Again, I had the pleasure of working with a truly excellent scientist. His approach to research is very precise and thorough, with the merits of each experiment being argued before, during, and after its implementation. John also has the highest prevalence of undergraduate students I’ve seen in a research lab, with about 40% of the research activities being carried out by undergraduates. These students were

routinely performing research at the same level as other members of the lab, including graduate students and post-docs, and demonstrated a level of knowledge and confidence that enabled them to stand up in a room full of researchers and argue a point. They were bright students who had been carefully mentored by John, and thanks to his example, I realized that the limit to undergraduate research was nothing more than the preconceived limits placed on them by their mentors. If one could take the time to guide the student through the processes of learning, then the sky (or at least publication in *Science* magazine) was the limit.

In my own research lab, I relish the opportunity to work with undergraduates. Unlike graduate students, who are already firmly fixed on a path to becoming a scientist, most undergraduates are still trying to figure out life, questioning their motivations, where they are going, or who they want to be. As a result, the fun of working with undergraduates is not simply the reward of teaching them how to do good research, but also helping guide them with their decisions about life.

Techniques in Teaching

To be an effective teacher, I try to incorporate many of the lessons I've learned about effective research from my mentors, Norm and John. The most critical piece to teaching good research technique is to help the student establish "What's the question?" To help the students do this, our lab has very defined questions in microbial ecology that we try to address. At the beginning of every student's project, I sit down with them, help them define their question, and hopefully provide the student some feeling of ownership of their research. An example would be, "What is the source of organic molecules to a microbial cave community?" We then write the student's question on a blank sheet of paper and work through a series of possible experiments with which we will attempt to answer the question. These experiments are written down in the form of a flow diagram as they relate to the central question. As a result, if students get lost or confused in their research, we simply pull out the flow diagram and determine where their experiment fits into the big picture. Such diagrams also help me to effectively keep track of numerous students working on diverse projects within the lab. Finally, students' results are plugged back into the flow diagram, helping us to formulate a hypothesis to answer their "question." From this come our future questions.

Understanding much of the research we carry out in the lab requires a very broad background in biology, chemistry, and math and proves intellectually challenging even to seniors. To help students better understand some of this complexity, we have weekly lab meetings and a journal club. One trick I've learned to encourage active participation is to have plenty of food available, either in the form of pizza (lab meetings) or candy (journal club). Not only does this encourage regular attendance, but distracted snacking can actually help a student to stay focused.

At lab meetings, each student is expected to take turns presenting his or her research and current results. In doing so, students reiterate not only their question, but how this question fits into the bigger picture of microbial ecology and why it needs to be addressed. The first time students present, understandably, they're nervous wrecks. But as time progresses, they become more confident in their abilities and more effective communicators. Other students are actively encouraged to participate in these meetings by asking questions and evaluating results, improving the student's collaborative ability and developing skills to help him or her objectively analyze and overcome potential problems. Of course, as the principal investigator, I'm always willing to jump in and explain a concept or procedure that is unfamiliar.

Our journal clubs involve a student picking a peer-reviewed research paper that is relevant to his or her research and presenting it to the group. While this is commonplace in graduate departments, it is quite a challenge for undergraduates. Nonetheless, students are expected to communicate the paper in an understandable manner to all those attending. To do this, I encourage students to ask as many questions as they need to prepare their presentation and try to provide as much supporting material as necessary to facilitate this. The first time I presented a paper in this manner as an undergraduate, it was a complete and unmitigated disaster. I remember seeing a professor and seven graduate students staring back at me, open-mouthed with shock and awe at my world-class bad presentation. I always like to share this anecdote with students before they present and emphasize that this failure simply encouraged me to learn how to become a better presenter. With a large lab group, students are only required to present two papers during the summer research period, during which time their lab and research duties are limited to allow them time to prepare. The results of this approach are especially

rewarding, with students becoming more actively involved in their science learning and subsequent research design. I think I actually jumped up and down and clapped my hands with glee the first time a student came to me with her own research design!

Undergraduates as Effective Researchers

In establishing my own research lab, I am able to bring together my understanding of cave processes and microbial ecology and give my students opportunities to carry out some cutting-edge research. Our work is geared toward understanding how microorganisms are able to survive in extremely starved environments. Caves, because of their geologic isolation and the absence of sunlight energy, are an extremely starved environment in which microscopic life subsists by scavenging available nutrients. In fact, the majority of energy that is available to the organisms in cave environments may come from soil detritus that filters into the cave through the host rock or from atmospheric gases bringing in energy-rich organic molecules from the surface. In such starved environments, the common wisdom suggests that a limiting energy source should result in limited species diversity. However, our previous work suggests that, in fact, the microbial communities in caves demonstrate an astounding level of microbial diversity. Studying caves also allows students the opportunity to travel to some pretty exotic locations to carry out research. These trips also function to encourage students to consider summer research projects, rather than summer jobs in a service industry, and act as a reward system for productive research. There are some limitations to where I can take the students, as caves are an intrinsically dangerous environment that require extensive training to negotiate safely. However, I've found that students are actively improving their cave exploration skills independently of my laboratory, increasing the potential sampling locations they are able to reach. Figure 1 shows students collecting microbial samples 750 feet underground.

I presently have eight students in my lab, with educational backgrounds ranging from a high school junior to undergraduate seniors. To help with such diverse levels of education, I have established a strong peer-mentoring network, with the more senior students mentoring the more junior. This greatly reduces my practical teaching responsibilities (such as showing a student how a pipette works) and



Figure 1. Nicolas Taylor (left) and Adin Pemberton collect microbial samples 750 feet underground in Carlsbad Caverns, New Mexico.



Figure 2. Jennifer Page counts bacterial cells for a cultivation experiment.

allows me more time to help guide the student through their research project, grasp the science that underpins it, and prepare their results for publication. To address the questions of how microorganisms can survive extreme starvation, mobilize, and acquire nutrients and to understand the ecological processes that drive species diversity in these environments, we've established a cross-disciplinary working group at Northern Kentucky University that includes researchers from both the Departments of Chemistry and Department of Physics and Geology. As a result, undergraduate students are working in a cross-disciplinary environment, with geology students regularly attending our lab meetings. We hope to extend this collaboration to include the math department, as we attempt to mathematically model these complex microbial systems. Such a cross-disciplinary approach to research allows the students to develop potentially unique abilities that will allow them to be very competitive when either looking for jobs or eventually applying to graduate school. Currently, my students are carrying out research using techniques including DNA isolation, purification and cloning, the polymerase chain reaction, RNA purification and reverse transcription, molecular phylogenetics, gas chromatography, liquid chromatography, fluorescent in situ hybridization and microscopy, scanning electron microscopy, and energy dispersive X-ray spectroscopy. I should also mention that everyone in the lab is expected to wash their own glassware!

The students in my lab are learning cutting-edge research, and I strive to make their projects relevant and important with regard to addressing the big picture as it relates to microbial ecology. In doing so, I take particular offense to the notion that my students are involved in a research "experience." Both my undergraduate students and other students I've worked with in research labs are carrying out productive research on par with anything being done in graduate departments. Figure 2 shows a student working on such an experiment. Granted, they may have more questions, problems, and mistakes than a graduate student, but I've never heard anyone refer to a graduate student's research "experience." To call the research that undergraduates carry out an "experience" undermines the work they do and the confidence they have in their own abilities, often the biggest obstacle to their own success. I therefore propose we remove the word "experience" from the work that our students carry out and call it what it is: "undergraduate research."

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