LEARNING THE PROCESS OF SCIENCE: THE CASE OF UNDERGRADUATE RESEARCHERS AND THE NATURE OF SCIENCE

This research documents the beginnings of a larger project in which undergraduate physics and biology researchers' conceptions of the nature of science were probed during their summer research experiences. Expectations of faculty mentors and the conceptions of students were investigated and compared. Although students engaged in undergraduate science research perceive great benefit as a result of the experience, these benefits do not necessarily correspond with the benefits expected by faculty mentors.

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Prologue

Ten years ago I was working towards finishing a degree in physics. As part of that experience, I had participated in summer assistantships in which I cooled superconducting samples, soldered wires, built low-pass filters, washed some glassware, programmed computers to sample from the external world, and made a temperature controlling system for protein solution samples. I had fun. I was dabbling in science, and it felt as though in some small way I was accomplishing something that was "real."

But during the last semester of my last year of college I was doing my own research, making a thin layer of water with just a little bit of scale like gunk within it (to make the fluid murky enough to see how it was moving around). I remember working in a shop, tapping some holes, polishing a copper plate, mounting a film heater, setting up cameras, writing a grant proposal, and gathering data. I was doing all of the things that real researchers do. In fact, I really think that I became a scientist as a result of this experience and the ones that had preceded it. The thing is, I still don't really understand what that means. Further, I look back on those experiences and all that I learned and the data I collected in the form of a bunch of mesmerizing pictures, and I now wonder what I was *supposed* to be learning from all of that. What was it that my own educators thought I was learning from all of this? I truly feel as though I "became" in some way -- it was a kind of right of passage as a researcher (although it is interesting to note that I had to "re-become" and go through a different right of passage in order to do educational research, but that's another prologue of another paper).

Last year, in the process of searching for a new dean for my university's College of Science, a candidate (the successful one, in fact) emphasized his desire to expand and support our undergraduate research programs. He stated that doing research allows students to understand the "process of science". Upon hearing this, I wrote it down immediately, for it occurred to me that this is a common sentiment, yet it begs at least two questions: What is this "process," and what exactly is it that we want our students to learn about it?

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My research is about research itself. With the expansion and emphasis of undergraduate research programs in colleges and departments of science, I wonder what it is that we all expect to achieve from these. I wonder what our administrators imagine these goals to be, what faculty imagine them to be, and what students imagine them to be. And, with all of these "imagines," I wonder what *really* is learned, experienced, and attained as a result. In my own reflections upon my own undergraduate experiences, I still think that the learning outcomes were nebulous, yet the experience itself invaluable.

This paper touches upon three themes. First, we must consider what it is that science education reforms are calling for. What kinds of experiences should our undergraduates really be getting, and how do these meet the goals of science education? Are our science majors simply to become scientifically literate, or should they shoulder a greater responsibility? If so, how is this accomplished? Do the goals we might have for our science majors overlap with those of all citizens, and if this is the case, does the undergraduate research experience inform not only how we should or should not be educating science majors, but also how we should be pursuing education on a grander scale?

Second, my research begins to look at what the mentors of undergraduate researchers suggest that the goals of these programs should be. These faculty are genuinely happy – no, thrilled – to be a part of this particular process, and they are so for explicit reasons. We should consider these in comparison to the goals of the grander community.

Finally, this work makes headway in regards to what undergraduate science researchers really take away from their experience. In particular, I investigate what these learners' conceptions of the nature of science (NOS) are before and after this experience. There are themes within these conceptions that can be outlined, and these suggest avenues of future research.

The setting

While some college science departments have traditionally welcomed undergraduates into the research laboratory, there is an increasing trend towards greater inclusion of undergraduate scientific research. Many graduate programs go so far as to not only recommend undergraduate research experience, but require it for admission to their programs. In addition, traditionally undergraduate institutions often require faculty to pursue research programs at the same time that these institutions emphasize the importance of educating students; thus the use of undergraduates in the research lab becomes a viable, though time intensive, endeavor.

During a summer research experience at a regional university in the western U.S., undergraduate researchers and their faculty mentors were given questionnaires and interview probes in order to elicit their perceptions of the research they were undertaking and their views regarding the nature of science. A total of six undergraduate researchers from physics and biology participated in this part of the research, completing questionnaires and interviews both at the beginning and end of their summer experience. In addition, three former physics students of the institution were questioned about their previous experiences as undergraduate researchers.

Although some other work in the U.K. provides us with a useful start (Ryder, Leach, & Driver, 1999), little work has been done to consider the goals and effects of recent undergraduate research efforts in the U.S. And yet there is an interesting milieu to be investigated. Undergraduate researchers are taking on real, authentic research situations and are often viewed as collaborators rather than students to be directed. On the other hand, the experience is couched within the educational arena – these are still our students, and there is a general consensus that learning is taking place in these situations.

So, what is it that these students are actually learning, and how does it compare to what their mentors are expecting/hoping for them to learn? When asked informally, many mentors will justify undergraduate research as a means for students to learn the "process of science," or similarly, "I expect that [the students] will find out a bit about how science is done." Such statements imply that students are expected to develop understandings regarding the nature of science (NOS). It is clear from previous research that NOS conceptions have been difficult for students and teachers at all levels to fully understand (Abd-El-Khalick, Bell, & Lederman, 1998; Abell & Smith, 1994; Lederman, 1992, 1998; Southerland & Gess-Newsome, 1999; Southerland, Gess-Newsome, & Johnston, 2003). What can be demonstrated is that instruction that most explicitly addresses NOS concepts (Abd-El-Khalick & Lederman, 2000), encourages learners to be aware of and reflect upon their own conceptions (Akerson, Abd-El-Khalick, & Lederman, 2000), and/or causes dissatisfaction with their previous conceptions (Akerson & Abd-El-Khalick, 2000) is most effective (though not completely effective) at enabling the learning of NOS understandings most compatible with the standards of science education reform (AAAS, 1990; National Research Council, 1995). This begs the question: How effectively does an undergraduate research experience meet these kinds of criteria? If these criteria are not being met, does undergraduate research experience offer an additional avenue towards understanding NOS concepts? If NOS concepts are not being learned, are there other benefits of these experiences? Do these other benefits supercede the learning of NOS and satisfy the goals of faculty mentors? Do they satisfy the criteria and goals of science education and its view of "science literacy" – and does it matter?

Methodology

The 6 students who were on campus at the time of this study were interviewed, using the following list of questions as initial probes. Questions 6-10 were first used in work done by Ryder et al. (1999).

1. What is your research about? What is your role in this research project?
2. Why are you doing this research?
3. Why do you think the research itself is important?
4. What is science?
5. What is the purpose of science?

6. How do scientists decide which questions to investigate?

7. Why do scientists do experiments?

8. How can good scientific work be distinguished from bad scientific work?

9. Why do you think that some scientific work stands the test of time whereas other scientific work is forgotten?

10. How are conflicts of ideas resolved in the scientific community?

For each response, follow-up questions were asked where it was necessary to clarify the student's meaning. These questions were also asked in the form of a questionnaire to the 3 students who were already graduated and at other institutions or places of employment. Additionally, any post interview or questionnaire included the question, "What did you learn from this experience?" and also gave students the opportunity to freely comment on anything else about undergraduate research.

Faculty mentors were also asked a set of questions in the form of an emailed questionnaire. Their questions consisted of the following:

1. Why do you use undergraduates in your research?

2. What benefit do you expect your undergrad researchers to get as a result of doing research with you? What do you ultimately want them to gain from this?

3. What do you gain from this collaboration with undergraduate researchers?

4. Are there any other questions you think I should be asking that you really want to answer?

Interview transcripts and questionnaire data were coded for recurring patterns and used to synthesize a preliminary set of findings. This was done by following the lead of Strauss & Corbin (1998), analyzing the data in three stages. First, data were read through and tentative themes and recurring ideas were noted. This was followed by a second reading of the data, using the themes identified in the first round to determine whether or not these themes were actually recurring or were simply spurious. Spurious ideas were eliminated, and the more recurring ideas were kept, so that a third analysis of the data could be used to assemble data pertaining to each theme.

It should be restated that this particular study is an initial attempt at this line of inquiry. It is simply looking for preliminary results to be used to determine future questions. The themes suggested in the following findings are not meant to be a definitive set; rather they suggest the kinds of conceptions and attitudes and conceptions that students and faculty involved in undergraduate research seem to have and seem to merit further study. This research should be the beginning of future projects which will produce more extensive probes and more testable claims.

Faculty goals

Faculty participating in undergraduate research (i.e., use undergraduates as assistants in the laboratory, in the field, or otherwise in order to get research done) all do so quite willingly and enthusiastically. At the institution in which this study took place, graduate students simply do not exist. In addition, the university itself is traditionally a teaching institution. At the same time, tenure-track faculty are expected to maintain a research line that is publishable in refereed journals and conference proceedings. Teaching loads at this institution are relatively high in comparison to those of traditional research institutions with large numbers of graduate students. (For example, teaching two lower division courses, an upper division course, and a lab in a single semester would be fairly typical.) So, a potential strategy and compromise for keeping true to the educational mission of the university and towards productivity in research is to enable undergraduate students to assist with such research.

There are no delusions about this prospect, however. Faculty realize and experience the fact of the matter that the amount of work necessary to guide and mentor undergraduate students is substantial. Although these students are advanced (typically juniors and seniors) and talented, they simply have less experience with science and their respective disciplines than graduate students. One faculty member laments that the presentations of her undergraduate students at conferences derive more angst for her than her own presentations, for the amount of mentoring required and the amount of inexperience in these students is especially apparent in these situations. At the same time, the pride with which these faculty refer to their students is impressive.

Faculty expect great learning gains, both cognitive and affective, in students who participate in undergraduate research. These include the following themes:

<u>Appreciation for science</u>

“I want them to experience the joy of scientific discovery,” notes one faculty mentor, a sentiment echoed by others. Although the institution from which these students and faculty come devotes itself primarily to undergraduate education, it is clear that the scientists involved are serious researchers, and they themselves take great joy in the process and findings of science. They suggest that this attitude is something that others may be most apt to subscribe to if they have had a one-on-one, authentic science experience that they would not normally gain from a classroom setting.

Another faculty mentor makes it explicit that the freedom from the traditional classroom allows her students to have more “fun”. She and others suggest that this should be a legitimate goal of this experience for undergraduates. They should take away some satisfaction and joy in the work that they are doing. In addition, these students get to experience something that is potentially more freeing than what is offered in typical coursework: “This is the part of their science education where they get to have their own ideas, instead of learning about everyone else's in the academic setting.”

<u>The process of science</u>

At this institution, it is common to hear of administrators speak highly of the undergraduate research program at the campus, and particularly note that this program and its projects allows students to understand the "process of science". This attitude is reflected in faculty attitudes as well. For example, a faculty member in a biological science states that:

> *Research is an excellent way for students to learn about science, how the scientific method is implemented, how experiments are set up and then carried out, and using critical thinking processes to work out the problems (troubleshooting). Research demonstrates the difficulty and time to complete a refereed publication and to present the study at conference venue.*

Similarly, a mentor from physical science says:

> *Also, I expect that they will find out a bit about how science is done. How do we come up with ideas in the first place, and what is the process for chasing them down.*

In these statements there is a very grandiose kind of goal. It is hoped that these students can learn about multiple pieces of the scientific process, *and* how these processes work together to create scientific knowledge.

<u>Valuable skills</u>

Faculty mentors were also consistent in their description of the individual and specialized skills they believed that students would learn in the research setting. Although many of these skills are those that are emphasized in regular coursework, a strong claim was made that these skills are particularly focused upon in the research setting:

> *I ultimately want then to develop the skills of doing science in all aspects: learning how to design experiments or field work, working with groups when this occurs, developing oral and written communication skills.*

These kinds of skills are diverse, yet ultimately agreeable to many faculty mentors, as demonstrated in the similarities between the previous statement and the following:

> *[Undergraduate research] allows students to improve/develop skills in these areas: scientific reasoning, experimental design, statistical analysis, and communication, especially writing.*

<u>Goals and future</u>

Other suggestions from mentors are more pragmatic in terms of what they will offer for a student's list of accomplishments. Often, a faculty member who would give a "process of science" reason for conducting undergraduate research would follow it with a secondary objective of "giving them the practical experience which should help them in their career paths."

It is noted by several mentors that the experience helps students to decide what they might want out of further education, and that it may help them to attain their future goals:

> *It helps the students explore another career option (a research-based one) in a direct way, and at the very least provides them with experience that might help meet other needs. These would include the need to have a letter of reference from someone who has worked very closely with them and the requirement to have had research experience, as many medical schools now expect.*

Similarly:

> *Ultimately, I want them to be able to use this experience to help define their long term goals. Whether they love research or hate it, it's best that they learn that now, before they've spent years chasing a graduate degree they may or may not want.*

All of these attitudes, skills, and concepts that are hoped for by various faculty mentors sound worthwhile and are consistently described. This, of course, demands the next question: What do the *students* actually gain in attitudes, skills, and concepts, and how are these related to faculty goals?

Student conceptions

Student conceptions of the process of science and what they learned were varied, but definite themes are easily distilled from the data. These themes focus on two aspects of student conceptions. First, what do these undergraduate researchers view *science* to be after having experienced it firsthand? Second, what do the students view to be the benefits of their experiences as researchers?

Views of science

Overwhelmingly, students who participated in these projects viewed science itself in a very pragmatic manner. All students who were interviewed or questioned made at least some reference to the usefulness of science, and most of these students described the usefulness of science to be at the forefront of its purpose.

This attitude manifested itself in various ways. All students surveyed or interviewed portrayed science as a way to get some kind of answer or solution: "Science is a method for answering questions," or "To gain fact based knowledge about our world and to responsibly use that knowledge to the benefit of those in the world." This theme was common throughout interviews and written responses. When asked for more specifics, or when probed about other details of science, these researchers showed almost as much consistency to cite the use of science as a way to improve life or solve problems. In this vein, science as "problem solving" was a popular analogy.

Students in the life sciences were especially apt to describe the medical applications of science. When describing the importance of their work, these students often compared it to medical applications, either to belittle their own work or to show that the work could be extended eventually to medical applications. In other questions in which the longevity of science knowledge was discussed, these students referred to the medical applications as well: how disease has led to scientific discovery, how a scientist's choice of questions could depend on medical application, or how their own personal goals and interests in science are driven by an interest in future research or practice in the medical field.

It must be pointed out that these particular views were identical before and after the research experiences. Although students gained understandings on the "doings" of science in particular situations (see next subsection), these views of science as a whole were the same both before and after their experiences. Students would make claims that they had "a better appreciation for [science] research," but would describe this in terms of the practical skills and specialized experiences involved in their particular work.

Practicalities of doing research

One thing that both faculty mentors and students had in common in the perceived goals and gains of undergraduate research instruction were the specialized skills and practices that were manifest in a particular line of research. "It turned out to be much more lab work: running tests, following procedures, and fiddling with instruments," said one student – a common sentiment among these researchers. Although all students' impressions of research were positive, at the same time they were focused upon the practicalities of being in a particular research setting. Thus, when asked, "What did you learn [as a result of this experience]?" these students each had at least one of the following skills to describe:

- Problem solving and analysis: Students were apt to describe the day-to-day issues experienced in the lab that needed to be "fixed" before they could continue forward. These ranged from preparing a biological sample properly to getting a computer code to work properly. This level of problem solving, while not what these students would explicitly define as science, is often what they'd describe themselves doing as scientists.

- New laboratory skills: Any student who was in a laboratory (as opposed to being in the field or doing computer work) was making measurements or preparing samples. When describing their research, students were able to describe these aspects of the research in great detail, whether it involved putting a protein into a "gel" in order to be analyzed, scanning samples with an atomic force microscope, or "after isolating DNA from tissue, I performed molecular sequencing tests." These students could describe these processes both in terms that were technical, as well as in terms that the interviewer could picture; but their first set of vocabulary was that of the lab and the discipline.

- Using computers/programming: One student interviewed was actually writing computer programs to modify and analyze astronomical images, while other students were using computers to collect and organize data. In these cases, student researchers described this as an important skill to learn in order to do research.

- Collecting data and doing statistics: In typical class work, the "data" that students collect was view differently than the data they were collecting in their research experiences. Student researchers were impressed with how difficult it was to get data, whether it was in the field and counting populations of ants and crickets to extracting proteins to analyzing samples with an atomic force microscope. One student noted that even the method of keeping a notebook to collect data was different in this case than it was in his scholastic labs. In the case of one student who was analyzing data already collected, his only negative comment about his research was that there were “no data to collect.”

- Reading journal articles and doing literature searches/review: Some students, though certainly not all, read journal articles related to their research. In such cases, this was often the first time that they had experienced such sources of information. Finding the information and reading it – in comparison to their traditional science texts – was described as a new and important skill.

- How to write: For students who were completing research and disseminating results in a written form, the process of writing in this manner was a skill they described as having learned or experienced. Analogous to how journal articles are different from textbooks, this level of formal writing, citation style, and presentation of data was described as a new skill.

It was interesting to me, the investigator, to listen to the wide variety of skills and abilities that these student researchers had picked up and mastered while experiencing the research opportunity. All students prominently mentioned at least one such skill. In contrast, none of the students mentioned anything about learning about the nature of science on a grander level. Their comments about science were reserved for the finer details of working in the lab, the field, or the library.

<u>Affective gains</u>

“The experience gave [me] a chance to participate in science on a professional level.” Although students did not necessarily talk about “science” in a grand sense (instead focusing on the minutia of their project and their skills), these students did describe the gains derived from the experience with wider, more colorful brushstrokes. Students describe working with faculty mentors and having the opportunity to participate in the scientific community as something that they found personally very important to them. In doing research, students describe being part of the scientific community and “feeling like and investigator” within it.

Making personal connections to faculty was another intangible that students often voiced. “I came to enjoy . . . associating with faculty outside the classroom,” notes one student. This opportunity is echoed in other student responses, even though in most cases the student work was guided by the faculty, but students were in the lab, in the field, or at a computer by themselves or with other student researchers. These undergraduate researchers all enjoyed the balance between being mentored by faculty, but also being left to do things on their own.

When asked about why they got involved in research in the first place, students tended to note the benefits of learning new skills (as described above), and additionally in order to better promote themselves on graduate school applications. Most students explicitly described the entrance requirements for future programs or the preparation provided by the experience for future careers or schooling as being one of the most important reasons for pursuing undergraduate research.

Discussion

There are some comparisons that can be made in the discussion of the data. Looking at students' views of science and the research process, we can compare these conceptions to those of both science education reform literature (AAAS, 1990; NRC, 1995) and the goals of the faculty mentors.

When describing science and the scientific work that they did, these students described the "nuts and bolts" of the process: data, skills, and problem solving. This is in subtle yet salient contrast to many of the concepts that are advocated as part of the NOS (AAAS, 1990; NRC, 1995). Such concepts include (but are not limited to) ideas such as the tentative nature of science knowledge, the process of science within society and within the societal structure of scientific peers, and the ethics of science. For any of these concepts, students could speak to these topics to a degree, but more research is really necessary to describe their complete understandings of these concepts. However, when students were asked, "What did you learn?" they *never* described anything on the grander level of science, but focused on the much more focused and specific aspects of their particular experience within their particular discipline.

Faculty *did* talk about learning the "process of science" on a grander level, though perhaps phrases like this are grand and vague enough that mentors could actually mean many different things by statements like this. On the other hand, faculty quotes like, "How do we come up with ideas in the first place, and what is the process for chasing them down," suggest that the "process of science" really does refer to the "big" picture after all. In this study, faculty were not probed deeper to understand all of the details of what they meant.

Although not conclusively shown, these data support previous findings (Ryder, Leach, & Driver; 1997) that student researchers emphasize the empirical and objective nature of scientific knowledge, describing new fields of study largely as a means to gather more information. Similarly – perhaps even in coordination with this conception – most of these students emphasize the usefulness of scientific knowledge to either help technological advances or to improve human health. That is, students meld science and technology into one, giving science a utility to help humanity. Interestingly, the one student who did not voice this view was studying astrophysics. It is not clear from these data if a student's view of the purpose of science determines the research that they pursue, or if the research they pursue helps them to determine their personal purpose of science.

These results suggest that, even though students enjoy and perceive a great benefit from the experience of working in research labs, the exact benefits are unique to each individual and each research setting. Understanding the "process of science" is a nebulous task, and may be more than what we can expect from a research experience with implicit goals. On the other hand, all of these students seem to be learning a bit about how to do some specific tasks in the research labs, feeling the part of a scientist, and gaining an experience that are invaluable.

Future questions

Even at the onset of this research, the main objective was to look for future questions to begin asking and probing more deeply. This study shows a general landscape of student and faculty conceptions about science and scientific research and the gains of doing such research, but it leaves open several questions, such as:

- Are there any changes in students' views of NOS as a result of doing science research? If not, is this a cause of the research environment itself, or is it simply a matter of *not* having explicit aims towards teaching/learning NOS in these settings? If these goals *did* exist, and if NOS were taught explicitly, would the research experience further help students to understand NOS concepts in a more concrete manner (as compared to reading and discussing philosophical pieces)?
- Do faculty mentors hold more specific goals for students in the undergraduate research setting? If so, what are they? If they are confronted with this question, would they offer a different kind of experiences?
- What is the nature of NOS for "scientist" students as opposed to non-science students? In most discussions of "science literacy," it seems that we are describing a general education, what's-necessary-to-be-a-citizen kind of literacy. These researchers are much more sophisticated in their science background, and they are using/doing science towards much different ends than the general audience. Should we suggest a different set of goals for them? Why?
- If we were able to get a more thorough painting of NOS understandings of students, how would they compare to their mentoring faculty? Assuming that they're different, can we pinpoint a cause for this difference? In other words, at what point in a scientist's career/education is there a change in NOS conceptions – or does such a change even take place?

The questions could continue. The point of presenting this research – or any paper – perhaps is to see the questions flourish and propagate. I am confident that there are more questions to ask, more concepts to probe, and more work to be done in general.

Epilogue

Two days before leaving for this conference, the university at which this study took place held its first annual undergraduate research symposium. Oral presentations and poster sessions filled an afternoon and a student union, with fields as widely ranging as psychology and physics being represented. Everywhere there was anxiousness and excitement as the usual trials and celebrations took place. I watched as one group of students tried to retrofit a display panel to fit their particular poster, and another student and faculty mentor splitting up to find an additional overhead projector. In all, it looked and felt just like "real" research. In fact, it was. People asked questions, made comments, and submitted suggestions. We all applauded at the end of each presentation, and the students seemed to leave with a sense of accomplishment. If this is what it is all meant to do – and certainly this *is* something – then the experience seemed to have worked.

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