Keynote Address for the Biology REU Site Directors' Meeting

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> *A quote:*
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> *"It's kind of exciting…You don't get the result and you get a little bit disappointed. But you try to improvise and next time you end up getting a good result and you get excited. So you kind of want to do it more… It's always an excitement, that's what I think, using your basic knowledge of what you learned before and try to use that to … get a result and you get happy about it."* (CASPiE student, Spring 2006)

As scientists, we know that research is the foundation upon which our profession is based. And we place high value on learning how to carry out research as part of the process of learning to really *be* a scientist. Many of us can think back to an experience as an undergraduate that was particularly inspiring and helped to propel us along the path to being professional science practitioners. But what made that experience particularly valuable for us? Perhaps, like the student whose quote I read, it was the sheer excitement of being intellectually engaged in the process of discovery – of failing initially and then turning that failure to success through a synthesis of concepts, skills and creativity.

Now that we find ourselves in the position of planning and administering programs for undergraduate research, we may be asking a complementary set of questions: what are the underlying skills and concepts that define the process of "learning how to carry out research"? How can we structure programs to best achieve these learning outcomes? And, of course, how do we know if our students *are* achieving these when they are involved in a research-related educational experience?

As a component of the training of a scientist that is universally held in high regard, we expect an undergraduate research experience to impart those skills that can turn someone from simply a student of science to a practitioner of science. With respect to science *knowledge* and laboratory *skills*, scientists from different disciplines would describe different technical skills that students need to master that particular field. A chemist, for example, would consider it unthinkable for a student to graduate without being able to carry out a titration, or interpret a simple NMR spectrum. A physicist might not find *these* specific skills to be critical in *her* own field. There are, however, certain outcomes of a scientific research experience that cut across disciplinary boundaries as ones that contribute to being a scientist and a citizen in our globalized knowledge economy, and that we find consensus about.

For example, the American Association of Colleges and Universities developed a set of recommended "Essential Learning Outcomes" for a college education. In the Intellectual and Practical Skills category they list: inquiry and analysis, critical thinking, creativity, communication, quantitative literacy, information literacy, teamwork, and problem solving. The set also includes Integrative and Applied Learning for the application of knowledge and skills to new settings and complex problems. Clearly this list has significant overlap with the types of outcomes that many, if not *all*, of us would anticipate from a high-quality research experience in the sciences.

The AAC&U's recommended Essential Learning Outcomes are well aligned with research studies and other publications that examine educational policy and practice. Studies have noted that the types of benefits that *can* result from research-related educational experiences include the development of critical thinking, problem-solving skills, and communication skills; learning to work collaboratively in teams; integration into the culture of the discipline, and increased confidence in one's ability to learn and *do* science align with AAC&U's list. It also deepens the understanding of the nature of research and, therefore, the nature of scientific knowledge - how it is constructed and how evidence is used to support scientific assertions – which is critical not only for practicing scientists but also for a voting public to understand.

These broader outcomes of a research experience are also well aligned with the types of skills that employers, in general, are looking for. In May of 2007, the National Research Council Board on Science Education held a workshop to identify what were referred to as "21st century workforce skills." While the terminology is different, the skills have an unmistakable overlap with those I've listed as benefits of research. The 21st Century workforce skill list includes adaptability, complex communication skills, non-routine problem-solving skills, self-management/self-development, and systems-level thinking. A follow-up Board on Science Education workshop in February of 2009 explored the idea of using *science* as the domain through which these 21st century skills could be taught. That workshop was focusing on science education in the precollege (or K-12) levels, but I believe there are also important lessons in their conclusions that relate to engaging *undergraduate* students in research. The workshop participants concluded that…the development of science process skills (such as designing an investigation, formulating a scientific explanation based on evidence) is closely connected and mutually reinforcing (National Research Council, 2007a)…of the five 21st century skills. For example, constructing a scientific explanation that includes a claim, evidence, and reasoning to support the concept develops both adaptability and complex communication skills; designing investigations develop non-routine problem solving skills; and understanding of complex scientific questions would be evidence of systems-level thinking.

I would like to emphasize that the list of educational activities that are believed to contribute to development of these 21st Century workforce skills, or to the essential learning outcomes, are activities that engage students at *high cognitive levels*. We know there are many ways to teach a course, some of which engage students in learning at a deeper level. The same is true for research experiences. There are different ways to engage a student who enters into a research lab, and some of those ways will be higher quality experiences than others. Let me provide you one additional example from the K-12 arena. The National Science Education Standards report from the National Research Council (NRC) provides a set of standards that (quote) "outline what students need to know, understand, and be able to do to be scientifically literate at different grade levels". Throughout that report, "science as inquiry" is recommended as a major category of the content standards for all grades from K through 12. The NRC followed this report by a publication devoted entirely to defining the term 'inquiry'. This publication describes a pedagogy in which students (quote) "engage in many of the same activities and thinking processes as scientists", including making observations, *formulating questions*, gathering evidence in a reproducible manner, *making scientific claims based on evidence* and existing scientific knowledge, *communicating results*, and revising the explanation or revisiting the experiment based on feedback and critique from the community. Therefore, these are the types of learning gains that we want to target in our programs and assessments.

So, what is the evidence that undergraduate research programs can, or do, provide these high quality research experiences? SRI International conducted a nationwide study of undergraduate research opportunities (both federally funded and non-funded) through a series of surveys administered between 2003 and 2005 (Russell, Hancock, McCullough; Science; V316; 4/27/2007). You can find a complete set of reports, data and instruments at their website, but I would like to highlight one set of data that they presented in their final report. Of nearly 1800 students who reported being involved in STEM undergraduate research, the SRI team asked them to indicate which types of research activities they had engaged in, from a list of 17 items…now we all get to exercise our skills of imagination because if I had a PowerPoint show going, at this point I would be pointing to a bar graph with a series of bars organized from largest to smallest. Nonetheless, even without the usual crutch of visual aids, I'll endeavor to describe to you what I, personally, felt were surprising and not terribly encouraging results.

Only 59% of the students reported that they understood the "big picture" of the project they were working on. With respect to opportunities to communicate results: only 46% of students reported that they gave oral presentations, and only 24% gave poster presentations (overlapping group); only 17% attended conferences (student or professional); and perhaps most disappointing only 13% had been engaged in authoring or co-authorng a paper submitted for publication. On the other hand, 80% collected or analyzed data. It seems then, that the vast majority of students engaged in undergraduate research are being engaged at only the lowest-common-denominator level, a level that may not even be achieving what the National Research Council recommends for K-12 students. While 58% of students in the SRI study reported that they prepared a final written research report, the authors of the study state, in a paper published in the journal Science in 2007, that (quote) "some commonly assigned research activities – preparing written final reports, in particular – tended to be *unrelated* to positive outcomes.(") Instead "Students…who became involved in the culture of research – attending conferences, mentoring other students, authoring journal papers, and so on – were the most likely to experience 'positive' outcomes, such as increased interest in a STEM career." (close quote). The other positive outcomes listed by these authors included understanding of how to conduct research, confidence in research skills, and awareness of what graduate school will be like.

It seems, then, that simply inviting a student into the laboratory to participate in an established research project may not be enough to make the research experience a maximally valuable one. How, then, do we create a research-based educational experience for our students that supports the highly desirable learning outcomes I described earlier?

The Council on Undergraduate Research recently published a book called *Broadening Participation in Undergraduate Research*. The book emphasizes that there is no one-size-fits-all formula for the *right* way to structure an undergraduate research program. But there are examples of successful programs that can be examined for guiding principles and best practices. I highly recommend the book since it provides many and varied examples of successful undergraduate research programs.

Among the goals of this book is the re-visioning of traditional undergraduate research experiences so that groups who are typically not engaged in them *can* be. These groups include 1st and 2nd year students, students with disabilities, students from low-income families, or underrepresented ethnic and racial groups, for example. This idea builds on the recommendations of the 2007 report from the National Academies, *Rising Above the Gathering Storm*, which asserts that "increasing participation of underrepresented minorities is critical to ensuring a high-quality supply of scientists and engineers in the United States over the long term." A particular bonus is that researchers have found that the benefits from "engaged" learning, such as undergraduate research, are greatest among students from underrepresented groups than for majority students (AAC&U and SRI report). So, bringing these students into the activities would have a pronounced effect on their gains.

But typical summer research programs are apparently not reaching a large swath of the potential undergraduate researchers out there. A three year study of 65 Chemistry REU sites (Grabowski, 1998, unpublished) and almost 2000 program participants showed that 95 to 96% of participants in REU programs were rising juniors or higher (rising seniors or just graduated) with the majority being rising seniors (about 62 to 65%). Furthermore, 79% of the 8000 *applicants* to these programs were white, and another 10 to 12% were Asian. If we think, then, that undergraduate research programs are doing anything to help with the "leaky pipeline" problem, we need to think again, because only those who have already made it through most of the pipeline, or were never in any real danger of leaving it, are getting to play in the lab.

Finding new ways to reach out to student populations that have not typically engaged in undergraduate research opportunities would be a good first step. From the SRI report that I described earlier, of the STEM *graduates* surveyed who had *not* been involved in undergraduate research (about half of all students surveyed), two of the four most common reasons given were "I was not aware that research opportunities were available to me" (28%), and "It never occurred to me to do research" (19%). You will find that not knowing about the availability of research opportunities is a particular problem among students from minority and low-income groups, where a disproportionate number represent first-generation college goers in their families. As a result, they don't benefit from the same types of guidance about available and valuable opportunities that students do who have had siblings, parents, other family members and friends attend college before them.

The idea of engaging students as early as possible in their college careers has been echoed in numerous publications and reports, including several of the ones I've mentioned. The Science paper summarizing the SRI study of URO's concludes with "the earlier the better… greater attention should be given to…providing URO's for college freshmen and sophomores." In a 2007article in Inside Higher Ed, Peter Bruns of the Howard Hughes Medical Institute is quoted as saying, "You have to sort of think of undergraduate research the same way you think about voting in Chicago – early and often." It turns out that engaging students early in undergraduate research, however, is easier said than done. There are particular challenges that exist for doing this.

One of those challenges is the faculty themselves. Many have preconceptions about how much students should have already learned in college before they can be productive in a laboratory. For their own part, the younger students are sometimes a barrier as well – they do not identify themselves as capable, they may be afraid of taking on something that requires them to be independent thinkers, or they may simply be unaware that opportunities exist for them. But a reconceptualizing of the research experience can help to bridge the gap between where students are and where they and their mentors think they should be in order to carry out research. In fact, inclusion of first- and second-year undergraduates in research projects has the potential to change the nature and management of research projects themselves. One way this occurs is by allowing different perspectives or questions to be raised by a diverse set of participants, possibly opening up new areas of research.

I'd like to tell you about an undergraduate research program that I have been involved with since 2004. The program is called CASPiE, which stands for the Center for Authentic Science Practice in Education. CASPiE was originally funded by the Chemistry Division at NSF through its Undergraduate Research Centers or Collaboratives program. The CASPiE program engages 1st and 2nd year students in real research as part of their regular laboratory courses. This approach ensures that all students in the mainstream undergraduate science courses have the opportunity to do research, without needing to apply to special programs or add to their already overwhelming course load. For those who wouldn't have thought themselves capable of doing research, the program provides them with a low-commitment way to test the waters.

The program functions by having researchers select one part of their ongoing project that a team of undergraduates could realistically contribute to through data collection or development of specimens (such as through an organic synthesis project.) This is written up as a research "module" that is intended to take place over a period of 6 to 8 weeks, or about half of a typical college semester, with the traditional 3 hours per week laboratory schedule that undergraduate courses employ. The modules begin by laying out the background ideas for the project in "big picture" language – why do we want to do this research, what are the big questions, and how will you (the student) be contributing to our ongoing work? Thus, the student is brought in as a collaborator from the very beginning – not simply as a "trainee." The first two or three lab sessions are "skill-building" sessions in which students are taught how to carry out a particular reaction or assay, or use a particular instrument. These laboratory sessions have procedures that are fairly prescribed because they are intended to build the "toolkit" that students will put into place in the last few sessions of the module. Those last three or four sessions are ones where students, generally working in teams of three or four, design an experiment to address a research question. The results of their experiments are provided to the author of the module, the researcher, with the intention that these will contribute to their ongoing work. The data of the students in the class as a whole are pooled, or a library of samples is created and these are sent to the researcher to test further. While each individual student is only getting 18 to 24 laboratory hours of contact with the research, the replication by large numbers of students helps ensure that the researcher can mine the information for useful leads for the next step. We have now successfully included student work form this CASPiE model in three scientific publications to date. But even that is not a true measure of the usefulness of the student work because much of it serves as a precursor step to additional research to be carried out by graduate students or others.

The original Chemistry CASPiE program currently has eight modules in existence and is now operating at 17 higher education institutions, ranging from 2-year colleges to research-intensive universities, and one university in Australia. Just over 4000 undergraduate students have now been through a CASPiE course in either General Chemistry or Organic Chemistry at one of these institutions. Furthermore, while the modules we've developed are specific to chemistry courses, this *model* of undergraduate research is not, and it is now spreading. A group of faculty in Atmospheric Sciences received funding two years ago to develop a CASPiE course in their discipline and last year the same happened in the biology department at Purdue. Both of those departments are now implementing a CASPiE first-year course with modules they have developed. Another unforeseen extension of the CASPiE program that has taken place is in its grade level reach: high school teachers began attending the CASPiE workshops that we offered at conferences, and began adapting some of the modules for their students. At first, this was primarily for science fair sorts of activities. Now, however, we have a small cadre of high school teachers that has begun working with the CASPiE staff to adapt full modules to high school courses. These have been implemented at four schools to date, with more planned for the future – the exact number will depend on whether we're successful in obtaining funding for this particular branch of the program.

Of course, we have had an external evaluator working with us from the beginning to look at the outcomes of our program. In addition, my own research group has carried out studies of a more qualitative nature to try to get a deeper understanding of the student experience in this new format for undergraduate research. I'm pleased to be able to say that the results are quite positive. Our evaluators developed and implemented a survey-based instrument that is administered at the beginning and end of each semester to students in the CASPiE courses and in equivalent non-CASPiE courses, where those exist. With factor analysis of the survey items, they established six subscales for measurement and comparison: interest in chemistry or science, connection between science class and real life, perception that the laboratory activities are authentic science, perceptions that the laboratory is contributing to their learning in the course, belief that they are able to learn chemistry, and the value of collaborative learning in the laboratory course. I will summarize some of the findings along these subscales:

- *When comparing between CASPiE students and non-CASPiE students:*
    - Significant differences exist in the "Interest in Chemistry/Science" subscale. Involvement in CASPiE modules <u>maintained</u> CASPiE students' interest in chemistry and science, while it was seen to <u>decrease</u> over the semester for the non-CASPiE chemistry courses.
    - Significant differences exist in the "connection to real life" subscale. Involvement in a CASPiE module <u>increased</u> student understanding of the relationship between science class and real life practices, while the mean score of non-participating students' on this subscale <u>decreased</u> after completing chemistry courses without CASPiE modules.

  - Significant differences exist in the “Authentic Scientific Lab Practices” subscale, with CASPiE students reporting an increase in their perception and non-CASPiE students reporting no change in their perception.

  - In the “Perception of Learning through Lab” subscale, CASPiE students reported significantly more positive perceptions of learning through lab than did non-CASPiE students.

  - Significant differences exist in students’ belief that they can learn science through lab. Involvement in CASPiE modules maintained CASPiE students’ perception of their understanding of chemistry knowledge, while the mean score of non-CASPiE students on this subscale decreased significantly by the end of their non-CASPiE chemistry courses.

  - CASPiE students had a significantly higher mean score on the “Value of Collaborative Learning” subscale following completion of a CASPiE module, while non-CASPiE students’ mean score showed no change (in spite of their working in collaborative teams in the non-CASPiE courses).

- *With respect to gender differences:*
  - Female CASPiE students reported that involvement in CASPiE modules (a) helped them better understand the relationship between science research and real life practices, (b) provided more experiences with authentic scientific lab practices, and (c) resulted in more positive perceptions of their understanding of chemistry knowledge. Females who were not involved in CASPiE reported no such changes.

- *With respect to minority versus white students:*
  - Non-White CASPiE students reported that they had (a) more interest in chemistry and science, and (b) more positive “Perceptions of Learning Chemistry through Lab” than did White CASPiE students.

Additional statistical analyses show significant increases in agreement for students in the CASPiE research classes to, among others, the statements “In this lab course, I must understand the big ideas behind each experiment in order to do well”, “I have a better understanding of the process of scientific research as a result of this laboratory experience,” and “The lab experiences in this chemistry course made me realize I could do science research in a real science laboratory.” It is worth noting that, for students in the traditional courses, we saw significant *decreases* in agreement to those same statements over the semester.

A further study was carried out comparing our research-based CASPiE curriculum to a long-established inquiry-based curriculum and to a traditional curriculum. Qualitative *and* quantitative data analyses from this study demonstrated that, compared to the other two curricula, students in the research-based curriculum demonstrate a much deeper understanding of the main scientific concepts in their experiments, report significantly more confidence in their ability to explain their experiments, and are better able to propose further investigations that could be carried out for their experiment.

We're continuing to collect data on the outcomes of a CASPiE experience, particularly with respect to longitudinal effects. But even what we have seen so far has been very encouraging. We may not be turning every CASPiE student into a scientist, but we know we are providing all of them with early training in scientific ways of thinking and an introduction into the culture of science. We know that this early preparation through a research-based course curriculum can prepare students for more fruitful engagement in research in later years, regardless of their chosen field of study, and that getting them engaged early means that their later activities can be at higher levels.

Hopefully I've managed to convince you that different approaches to undergraduate research can be taken, and can be successful. That, in doing so, we can engage groups who haven't always found research experiences accessible to them, but who are capable of making valuable contributions. If I haven't convinced you, I hope I've at least provided some food for thought.

In a society where virtually every sector of the workforce is influenced by STEM-based developments, the broader learning outcomes become increasingly important – perhaps even more so than a single body of skills or content knowledge. In their future careers, these skills will allow our students to contribute to solving problems, addressing issues and answering questions that are complex, multidimensional and truly interdisciplinary.

I'd like to finish by reading an excerpt from a letter that a student sent me more than a year after taking my CASPiE course:

> Several days into the semester I walked into your office and begged you to sign me into your class. At that point I did not realize it was a Caspie section, nor did I know what Caspie even was. I only knew that I had to take the coruse and all of the sections were full. After you briefly explained what the Caspie section would encompass I was honestly thinking, "Oh jeez I really don't want to have to do extra work. I just want to take the required course!" ...but I was desperate so I feigned interest.
>
> Contrary to my initial dismay, I absolutely loved Caspie. Contributing to Dr.

Feruzzi's research made the labs feel significant and therefore more interesting. Recently I read an article in our local newspaper regarding Dr. Feruzzi's research, and I felt extremely proud to have participated.

Furthermore, the independent research project at the end of the semester was a phenomenal learning tool for me personally. It truly was an invaluable stepping stone in the process of transitioning from a passive student into an active researcher. It was my first opportunity to be a real scientist.