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# A Perspective on How to Improve Undergraduate Research Education in the Physical Sciences at USC

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# A Perspective on How to Improve Undergraduate Scientific Research Education in the Physical Sciences at USC

By

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## Thesis Summary

My years at the University of South Carolina have been some of the most challenging and edifying periods of my life. I have been blessed by having a great professional and chemistry mentor in Dr. John L. Ferry who has helped me engage in scientific research in a meaningful way. As I watched other chemistry students, in particular, struggle with understanding what research really was and even how to understand the results and methodologies of it I felt that this was a huge issue that could be rather simply fixed. I have been privileged to apply for and receive a Magellan Fellowship that helped and encouraged me do my own research but that was basically the only outlet I saw in which my peers were doing real research and not just lab work in the name of research (i.e. simple lab duties that did not contribute to the intellectual field of the discipline of chemistry, or require further exposure to it). I believed that such exposure to and understanding of scientific research would be very beneficial to both students as they graduate and the university. So, I set on a mission to gather and review research that has been on such topics and to evaluate the specifically scientific (by that I mean physical sciences and engineering) research program at USC and compare it to the metrics and specifics that have been determined to be consistently part of top tier undergraduate research programs. During this process I learned a lot about university administration of such an endeavor. My study and proposal in the next several pages is far from a perfect plan for the university because, though I have learned a lot, I surely do not know as much as the administrators and tenured faculty that are involved in such high level decisions. My main hope is that the faculty and administration will read what I have to say, learn how their actions are perceived by at least one involved student, and then evaluate my suggestions for improvements.

## INTRODUCTION

The formalized practice of undergraduate research in the sciences is still relatively new in the United States. The first intimations of undergraduate research funding and encouragement on a national, institutionalized level occurred when the National Science Foundation (NSF) met in 1953 and discussed improving science education for undergraduates, with research being deemed a worthy component of that plan. Initially, however, noticeable change was slow enough that even today many leading researchers and educators point to 1969 when the Undergraduate Research Opportunities Program (UROP) was founded at MIT as a critical example of undergraduate research becoming a priority at individual universities. Arguably the biggest leap forward in undergraduate research did not even occur until nearly 20 years later (1986) when the NSF developed its now widely marketed Research Experiences for Undergraduates (REU). This steady progression of institutional focus on undergraduate research that began near the turn of the 20$^{th}$ century has only picked up steam. In fact, today many top research universities have elaborate and intensive undergraduate research programs, some optional some mandated, that seek to train STEM majors to be able to conduct research in their careers after matriculation. [1]

Across the United States major research universities are faced with the challenge of identifying, educating and training the next generation of young scientists in the art and science of research. The problem that most universities eventually encounter is that undergraduate students are ill prepared for research at graduate and oftentimes even undergraduate levels. Faculty and staff see that either when undergraduates attempt to perform research or graduate students come into their graduate program, many are ill prepared for full time scientific research or even uninterested in the possibility. This is a shame because with increased exposure to research comes increased interest in the STEM disciplines as career fields.[2, 3,4,5] So not only is it a wasted opportunity to take students excited about STEM disciplines and not teach them research, but also teaching more students about research might indeed convince students from other disciplines to check out STEM majors for themselves.

Several organizations were formed to help universities solve this problem and create excellent undergraduate research programs. The Council on Undergraduate Research (CUR) sponsored a paper on the *Characteristics of Excellence in Undergraduate Research,* which went through the qualities a university must have to have a great undergraduate research program. After review of those, the University of South Carolina would appear, to at least one student observer and based on conversations had with faculty, to have roughly completed 21.5 of the 61 categories. Although it is possible that more are actually met, and indeed hopefully that is the case, the author can only go on his own experiences and conversations with both students and faculty. Therein there is a lot of room for improvements to be made, some minor but many quite major. For the rest of the paper that will be much of the guideline and rubric that will be used to compare what this program is and what it should be. It will not be the only metric however, and recommendations will also be made based on other research and papers as well, culminating in a plan that the University of South Carolina might follow to foster an overachieving undergraduate research program.

As a school and university, the University of South Carolina College of Arts and Sciences should be very interested in what it can do to produce students in the STEM disciplines who are interested in and pursue graduate degrees. The benefits in program recognition, student outcomes and external funding speak for themselves but if for no other reason, it demonstrates the ability to teach research well. Numerous studies have shown that the benefits of undergraduate research participation make having a research program worth having.[6, 3,7,8] A recent 2013 study by Eagan, et al. found that, after accounting for many different variables, a research program increased the intentions of a STEM major to pursue graduate or professional degrees by ~14-17%.[9] Though this is indeed a modest increase those are not numbers to be ignored for they represent a significant number of students. Some studies found the numbers to be nearly double those found by Keagen et al.[10] Higher degrees means more job opportunities in a job market that, specifically in the STEM disciplines, often requires advanced degrees for above entry level positions. Despite the news that the job market is tightening for Ph.Ds studies referenced in an issue of *Science*, stating that the unemployment rate for STEM Ph.Ds was ~2% which is far below that of the national jobless number. [11]

## How to Solve the Problem

There are several steps that must be taken to reach the goal of graduating research prepared STEM majors by addressing the unpreparedness in undergraduate science students. Some of this unpreparedness has to do with a lack of dissemination of knowledge on research opportunities; some of it has to do with a lack of knowledge on the practices and purposes of research. The most obvious and easily rectifiable problem is that students are not equipped with a precise, useful definition of research. This has issues in two manifestations. First, they oftentimes refer to the manual, repetitive labor necessary to keep a lab running as 'doing research.' Secondly, it is used to describe any sort of scientific inquiry that is original to them. For this thesis and plan for the University of the South Carolina, the first step towards fixing this problem is to provide a succinct definition of scientific research for the University to use. This working definition would guide the University in how it taught and measured success in research and give students a metric to determine what constitutes scientific research and what does not.

The National Science Foundation created a Joint Committee to define research. They sought to illuminate the guiding principles identified in a previous study by the National Research Council in 2002. They defined research as (1) posing significant questions that can be investigated empirically, (2) linking empirical research to relevant theory, (3) using designs and methods that permit direct investigation of the question, (4) guided by a coherent and explicit chain of reasoning, (5) replicating and generalizing across studies, and (6) attending to contextual factors.[12] This is obviously a detailed and well-planned map for what research is and what it should do, but it is not succinct enough to capture the attention and memory of students who are notorious for having shorter and short attention spans. Therefore, here is a more succinct (working) definition that the University might use.

> Worthy scientific research uses coherent and explicit chains of reason to empirically investigate significant, replicable questions, whose importance can be generalized across fields of discipline.

Fixing this problem will not be accomplished in one step. In fact, a five step system should be used to address the problem. Broadly speaking those steps are (1) teaching towards research, (2) teaching about research, (3) requiring every STEM student to do undergraduate research under approved faculty, (4) reforming the Magellan Scholarship program and (5) a graduate school and industry specific class as well as a research/information science specific class.

Teaching towards research has a few simple meanings. First, it compels that professors doctor their homework and exercises to be more research-like in their testing of student knowledge. Though several STEM courses taught at USC, specifically in the chemistry department, do take on a 'real-world' research focus, most classes only require homework and testing that is route learning of knowledge without forcing students to learn to think and apply. Improving teaching requires following several well-established approaches and defining improvement as teaching accordingly instead of a momentary assessment of what students are learning.[13] The effects of this manner of teaching would probably be lower scores initially but eventually much higher scores in that and subsequent classes as students learn how to approach problems that might not have encountered several times before. Although such an overhaul of course curriculum really should not be unduly difficult, faculty members are often not going to change while their own research is their primary focus and not instruction.[14] Therefore, they must be given incentives, monetary or otherwise, to encourage improvements in teaching methods and styles. [15]

There exist already several on campus examples of professors who teach and test in this manner. Dr.'s Ferry and W. Outten incorporate research like problems into homework sets and research case studies into classroom exercises, respectively. Students in their classes have found that both are very helpful, partially due to their challenge, in cementing methods and theories taught in the classroom. In the case of Dr. Ferry's class he teaches almost directly from papers (CHEM 623) and from approved textbooks in others (CHEM 311 etc). What sets his class apart from others is what he requires after that. In most classes professors teach through a set of equations or concepts and then have simple direct problems for student to solve from the back of the textbook. Not so for Dr. Ferry's students. They are given broad questions that require combining multiple equations, concepts, and approaches that forces them to consult the litany of scientific papers available at their disposal. Through this process they learn several key factors that can one day help them in scientific research that other students do not learn in normal lecture classes. First, students have to work together on each assignment in order to get it done in time. This oftentimes serves as an introduction to the collaborative and co-operational world of scientific researchers that is necessary to push research forward.[16] Secondly, it introduces students to the practice and exercise of finding sources in scientific literature. They learn to sift through journals and articles that might be helpful. Citations become very important because it is through the process of citing an article that students can see that science is not a neatly packaged table with fully agreed upon values, rather, it is a web of oftentimes directly disagreeing articles that students then have to make a series of judgment calls on as to which ones are more valuable and trustworthy to cite and use. Lastly, students gain the benefit of confronting problems that require a deeper understanding of what they learned and not just route memorization. Never once was a problem phrased such that, in simplified terms, given X and Y solve for Z by remembering the singular equation learned in class. Each problem had a process students had to follow in order to solve and by joining in that process they were able to take away much more from homework and tests. In much the same manner students studying under Dr. WF Outten are given case studies, often based on real scientific research that they must work through after hearing a lecture. The only difference in learned student outcomes is the literature review process is not as integral to case study completion but it still serves to teach students the valuable lessons of group collaboration and a break from routine problems.

Case studies and similar teaching methods have been the primary methods of choice for years in teaching business classes but recent research has even shown them to be effective tools to use in the science classroom. In several studies researchers found that student outcomes improved by statistically significant amounts over the traditional lecture style teaching methods in teach collegiate biology and 200-level anatomy.[17, 18] These results are enough, when considered in the light of their predominant use in business courses, for STEM classrooms to give them some attention as a viable way to teach so that students learn better and are exposed, even in an elementary sense, to what is going on in research today and how they can approach problems that are not immediately solvable with a mere equation.

Teaching about research is different from teaching towards research in that it explores what research does, why it is done and how it is accomplished. Studies have shown that a major influence into whether or not students pursue postgraduate degrees in the STEM professions is the amount of interaction with faculty and with other high achieving students in similar fields.[19, 20, 21] As a student progresses in his discipline in this manner, surrounded by high achieving peers and faculty, he will begin to identify himself as a scientist which, according to Carlone and Johnson's 2007 paper, increases the likelihood that he will become more connected to his discipline and more likely to pursue graduate studies (i.e. scientific research).[22] Eagen, et al. found that increased interactions with graduate students and mentorship under faculty resulted in much higher levels of intention to pursue post-undergraduate careers in STEM research and higher degrees.[9] The two ways USC should try to fix the lack of systemic faculty mentorship of STEM students is by employing (1) individual apprenticeship and (2) course-based, cohort experiences. There have been numerous studies on each of these topics that direct this plan for USC.

First, a review of apprenticeship. Apprenticeships is focused on actively engaging students in scientific inquiry by contextualizing it in the research of a particular scientist.8 Students work and learn directly from the scientist as he/she pursues his/her agenda. The student gets to both learn and contribute to the progress of the research by doing the science that is necessary, with equipment and procedures supervised by the scientist. This enables students to not just learn about the process of scientific inquiry, but also become a part of the scientific community.[23] Such a relationship allows for many teachable moments in which the apprentice can develop a skill or realize a truth that might not have otherwise come up in either the classroom or strictly independent research. This program would be most useful in a STEM student's second year of collegiate education, as many sources have shown that apprenticeship programs among talented high school students showed little improvement in understandings of scientific inquiry.

Faculty are the most important aspects of this equation for students to have a successful research experience. With that in mind the University of South Carolina needs to encourage and reward scientists who come alongside undergraduates to train the next generation of scientists. Such an approach would require the university to do three major things in regards to its treatment of professors who mentor apprentices. First, the administration would have to protect the time of faculty so that they might engage students as mentors.[15] This would involve possible reducing teaching loads or at least allowing mentors to count time spent on mentorship as course taught hours. The administration would also have to come up with a system for reassigning time to faculty members to pursue their other research interests and goals so that particularly external funding does not slow down. Secondly, the administration would need to make mentorship an important part of a tenure track decision. [15] Such an action would reinforce the importance of undergraduate research to the health of the university and the discipline as a whole. Lastly, the administration would have to come up with some sort of financial compensation for the faculty member's time and appropriation for the research expenses undergraduate research incurs. [15] Otherwise, faculty members will be very reluctant to take on undergraduate researchers who would just be taking money away from the grants won for other projects.

Another way students can learn about research is to be required to do research, probably in groups, under an approved faculty member for an entire semester before they graduate. This method promises a best of both worlds scenario for the students and the scientist. Not only does the student engage himself in scientific inquiry, but also by testing and teaching certain methods and practices as the need arises faculty members can identify and rectify issues in their students' research understandings. This promises exciting dividends for faculty members as they are given better-equipped researchers as well as teaching a group of more committed and motivated students who see the applications for the material being taught. A course-based research experience such as this one offers all the benefits that come with the apprenticeship approach along with the benefits of case study methods of scientific instruction. For understanding most aspects of scientific inquiry this might be the best option as illustrated by studies such as Mullan, Weston, Rich, McLennan's where they look at the impact of a research-based curriculum on the improvements in understanding of research activities in medical students.[24] They found that compared to when the students started they increased knowledge and understanding drastically in the areas of (1) defining a research question, (2) writing a research protocol, (3) finding relevant literature, (4) critically reviewing literature, (5) using quantitative/qualitative research methods, and (6) writing and presenting a research report. The only areas that did not see improvement were in publishing results, applying for research funding, and analyzing and interpreting results. Each of these areas could be rectified using other methods.

Another method in preparing STEM students for scientific research already exists somewhat within USC Honors College but should be built on by the College of Arts and Sciences. That is the requirement for a semester of research with an approved faculty member in order to earn a STEM degree with research distinction. Such a requirement will be differentiated from apprenticeship and course-based programs in one major area in particular: independence. It will require that students become more independent in their completion of tasks for their research. A major complaint among research professors is that oftentimes students are not able to work in an independent manner on their projects. Part of this can probably be contributed to a lack of understanding and comfort that many students have regarding research even by the time they graduate. Between apprenticeship, course-based research, and classroom instruction geared towards research, students should be prepared for more independent research by the time they are in their 3$^{rd}$ (or 4$^{th}$) year. Such research could include a new project that a student brings to a professor but will most likely be a project that a professor has that he/she might not want graduate students to work on but needs to be completed. Such ancillary research needs often come up in the middle of a big push for a paper or major project. Students would thereby have the opportunity to apply what they have been learning for the 4 or 5 semesters previous in a way that might contribute to the intellectual scientific community at large.

This class will not be necessary or even helpful for every STEM major. Hopefully, the other courses would have given students an idea as to whether or not they are interested in pursuing research. This offering would be for those who are pretty sure they want to pursue research post-graduation, most likely at some form of graduate school. A program such as this would give students an even more intimate understanding of what it takes to be part of a research group by having to attend group meetings, update the overseeing professor on progress and make the majority of one's decisions independently.

A major positive program USC already has in place is the Magellan Scholarship program but there are still some reforms that must be made. The first action the administrators of the program should take is appearing in STEM classes and organizational meetings to explain the process. By exposing more students to research and funding in a face-to-face manner will be far more effective than just sending out the countless emails sent out letting students know about the opportunity. Secondly, those in charge need to make it a more competitive and selective process. It needs to reward students who are not merely doing lab work for professors but are actually coming up with and recommending new projects that could add to the intellectual community here at USC. Another way to do this is to encourage professors to identify and work with undergraduate students that show potential to do such research. The Magellan Scholarship should even become a viable option for funded summer research and stipend. If the process became more competitive the same amount of funding could be given to fewer students resulting in enough funds to pay student salaries over an extended period of time and/or provide funding such that they can complete an awesome project and even pay travel expenses to present it at larger conventions and symposiums than Discovery Day.

At first this may seem a little counterintuitive in recommending that fewer undergraduate students be given funding to do research. However, as more students learn about the realities of research worth doing, some will decide that research is not for them. The true benefit to the University, however, is that those who remain interested will be more likely to produce better work and reflect better on the

University overall. Also, students on the cusp might not achieve Magellan funding but it is possible that their faculty mentor or even the university could provide them funding another way.

The Magellan Scholar program could also be mended such that the mentor does not necessarily have to be a professor at the university but could be an employer in a related field such that the program could almost be leveraged into a co-op/internship. Scientific internships have been demonstrated to produce more job offers to engaged and excited students, with recent studies finding that over 60% of interns received at least one job offer.[25] For such students whose projects are very successful there should be a secondary fund for post-graduation if a patent is achieved and it is possible to market the project. This is where the Magellan program could teach students too about the importance of collaboration. By providing avenues, both informal and formal, for business investors to invest money into their projects, students can learn a lot about the world of grant writing and presenting to potential investors. Such a skill will make students not only far more marketable in the industrial arena but also identify them to other graduate schools as students who have the potential to be great Ph.D. candidates and maybe even post-docs and academics after that.

The last step in the five-step plan is the creation of two classes. The later one informs students on graduate schools and careers in research and science in general. According to Sowell's 2008 study, the completion percentage of a Ph.D. in Chemistry within 10 years is only 62% across all institutions.[1] This statistic is behind several engineering and life science disciplines and seems to show that some students are coming into the graduate program ill-prepared for the demands of full time scientific research. In fact, there is a class already, CHEM 401 that fulfills several of these requirements but not completely. First, the class should be made mandatory or at least very strongly encouraged. Secondly, the curriculum should be rewritten such that graduate program advisors and directors could come in and discuss graduate school. Third, though there exists already several good industrial contacts, those of other faculty at the university should be leveraged to get in keynote speakers to discuss with the class what they do, and maybe even identify students who might come work for them at some point. Students need to be taught how to evaluate the strengths and weaknesses of different chemistry graduate programs and how to identify professors they would be interested in working with.

The earlier one (probably for 1$^{st}$ year students) would combine two courses offered by the University now (LIBR 101, UNIV 101) and present them to STEM majors with a marked increase in focus on scientific research. For example, in LIBR 101 students learn how to use online article databases that the University has subscriptions to. In RSCH 101 students would further learn each of the science databases and how to best use them (Web of Science, SciFinder, ScienceDirect, etc.). This is an important aspect of learning literature review that is necessary for anyone interested in pursuing research, similar to a political science major reading the news. In a similar manner UNIV 101 teaches students how to get the most out of their college experience by teaching them the ins and outs of USC. In RSCH 101 students would learn the ins and outs of things that matter to science students such as suggested classes to take per semester, professors' research foci, the Magellan program, tutors and tutoring opportunities, internships, REUs, etc. etc.

Taken together, these two courses would provide STEM students, particularly chemists, an incredible array of tools to help them make well-informed decisions regarding their careers.

The outline below is the proposed course schedules over four years that students wanting to graduate with a B.S. in Chemistry would have to follow.

| Year | Fall Term | Spring Term |
|---|---|---|
| Freshman | -CHEM 111, 111L-General Chemistry and Lab<br>-MATH 141-Calc 1<br>-ENGL 101<br>-PHYS 211, 211L<br>-GFL<br>Total Hours: 17-18 | -ENGL 102<br>-GFL<br>-CHEM 112, 112L<br>-MATH 142 Calc II<br>- RSCH 101-Replaces UNIV 101 and LIBR 101*<br>Total Hours: 18 |
| Sophomore (Magellan Application eligible in Spring) | -GHS<br>-GFL<br>-MATH 241<br>-CHEM 333, 333L<br>-PHYS 212, 212L<br>Total Hours: 15-18 | -AIU<br>-CHEM 322, 322L<br>-CHEM 334, 334L<br>-MATH 242 or higher<br>Total Hours: 15 |

| | | |
|---|---|---|
| Junior (Magellan Eligible) | -AIU<br>- CHEM 49x-undergraduate research in chemistry (GROUP session)*<br>-CHEM 550 or 555<br>-CHEM 541 or 542, w/ lab<br>Total Hours for Semester: 15 | -GHS<br>-CHEM 541 or 542, w/ lab<br>-CHEM 49x-undergraduate research in chem (INDEPENDENT)*<br>-CHEM 401 (required)*<br>Total Hours: 15 |
| Senior (Magellan Eligible) | -CHEM 511<br>-Minor<br>-CSCE 206<br>-Minor<br>-GSS<br>-CMS, INF, VSR<br>Total Hours: 18 | - CHEM 621, 621L<br>-Minor<br>-Minor<br>-Minor<br>-GSS<br>-CMS, INF, VSR<br>Total Hours: 18 |

Quantitative measurements are often necessary for understanding the impact and success of education on the mass scale. Therefore, a system in which students can earn a certain number of points per research based class, experience, etc. would be valuable in determining which students are truly on their way to becoming research scientists. Each student wishing to earn a B.S. in physical sciences will be required to receive 5 research points. It makes sense that in a world increasingly driven forward by advances in research students should have at least a basic understanding of what that entails and how to glean information about it out of sources. Additionally, if students reach 10+ research points they will be rewarded with a research distinction to their degree as well as other potential prizes (left to the discretion of the College of Arts and Sciences and USC administration as a whole). Each category they can/will earn points for is listed below.

| Course/Experience | Point Value | Required: Yes or No |
|---|---|---|
| RSCH 101 | 1 | Yes |
| CHEM 49x (group) | 1 | Yes |
| CHEM 49x (independent) | 2 | Yes |
| CHEM 401 | 1 | Yes |
| Paper Authorship | 4 | No |
| Patent | 4 | No |
| Magellan or other funding awarded | 3 | No |
| Independent Research over the Summer session (ex. NSF REU or other) | 2 | No |

Many students already have done some or all of these research activities but by institutionalizing and giving values to these activities students would be better recognized by their peers and identified by the administration for awards, funding and further mentorship. It would also serve to distinguish USC graduates among science graduates from other large research institutions. Additionally, students could graduate with a research distinction that represented a lot of valuable work and would certainly make graduates more impressive candidates for both jobs and graduate schools.

## CONCLUSION

The University of South Carolina does a lot of things right in trying to inspire, train, and fund the next generation of research scientists. However, both local and national trends demonstrate that a lot remains to be done if we as a society can look towards the future and feel that those in charge with progressing the country, and the world, have the tools, resources, and numbers necessary to accomplish what needs to be done in the physical sciences. This thesis contains an outlined a plan for this University to follow that hopefully would rectify many of the issues that stand in the way of accomplishing the aforementioned aim, specifically within physical sciences. Many national leaders have touted scientific research as the way forward for this country as problems such as cancer, lack of efficient renewable energies, and a job market that favors intellectual property to mere assembly line manufacturing define the United States in the 21$^{st}$ century. This University stands on the brink of producing science graduates who, even without doctoral degrees, have been exposed to the methods, mindsets, and habits that demarcate effective research scientists. All that remains for the University to do is to make this a priority in both funding and planning and consistently following through on that plan and the promises made thereof.

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