ASEE's 123rd Annual • Conference & Exposition • New Orleans, LA • June 26-29, 2016

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Paper ID #15473

Undergraduate Research in Science as an Elective Course for Engineers

Dr. James O'Brien, Wentworth Institute of Technology

James G. O'Brien is an associate professor of Physics at Wentworth Institute of Technology in Boston, MA. James is currently pursuing educational pedagogies in engineering education through game-ification of education and the design of competitive table top games which engage students in an exciting atmosphere to help facilitate learning of essential physics concepts. Aside from a love of gaming and its role in education, James is also the Vice President of the International Association of Relativistic Dynamics, an international organization of physicists whose research revolves around the study of relativity and gravitational research.

Dr. Gergely Sirokman, Wentworth Institute of Technology
Dr. Franz J Rueckert, Wentworth Institute of Technology

Dr. Rueckert is an experimental physicist specializing in condensed matter. His research interests include magnetic and electronic properties of perovskite materials and, more recently, novel approaches to physics education.

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Abstract

Undergraduate research has become more and more integral to the functioning of higher educational institutions. At many institutions undergraduate research is conducted as capstone projects in the pure sciences, however, science faculty at some schools (including that of the authors) face the challenge of not having science majors. Even at these institutions, a select population of high achieving engineering students will often express a keen interest in conducting pure science research. Since a foray into science research provides the student the full exposure to the scientific method and scientific collaboration, the experience can be quite rewarding and beneficial to the development of the student as a professional. To this end, the authors have been working to find new contexts in which to offer research experiences to non-science majors, including a new undergraduate research class conducted by physics and chemistry faculty. These courses are inherently interdisciplinary. Students in the engineering and computer science fields step into physics and chemistry labs to solve science problems, often invoking their own relevant expertise. In this paper we start by discussing the common themes and outcomes of the course. We then discuss three particular projects that were conducted with engineering students and focus on how the undergraduate research experience enhanced their already rigorous engineering curriculum.

Keywords

Undergraduate research, Physics Education, Laboratory Instruction, Interactive Learning, Physics Pedagogy

Introduction

Science courses are a long standing cornerstone of engineering curriculum across the country. The particular Science requisites, however, depend on the program in question. Some schools restrict science courses to just the introductory sequence, while others have some upper level elective science courses to supplement their core engineering offerings. One failing of STEM education is that students in many of these learning environments are not exposed to the symbiotic relationship between the sciences and engineering. A mainstay of engineering curriculum is the design and implementation of project based learning. This approach is mirrored in the sciences, usually as undergraduate research in a particular subfield of the science. It is during this endeavor that students are challenged to think independently and use their full set of skills in order to address an unsolved problem. This requires a strong command of the scientific method, and most importantly creativity and ingenuity, both of which are common themes in engineering culture. It is the belief of the authors that participation in scientific research has a twofold benefit for engineering students. First, it highlights the underlying connections between

science and engineering. Second, it allows students in a pure engineering program to refine their creative and problem solving strengths in an interdisciplinary project.
The benefits of introducing undergraduate science research into our institute's curriculum is supported by a significant amount of research into the impact of such activities on scholarly achievement in a number of fields. David Lopatto has published extensively on the positive impact of undergraduate research on academic programs. [1-5] Undergraduate research is shown in these publications to be key to producing engaged scientists for the future. Hinkel and Henke [6] show explicitly the positive impact participation in undergraduate programs has on future student achievement and employment. In light of this information it is almost unforgivable not to offer these opportunities to students who are willing to avail themselves of them.

Science research courses give students the opportunity to step outside of their comfort zone and appreciate the versatility of their education. The knowledge and skills these students master in their engineering program are applicable across numerous situations and disciplines, and applying them to solving science problems drives home this point. The authors believe that this greatly enriches the students' education and future value in the work place. To foster this interdisciplinary learning environment, the authors have begun implementing an upper division undergraduate research course in either chemistry or physics for engineering students of all sub-disciplines. As a further benefit, students are able to incorporate these courses into a science minor. It should also be noted that this work is being conducted at an engineering school with no pure science majors. In the following sections, we will discuss the common learning outcomes of the course and the benchmark results of students who have already completed the course. We will then highlight three specific projects in order to discuss the types of projects possible within the context of this approach.

Course Learning Outcomes

The purpose of the course designed by the authors is to give students an opportunity to go above and beyond their typical course work and devote time to a research project in one of the pure sciences. We should note that students do occasionally engage sciences faculty in advisory roles in their senior projects, but this research course is exclusively science focused. Students gain an opportunity to learn about topics, which can potentially be incorporated into their capstone efforts. A significant challenge was to formalize this work, as previously, students had only been informally involved with faculty research. Creating a course specifically for conducting such research has several advantages. First, as an official course, students must register and pay for the experience. This applies an additional sense of responsibility on the part of the students to give the project the required amount of time since a formal grade is associated with it. Moreover, it forces guidelines and measureable expectations on the part of the faculty in conducting their course. Second, the act of registering ensures the experience is noted and documented on their transcripts. This is a huge advantage given the interdisciplinary nature of the current job market and provides students with an additional positive mark to differentiate them for potential employers. Lastly, from the instructor's standpoint; it forces the conversation as to what is feasible and what can be accomplished in a reasonable time frame for non-science majors. In order for this course to achieve the specified goals, a set of measurable and uniform learning outcomes had to be designed that were independent of the discipline and project itself.

The Learning outcomes of the course are defined as follows:

1) Collaborate on a project proposal in a pure science.
2) Find and identify relevant scientific articles related to the projects description and extract relevant information.
3) Identify and contact an external collaborator on the project.
4) Describe and discuss the project, its history and outcomes to a scientific audience.
5) Create a final scientific paper worthy of local or peer reviewed publication.
6) Create and deliver a final scientific presentation worthy of local or peer reviewed dissemination.

The rationale for these outcomes is important. The first outcome was stated in order for the students to be involved from the outset in defining the scope of the project. The second was included as a key focus of the course would be to increase scientific literacy of the students involved. The third outcome is one that we specifically added due to the vision of our host institute. At Wentworth Institute of Technology, externally collaborative learning is at the heart of the educational environment. The fourth outcome is regarding perspective. If a student is to devote such time to a project, they should be able to discuss the history and relevance of the project to people in the field. Lastly, outcomes five and six give the student an attainable and clear goal for the project. These goals also serve as motivation for senior level students to add to their growing resumes. It should also be noted that these outcomes are also easily matched to engineering accreditation outcomes such as the ABET a) through k) rubrics.

General Discussion

We should note that this type of course is not intended as an open elective, but instead as a final course for the completion of a minor in the sciences. Thus, students would likely already have relationships established with the faculty with whom they will conduct research. Often, the process of planning out a project will take place over a semester preceding the research course itself (for example in Physics, while a student is still taking modern physics). Since research projects typically take quite some time to actually start up, this lead in time is essential to get documents, papers and sourcing established. Student groups (anywhere from 1-5 students) are typically identified and formed before the beginning of the research semester. These groups are based on a combination of student interest in the research topic and interdisciplinary groups are often established to cover knowledge gaps where needed. The course is four credits across any scientific concentration. As a final point, the grading of the course is tied to the outcomes and overall experience rather than the "product" of the research. Even at the graduate level, the outcomes of pure research can rarely be predicted. For our undergraduates, missteps can be as instructive as success, perhaps even more so. In a single semester, it is the process, which is most valuable.

Learning Outcome Measurements

Since the course that we are discussing is a slight departure from the norm, typical measurable materials such as exams and quizzes are ill suited for the experience. Moreover, since the projects are tailored to specific interdisciplinary groups of students, even homework assignments lose their traditional meaning. Clear expectations and deadlines are essential for work associated with the course. For example, the first deadline is 2 weeks into the semester, when the "Project Proposal" is due. As students often have some idea of what their project will be about before the semester starts, their first two weeks can be spent on research and asking for clarification from the faculty teaching the class. The product of this work is a clearly written schedule about how the students plan to proceed. This document is not considered a fixed agenda, but instead serves to lay out expectations. The document is constantly updated and discussed throughout the semester. A draft of the other deliverables (poster presentation and/or paper) is due at midterm, and the final versions are due at the time of finals. This allows time to continuously document the process as well as allow for refinement of the project based on previous successes and hurdles.

Outcomes two and three are first to be assessed, through the students' action plan, and their work in establishing relationships with any outside collaborators. Often, the external collaboration is satisfied through requests for clarification or elaboration of a theory or technique from article authors. Outcomes four, five, and six are all measured by the deliverables. Outcome four is measured by a group of faculty who critique both the poster and oral presentation at both midterm and finals. Since it is the goal of any research project to be publicly disseminated, our intent is to have the work accepted for poster or oral presentation at either a local or national conference. Since we have begun offering this course our institute's activity has grown from zero students presenting at regional or national science conferences to six disseminations in three semesters, with two of them leading to peer reviewed publication with students as co and first authors. Being at an institution with limited scientific facilities and support, we view this as a huge triumph and a testament to the capability of the students. Even in an area outside their core curriculum, students excel when they have the motivation, opportunity, and interest to explore. Below, we highlight three projects from across several disciplines that have been conducted by Wentworth students.

Project: *Comparison of Gravitational Models for Dwarf Spiral Galaxies*

In the summer of 2014, this project was conducted with a group of six students of various engineering and computer science majors. Students were to first become familiar with several gravitational models of spiral galaxies such as Modified Newtonian Dynamics, Cold Dark Matter and Conformal Gravity. The students developed a working knowledge of the context, applications and key equations for each. They were then tasked with finding external contacts, usually astronomers, in order to obtain recent and relevant data with which they could compare these models. After obtaining data and learning how to parse this information into an understandable and useful data set, the students wrote numerical simulations to model the data against the theoretical predictions. Since students are working with physical data and comparing models, an evaluation can be made as to which theory explains the data best and why. Models can then be extended to include fine tuning effects such as rotation, bulge modeling and gas fitting (see [7] for example) in order to demonstrate the refinement process. By the conclusion of the project, all of the stated learning outcomes were met, and students disseminated the work at two regional conferences, one in poster format and one in paper format. The work was then typeset and is now in review at Monthly Notices of the Royal Astronomical Society. The lead student took a particular interest in the project, deciding to apply what he learned to the Milky Way galaxy, and was recognized as a co-author for a publication in the Journal of Modern Physics [8].

Project: Biodiesel

This project arose from student interest. A group of students particularly interested in renewable energy approached a faculty member with a desire to synthesize biodiesel from used vegetable oil. This particular project had an applied chemistry aspect as well as an engineering aspect. It has also spanned multiple semesters, and thus communicating to future generations of students has also become an important point in this project. The first phase of the project involved experimentally determining ideal conditions for the synthesis of biodiesel. Although the synthesis is a known process, local conditions and feedstocks generally require that optimal conditions be experimentally determined. One student group spent a semester planning out and executing a series of experiments to optimize the conditions given our materials. A second phase was the design and construction of a biodiesel processor, which had the capacity to conduct the chemistry on a large scale. Several student groups worked on this multi-semester project, as the reactor was designed, built, and finally tested over a year. This project had to be continually documented, and each group presented their work at (our institute). The work done by these students has been presented at several local and national conferences as well. [9]

Project: Superconductors Synthesis and Analysis

Students interested in an understanding of physics beyond the classical introductions are often very enthusiastic regarding our Modern Physics class. This project was the result of two such students seeking an understanding of quantum effects at the macroscopic scale. In this ongoing effort, students attempt to fabricate and quantify high-temperature superconducting ceramics. By first examining and discussing the literature, the students were introduced to a celebrated topic in condensed matter and the current limits of our scientific knowledge. While much has been discovered, the full mechanism of high temperature superconductivity remains unknown, and the topic has remained at the forefront of research efforts for more than a century [10]. After reviewing the techniques, the students then designed recipes for sample preparation, including multiple grindings and high temperature annealing. Students explored the finer points of crystal growth methodology by altering pressures, temperatures, firing duration, and gas environment. These were performed in partnership with our material science laboratory through the Mechanical Engineering department. The initial goal is an understanding of the process to produce a superconducting puck capable of displaying magnetic levitation via the Meissner effect. As with any experiment, favorable results are not guaranteed. This is itself a valuable lesson, and this project will require continued work over several semesters. As successive students add to the project, we hope to develop an educational condensed matter laboratory package for our upper division classes. A continuing issue at institutions focused on teaching is the lack of laboratory equipment compared to more research-minded campuses. This project therefore encourages collaborations with local research universities for more in depth analysis of our materials. This exposes our students to the larger scientific community and underscores the applications of their engineering skills is novel areas such as scientific instrumentation and measurement techniques.

General Assessment and Deliverables for all Projects

In order to assure consistency in this course, the learning outcomes must be met for all projects. This means that all student research must adhere to the standards independent of the "results" of the research. Although only three projects in particular were highlighted in this paper, some general comments on course sections should be noted. The first learning outcome is easily delivered and measured, as the course is contingent on the student preparing a plan for research in applied science. The second learning outcome is assessed via the initial deliverable, which is a project proposal. In this item, students are required (with guidance) to perform the relevant searches to understand the background of the chosen project, and have some idea as to how to advance or further the topic. Much of this work is done by reading, but students inevitably need to contact at least one external collaborator and either ask specific questions or request specific data. All of these correspondences are tracked and stated in the proposal and hence can be evaluated. Learning outcome number four is tied directly into the midterm and final presentations. Although we do not expect students to become instantaneous experts in their chosen field, they should be able to demonstrate expertise above and beyond a casual observer. We view the students as active participants in the field who should be able to capture the essence of the work, including its history and relevance. Students are then expected to be able to field questions about the topic appropriate for budding researchers. The expectation is for them to be have sufficient mastery of the material to be able to present at a regional or national conference in an undergraduate symposium. It falls to the faculty members to properly guide and motivate students through the research process. The first four learning outcomes are critical in supporting the final two learning outcomes. Each student who has taken this course has prepared both a poster and a presentation with the hopes of presenting them at a conference external to Wentworth . Since, like any other course, students will fall into a spectrum of grades, not all of these were later brought to conferences, but posters of all of the projects are showcased at the Wentworth student poster and expo event. This is a requirement of the course and helps keep expectations and deadlines in view for the student. Many students take their work extremely seriously, and the most diligent have been rewarded with the opportunity to present at prestigious events. These presentations greatly bolster student resumes and enshrine their contributions to the larger scientific collective outside their major. It is in this respect that we feel the course has been most successful, especially given that we are at a school with no pure science major. Several students have since reported that their undergraduate research experience was integral in obtaining a permanent job, often before graduation. Students have a confidence and self-motivation that was fostered by this course, which can be a strong differentiating factor for potential employers when comparing resumes.

Conclusion

The authors' goal was to create a course in which students could conduct undergraduate research in the sciences at an engineering school with no science programs. A general set of learning outcomes was constructed encapsulating what any good scientist should learn from their first research experience. As detailed in the three projects presented as examples, the course has seen tremendous success. Engineering students have shown themselves to be both interested in, and capable of, interesting and novel scientific work. Both the students and the Sciences faculty have benefited from this novel approach to undergraduate research. More information on this work, including complete syllabi for this course can be found at www.myweb.wit.edu/sirokman.

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