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Physics in “real life”: accelerator-based research with undergraduates

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Abstract

All undergraduates in physics and astronomy should have access to significant research experiences. When given the opportunity to tackle challenging open-ended problems outside the classroom, students build their problem-solving skills in ways that better prepare them for the workplace or future research in graduate school. Accelerator-based research on fundamental nuclear and particle physics can provide a myriad of opportunities for undergraduate involvement in hardware and software development as well as “big data” analysis. The collaborative nature of large experiments exposes students to scientists of every culture and helps them begin to build their professional network even before they graduate. This paper presents an overview of my experiences - the good, the bad, and the ugly - engaging undergraduates in particle and nuclear physics research at the CERN Large Hadron Collider and the Los Alamos Neutron Science Center.

Peer-review under responsibility of the Scientific Committee of the Conference on the Application of Accelerators in Research and Industry

Keywords: undergraduate research, education

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1. Background

Research experiences are a critical part of training undergraduate students in physics. By getting them outside of the textbook-problem-solving classroom and turning them loose on open-ended questions, they are released from the virtual world of rigidly structured learning into the real world of physics as it is practiced, where problems are complicated, messy, and don't always have an answer. Research experiences provide opportunities to “learn by doing” in a setting that prepares them for a broad spectrum of career trajectories. Nationwide, the fraction of students with a bachelor's degree who end up in academic careers is very small (~5%). Most of our students will seek and obtain private-sector employment.

In 2016, the Joint Task Force on Undergraduate Physics Programs (J-TUPP), Heron and McNeil (2016), convened by the American Physical Society and the American Association of Physics Teachers, released their final report to answer the question: “What skills and knowledge should the next generation of undergraduate physics degree holders possess to be well prepared for a diverse set of careers?” They formulated a set of recommendations to physics departments and faculty members to effectively prepare graduates for success in diverse careers. Many of their recommended actions can be partially addressed through meaningful experiences that connect research activities to future career opportunities. Figure 1 from the J-TUPP report shows projected growth of non-academic jobs for STEM majors. Computer specialists are expected to be in particular demand. It is noteworthy that data collection, software development, simulations, and analysis are all skills that undergraduates can develop working on accelerator-based research projects. Students with these skills will be very competitive for high-paying careers in industry or graduate study in STEM fields.

Providing students with the opportunity to build marketable skills through accelerator-based physics research has been one of the hallmarks of my ten year career as an undergraduate educator in physics at California Polytechnic State University (Cal Poly) San Luis Obispo. Cal Poly is one of the 23 campuses of the California State University system. The university has a “learn by doing” emphasis for the educational experience of its predominantly undergraduate population of 20,000+ students, encapsulated in its motto *discere faciendo (i.e., learn by doing)*. Part of the university’s mission is to provide students the opportunity to get directly involved in research at the frontiers of knowledge through interaction with faculty. The university is also committed to enhancing opportunities for under-represented groups and is committed to fostering a diverse student body. The College of Engineering enrolls the largest fraction of Cal Poly undergraduates (~26%), followed by the Colleges of Agriculture (~20%), Liberal Arts (~16%), Business (~14%), Architecture & Environmental Design (~8%), and Science & Mathematics (~16%).

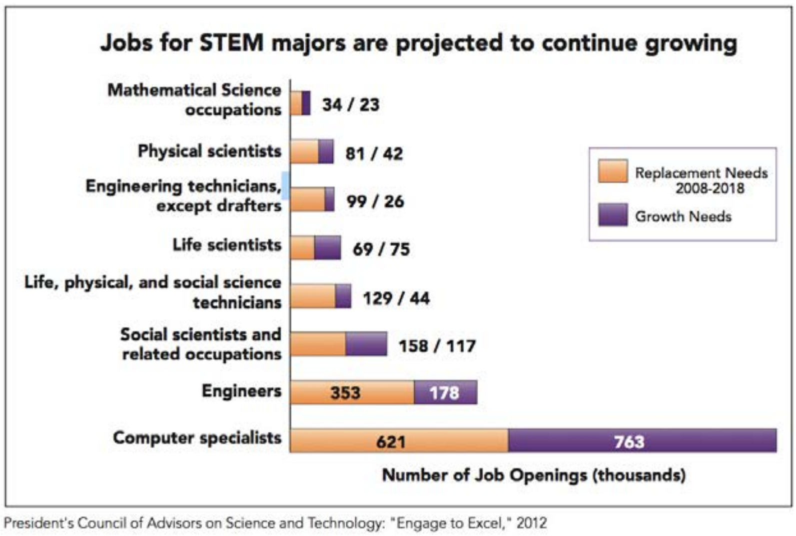

Fig. 1. Projected growth of non-academic jobs for STEM majors. From the J-TUPP Phys21 report, Heron and McNeil (2016).

At present, the distribution of male (~49.9%) and female (~50.1%) students at Cal Poly is more balanced than the current national average (~57% female), Saavedra et al. (2015).

The Department of Physics, in the College of Science & Mathematics, offers Bachelor of Science and Arts degrees in physics, and minors in astronomy and geology, with approximately 194 students currently enrolled. There are 32 tenure-track faculty, for a student-to-faculty ratio of 6:1, compared with the University average of ~19:1. The department has a growing group in physics education research. Presently, there are fifteen full-time lecturers and five part-time and retired faculty members teaching courses in physics and geology. The size of the department reflects the need to educate a large number of students in introductory physics across all technical disciplines coupled with small class sizes (maximum of 48 students per section) and no graduate teaching assistants.

The teaching load for tenure-track faculty is twelve weighted teaching units per quarter, or approximately twenty student contact hours (including office hours) per week. However, the university has some discretionary funds allocated to subsidize teaching release time for faculty members engaged in research projects with undergraduate students, particularly for those who have procured external grants. Consequently, there are ample opportunities for all students to become engaged in active novel research projects.

The curriculum for physics majors includes a senior project that is often the continuation of paid summer internships undertaken with faculty members within the department. Student stipends can come from external research grants or from internal programs, such as the Frost Summer Scholars Program, established in 2015 by a generous donation from a Cal Poly chemistry alumnus, to provide summer stipends to students engaged in scholarly activities with faculty in the college.

Cal Poly has one of the largest (in terms of degrees granted) and most successful undergraduate physics programs in the United States, AIP Statistical Research Center (2016). Only about 10% of all physics programs in the United States regularly award more than twenty degrees per year, and most of those are at PhD granting institutions. A relatively small group (18%) of bachelor's-only departments averaged ten or more physics bachelors. These same departments awarded 43% of the physics bachelors conferred by the bachelor's-only departments. For 2012-2014, Cal Poly had an average of 30 B.S. and B.A. degrees in physics awarded each year, second only to SUNY Geneseo for undergraduate institutions and comparable to the numbers at such PhD granting institutions as Yale University and the University of Wisconsin, Madison.

The physics department has a strong record of preparing students for advanced degrees in physics, often at top tier research institutions. Between 2010 and 2015, we estimate that approximately 30% of Cal Poly physics graduates in a given year entered Ph.D. programs in physics and related disciplines at institutions as varied as University of Colorado, University of Oregon, Kent State University, UC Santa Cruz, UC Davis, and UCLA, among others. Another 20% have sought advanced degrees in engineering, mathematics, law, and business. Roughly 10% of our majors seek a career in teaching by entering credential programs at Cal Poly or other institutions. The rest have obtained employment, typically in high-technology firms or software development. Companies and agencies hiring our graduates in the last five years include Apple, Calix Telecommunications, Jet Propulsion Laboratory, Recurrent Energy, Linear Technology, and Accenture.

The focus on hands-on skill development has been instrumental in the success of our students. In addition to traditional coursework and extensive laboratory experiences, our department encourages participation in research through a seminar course that I developed in 2011 and continue to run primarily targeting sophomores and entering transfer students. The course is called "Introduction to Physics Research" and is designed to connect students with faculty research opportunities at Cal Poly or elsewhere before they start their senior projects. The course is offered every year and faculty members use this seminar as a recruiting tool for students. Overall, the course has increased the participation of students in on-campus research early in their careers so that they have the opportunity to either sample multiple projects or to concentrate on one area for their entire undergraduate career.

2. Accelerator-based projects

I am an active collaborator in two accelerator-based projects in fundamental particle and nuclear physics: ALICE at the CERN Large Hadron Collider, ALICE (2017), and the Neutron Induced Fission Fragment Tracking Experiment (NIFFTE) at the Los Alamos Neutron Science Center, NIFFTE (2017). Through these projects, I am able to provide hardware and software development experiences, data analysis, and collaborative research with scientists from many diverse backgrounds.

The ALICE experiment is a large collaboration with over 1800 members at 174 institutions in 41 countries seeking to study the properties of the hot, dense material called the quark gluon plasma, which is created in nuclear collisions at the world's largest particle accelerator in Geneva, Switzerland. My interest and area of expertise are in large transverse momentum hadrons and detecting the energy loss of heavy quarks in the plasma. I have been funded for ten years through the National Science Foundation Research at Undergraduate Institutions (NSF-RUI) program. In 2016, I was awarded a Major Research Instrumentation grant from the NSF to develop, construct, install, and commission half of the Fast Interaction Trigger (FIT) detector for the ALICE upgrade program, which will provide hardware experiences for undergraduates at Cal Poly. The collaborative nature of this large experiment gives students the opportunity to develop connections with scientists at other institutions both here and abroad, potentially opening channels to future educational and career trajectories.

NIFFTE is a collaboration of seven institutions and approximately 25 scientists and students whose goal is to develop and deploy a novel, high granularity, pressurized Time Projection Chamber (TPC) to measure fission cross-sections of the major actinides to sub-1% precision. These measurements are expected to enable significant advances in nuclear reactor design and advanced fuel cycle efforts. I contribute expertise in software and data analysis for TPCs as a lead software coordinator and serve as chairperson of the NIFFTE Executive Council. My efforts with NIFFTE have been funded through grants from the Department of Energy's Nuclear Energy at Universities Program (NEUP) and the National Nuclear Security Administration's Stockpile Stewardship Academic Alliance (SSAA) program as well as subcontracts from Lawrence Livermore, Los Alamos, and Idaho National Laboratories. We have published a summary of the detector's capabilities, including Cal Poly student co-authors, Heffner et al. (2014), while data collection and analysis are currently in progress.

3. Computational physics projects

In addition to the externally funded projects described previously, I have worked with students on computational physics research and particle detector hardware development. The computational physics research was borne out of curricular development that I undertook in order to better prepare Cal Poly physics students for research projects that involve intensive data analysis. Our required curriculum has only one course in learning software, coding, and computational tools. Given that the software and analysis tools used for conducting research with ALICE and NIFFTE present a significant learning curve for physics majors without adequate coding preparation, I developed a 10-week project-based course on computational physics from 2012-2014 for students to gain skills with modern scientific computing tools, while learning the fundamentals of numerical methods and data analysis, Klay (2014a). These skills are easily transferable to other projects and the course provided the basic training to make students competitive for the growing number of computer specialist jobs seen in Figure 1. Over 120 students benefited from the course and emerged better prepared to conduct research with computational tools. The course materials are freely available online, Klay (2014b), and have been adapted into workshop materials for prospective research students and also to educate early service K-12 teachers on how to code so that they can incorporate coding to their classrooms. For instance, several specific projects from the course were expanded into full senior projects for students who wanted to improve their coding skills in preparation for employment.

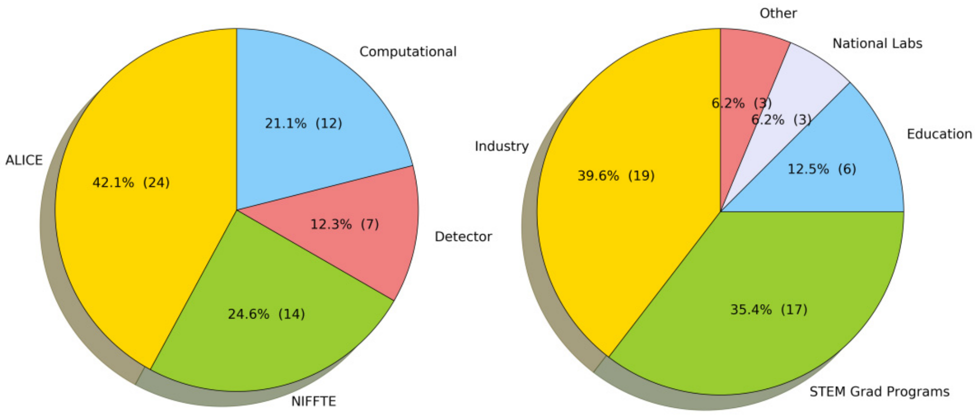

Fig. 2. Distribution of students by project and initial outcomes beyond Cal Poly.

4. Student involvement and outcomes

Over the course of my ten-year career in academia, I have worked with or helped direct 48 students on 57 different research experiences. Figure 2 shows the breakdown of which projects the students were engaged in and where they ended up after Cal Poly. (Most of the students in the “Other” category are comprised of those still completing their degrees. One student is deceased.) Some of these students were jointly supervised on these projects by me and by colleagues at Lawrence Livermore and Los Alamos National Laboratories through summer internships facilitated by our collaborative relationships. The variety of projects completed include conducting data analysis, developing software and hardware, collecting data, performing quality assurance, creating and analyzing simulations, creating visualizations, and designing electronics. Twenty of these students had the opportunity to travel to CERN to participate in ALICE beam tests, data collection, and analysis, giving them a once in a lifetime experience, ALICE Matters (2016a,b).

A crucial component of research and learning best practices is communicating results to the broader community, either visually, in writing, orally, or as online resources. All students in my group are expected to prepare and deliver posters or oral presentations and a subset write Cal Poly senior projects on their work. Over the last ten years, twenty-one students have presented their work in talks and posters at external conferences such as the APS Division of Nuclear Physics and regional APS annual conferences, while fifteen presentations were also given locally at Cal Poly. Fifteen students completed senior projects that are published through the Cal Poly Digital Commons, Kourjanskaia (2016), Gamble (2015), Tzekov (2015), Song (2015), Thompson (2014), Rexrode (2014), Pavlov (2012), Williams (2010), Donoghue (2010), Boswell (2010), Brown (2010), Coulombe (2010), Carlson (2009), Pourroy (2007), and there are two currently in progress. One student developed an open-source computational tool for nuclear physics that is freely available online, Rexrode (2014). For exceptional work on their projects, seven of the students have been included as co-authors on peer-reviewed research papers and technical reports from ALICE, Allen et al. (2010), Abeysekara et al. (2010), ALICE (2008), and NIFFTE, Heffner et al. (2014).

5. Challenges

Working with students on novel fundamental research at a predominantly undergraduate institution has its challenges. These fall into three primary categories: technical, logistical, and sociological. The technical challenges include lack of student preparation in computer programming and data analysis, and the overhead associated with connecting them to collaboration resources such as CERN computing accounts. Logistically, managing the risk of traveling internationally with undergraduates requires significant paperwork and liability assessment. Long summer stays in Switzerland need to be adequately supervised to ensure the students stay focused on their research tasks and are good representatives of the University. For me, the challenge is balancing research mentoring with classes and other responsibilities that shift from term to term and summer versus the academic year. Fortunately, adequate external funding has been available for me to take a reduced teaching load during the year for research activities and to compensate me for mentoring summer research projects. When these sources of funding are not available, there are some internal resources that can be requested to ensure continuity and progress on projects, but these are competitive and not guaranteed.

Students come from a wide variety of backgrounds. Some have limited means and absolutely need financial support for them to be able to participate in summer research. Others choose to obtain course credit for their work. The skill-sets they start with vary considerably and it is sometimes impossible to predict whether they will be a good fit for the challenges of accelerator-based research. I have been pleasantly surprised by students for whom I initially had low expectations, while several students with adequate skills lacked the motivation and independence to be effective in open-ended research. If those students learn from their experience that a career focused on research is not right for them, then the effort was not a waste.

Finally, finding projects within large collaborations that are appropriate for undergraduates can be tricky. The students are motivated to answer big questions with their data analysis and dream of publishing their results. However, bringing an analysis project to presentation or publication stage requires a lot of steps, internal vetting, and approval. More narrowly focused service related projects are not as attractive to the students, but can be incredibly useful to the collaboration. In my mentoring, I endeavor to give students a balanced experience where they contribute in a meaningful way to the experiment, but are shielded from the fast-paced, demanding analysis topics of highest interest. They could easily be overwhelmed if they are expected to deliver calibrations or results on a schedule that doesn't take into account the other academic demands on their time.

6. Conclusion and outlook

The NSF MRI grant to develop the ALICE FIT detector locally at Cal Poly in collaboration with colleagues at Chicago State University, another predominantly undergraduate institution, will enable me to provide research opportunities with more significant hardware experience than in the past. The detector development activities we will engage in are readily accessible to students who have completed our upper division laboratory sequence, and even more junior students can be mentored to effectively contribute. In the next few years, we will acquire the detector components, mount the quartz radiators to segmented silicon photo-sensors, build a laser distribution system to illuminate each radiator, build a test stand to measure the light collected by the photo-sensors, and characterize the response of each detector. In the longer term, we will participate in the installation and commissioning of the detector in ALICE at CERN. These will be once in a lifetime experiences for many of these students.

Working with undergraduates on accelerator-based research projects is fun, rewarding, challenging, and definitely worth the effort. They are enthusiastic and often bring unique perspectives to the group. While most of them will not continue on to become career scientists, it is critical that their experience show them both the value of the experience to themselves and the broader impacts on scientific knowledge, technology transfer, and workforce development. They will be decision makers and stakeholders who need to understand the value of our national investment in fundamental research. The Next Generation Science Standards, NAP (2012), being implemented in K-12 education emphasize that learning experiences should involve the following:

- defining problems
- planning and carrying out investigations
- analyzing and interpreting data
- developing and using models
- developing explanations and designs based on evidence

- applying and using scientific knowledge
- communicating information

The above sound exactly like research. I look forward to welcoming the first generation of students educated with these standards in the next few years. They will already be primed to embrace the methods and practices of research. The opportunity to significantly contribute to novel fundamental research as a student will be in their grasp.

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