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RESEARCH ARTICLE

The role of undergraduate research in physics education

El papel de la investigación de pregrado en la educación de la física

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ABSTRACT

Research experiences can benefit undergraduate students by providing hands-on experience in research, helping them develop critical thinking, problem-solving and analytical skills. Also, it helps them in establishing professional networking, career exploration, and demonstrable experience for future employers. In this article, the different types of undergraduate research experience that exist are explored. The article annotates several investigations of the benefits of undergraduate research experiences, including two that relate research experiences to the continuation into graduate school. This work also presents statistical data from the author's university of affiliation, to conclude that undergraduate research is the strongest motivator there is for students to continue with graduate studies.

KEYWORDS: undergraduate research; physics; education; graduate studies.

RESUMEN

Las experiencias en investigación pueden beneficiar a estudiantes de pregrado al proveerles experiencia práctica en la investigación, ayudándoles a desarrollar pensamiento crítico y habilidades analíticas y de resolución de problemas. También, les ayuda a establecer colaboración en redes profesionales, en la exploración profesional y a adquirir experiencia demostrable ante sus futuros empleadores. En este artículo se presentan los diferentes tipos de experiencias investigación de pregrado. El artículo da algunos detalles de varias investigaciones sobre los beneficios de las experiencias de investigación de pregrado, incluyendo dos que relacionan las experiencias de investigación con la continuación en estudios de posgrado. Este trabajo también presenta datos estadísticos de la universidad a la que el autor está afiliado, para concluir que la investigación de pregrado es el motivador más fuerte para que los estudiantes continúen con estudios de posgrado

PALABRAS CLAVE: investigación de pregrado; física; educación; estudios de posgrado.

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I. INTRODUCTION

Undergraduate research can be beneficial in career development in several ways. It provides hands-on experience in conducting research and developing critical thinking, problem-solving, and analytical skills, which are highly valued in many careers. It also allows students to work closely with faculty and other professionals, providing opportunities for mentorship, networking, and career exploration. Additionally, undergraduate research can help students build a strong resume or CV, demonstrating to future employers or graduate schools their ability to work independently, think creatively, and contribute to the advancement of their field.

In spite of these obvious benefits, the literature is still in the early stages of understanding how student researchers become integrated into communities of practice and develop science identities, and much less how these research experiences motivate students to pursue graduate degrees.

This is the central topic of this article.

TYPES OF UNDERGRADUATE RESEARCH

There are many examples of undergraduate research projects in physics, including:

1. Experimental research in a laboratory: Undergraduates may work on experimental research projects in areas such as optics, materials science, or condensed matter physics. For example, they may help design and build an experiment to investigate the properties of new materials or the behavior of light under different conditions.

2. Computational research: Undergraduates may work on computer simulations of physical systems, such as molecular dynamics, simulations of nuclear reactions or simulations of fluid dynamics. They may also use programming languages like Python, FORTRAN, MATLAB, GEANT4, LabView, or C++ to implement numerical methods in solving mathematical problems.

3. Theoretical research: Undergraduates may work on theoretical research projects in areas such as quantum mechanics, nuclear and particle physics, or astrophysics. They may help develop mathematical models to explain physical phenomena or conduct calculations to predict the behavior of particles in different conditions.

4. Interdisciplinary research: Undergraduates may work on projects that integrate physics with other disciplines, such as biology or engineering. For example, they may work on developing new technologies that incorporate principles of physics for medical or environmental applications.

Overall, undergraduate research in physics can provide valuable opportunities for students to gain hands-on experience in conducting scientific research and contribute to the advancement of their field. Undoubtedly, research experience can be of benefit for undergraduate students, but it is not clear if the benefits extend to the area of motivation or encouragement for graduate studies. There have been several studies that help us refine the benefits undergraduate research provide to students, in particular, to physics and other Science, Technology, Engineering, and Mathematics (STEM) students, some of these are presented in the following section.

In the following, several studies of research experiences are discussed.

APPRENTICESHIP RESEARCH EXPERIENCES

Thiry and Laursen studied how undergraduate students learn and develop research skills through apprenticeship-style research experiences [1]. Their work focused on the concept of "scientific apprenticeship," which involves working closely with a mentor in a research setting to develop skills and knowledge.

Current interest in undergraduate research (UR) among science educators stems from the traditional role of research apprenticeships in preparing scientist and concerns about the current scientific workforce. Although recent research has demonstrated the benefits of UR for STEM students, little is understood about how student-advisor interactions contribute to these benefits. Thiry and Laursen used Situated Learning Theory to examine the role of these interactions in apprenticing undergraduate researchers. A brief description of Situated Learning Theory is in Appendix A.

The qualitative study of Thiry and Laursen examines interviews with a diverse sample of 73 undergraduate research students from two research-extensive institutions, articulating a continuum of practices used by research mentors in professional socialization, intellectual support, and personal/emotional support. Novice and experienced students had different needs, while underrepresented minority and female students gained confidence and broadened future possibilities. The advising role of research mentors of students at the undergraduate level has a dual scientific and educational aspects, both of which are significance in shaping the students' identities and career trajectories [1].

NETWORKED RESEARCH EXPERIENCES

Thompson, Conaway, and Dolan studied the concept of networked research experiences, which involve collaborations between students, faculty, and other professionals across different institutions and organizations [2]. Their work has focused on understanding the benefits and challenges of networked research experiences for undergraduate students. A brief description of Networked Research Experience is in Appendix B.

The Thompson-Conaway-Dolan work discusses the increasing emphasis on integrating research experiences into undergraduate biology education and the use of multi-institution and interdisciplinary research networks. Unlike traditional apprenticeship models, networked research provides opportunities for students to develop relationships with multiple faculty members and students working in different areas of the project. The study aims to examine how students in the network develop social ties and the extent to which a networked research experience contributes to the development of social, cultural, and human capital. The study highlights the need to understand how students gain access to research experiences and the elements of research participation that lead to desired student outcomes. Overall, their study suggests that networked research experiences offer new models for involving undergraduates in research and provide opportunities for students to develop a range of skills and knowledge beyond traditional apprenticeship models.

Furthermore, Thompson, Conaway and Dolan discuss how undergraduates participating in a biology research network utilize and develop different forms of capital important for success in science research. Through a qualitative approach framed by capital theories, the study identified that undergraduates drew upon human, cultural, and social capital to gain access to the network. Undergraduates built multidimensional social ties with faculty, peers, and others, which yielded social capital that can be drawn upon for information, resources, and support [2]. They also developed cultural capital in the form of a scientific habitus and human capital in technical, analytical, and communication skills in scientific research. However, most of the students had limited cross-institutional capital, except for students in one institution that housed three research groups.

The study highlights the importance of developing different forms of capital to access opportunities in science beyond the network, and the need for students to be aware of the resources they have developed that can be used in other scientific contexts.

UNDERGRADUATE RESEARCH AND STUDENT WELL-BEING

Walkington and Ommering argue that undergraduate research can contribute to student well-being, particularly in the context of increasing numbers of university students experiencing mental health problems [3]. Their work uses Self-Determination Theory to argue that fulfilling the needs for autonomy, competence, and relatedness fosters well-being. A brief description of Self-Determination theory is in Appendix C.

Walkington and Ommering use authenticity as a lens to understand undergraduate research experiences, their investigation suggests that authentic research-based learning can promote well-being through effective curriculum design and mentoring.

Two case studies are used to demonstrate how curriculum design and mentoring pedagogy can enhance authenticity in research, student motivation, and well-being. The investigators emphasize the importance of early and embedded research-based learning, attention to the quality of learning spaces, and effective mentoring relationships to ensure the well-being of all involved. Overall, they advocate for the use of undergraduate research to stimulate well-being among students and provide an entitlement for all students to engage in authentic research-based learning.

UNDERGRADUATE RESEARCH AND RESEARCH SKILLS IN GRADUATE SCHOOL

Gilmore, Vieyra, Timmerman, Feldon, and Maher investigated the relationship between undergraduate research experiences and research skill performance in graduate school [4]. Using an empirical assessment of research skills, they examined the effects of various research experience characteristics such as duration, autonomy, collaboration, and motivation.

Results indicate that undergraduate research experience is positively associated with research skill performance in graduate school. Duration of the research experience was found to be the most strongly correlated with increased research skill performance, while autonomy and collaboration were emphasized in student interviews. The study recommends incorporating research experiences into undergraduate science curricula and creating centralized offices of undergraduate research, along with faculty incentives for involving undergraduates in research.

PERSONAL AND PROFESSIONAL GAINS FROM RESEARCH

Thiry, Weston, Laursen, and Hunter used a combination of methods, including interviews and surveys, to compare the perceived cognitive, personal, and professional gains of novice and experienced undergraduate students who participated in scientific research [5]. A study of 73 entry-level and experienced undergraduate students in four UR programs at two research extensive universities used in-depth interviews and the URSSA instrument to assess the impact of UR on students' cognitive, personal, and professional development.

Students who had more experience with scientific research reported a number of benefits, including a deeper understanding of the research process, improved personal and professional skills, and a greater sense of accomplishment. This study, like [4], found that multi-year undergraduate research (UR) experiences benefit students. These findings have implications for UR program design, advising practices, and funding structures. The URSSA is briefly described in Appendix D.

EDUCATIONAL VALUE OF EXPERIENTIAL RESEARCH

Thiry, Laursen and Hunter studied the educational value of experiential education, including laboratory and project-based coursework, as well as internships, co-ops, and research, which has long been emphasized in undergraduate education in STEM disciplines [6]. However, evidence from well-designed research and evaluation studies about the educational value of experiential education is sparse. Only recently have the benefits of undergraduate research been explored, and the value of internships and other professional opportunities has been even less well demonstrated.

Despite the limited evidence on the educational value of experiential education in STEM, research and inquiry-based learning are still widely promoted and supported by faculty, institutions, and funders. In 1998 [7], and again in 2020 [8], the Boyer Commission called for research-based learning to become the standard in undergraduate education, and the number of student research programs and institutions offering them continues to grow. Additionally, many institutions are considering incorporating research-like components into regular coursework. In light of these trends, it is crucial to further explore the role of research and other experiential educational activities in undergraduate STEM education.

Although co-curricular activities are commonly believed to enhance undergraduate learning and development in STEM fields, there is a lack of systematic, multi-institutional research examining the outcomes of student participation in these activities on their learning and professional growth. This study conducted interviews with 62 STEM majors from four liberal arts colleges who participated in a range of out-of-class experiences such as internships, jobs, and undergraduate research at government laboratories and research universities.

The study explores whether the benefits identified in the literature on undergraduate research experiences apply to other forms of experiential learning in STEM undergraduate education. Using an analytic framework developed to categorize benefits, the study examines the gains reported by graduating seniors through their curricular and co-curricular experiences, drawing on sociocultural theories of learning to contextualize the findings and their implications for faculty and others interested in supporting deep learning and professional development in STEM undergraduates.

Several studies suggest that undergraduate research experiences can have a positive impact on students' decisions to pursue graduate studies in STEM fields, as well as their overall academic and career goals. In this section, we review some of these investigations.

THE HATHAWAY-NAGDA-GREGERMAN STUDY

Hathaway, Nagda, & Gregerman evaluated how participating in Undergraduate Research Opportunity Program (UROP) influenced several key outcomes related to students' pursuit of graduate education [9].

The initial research design involved an experimental-control group comparison, but many of the non-UROP students in the control group reported having engaged in some form of undergraduate research activity. Therefore, the study was reconfigured to compare three groups: UROP participants, students who participated in other types of undergraduate research, and students who did not participate in any undergraduate research.

The results showed that undergraduate research participation had a consistently positive impact, as students who engaged in undergraduate research were more likely to pursue graduate education, continue with research after completing their undergraduate studies, and use faculty for job recommendations compared to those who did not participate in undergraduate research.

The findings also revealed that UROP had a unique relationship with the pursuit of professional degree programs, which are typically more competitive and challenging than two-year graduate programs, particularly for underrepresented students of color.

The chi-square analysis showed a significant relationship between students' research experiences and their pursuit of graduate or professional education. Of the students who pursued some form of graduate education, 81.5% of UROP participants, 82.0% of students who participated in other types of research, and 65.4% of students who did not participate in research pursued postgraduate education. The results indicated that UROP and other research students were significantly more likely to pursue postgraduate education compared to students who did not participate in research.

THE 2003-2005 WEB SURVEY

The study conducted by Russell, Hancock and McCullough utilized four web-based surveys, spanning from 2003 to 2005 and involving nearly 15,000 participants [10].

The initial survey included around 4,500 undergraduates and 3,600 faculty, graduate students, and postdoc mentors who had taken part in UROPs supported by eight National Science Foundation (NSF) programs with a significant undergraduate research component during 2002 or 2003. Two years later, approximately 3,300 of these undergraduates responded to a follow-up survey.

The findings indicated that UROPs boosted understanding, confidence, and awareness among students. Specifically, 73% of surveyed students reported an increase in their awareness of what graduate school entails. Additionally, UROPs contributed to higher expectations of obtaining a PhD, with 29% of respondents stating that they had "new" expectations of pursuing a PhD Before attending college, they had not expected to obtain a PhD, but now they did. According to the STEM survey, 19% of sponsored researchers, 12% of nonsponsored researchers, and only 5% of non-researchers reported having "new" expectations of obtaining a PhD after participating in UROPs.

II. METHODOLOGY

Although far from being an unbiased sample, the experience of the author as mentor of over 105 students, allows him to present his case in statistical terms. The author has been a professor of physics at his university of affiliation for 34 years and has had students performing research with him throughout his career.

The author's research projects have been in theoretical nuclear physics (with heavy emphasis on computational studies), experimental materials science, gravitation, astrophysics, physics education, and on applications of mathematical methods in social sciences.

In sum, the author has over 120 refereed articles that have accumulated over 2,000 citations, has written several books and countless general-audience articles for magazines and newspapers. His mentoring efforts have been recognized by The White House with the PAESMEM Award, by the journal Nature with the Mentoring Award, by several professional organizations, such as the American Physical Society, the Mexican Academy of Science, Society of Mexican American Engineers and Scientists (MAES), Society of Hispanic Engineers and Professionals (SHEP), and the like.

The students can be classified as undergraduate, masters and others (the university of affiliation does not have a PhD in physics).

A separate classification is that of the peer leaders that assisted the author in implementing the Peer-Led Team Learning (PLTL) method of teaching. Through the National Science Foundation grant "An Integrative Science Success, Teaching and Retention Program for STEM Education", three other professors and the author implemented PLTL in six math, chemistry and physics courses for science and engineering students.

For that program the author mentored undergraduate students to turn them into Peer Leaders (PLs) through direct apprenticeship, workshops designed to teach methodologies for constructivist learning, inquiry-based teaching, to induce teamwork, use of in-class demos, and many other active learning strategies.

The author's mentoring has also reached several high school students. Unfortunately, only anecdotal information is known about their whereabouts; but it is known that several won science competitions in local school districts, and one is about to complete a PhD in Chemistry at Rice University.

III. RESULTS AND DISCUSSION

Table 1 shows the distribution of students among the undergraduate, masters, and other classifications. The great majority of the undergraduate students have been physics majors and, except for two, all undergraduate have been of Hispanic origin or Mexican nationals. Eight of them have completed non-required B.S. thesis and about one third have co-authored refereed articles. As shown in Table 1 (and in Figure 1), over half of the author's advisees continued to graduate school, mostly for PhD in physics, and a few for terminal MS degrees.

TABLE 1
Distribution of Students Classified as Undergraduate, Masters, and Others

Classification	Number	Number continuing to graduate studies	Percentage
Undergraduate students	46	25	54%
Master's students	35	32	91%
Peer leaders	24	16	66%
Other (high school, foreign, etc.)	6	N/A	N/A

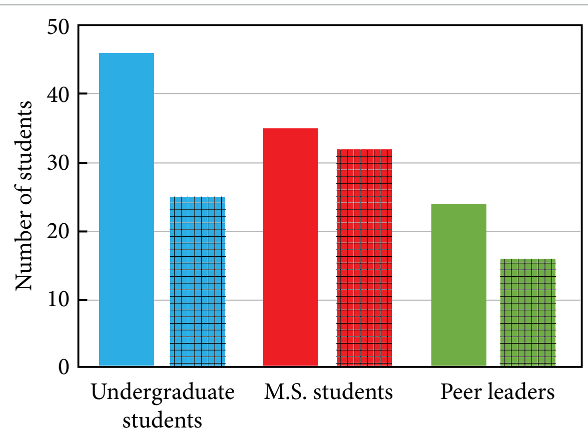

Figure 1. Data from Table 1. The hatched bars correspond to those students know to have continued to graduate studies.

The master's students are more international with a large portion from the USA and Mexico, but several from Bangladesh, Canada, Chile, China India, Mongolia, and Montenegro. All students have completed theses under the author's supervision and 23 co-authored refereed articles. A huge 91% continued for PhD studies mostly in physics, but a few in geophysics, computer science, material science, environmental science, and engineering.

The PLTL program that lasted from 2008 to 2013 impacted thousands of students, improved retention rates, and was adopted by biology and engineering classes. An unexpected result was that during the five years of operation, the 24 students mentored by the author became very strong in math and physics and got motivated to pursue graduate studies. Out of such group, 16 students (66%) continued to PhD studies in physics and engineering.

The gain in interest produced by the participation of students in research projects can be estimated by comparing to data of the American Institute of Physics (AIP), which indicates that on average only about 15% of undergraduate physics students continue into PhD studies. Since the UTEP results are all higher than 54%, we can conclude that participating in research projects indeed serve as strong motivator for PhD studies.

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The American Institute of Physics (AIP) [11] compiles data of the number of students earning BS and PhD degrees in physics and related areas, and it further subdivides them in gender, ethnicity, etc. Although the AIP data is the best there is, it does not allow an easy calculation of the number of students that continue form undergraduate to graduate studies, especially because there is a lack of data of the 1st year PhD students. Some of the published numbers, however, permit to establish an estimate of the proportion of students that continue into PhD studies after graduation.

In the period from 2011 to 2019, 5,259 Hispanic students earned a BS in physics and, alternatively, in the period 1997 to 2017, 359 Hispanic students earned a PhD in physics. Prorating these numbers to a period of 8 years, at best the percentage of BS graduates that continued to PhD studies (and graduated) was of the order of 2.73%.

An independent percentage can be estimated by the number pf BS degrees in physics awarded to Hispanics in 2019, 1900, and the number of PhD degrees earned by Hispanics in the same year, 42; although these numbers do not correspond to the same students, they allow to determine a ballpark figure of 2.21% of student transfer flow. It is clear that these numbers are extremely low to any of the percentages of student transfer observed in Table 1.

IV. CONCLUSIONS

Research experiences can be a motivating factor for undergraduate students to pursue graduate studies, but it is not always the case. The impact of research experiences on students' decision to pursue graduate studies can vary based on several factors, such as the quality and depth of the research experience, the student's personal interests and goals, the mentorship and support received during the research experience, and the overall academic and career environment in which the research was conducted.

Research experiences can provide students with a first-hand understanding of what it is like to conduct research in their field, which can help them develop a stronger sense of purpose and direction in their academic and career pursuits. This can be particularly impactful for students who may not have been exposed to research before or who may not have had a clear sense of what they wanted to do after completing their undergraduate studies.

Additionally, research experiences can also provide opportunities for students to develop strong relationships with faculty mentors and peers who share similar interests and goals, which can help create a sense of community and support that can be beneficial for students as they navigate their academic and career paths.

Overall, while research experiences can be a motivating factor for some undergraduate students to pursue graduate studies, it is important to recognize that this is not always the case and that students' decisions to pursue graduate studies are influenced by many different factors.

In conclusion, at least for Hispanics, the participation in undergraduate research programs appears to increase tremendously the percentage of students that graduate with a BS in physics and continue into PhD studies.

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APPENDIX

A. Situated Learning Theory

Situated Learning Theory is a learning theory developed by Jean Lave and Etienne Wenger in 1991 [12] that proposes that learning is fundamentally situated in social and physical contexts.

The theory argues that knowledge is constructed through social interactions with others in authentic, real-world settings. According to this theory, learning takes place through legitimate peripheral participation in a community of practice, where novices engage in meaningful activities and gradually develop their knowledge and skills by observing and collaborating with more experienced members of the community.

The theory emphasizes the importance of context and practice in learning, and it suggests that learners should be given opportunities to participate in authentic activities that reflect the practices of the communities they are trying to join. Situated Learning Theory has been applied in a variety of educational contexts, including in vocational training, apprenticeships, and informal learning environments.

B. Networked Research Experiences

Networked research experiences [13] involve collaborating across disciplines and institutions to investigate complex research questions, providing new contexts and models for involving undergraduates in research.

In contrast to the traditional apprenticeship model of research, where a student participates in research under the guidance of a single faculty member, Thompson, Conaway, and Dolan explain that:

> students participating in networked research have the opportunity to develop relationships with additional faculty and students working in other areas of the project, at their own and at other institutions [2].

This approach allows students to engage with a wider range of perspectives and expertise, and to build multidimensional social ties with a variety of mentors and peers. By doing so, students can develop various forms of capital that are important for success in science research, such as social, cultural, and human capital, which can be drawn upon for information, resources, and support.

Networked research experiences can afford opportunities for students to develop technical, analytical, and communication skills in scientific research and help them to learn to think and work like scientists, which can be valuable as they pursue careers in science or other fields.

C. Self-Determination Theory

Self-Determination Theory (SDT) [14] is a framework for understanding motivation and personality development. It is based on the premise that all individuals have basic psychological needs that must be met to facilitate well-being and optimal functioning. The three basic psychological needs are autonomy, competence, and relatedness. Autonomy refers to the need to feel in control of one's own behavior, competence refers to the need to feel capable of achieving goals, and relatedness refers to the need to feel connected to others and to belong.

SDT posits that people are naturally inclined to seek out environments that support their basic psychological needs, and that when these needs are met, people are more likely to engage in activities that promote well-being, such as personal growth, relationships, and learning. In contrast, when people experience environments that undermine their basic psychological needs, they are more likely to experience negative outcomes such as burnout, anxiety, and depression.

In addition to the basic psychological needs, SDT also highlights the importance of intrinsic motivation, which is the drive to engage in an activity because of the inherent satisfaction or enjoyment it brings. Intrinsic motivation is seen as critical to well-being and optimal functioning because it leads to more sustained and self-directed engagement in activities, and to greater creativity and persistence in problem-solving.

SDT has been applied to a variety of areas, including education, healthcare, and the workplace. In these contexts, it is used to design environments and interventions that support individuals' basic psychological needs and intrinsic motivation, in order to promote optimal functioning and well-being. For example, in education, SDT suggests that providing students with choices and opportunities for self-direction can increase their sense of autonomy, while providing support and feedback can increase their sense of competence. Similarly, in the workplace, creating a supportive and collaborative environment can foster employees' sense of relatedness, while giving them autonomy and meaningful work can increase their intrinsic motivation and engagement.

Overall, Self-Determination Theory provides a comprehensive framework for understanding human motivation and well-being and has been widely used to guide the design of interventions and environments that support optimal functioning in various settings.

D. The Undergraduate Research Student Self-Assessment

The Undergraduate Research Student Self-Assessment (URSSA) [15] is a quantitative instrument designed to assess undergraduate students' cognitive, personal, and professional gains from engaging in scientific research.

The instrument was developed by a team of researchers in 2010 and includes questions on research-related skills, personal attributes, professional goals, and research-related experiences. It is a widely used tool for evaluating the outcomes of undergraduate research programs, with over 10,000 students completing the survey as of 2021. The URSSA can provide valuable insights for program design, advising, and funding decisions related to undergraduate research experiences.

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