The Mathematics Enthusiast

Manuscript 1571

Recommendations for course-based undergraduate research experiences in mathematics

Rommel J. Miranda

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Rommel J. Miranda[1]
Towson University

Abstract: Course-based undergraduate research experiences (CUREs) have benefits for course instructors, undergraduate STEM students, and underrepresented students. CUREs consist of five essential components which include the use of science practices, discovery, broadly relevant or important work, collaboration, and iteration (Auchincloss et al., 2014). Over the past decade, a broad range of CUREs have been developed within and across STEM disciplines. However, resources to assist instructors to develop CUREs in mathematics are limited. The purpose of this paper is to provide an overview of the extant literature on course-based undergraduate research experiences (CUREs), especially in mathematics, to provide future directions for reforming mathematics courses to incorporate research experiences through CUREs, and to provide recommendations for developing CUREs in mathematics.

Keywords: course-based undergraduate research experiences, CUREs, mathematics, STEM

Introduction

It is essential that undergraduate students have an opportunity to participate in mathematics in a meaningful way. The undergraduate years are a critical period during which students begin to develop mathematical literacy and mathematical modeling skills. It is also an ideal time to develop the potential of future mathematicians. The opportunity is large, considering that approximately 40 percent of freshmen entering college plan to study science, technology, engineering, and mathematics (STEM) each year in the U.S. (Skomsvold, Radford & Berkner, 2011). However, the opportunity is short-lived, since most of these students switch to non-STEM disciplines before they have completed their sophomore year. Reports indicate that students in postsecondary STEM programs are likelier than those in non-STEM fields (35 versus 29 percent) to change majors (Lederman, 2017). Notably, students who start out studying mathematics are the most likeliest to change majors with 52 percent of these students choosing to major in something else (Lederman, 2017). Additionally, the six-year baccalaureate attainment rate is 63 percent for students who begin college at a four-year institution and 33 percent for those who begin at a two-year

[1] Rmiranda@towson.edu

institution (NCES, 2021). In a longitudinal study, the baccalaureate attainment rate is 68 percent for students whose parents had a baccalaureate degree, but only 24 percent for first-generation students (Chen & Carroll, 2005). Thus, providing effective mathematics experiences to undergraduate students is especially important.

In light of these alarming statistics, the development of course-based undergraduate research experiences (CUREs) is rapidly becoming an increasingly popular strategy for STEM course instructors to provide students with more meaningful experiences by engaging them more actively in their learning (Kuh, 2008). The purpose of this paper is to provide an overview of the extant literature on course-based undergraduate research experiences (CUREs), especially in mathematics, to provide future directions for reforming mathematics courses to incorporate research experiences through CUREs, and to provide recommendations for developing CUREs in mathematics.

Essential components of CUREs

There is growing consensus about what constitutes CUREs in the natural sciences (Dolan, 2014). CUREs consist of five essential components which include the use of science practices, discovery, broadly relevant or important work, collaboration, and iteration that differentiate CUREs from other research experiences (Auchincloss et al., 2014). CUREs can be distinguished from research internships with regard to scale, mentorship structure, enrollment, time commitment, and setting (Auchincloss et al., 2014). CUREs are open to all students in a credit-bearing course, where students invest time inside of class in a teaching lab, while research internships are only open to a few selected or self-selecting students, where students invest time outside of class in a faculty research laboratory (Auchincloss et al., 2014). In addition, CUREs may offer different opportunities for student input and autonomy in comparison to research internships (Patel et al., 2009; Hanauer et al., 2012; Hanauer and Dolan, 2014).

CUREs can also be distinguished from inquiry-based laboratory learning contexts. The broader relevance or importance of students' work in CUREs extends beyond the course, while the broader relevance or importance of students' work in inquiry-based learning contexts is limited to the course

(Auchincloss et al., 2014). Additionally, the research outcome is unknown to both students and instructors and research findings are novel in CUREs, while the research outcome may or may not be known to students and instructors and the research findings may be novel in inquiry-based laboratory learning contexts. Correspondingly, ideal research experiences in mathematics needs to be based on substantial topics in which students should engage in the study of non-trivial and not-too-esoteric mathematics; challenging at a variety of different levels in which students with different backgrounds and interests are able to engage in each project; approachable with a variety of different methods in which students that are interested in theoretical, computational, abstract, or concrete work are able to choose their own approaches; incrementally attainable, where at least partial results are within reach yet complete solutions are not easy so that no student wants to spend long hours of hard work and not feel productive; and new and unsolved for which the results attained by students are at least in theory, publishable (Bajnok, 2007).

Range of CUREs

A broad range of CUREs have been developed within disciplines as well as across disciplines such as biology, chemistry, physics, mathematics, earth and planetary science, and geography (Sun, Graves, and Oliver, 2020). Specific topics include genetics, physiology, microbiology, ecology, cell and molecular biology, evolution, general chemistry, organic chemistry, analytical chemistry, biomechanics, and engineering design (Dolan, 2016). However, published descriptions of CUREs are much more prevalent in life sciences and chemistry than in other STEM disciplines (Dolan, 2016). Opportunities for undergraduate research in disciplines such as physics, mathematics, astronomy, and computer science occur primarily through research internships (Dolan, 2016) in faculty research laboratories. The absence of undergraduate involvement in mathematics research has been attributed to lack of student capabilities at the undergraduate level, the nature of mathematics as a discipline, and historical lack of funding for research experiences for undergraduates (REUs) in mathematics (Peterson and Rubinstein, 2016). The Center for Undergraduate Research in Mathematics offers REUs and supports to small teams of students engaging faculty-mentored mathematics research for pay (Dorff, 2013). Although there are several examples of course-based mathematics projects (Peterson and Rubinstein, 2016), these projects are typically inquiry-based learning contexts (Laursen et al., 2011) that aim to develop students' mathematical thinking skills and preparation to participate in REUs. While there are also many resources regarding REUs that assist faculty in teaching mathematics with the possibility of incorporating research-like experiences in mathematics classes, as well as designing research experiences outside of the classroom (Abernathy et al., 2017; Peterson and Rubinstein, 2016), resources to assist instructors to develop CUREs in mathematics are limited.

Assessment of CUREs

A systematic approach to assessing CUREs is to (1) identify the learning outcomes, (2) select an assessment aligned with learning outcomes, and (3) interpret results (Shortlidge & Brownell, 2016). In this approach, instructors identify their anticipated CURE learning goal, design CURE curriculum with learning goals in mind, and identify if an assessment instrument(s) measure desired outcomes (Shortlidge & Brownell, 2016). If instructors use an existing assessment instrument, they should consider the population the instrument was developed on and determine if the population matches theirs, as well as the necessary time investment and their ability to administer, score, and analyze results (Shortlidge & Brownell, 2016). If existing assessment instruments are not appropriate, instructors can develop or collaborate with experts to design a situated assessment that is tightly aligned to the context of their course (Shortlidge & Brownell, 2016). After the assessment instrument is administered, instructors should carefully interpret the results of the assessment (Shortlidge & Brownell, 2016).

Range of research experiences in mathematics

This section will provide an overview of research experiences that are embedded within mathematics courses or within integrated science and mathematics courses from the extant literature. It is important to acknowledge that some of the referenced studies in this section are not typical credit-bearing mathematics courses. They are part of grant-funded, non-academic programs that supplement mathematics learning. Thus, the range of research experiences in mathematics center on the following three areas:

CUREs for mathematics majors, CUREs for non-mathematics majors, and CUREs in supplemental learning.

CUREs for mathematics majors: An Experimental Mathematics course at Valparaiso University facilitates students' abilities to ask and explore their own research questions partly based on problems chosen by the instructor. The course is designed for junior and senior majors who have more extensive background than first year students. The course emphasizes experimentation across the curriculum in which students develop their own questions and bring their own novel approaches to answering those questions. Problems come from combinatorics, number theory, algebra, analysis, and geometry, with an aim that students see experimentation as something that permeates the discipline of mathematics. Students start their semester-long research project in the first few weeks of class so that they have enough time to generate more possible avenues of independent exploration. The highlights of the course is that students complete a research project, take ownership of all phases of inquiry from selecting a problem, to writing code, to making conjectures from the resulting data, and to proving their own conjectures (Pudwell, 2017).

Similarly, an introductory Experimental Mathematics course at Ithaca College engages first-year mathematics majors in a research project during the final three weeks of the semester. The instructor ensures that students have a solid understanding of their project's background so that students can delve more deeply into their own research projects by the time the final three weeks of the semester approaches. The course serves as a gentle lead-in to later research experiences in upper level courses (Brown, 2014).

Moreover, an introductory mathematics course at Simpson College for first-year students focuses on skills required to successfully complete undergraduate research, course goals, graph theory topics covered, students feedback, and instructor reflection (Czarneski, 2013). Similarly, a laboratory course in mathematics at MIT involves undergraduate students in research projects. The primary emphasis of the program is to allow students to discover mathematics previously unknown to them in a "research-like" process while earning credit towards their degrees (Peterson and Rubinstein, 2016).

CUREs for non-mathematics majors: An introductory 10-week quantitative CUREs at University of California, Davis, combines microbial culturing with mathematical modeling using student-generated data (Furrow et al., 2020). The course helps students build quantitative skills that are commonly used in biology research. Students culture and isolate halophilic microbes from environmental and food samples, perform growth assays, and then use mathematical modeling to quantify the growth rate of strains in different salinities. The classroom application of microbiology methods, combined with mathematical modeling using student-generated data, provides a degree of student ownership, collaboration, iteration, and discovery that makes quantitative learning both relevant to students. With regard to discovery, students are responsible for each step of semester long project by selecting their samples and media, maintaining their cultures, and making their own decisions about how to revise their models. Because project ownership may be a critical mediator of students' overall benefits in CUREs (Corwin et al., 2018), the course aims to develop students into independent lab practitioners who are progressing their own projects.

Similarly, a Freshman Research Initiative CUREs at the University of Texas at Austin integrates biology and mathematics to engage students in designing, conducting, interpreting, and reporting their own inquiries and in research projects related to faculty members' ongoing research (Beckham et al., 2015).

CUREs in supplemental learning: The Preparation for Industrial Careers in Mathematical Sciences (PIC Math) program is designed to prepare students for industrial careers by engaging them in research problems that come directly from industry. The PIC Math program provides professional development for faculty to make industry connections in their courses to provide research experiences for their students to work on real problems coming directly from business, industry, or government. A major component of PIC Math involves students working as a group on a semester-long undergraduate research problem from business, industry, or government (https://www.maa.org/programs-and-communities/professional-development/pic-math). Support for this Mathematical Association of America (MAA) and Society of Industrial and Applied Mathematics (SIAM) program is provided by the National Science Foundation (NSF) and the National Security Agency (NSA).

Benefits of CUREs for instructors

Over the past decade, many CUREs that have been developed provide research experiences to a more inclusive and diverse student body (Bangera and Brownell, 2014), allow more undergraduate students to obtain research experiences, and expose more undergraduate students to STEM processes (Oufiero, 2019). Studies reveal that some instructors develop and teach CUREs because of the potential to publish and teach content that is closely related to their research agenda (Lopatto et al., 2014; Shortlidge et al., 2016) or the research of collaborators (Dolan, 2016). Additionally, buy-in from course instructors for CUREs may depend on the likelihood that students will produce results that are publishable, or can at least move research forward (Dolan, 2016) through a semester-long inquiry into a topic within the research expertise of course instructors (Auchincloss et al., 2014).

Benefits of CUREs for undergraduate students

Undergraduate student participation in CUREs can benefit student learning by helping students gain research skills (Shaffer et al., 2010) and improving both their persistence in STEM and their attitudes toward science (Brownell et al., 2012; Freeman et al., 2014; Jordan et al., 2014; Olimpo et al., 2016; Rodenbusch et al., 2016). Research suggests that CUREs can improve undergraduate students' self-efficacy (Shaffer et al., 2010) and that undergraduates engaged in research are more likely to persist in science and mathematics classes, complete their degree, and pursue STEM fields in their careers and postgraduate education (Barlow and Villarejo, 2004; Bauer & Bennett, 2003; Seymour et al., 2004). Several CUREs also show an increase in quantitative learning outcomes (Brownell et al., 2015; Kirkpatrick et al., 2019; Murren et al., 2019). However, these courses typically focus more on data and figure interpretation than on mathematical modeling (Furrow et al., 2020). Additionally, the experience of communicating research findings to an external audience with a vested interest in the work, such as during a professional conference or through a community report or peer-review publication, may be particularly motivating to students (Dolan, 2016). However, the effects of participation in CUREs on undergraduate students' interest has less to do with time spent and more to do with the nature of the work and the extent to which students have opportunities for ownership (Hanauer et al., 2012).

Benefit of CUREs for underrepresent students

Some reasons for the underrepresentation of particular groups of students in STEM careers cited in the extant literature (Theobald et al., 2011) include inauthentic experiences in undergraduate STEM courses (Brownell et al., 2012) and the lack of rigorous science academic preparation prior to college (Museus et al., 2011). In addition, research internships tend to be given to those students who early on express a desire to conduct research, have superior grades, and who are already familiar with research being conducted at the university (Estrada et al., 2011). There are disadvantages for undergraduate students who transfer to universities and struggle, have significant jobs or family responsibilities, are unaware of research opportunities and the advantages to engaging in research, or are from underrepresented groups in STEM fields (Estrada et al., 2011; Maton & Hrabowski, 2004). To address these issues, CUREs can help to broaden both retention in STEM fields and research participation, especially for underrepresented undergraduate students. CUREs can provide opportunities for large numbers of undergraduate students who have been typically underrepresented in STEM careers to engage in relevant STEM content through research experiences (Ing et al., 2020). CUREs can also be integrated into introductory-level courses (Dabney-Smith, 2009; Harrison et al., 2011) and have the potential to exert a greater influence on students' academic and career paths than research internships that occur late in an undergraduate's academic program (Hunter et al., 2007). Studies show that CUREs may increase inclusion and broaden participation in STEM by providing opportunities for undergraduate students to become aware of research experiences and their potential benefits, by becoming familiar with the cultural norms of science, and by interacting with faculty in ways that allow them to access additional research opportunities (Bangera and Brownell, 2014). Additionally, studies show that CUREs help retain undergraduate students, including those from groups typically underrepresented in science and mathematics (Barlow and Villarejo, 2004; Hathaway et al., 2002; Hunter et al., 2007).

Future directions

CUREs provide undergraduate students with research experiences in a course setting, through observations, modeling and mentoring, and afford them both skill development and a contextualized understanding of scientific and mathematical research. The goal of these courses is to teach research techniques to students and to provide them with opportunities to make new discoveries with instructors in tandem. Additionally, CUREs bring research experiences to a large, diverse group of students early in their undergraduate science or mathematics careers. CUREs also provide opportunities for more students to participate in the entirety of the scientific and mathematical process while also contributing to the instructor's scholarship program. Thus, reforming mathematics courses to incorporate research experiences through CUREs may help to sustain programs by promoting the scholarship success of course instructors and their own retention. However, the issue of scalability of undergraduate research programs in mathematics is a significant challenge. To address this issue, avenues for potentially transitioning REUs in mathematics to semester long, credit-bearing CUREs in mathematics should be explored. Additionally, avenues for engaging mathematics students in other forms of relevant research, for instance by developing CUREs at the intersection of mathematics and other disciplines should be explored (Dolan, 2016). Although the 5 essential components of CUREs align well with science courses, it is not clear whether these components align well with mathematics courses. Thus, determining what constitutes CUREs in mathematics should be explored. Moreover, since there are limited resources to assist instructors to develop CUREs in mathematics, there is a strong need for instructors of CUREs in mathematics to share descriptions of their courses and lessons learned via practitioner publications in mathematics.

Reforming mathematics courses to incorporate research experiences through CUREs cannot occur without effective professional development programming. In order to effectively develop and assess CUREs in mathematics, quality professional development programs for course instructors are needed to promote meaningful and inclusive teaching practices. The Yale Center for Teaching and Learning (2018) expresses that inclusive classroom environments are sustained when instructors and students work together for thoughtfulness, respect, and academic excellence, and that inclusive teaching strategies strive to serve the needs of all students, regardless of background or identity. The Howard Hughes Medical Institute (2018) also states that inclusive excellence is more than an end goal. It is a core dynamic stance taken to ensure that institutions and individuals are predisposed and positioned to desire, foster, recognize, and require the actions and outcomes that are necessary for inclusion to occur, and indistinguishable from excellence in science and mathematical discovery and innovation. Thus, to broaden both retention in STEM fields and research participation, especially for underrepresented undergraduate students, professional development programs for CUREs should include diversity, equity, and inclusion training for instructors.

Addressing the challenges to providing meaningful and effective mathematics experiences to undergraduate students will require more than the efforts of a few individuals who implement isolated initiatives. Instead, a collective approach by multiple stakeholders is necessary to achieve lasting change. A successful strategy will be grounded in an understanding of the barriers that limit students' opportunities to excel in mathematics and an aspirational vision shared by the faculty and administrators. Thus, barriers that prohibit the development of CUREs in mathematics as well as institutional change should be examined.

Acknowledgement

This work was supported by an Inclusive Excellence grant from the Howard Hughes Medical Institute for the Towson University Research Enhancement Program.

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