Course-based Undergraduate Research Experiences: Current knowledge and future directions[1]

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Abstract

Course-based Undergraduate Research Experiences (CUREs) have emerged in recent years in response to studies showing the benefits of undergraduate research internships and to national calls to engage many more STEM undergraduates in doing research. The purpose of this paper is to summarize the state of knowledge about CURE instruction, including shortcomings in the knowledge base and recommendations for future research and practice.

CUREs are distinctive as learning environments because they afford students opportunities to make discoveries that are of interest to the broader scientific community or other stakeholders outside the classroom. CUREs also engage students in iterative work, during which they repeat and build on aspects of their own and others' work in order to ensure the trustworthiness of their findings and generate meaningful scientific knowledge. Communication and collaboration are thought to be important elements of effective CUREs, but the importance of producing scientific publications versus other meaningful products remains an area of debate.

Numerous student-, faculty-, and institution-level goals have driven CURE development, especially in the life sciences and chemistry. These goals include the desire to improve students' persistence and success in STEM and in college, to make research accessible to a larger and more diverse group of students, and integrate to the teaching and research efforts of faculty. Introductory-level CUREs are thought to exert greater influence students' educational and career trajectories, while upper-level CUREs are useful for to students confirm their interest in pursuing science-research related educational or career paths. Small- and large-scale CUREs have been developed that engage students in addressing common and diverse research questions. CUREs themselves vary widely in duration, costs, and operations. There are only a few published examples of CURE being implemented in two-year colleges or minority-serving institutions.

Students who participate in CUREs develop content knowledge and technical skills specific to the area of research. They also develop confidence in their ability to do science and a sense of

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[1] This paper was commissioned for the Committee on Strengthening Research Experiences for Undergraduate STEM Students. The committee was convened by the Board on Science Education with support from the National Science Foundation. Opinions and statements included in the paper are solely those of the individual author, and are not necessarily adopted, endorsed, or verified as accurate by the Board on Science Education or the National Academies of Sciences, Engineering, and Medicine.

ownership of their research. Few studies of CUREs to date make use of valid and reliable measures of student outcomes, or study designs and methods that control for student-level differences. Additional research is needed that makes use of theory and methods from the social sciences to more fully understand how CUREs operate, how students and faculty benefit from this unique learning environment, and how challenges to adopting, implementing, and sustaining CUREs can be overcome.

Introduction

National calls to transform undergraduate STEM education to align better with how people learn (Bransford et al., 1999) have emphasized the widespread involvement of undergraduates in research (American Association for the Advancement of Science [AAAS], 2011; Olson and Riordan, 2012). Undergraduate research experiences (UREs) have long been a part of training the next generation of scientists (Kinkead, 2012). Undergraduates who participate in research report cognitive gains such as learning to think and work like a scientist, affective gains such as enjoyment, psychosocial gains such as identifying as a scientist, and behavioral gains such as intentions to pursue graduate education or careers in science (Laursen et al., 2010; Lopatto and Tobias, 2010). Studies of undergraduate research experiences (UREs) have been criticized for relying on students to report their own knowledge and skill gains, using measures that lack validity and reliability, neglecting to use control or comparison groups, and failing to account for selection bias, or differences between students who choose to pursue UREs and those who don't (Brownell et al., 2013; Linn et al., 2015; Sadler and McKinney, 2010; Sadler et al., 2010). However, an increasing number of well-designed and well controlled studies are showing that UREs can influence a students' learning, development, and educational and career trajectory (Eagan et al., 2013; Hurtado et al., 2008; Schultz et al., 2011).

Terms and Definitions. The benefits of UREs are a major driver in national calls to involve all biology learners in doing research (American Association for the Advancement of Science, 2011). Because of their apprenticeship structure, UREs have primarily been available to a select few students. Students who gain access to UREs, which typically take the form of mentored internships in faculty-led research groups, stand out because of their academic achievement (Carnell, 1958), because they have the confidence to approach faculty directly about research opportunities, or because they have personal connections useful for finding and securing research internships (Thompson et al., 2015). In an attempt to scale-up research offerings and broaden access to research, educators have developed alternatives to the apprenticeship model of UREs (Wei and Woodin, 2011), including research- or discovery-based laboratory courses (National Academies Committee [NAC] for Convocation on Integrating Discovery-Based Research into the Undergraduate Curriculum et al., 2015; Olson and Riordan, 2012). These courses, which are the subject of this paper, have been called discovery-based research courses, course-based research experiences (CREs), and authentic laboratory undergraduate research experiences (ALUREs) among other titles. I will use the term "Course-based Undergraduate Research Experiences" or CUREs to draw attention to the fact that they are considered alternatives to

UREs and because the research that students do in CUREs occurs in the context of a credit-bearing course. I define CUREs as learning experiences in which *whole classes of students address a research question or problem with unknown outcomes or solutions that are of interest to external stakeholders.*

I will avoid using the term "authentic" because I believe the term "research" sufficiently captures the aim of CUREs to engage students in making discoveries and contributing to a broader body of knowledge. In addition, the term "authenticity" carries many meanings that have not been clearly defined or delineated in studies of CUREs or UREs (Alkaher and Dolan, 2014; Buxton, 2006; Chinn and Malhotra, 2002; Rahm et al., 2003; Roth, 2012). For example, in Rahm and colleagues' (2003) study of a high school student-teacher-scientist partnership, participants' notion of what made a project authentic was emergent rather than static or predetermined.

What is a CURE? The first published description I could find of research being embedded into an undergraduate course was from Fromm (1956), which describes Mount Mercy College's transformation of a senior chemistry seminar course to include a lab session in which students worked on publishable research led by faculty members in the department. Since that time, there has been an explosion in the development of CUREs, particularly in biology and chemistry, and a parallel growth in the debate regarding what constitutes a CURE and how CUREs may be distinguished from other forms of laboratory learning (Alaimo et al., 2014; Auchincloss et al., 2014; Buck et al., 2008; Fukami, 2013; Hatfull et al., 2006; Kloser et al., 2011; Lopatto, 2003; NAC, 2015; Spell et al., 2014; Weaver et al., 2008).

There is relative consensus regarding distinctions between inquiry lab courses and traditional lab courses, also known as confirmation, demonstration, verification, or "cookbook" labs (Weaver et al., 2008). Specifically, traditional labs spell out procedures for investigations that students follow to find predictable outcomes that demonstrate well-known and understood science concepts. In contrast, inquiry courses allow students to make decisions regarding at least some aspect of their investigations, such as how to collect or analyze data, how to interpret and communicate results, and even what questions or hypotheses to pursue (Buck et al., 2008; Weaver et al., 2008). The results of inquiry investigations may or may not be known to the broader scientific community, but generally are unknown to students and of limited interest to stakeholders outside the classroom (e.g., the broader scientific community).

There is growing consensus about what constitutes a CURE in the natural sciences (e.g., biology, chemistry, physics, math, earth and planetary science). CUREs have primarily been defined through their parallels to UREs and their distinctions from inquiry and traditional lab courses. One distinguishing feature of CUREs is the opportunity for students to make discoveries by collecting and analyzing novel data and producing results that are new to students and to the scientific community alike (Alaimo et al., 2014; Auchincloss et al., 2014; Hatfull et al., 2006; Spell et al., 2014). There is agreement that students' results must be of interest to constituencies outside the classroom, and connected to the larger body of scientific knowledge. Auchincloss and colleagues (2014) propose the constructs of "discovery" (i.e., novel results) and "relevance" (i.e., of interest to external stakeholders) as two features necessary for a lab learning experience to be a CURE. In follow-up work, Corwin (nee Auchincloss) and colleagues (2015b) present a measure of opportunities for students to make broadly relevant discoveries that is useful for distinguishing CUREs from traditional lab courses.

Auchincloss and colleagues (2014) also posit that students' engagement in scientific practices (Next Generation Science Standards, http://www.nextgenscience.org/next-generation-science-standards; accessed 1/6/2016) is a key feature of CUREs. These practices include reading scientific literature, designing some aspect of the project, analyzing data, making interpretations, communicating results, framing work in the larger body of knowledge, and engaging in collaboration (Auchincloss et al., 2014; Buck et al., 2008; Lopatto, 2003; Weaver et al., 2008). There has been little research aimed at documenting the extent to which students engage in these practices in different CUREs, including their level of responsibility for specific aspects of the work and time spent engaged in each practice (Buck et al., 2008). Accounts of what happens during CUREs are mostly offered by CURE instructors and developers and may not reflect students' actual practice. Studies of internship-style UREs suffer from this issue as well, although recent research has presented tools that may be useful for characterizing goings-on in CUREs in a way that is conducive to identifying key design features (Corwin et al., 2015a; Kardash, 2000; Robnett et al., 2015).

The Value of Communication and Publication. Although there is consensus that the practice of communicating results is an essential part of a CURE, there continues to be debate about whether students' work must be publishable in a peer-reviewed scientific journal (Hatfull et al., 2006), versus being made publicly available to audiences with a vested interest in the work (e.g., posted in a database, presented in a report to a community group) (NAC, 2015; Wiley and Stover, 2014). The value of communication has not been conceptualized or explored at any depth in CUREs, which would be worthwhile for a number of reasons. First, theoretical and empirical work in areas such as social learning theory (Bandura, 1977), active learning (Freeman et al., 2014), and writing to learn (Bangert-Drowns et al., 2004) suggest that engaging in oral and written communication should positively influence student learning. Second, the experience of communicating to an external audience with a vested interest in the work, such as during a professional conference or through a community report or peer-reviewed publication, may be particularly motivating to students. This in turn might influence the time and effort they put forth in completing the work, and the outcomes they realize as a result.

Faculty buy-in to CURE instruction may depend on the likelihood that students will produce results that are publishable, or can at least move research forward. Several studies of CUREs note science publications as important outcomes (e.g., Full et al., 2015; Hatfull et al., 2006; Jordan et al., 2014; Leung et al., 2015; Ward et al., 2014). In addition, studies of faculty experiences with CUREs have revealed that some faculty teach CUREs because of the potential to publish and to teach in a way that is tightly aligned with their research responsibilities (Lopatto et al., 2014; Shortlidge et al., 2016). It is important to note, however, that students may not value publishing as much as faculty do. Wiley and Stover (2014) attempt to gain insight into the value of publishing for students by comparing the behavior, attitudes, and research products of students completing the same life science CURE but with two different publishing-related conditions. In the first condition, students were given a vague promise that their work might be published in the future. In the second condition, students were told that, at the end of the course, their results would be posted in a database used by scientists doing related work. In the second condition, a greater number of students spent more time outside of class doing research-related work (e.g., making observations, executing experiments), spent more time beyond the end of the course finishing their work, and produced higher quality research reports than students who were promised a publication at some undefined point in the future.

Qualitative data from this study suggest that some students found the immediate promise of making their results available to scientists motivating (Wiley and Stover, 2014), Some students were excited that their work had a purpose beyond earning them a grade, while other students were focused on producing work of sufficient quality to make a worthwhile contribution to science. At least one student indicated that disseminating his work in this way was not motivating because it was irrelevant to his career path. Further research is needed to determine what forms of communication are motivating for students and faculty alike so that we can understand the latitude we have for designing CUREs. This research should examine the value of diverse forms of communication in ways that take into account student, faculty, and disciplinary differences, and make use of established measures of motivation or other processes that might be at work (e.g., the role of publication in students' identification as scientists).

Goals

National, institutional, and program goals. One of the main driving forces behind the growth of CUREs is the goal of offering research experiences at scale (AAAS, 2011; NAC, 2015; Olson and Riordan, 2012; Wei and Woodin, 2011). CUREs are considered one of numerous strategies for engaging students more actively in their learning (Kuh, 2008), with the aim of improving student achievement and persistence (Freeman et al., 2014). In particular, many colleges and universities see CUREs as a mechanism for improving graduation rates and retention in STEM majors. CUREs, which can enroll a broad range of students, have been recognized for their potential to exert greater influence on students' educational and career trajectories than UREs, which attract a self-selecting group of research-interested students, typically late in their undergraduate careers (Alkaher and Dolan, 2014; Auchincloss et al., 2014). Introductory-level CUREs in particular have been championed for their potential to “level the playing field” by functioning as a gateway to UREs. Bangera and Brownell (2014) argue that CUREs can increase inclusion and broaden participation in STEM because they serve as an avenue for students to become aware of UREs and their potential benefits, become familiar with the cultural norms of science, and interact with faculty in ways that allow them to access additional research opportunities.

Goals for students. In general, CUREs aim to support students’ development as scientists. This includes learning about the nature and practice of science and building skills in doing science, including thinking like a scientist, reading and evaluating scientific literature, communicating about science, and collaborating with other scientists. Since CUREs are often embedded into existing lab science courses, most CUREs aim for students to develop discipline-specific skills and content knowledge. CUREs may afford opportunities for students to develop knowledge, skills, or connections that help them gain access to UREs (Bangera and Brownell, 2014; Thompson et al., 2015), although this idea has not been tested in a systematic way. CUREs also afford opportunities to try research before committing to a more intensive URE, especially at the introductory level (Auchincloss et al., 2014).

Most studies of CUREs describe the experiences and outcomes of students who are STEM majors. The few CUREs that have enrolled non-majors have goals similar to the goals outlined for majors, such as developing students’ critical thinking skills and their understanding of the nature of science (Alkaher and Dolan, 2011, 2014; Caruso et al., 2009). Some CUREs aim to pique students’ interest in science or in research, especially in contrast to traditional lab courses (Caruso et al., 2009; Harrison et al., 2011). Others aim to improve students’ persistence in STEM, including their likelihood of completing a STEM major and pursuing further education or careers in STEM and in research (Bascom-Slack et al., 2012; Jordan et al., 2014). Although there are numerous published descriptions of CUREs offered at different grade levels and different institution types (described below), there is no clear delineation of goals for students at different points in their undergraduate careers.

Goals for faculty. Faculty report a broad range of goals for teaching CUREs, including the potential to integrate their teaching and research, positively influence their promotion and tenure, publish both science and education papers, broaden the impact of their research, identify, recruit, and train students to join their labs as interns, and generally benefit their own research programs (Fukami, 2013; Lopatto et al., 2014; Shortlidge et al., 2016). Faculty also report that teaching CUREs is more interesting and enjoyable than teaching other types of lab courses.

CURE Models

Despite their common goals, CUREs have been structured in a variety of ways, the most common of which are described below. Only a handful of CUREs are highlighted here, but many others are described in the CURE Network website (http://curenet.cns.utexas.edu/) and the National Research Council convocation report on discovery-based research courses (NAC, 2015). Examples in geosciences are also available on the Science Education Resource Center website (http://serc.carleton.edu/NAGTWorkshops/undergraduate_research/strategies.html).

National programs with a common research goal. Several national CURE programs are led by individual scientists doing research that requires many minds and hands. The Genomics Education Partnership (GEP; http://gep.wustl.edu/; Shaffer et al., 2010) is an upper division, national CURE program led by Sarah Elgin (Washington University in St. Louis). Every year, about a thousand GEP students enrolled in genomics and bioinformatics courses at diverse institutions annotate and finish gene models in *Drosophila* with the ultimate goal of understanding *Drosophila* genome evolution. The Science Education Alliance-Phage Hunters program (SEA-Phages; http://seaphages.org/; http://phagesdb.org/phagehunters/), spearheaded by Graham Hatfull (University of Pittsburgh), involves thousands of introductory biology students at diverse institutions in identifying and characterizing soil bacteriophage with the collective aim of studying their genetic diversity and evolutionary mechanisms (Hatfull et al., 2006). Faculty typically join these programs through an application process, attend centralized professional development to prepare them to teach the CURE, receive resources and help from a central support system, and engage in some level of collaboration and communication with other faculty teaching the CURE.

National programs with a common technology or framework. Other CUREs have been developed around a common experimental platform or technology. For example, the Genome Consortium for Active Teaching (GCAT; http://www.bio.davidson.edu/gcat/; Campbell et al., 2007; Walker et al., 2008) and its daughter program GCAT-SEEK (http://www.gcat-seek.org/; Buonaccorsi et al., 2014, 2011) support faculty and students in addressing their own research questions using a common technology, microarray-based gene expression analysis and high throughput sequencing, respectively. Two other examples of national programs using a common framework are the Small World Initiative (http://www.smallworldinitiative.org/), a nationwide effort to crowd-source the discovery of antibiotics, and the Partnership for Research and Education in Plants for Undergraduates (PREP-U; Alkaher and Dolan, 2011, 2014). PREP-U is an undergraduate version of the high school PREP project (http://prepproject.org/; Brooks et al., 2011; Dolan et al., 2008), in which students conduct phenotypic characterization of genetic variants of the model plant, *Arabidopsis thaliana*. In both of these programs, instructors lead students through a common experimental structure to examine their own unique sample.

Local programs. A handful of institutions have developed internal CURE programs that serve hundreds of students by utilizing numerous CUREs, such as the Center for Authentic Science Practice in Education at Purdue University (https://www.purdue.edu/discoverypark/caspie/; Russell et al., 2010), the Freshman Research Initiative (FRI) at University of Texas at Austin (https://cns.utexas.edu/fri; Beckham et al., 2014; Simmons, 2014) and the Vertically-Integrated Projects Program at Georgia Tech (http://www.vip.gatech.edu/; Abler et al., 2011). Each of these programs has a central administrative structure that supports numerous faculty representing a range of disciplines in developing and implementing CUREs related to their own research interests. Other institutions across the country are replicating these programs based largely on unpublished evaluation results.

Specific courses. Many faculty have developed and teach CUREs at their own institutions, which are related to their own research or the research of collaborators. Most ***published*** descriptions of CUREs are in the life sciences or chemistry (Table 1), and span a wide range of courses and topics, including: genetics, physiology, microbiology, ecology, cell and molecular biology, evolution, general chemistry, organic chemistry, analytical chemistry, biomechanics, and engineering design.

Table 1 likely under-represents the full range of CUREs being taught because many are not represented in the peer-reviewed literature. Only one published example of a CURE that was developed and taught specifically at a minority-serving institution was identified (Siritunga et al., 2011), although GEP, SEA-Phages, and other national CURE programs involve students and faculty at MSIs. Similarly, only one published example of CURE implementation at a two-year college was identified (Wolkow et al., 2014), although the Community College Undergraduate Research Initiative (http://www.ccuri.org/) has supported numerous two-year schools in developing and implementing their own CUREs.

Table 1. Summary of discipline, institution type, and level of published CUREs.

Discipline	Institution type	Level	References[2]
Life sciences	Two-year college	Introductory	(Wolkow et al., 2014)
	Comprehensive university	Introductory	(Bowling et al., 2015)
		Upper division	(Shanle et al., 2016)
	Predominantly undergraduate institution	Introductory	(Harrison et al., 2011; Russell et al., 2015)
		Upper division	(Makarevitch et al., 2015; Russell et al., 2015; Ward et al., 2014a; Wiley and Stover, 2014)
	Minority Serving Institution	Upper division	(Siritunga et al., 2011)
	Research university	Introductory	(Beckham et al., 2015; Boltax et al., 2015; Brownell et al., 2015; Burnette and Wessler, 2013; Chen et al., 2005; Fukami, 2013; Kloser et al., 2011, 2013; Shapiro et al., 2015; Simmons, 2014; Wolkow et al., 2014)
		Upper division	(Brownell et al., 2012; Chen et al., 2005; Drew and Triplett, 2008; Full et al., 2015; Harvey et al., 2014; Rowland et al., 2012[3]; Shapiro et al., 2015)
	Diverse institutions	Introductory	(Alkaher and Dolan, 2014; Bascom-Slack et al., 2012; Hatfull et al., 2006; Jordan et al., 2014)
		Upper division	(Alkaher and Dolan, 2014; Lopatto et al., 2008; Shaffer et al., 2010, 2014)
Chemistry	Predominantly undergraduate institution	Upper division	(Alaimo et al., 2014; Ruttledge, 1998)
	Research university	Introductory	(Beckham et al., 2015; Clark et al., 2015; Russell and Weaver, 2011; Simmons, 2014; Tomasik et al., 2014; Winkelmann et al., 2015)
		Upper division	(Pontrello, 2015; Tomasik et al., 2013)
Geoscience	Predominantly undergraduate institution	Introductory	(Gonzalez and Semken, 2006)
		Upper division	(Gonzalez and Semken, 2006)
	Research university	Introductory	(Ryan, 2014)
		Upper division	(Ryan, 2014)
Physics	Research university	Introductory	(Beckham et al., 2015)
Engineering	Research university	Upper division	(Abler et al., 2011; Full et al., 2015)

Published descriptions of CUREs are much more prevalent in biology and chemistry than in other STEM disciplines. It is possible that CUREs have yet to be developed in these disciplines because there is less pressure to serve many students than one finds in the life sciences or chemistry. Undergraduate research and design experiences appear to be a longstanding feature of coursework in the geosciences and engineering (Mogk and Goodwin, 2012), perhaps due to the

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[2] References may be cited multiple times if they span discipline, institution type, or level.

[3] This reference is the only publication I could find on a non-U.S. CURE, called an "ALLURE" for Active Learning Laboratory Undergraduate Research Experience.

close connections with industry and the availability of non-academic internships in these disciplines. Undergraduate research in disciplines such as physics, math, astronomy, and computer science still appears to occur primarily through internships, although the Center for Undergraduate Research in Mathematics has supported small teams doing faculty-mentored math research for pay (Dorff, 2013). Several examples of course-based math projects are described in "Directions for Mathematics Research Experiences for Undergraduates" (Peterson and Rubinstein, 2015), but these are generally characterized as inquiry-based learning (Laursen et al., 2011), and aim to develop students' mathematical thinking skills and preparation to participate in UREs. The dearth of undergraduate involvement in math 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 undergraduate research in math, although NSF has funded many URE-style Research Experiences for Undergraduate programs in math in recent years (Peterson and Rubinstein, 2015). Work needs to be done to determine whether there is indeed something unique about math that prohibits adaption to the CURE format. Avenues for engaging math students in other forms of relevant research, for instance by developing CUREs at the intersection of math and other disciplines (e.g., biology), should also be explored. In 2014, FRI at UT Austin conducted a promising pilot test of a mathematics-biology CURE, but it was not continued due to lack of funding. FRI is also home to one CURE each in physics and astronomy, and several CUREs in computer science (https://cns.utexas.edu/fri/research-streams; Beckham et al., 2015). Two FRI CUREs are interdisciplinary in nature, one integrating chemistry and chemical engineering, and the other integrating computer science and electrical engineering. Although CASPiE at Purdue University mainly offers chemistry CUREs, some include elements of physics.

Duration. CUREs vary widely in their duration, from a single two-hour lab class session (Tomasik et al., 2014) to multiple quarters or semesters (Abler et al., 2011; Alaimo et al., 2014; Beckham et al., 2015; Hatfull et al., 2006; Jordan et al., 2014; Shapiro et al., 2015). Most CUREs described in the literature span multiple weeks (Alkaher and Dolan, 2014; Boltax et al., 2015; Clark et al., 2015; Makarevitch et al., 2015; Pontrello, 2015; Tomasik et al., 2013), and dedicating an entire quarter- or semester-long course to a CURE is typical (Bascom-Slack et al., 2012; Bowling et al., 2015; Brownell et al., 2015; Chen et al., 2005; Drew and Triplett, 2008; Full et al., 2015; Harvey et al., 2014; Kloser et al., 2011; Lopatto et al., 2008; Russell et al., 2015; Russell and Weaver, 2011; Ruttledge, 1998; Shanle et al., 2016; Siritunga et al., 2011; Ward et al., 2014; Wiley and Stover, 2014; Winkelmann et al., 2015; Wolkow et al., 2014).

Only one study appears to have addressed the influence of duration directly (Shaffer et al., 2014). Shaffer and colleagues (2014) compared student reports of learning gains measured using the Survey of Undergraduate Research Experiences (SURE) across quartiles of time spent in class on the CURE (1-10 hours, 11-24 hours, 25-36 hours, or >36 hours). Not surprisingly, the more instructional time spent in class, the higher the reports of learning. Students' reports of interest in taking other courses in the area and interest in math and computer science in general were significantly different between the lowest and highest quartile, but with a smaller apparent effect than the effect of time on reports of learning. It is possible that the effects of CURE participation on student interest has less to do with time spent and more with the nature of the work – for example, the extent to which students have opportunities for ownership (Hanauer et al., 2012). The representation of time as an ordinal rather than continuous variable in this study makes it impossible to determine whether there is a necessary amount of time required for students to achieve particular outcomes. Further research is needed to determine the influence of duration on a variety of student outcomes in a range of CUREs (e.g., different levels, disciplines, institutions).

Financial support. There is little published information about the cost of CUREs, although they are generally assumed to be more cost effective than UREs for engaging students in research. They are also thought to be more expensive than traditional lab courses although the specific reasons for this belief are unclear (Shortlidge et al., 2016; Spell et al., 2014). There is no published comparative analysis of the costs associated with CUREs, inquiry courses, and traditional lab courses, such as differences in supplies or equipment or instructional staffing needs. Multiple descriptions of CUREs made note of the possibility of keeping cost per student low by selecting research projects that make use of materials typically used in traditional lab courses, by using procedures and samples that are less expensive with scale up (e.g., genome sequencing), or by using computational approaches (i.e., no disposable costs or equipment needed other than computers). The few papers that explicitly describe costs are in the life sciences, and estimate costs ranging from $20-$500 per student (Burnette and Wessler, 2013; Harvey et al., 2014; Rowland et al., 2012; Russell et al., 2015). Of the CUREs cited in this paper, 17 received funding from the National Science Foundation, six from the Howard Hughes Medical Institute, three from the National Institutes of Health, one from another federal agency, three from other private sources, and 12 from institutional funds in the form of instructional budget and internal grants for innovative education.

Mentoring. A mentor is someone who offers developmental guidance to a less experienced, typically younger individual (Kram, 1988). Mentoring is unique from other academic relationships (e.g., instructor-student, advisor-advisee) because the scope of influence is broader and there is greater potential for closeness and mutual benefit (Eby et al., 2007). CUREs are often conceptualized as the integration of a *mentored* research experience with a laboratory course. Yet, CURE instructors are rarely described as mentors, and there appears to be no direct examination of whether or how CURE instructors function as mentors. CURE programs have described the involvement of peer mentors (e.g., (Beckham et al., 2015), but there appears to be no research examining their specific roles in implementing CUREs, the extent to which these roles involve mentoring, or the impacts of peer mentorship on students in the CURE and the mentors themselves.

There is general agreement that mentoring college students can improve their success in terms of retention and satisfaction in college, the grades they earn, and their social integration into academic and disciplinary settings (Crisp and Cruz, 2009; Gershenfeld, 2014; Jacobi, 1991). Given that many CUREs aim to achieve these outcomes for students, there is a clear need to examine research on mentoring in general and on mentoring undergraduates in particular in order to apply lessons learned and study the applications and implications of mentoring in CURE environments. For instance, mentors are thought to provide two overarching forms of support: instrumental or career-related support and psychosocial support (Kram, 1985). Instrumental support includes “how to” types of support, such as coaching, giving challenging assignments, and networking. Psychosocial support includes providing encouragement, empathizing, and serving as a role model. In CURE, mentors might tailor the learning and research tasks to challenge students at different levels and be responsive to individual students’ educational and career interests. Mentors might also normalize the struggle of doing research, including sharing their own stories of persisting in the face of failure, and help students identify and attain new opportunities for growth for which the CURE has prepared them (e.g., research internships).

Other logistics. Most published descriptions of CUREs do not provide much detail regarding the other logistics of CURE implementation, such as student and instructor time commitments, the extent to which students spend time during or outside of class completing their CURE work, or whether there are prerequisites, co-requisites, or other limitations on enrollment. Some of this information is available through the CUREnet website (http://curenet.cns.utexas.edu/). Not surprisingly, the facilities required to implement CUREs are highly specific to the project and discipline.

Accessibility. The rapid development of CUREs, especially in the life sciences and chemistry, means they are becoming increasingly accessible to students. However, there has not been any local or national level analysis of the availability of CUREs to undergraduate STEM students. National programs have scaled up to serve thousands of students at diverse institutions each year. Local programs that serve significant percentages of STEM majors (e.g., FRI at UT Austin serves ~40% of the incoming freshmen in the College of Natural Sciences) are being replicated at other institutions, indicating that growth is certainly possible.

It is not apparent from reviewing the literature how many CURE offerings are the only option students have to earn a particular course credit. For instance, it is not clear whether all students completing an introductory biology course participate in a CURE, or whether there are non-CURE options to earn introductory biology credit. A number of studies (described below) compare outcomes of students who complete a CURE versus completing a traditional course, suggesting that students may be able to choose between the two types of courses. This presents a challenge for understanding the effectiveness of CUREs, since making CUREs optional has been shown to result in a volunteer effect (Brownell et al., 2013). Kloser and colleagues (2013) conducted a study aimed at determining the effectiveness of a CURE for non-volunteer students. They found similar learning outcomes and gains in self-efficacy as they observed for volunteers (Brownell et al., 2012), but no change in non-volunteers' interests in research, while volunteers reported increased interest in research. Thus, the positive outcomes observed for CUREs to date may be due in part to a volunteer effect at the student level. None of the studies reviewed for this paper made use of statistical methods for controlling for student level differences (e.g., regression analysis; Theobald and Freeman, 2014).

Although CURE advocates note their potential for broadening undergraduates' access to research (Alkaher and Dolan, 2014; American Association for the Advancement of Science, 2011; Auchincloss et al., 2014; Bangera and Brownell, 2014; Olson and Riordan, 2012), there are exceedingly few descriptions of CURE development and implementation outside of research universities and four-year liberal arts colleges. National CURE programs involve students and faculty at two-year colleges and minority-serving institutions, but the unique experiences of students and faculty in these environments are largely unexamined. This is a significant shortcoming in the current knowledge base because students and faculty in institutions with varied infrastructures for research and for teaching innovation are likely to experience more of the challenges and barriers associated with CURE instruction (described below). For example, in their comparison of CURE implementation at a two-year college and a research university, Wolkow and colleagues (2014) found that significant adaptation was necessary for both students and faculty in the two-year college to have a positive experience with the CURE.

How students from different backgrounds experience CUREs must be examined in order to inform the design and implementation of CUREs for diverse students in diverse environments. A study from Alkaher and Dolan (2014) illustrates this point. This cross-case analysis of the experience of diverse students completing the same CURE revealed that a high-achieving student who was a science major at a research university enjoyed the challenge and ambiguity inherent to the CURE and perceived the experience as an affirmation that he was doing what scientists do. However, a lower-achieving non-science major at a predominantly undergraduate institution perceived the challenge and lack of clear results as confirmation of her inability to do science. As CUREs are implemented more widely, it will be important to study the experiences and outcomes of students who differ in their sociodemographics, including gender, race, ethnicity, first generation college status, major, and discipline, as well as any interactions among these characteristics.

CURE Outcomes

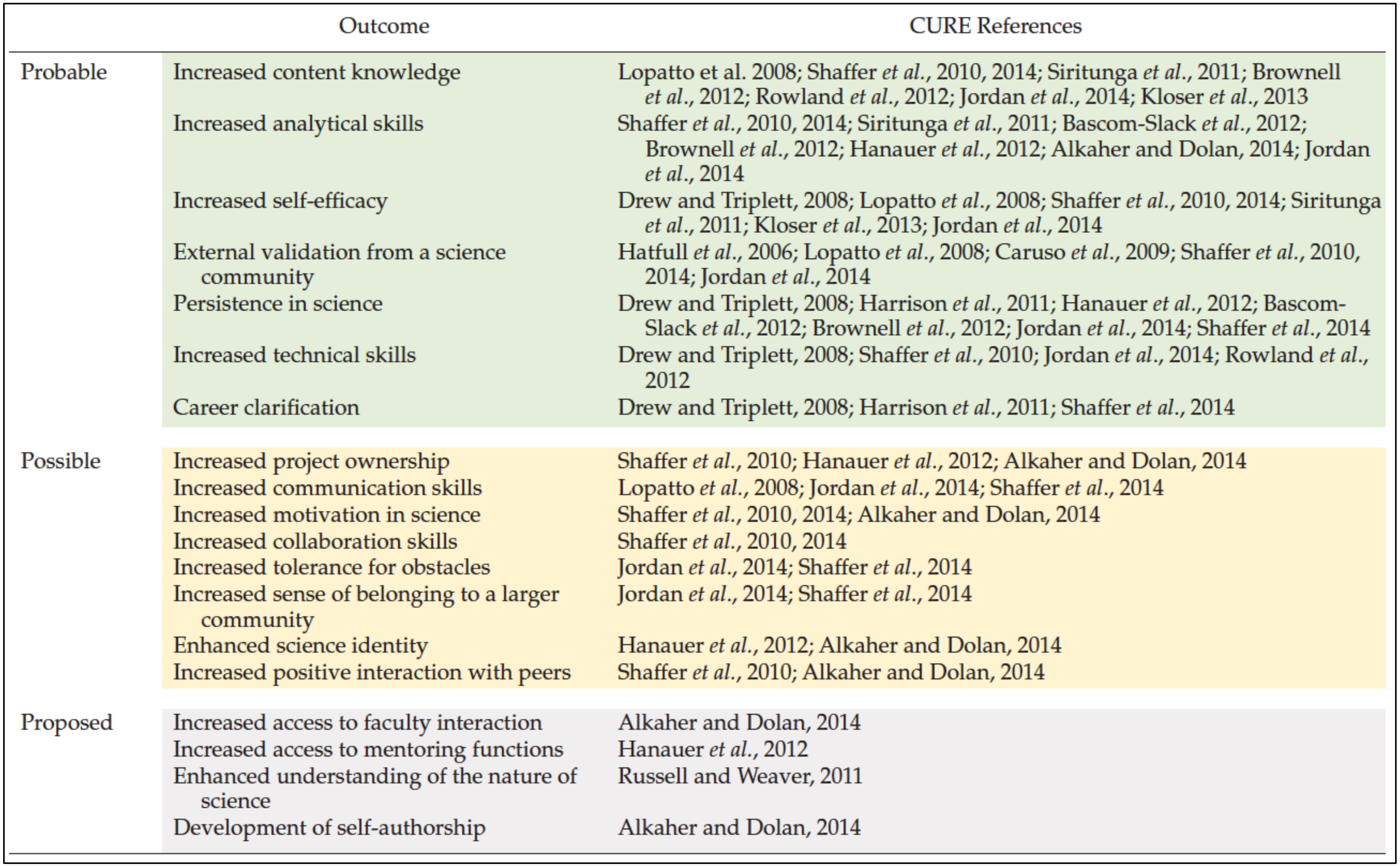
Overview. Given the focus on CURE instruction as a mechanism for making the benefits of UREs available at scale, there is great interest in the outcomes of CUREs for students and faculty alike. In a recent essay, Corwin and colleagues (2015a) systematically reviewed published studies of CURE student outcomes, and used the results to categorize outcomes based on the level of supporting evidence. Outcomes were designated as *probable* outcomes of CUREs if they were (a) investigated in a minimum of three studies, (b) measured in at least three different student populations (i.e., groups of students), (c) measured in at least three different courses or curricula, and (d) assessed using at least two different methods or instruments. *Possible* outcomes of CUREs were (a) investigated in a minimum of two studies, (b) investigated in two different populations, (c) measured in at least one course or curriculum, and (d) assessed using at least one method. *Proposed* outcomes were investigated only in a single instance, or were supported by learning theory, but were not present in the literature. Results of this analysis are presented in Table 2.

Studies of CURE instruction made claims about student outcomes in four main categories:

1. **Cognitive gains** such as increased content knowledge, improved understanding of the nature of science, or skill development, including analytical, technical, collaboration, communication, and experimental design skills;
2. **Psychosocial gains** such as increased confidence, self-efficacy, project ownership, sense of community, and scientific identity, as well as more frequent and fruitful interactions with faculty;
3. **Behavioral gains** such as staying in a science major, pursuing additional research opportunities, or enrolling in graduate school; and
4. **Affective and other "non-cognitive" gains** such as enjoying science class more and being more motivated (Duckworth and Yeager, 2015).

It is apparent from Corwin et al. (2015a) and careful examination of all of the references cited in this paper that most of these outcomes have only been studied in one or a few CUREs. Of the 40+ CURE papers reviewed here, >30% presented no data on student or faculty outcomes. About 30% of the papers described studies that included a comparison group. Aside from one study that made use of random assignment (Kloser et al., 2013), none of comparison group studies controlled for student level differences among groups. None of the CURE studies reviewed here disaggregated outcomes according to student demographics, most likely because samples were too small to conduct these analyses or demographic information was unavailable. Shaffer and colleagues (2010) attempt to do this on the basis of school characteristics, and do not find any significant differences.

Table 2. Support for CURE outcomes based on a review of relevant CURE literature. Green shading indicates probable outcomes, yellow shading indicates possible outcomes, and gray shading indicates proposed outcomes. (Corwin et al., 2015a)



	Outcome	CURE References
Probable	Increased content knowledge	Lopatto et al. 2008; Shaffer *et al.*, 2010, 2014; Siritunga *et al.*, 2011; Brownell *et al.*, 2012; Rowland *et al.*, 2012; Jordan *et al.*, 2014; Kloser *et al.*, 2013
	Increased analytical skills	Shaffer *et al.*, 2010, 2014; Siritunga *et al.*, 2011; Bascom-Slack *et al.*, 2012; Brownell *et al.*, 2012; Hanauer *et al.*, 2012; Alkaher and Dolan, 2014; Jordan *et al.*, 2014
	Increased self-efficacy	Drew and Triplett, 2008; Lopatto *et al.*, 2008; Shaffer *et al.*, 2010, 2014; Siritunga *et al.*, 2011; Kloser *et al.*, 2013; Jordan *et al.*, 2014
	External validation from a science community	Hatfull *et al.*, 2006; Lopatto *et al.*, 2008; Caruso *et al.*, 2009; Shaffer *et al.*, 2010, 2014; Jordan *et al.*, 2014
	Persistence in science	Drew and Triplett, 2008; Harrison *et al.*, 2011; Hanauer *et al.*, 2012; Bascom-Slack *et al.*, 2012; Brownell *et al.*, 2012; Jordan *et al.*, 2014; Shaffer *et al.*, 2014
	Increased technical skills	Drew and Triplett, 2008; Shaffer *et al.*, 2010; Jordan *et al.*, 2014; Rowland *et al.*, 2012
	Career clarification	Drew and Triplett, 2008; Harrison *et al.*, 2011; Shaffer *et al.*, 2014
Possible	Increased project ownership	Shaffer *et al.*, 2010; Hanauer *et al.*, 2012; Alkaher and Dolan, 2014
	Increased communication skills	Lopatto *et al.*, 2008; Jordan *et al.*, 2014; Shaffer *et al.*, 2014
	Increased motivation in science	Shaffer *et al.*, 2010, 2014; Alkaher and Dolan, 2014
	Increased collaboration skills	Shaffer *et al.*, 2010, 2014
	Increased tolerance for obstacles	Jordan *et al.*, 2014; Shaffer *et al.*, 2014
	Increased sense of belonging to a larger community	Jordan *et al.*, 2014; Shaffer *et al.*, 2014
	Enhanced science identity	Hanauer *et al.*, 2012; Alkaher and Dolan, 2014
	Increased positive interaction with peers	Shaffer *et al.*, 2010; Alkaher and Dolan, 2014
Proposed	Increased access to faculty interaction	Alkaher and Dolan, 2014
	Increased access to mentoring functions	Hanauer *et al.*, 2012
	Enhanced understanding of the nature of science	Russell and Weaver, 2011
	Development of self-authorship	Alkaher and Dolan, 2014

Theoretical framework. Few if any studies of CUREs present a theoretical framework for the design, implementation, or evaluation of the CURE. For example, undergraduates could be considered scientists-in-training with research as the defining practice of the scientific community. As such, theory related to communities of practice, legitimate peripheral participation, and cognitive apprenticeship (Brown et al., 1989; Lave and Wenger, 1991; Wenger, 1999) – or the extent to which students engage in meaningful, cognitively demanding practices of the discipline – could be used as a lens for examining what students do during CUREs and what outcomes they realize (or not) as a result. Social cognitive career theory (Lent et al., 1994), which relates learning experiences to outcome expectations, self-efficacy expectations, interests, and behaviors, could be used as a framework for understanding the experiences of students who are majors versus those who are non-majors. For example, non-majors may have lower expectations regarding their ability to do research (self-efficacy expectation) and perceive less personal value in publishing (outcome expectation), and thus may take different actions as a result of participating in a CURE (e.g., choosing not to enroll in another science course) than a STEM major would. Finally, social capital theory and social network theory (Archer et al., 2015; Bourdieu, 1997; Thompson et al., 2015) would be useful frameworks for examining the extent to which CUREs support underserved students in developing social resources important for gaining access to UREs or other valued resources such as scholarships, fellowships, or internships.

Cognitive gains. Studies that compared content knowledge gains between students in traditional lab courses versus CUREs either found that students made similar gains or that students in the CURE group learned more. Most of these studies were designed as pre/post studies with a comparison group, but did not control for student-level differences. The one exception to this is a study from Kloser and colleagues (2013), which made use of random assignment. The measures of content knowledge typically took the form of tests, quizzes, or rubrics unique to the subject of the CURE being studied, making it difficult to compare content knowledge gains that result from CUREs versus other lab learning experiences. There are a few exceptions to this. Russell and Weaver (2010) made use of structured interviews using an established protocol (Lederman et al., 2002) to examine students' understanding of the nature of science. They found that CURE students developed a more sophisticated understanding of the distinctions between hypotheses and theories and of the role of creativity in science than students completing a traditional lab course. Wolkow and colleagues (2014) made use of the Introductory Molecular and Cell Biology Assessment (Shi et al., 2010) to measure two-year and four-year college students' learning, contrasting participation in a CURE versus a traditional course, and found that students made similar gains across conditions. Ward and colleagues (2014) documented that students improved their performance on the Major Field Test for Biology (Educational Testing Service) pre to post CURE participation; this study did not include a comparison group.

The widespread use of project-specific assessments raises an important question about the value of measuring content knowledge gains from CURE instruction. Given that one of the goals of CUREs is to develop students' expertise as scientists, and that one always has limited time and resources for assessment, it may be that developing science practice skills is a more important outcome to measure. In addition, it may be less informative to examine what knowledge students gain and more informative to examine how students use the knowledge that they learn, using knowledge integration as a framework (Linn et al., 2015). However, engendering faculty and administrative buy-in to CURE instruction may require demonstrating that students are able to learn the same content in CUREs versus traditional lab courses (i.e., CUREs do no harm). Future research on learning content knowledge through CUREs should attend to the validity and reliability of the tests or rubrics used to measure knowledge (Kuh et al., 2014; Pellegrino et al., 2001), an aspect which has largely been unaddressed in studies of CUREs to date.

Studies of the skills that students develop through CURE participation have relied largely on student self-reports of skill gains. These gains have primarily been measured using the Survey of Undergraduate Research Experiences and the related CURE survey (Lopatto and Tobias, 2010). Fewer studies made use of the Student Assessment of Learning Gains (http://www.salgsite.org/; University of Colorado at Boulder; e.g., Ward et al., 2014) or instructor- or researcher-authored surveys. For the most part, CURE students report skill gains similar to or higher than those reported by URE students, (Abler et al., 2011; Bascom-Slack et al., 2012; Bowling et al., 2015; Brownell et al., 2012; Drew and Triplett, 2008; Harvey et al., 2014; Jordan et al., 2014; Lopatto et al., 2008; Makarevitch et al., 2015; Shaffer et al., 2014; Shapiro et al., 2015; Siritunga et al., 2011; Ward et al., 2014a; Winkelmann et al., 2015); and higher than those reported by students in traditional lab courses (Jordan et al., 2014; Lopatto et al., 2008; Pontrello, 2015; Russell et al., 2015; Tomasik et al., 2013). It is difficult to determine from this collection of studies whether students are simply becoming more confident about their skills (i.e., increased self-efficacy) or whether they are actually becoming more skilled as a result of participating in CUREs.

The SURE and CURE surveys have been critical, especially in the life sciences, for building the community's value of educational assessment and interest using common tools to compare student outcomes across learning experiences. However, student reports of their knowledge and skill gains can vary widely when compared to gains measured more directly by testing or expert assessment (Falchikov and Boud, 1989), which raises questions about what is being measured in these studies. Duckworth and Yeager (2015) also point out the issue of reference bias – the phenomenon that individuals rate themselves as more or less competent depending on their local environment or frame of reference. For example, a non-major may rate her skill gains lower if she is enrolled in a CURE that also has majors enrolled. The use of performance tasks to assess skill gains would avoid these issues and yield greater insight into the nature of these outcomes. For example, Brownell and colleagues (2015) conducted a series of tests of students' experimental design and data interpretation skills in a CURE versus a traditional lab course, and found no change in their skills and no differences between conditions. They argue that the tests became more difficult and thus demonstrated gains in skills, but the data presented to support this argument were limited.

Psychosocial gains. Recent research has aimed to understand the factors influencing underrepresented minority (URM) students' persistence in STEM. Research experience has been identified as one of these factors (Schultz et al., 2011). Work from Estrada and colleagues (2011) indicates that gains in students' scientific self-efficacy, scientific identity, and the extent to which they view scientific values as aligned with their personal values ("science values alignment") increase as a result of participating in research, and these changes predict both their intentions and their actual persistence in science. There has been no study to date that has examined the effect of CURE participation on students' scientific self-efficacy, scientific identity, or science values alignment using the established measures employed by Estrada and colleagues (2011). Shanle and colleagues (2016) developed their own measure of scientific identity, and observed no change pre to post CURE. This is most likely because the students in this upper division CURE already identified highly as scientists prior to their participation.

Developing a sense of community or belonging is another important factor predicting student persistence in STEM, especially among URM students (Hausmann et al., 2009; Hurtado and Carter, 1997; Locks et al., 2008). Because CUREs engage students in work that is important to the scientific community alongside peers and mentors, they may offer a more favorable environment than traditional lab courses for students to feel like a valued member of a community. Only one study has measured sense of community as an outcome for CURE students (Harvey et al., 2014), but this study did not make use of an established tool (e.g., Chipuer and Pretty, 1999; Loo, 2003; Rovai, 2002), making it difficult to draw conclusions or compare the findings with other learning experiences. Social capital theory and research on communities of practice (Bourdieu, 1997; Wenger, 1999) suggest that interactions with peers, faculty, and other mentors are likely to be important factors for student development. These interactions are likely to differ in their nature and frequency in CUREs versus traditional lab courses and UREs in ways that affect student outcomes. Network analytic approaches (Abler et al., 2011) and a recently developed network measurement tool (Hanauer and Hatfull, 2015) are likely to be useful for examining this.

Behavioral gains. A small group of studies have found that students report an increase in their intentions to pursue additional research opportunities and to enroll in graduate school, and do enroll at a higher rate in subsequent STEM courses and in graduate school (Bascom-Slack et al., 2012; Brownell et al., 2012; Harrison et al., 2011; Jordan et al., 2014; Shaffer et al., 2010; Ward et al., 2014). However, none of these studies control for student-level differences that could explain these outcomes.

Affective, attitudinal, and other non-cognitive gains. In general, students report that they enjoy CUREs more than traditional lab courses (Pontrello, 2015; Shanle et al., 2016; Tomasik et al., 2013; Wolkow et al., 2014). Students in some CUREs expressed appreciation that their work had value (Harrison et al., 2011; Wiley and Stover, 2014) or real-world connections (Tomasik et al., 2013). Attitudinal outcomes were measured using published instruments such as the Chemistry Attitudes and Experiences Questionnaire, the Colorado Learning Attitudes about Science Survey, and CHEMX, a measure of students' expectations about learning (Grove and Bretz, 2007), making it possible to compare the influence of these CUREs to that of other learning experiences.

Faculty outcomes. Most studies of CUREs have focused on documenting student outcomes. At least three studies have examined outcomes for faculty. In one study, GEP faculty report gaining access to technology, developing new collegial relationships, building their own confidence, and improving their local reputation as a result of their participation in the national CURE program (Shaffer et al., 2010). In a later study, GEP faculty reported a larger number of incentives for continuing with the program: gaining prestige, being involved in research, being a co-author on science publications, having access to a collegial community, growing professionally, and being able to teach in a way that made students more enthusiastic and motivated (Lopatto et al., 2014). The reasons that faculty have opted out of this or other CURE programs have yet to be explored.

Shortlidge and colleagues (2016) published the most comprehensive study of CURE faculty outcomes to date. They interviewed 38 faculty holding different types of positions and representing CUREs that were diverse in terms of institution, level, and sub-discipline within the life sciences. The majority of faculty reported that they found CUREs to be useful for integrating their teaching and research, more enjoyable to teach than traditional labs, influential for their promotion or tenure, and beneficial in terms of both publications and data useful for their own research. Fewer faculty in this study reported that teaching CUREs helped them to broaden their research interests and the impacts of their research, recruit and train good students, and improve their relationships with students. At present, there appear to be no studies of CURE faculty outcomes outside of the life sciences, and no studies that make use of comparison groups in examining faculty outcomes.

Features that make CUREs effective

A number of CURE instructors, developers, and evaluators have made recommendations for designing effective CUREs, including the following: CUREs should be technically and conceptually simple, compatible with flexible scheduling, involve multiple milestones, be structured such that students can work in parallel, include checks for data quality and a repository for sharing data, and include assessments that resemble the work of scientists (e.g., lab notebooks, presentations, publication-style papers) (Fukami, 2013; Hatfull et al., 2006; Kloser et al., 2011). This advice is based largely on the personal experience of people in the trenches rather than emerging from theoretical or empirical evidence. Fukami (2013) also recommends that instructors have expertise in the study system, but there has been no systematic investigation of the level or type of scientific or pedagogical expertise necessary to teach a CURE effectively. Future research should examine how faculty learn to teach CUREs effectively, including what kinds of content knowledge, pedagogical knowledge, and pedagogical content knowledge are needed to teach CUREs well.

Almost all studies of CUREs (and UREs) have treated them like a black box – a singular treatment that differs from traditional or inquiry courses in ways that are hypothesized to affect student outcomes. Only recently has there been any empirical work to identify the design features of CUREs that make them distinct from other learning environments and effective for students. One feature for which there is a reasonable level of evidence is the idea of ownership (Hanauer and Dolan, 2014; Hanauer et al., 2012), or the extent to which a student not only feels personal responsibility for the project but also identifies with the project in some way. Studies of levels of ownership students develop in traditional courses, UREs, and CUREs indicate that high levels of ownership may be unique to CUREs (Hanauer and Dolan, 2014; Hanauer et al., 2012). Corwin and colleagues (2015b) have also been able to distinguish CUREs from traditional courses using measures of opportunities for students to make broadly relevant discoveries and engage in iterative work. A next step in research on CUREs will be developing and testing models of how design features relate to student outcomes (Corwin et al., 2015b).

Designing and teaching CUREs

CUREs have only recently become the focus of systematic study, which limits the recommendations that can be made about “best practices” for designing and teaching CUREs. However, some recommendations can be made based on knowledge from the study of science teaching and learning in general. The following questions are intended to offer guidance on developing and teaching CUREs.

How will the CURE be integrated into the curriculum? If the CURE will be integrating into an existing course, how well does the research align with the learning goals for the course? Can the learning goals be revised to better fit the research without compromising student development? If the CURE will be a new course, how will it fit into students’ degree plans and help them achieve their educational or career goals? If the CURE is an elective course, how might this influence the population of students who enroll (e.g., those are more likely to take elective courses, such as honors students or students who don’t have work or family commitments) and outcomes they are likely to realize? How does this aligns with the goals of the course? Backward design and other curriculum design strategies can be used to address these questions (Wiggins and McTighe, 2005).

How will research progress be balanced with student learning and development? Ideally, students learn and develop in the process of moving the research forward. Sometimes the processes for achieving student outcomes and achieving research outcomes are not tightly aligned. For example, multiple rounds of data collection are often necessary to move research forward, but students will not learn anything new from repeatedly collecting data and instructors may not be inclined to dedicate precious class time to repeating experiments multiple times. In this case, learning and research could both be accomplished by reframing the work as a lesson on the importance of replication, the value of larger sample sizes and statistical power, or on the nature of science (Bell et al., 2003; Russell and Weaver, 2011; Schwartz et al., 2004). Alternatively, tasks that are not productive for student learning could be the responsibility of researchers outside of the class who can replicate or otherwise follow-up on students' work.

To what extent will students have intellectual responsibility and opportunities to "own" aspects of the research? As described early on, CUREs are likely to have greater influence on student outcomes when students themselves take responsibility for designing and leading aspects of the work (Hanauer et al., 2012). For example, students can be responsible for selecting methods, making decisions about how to trouble-shoot experiments, developing their own claims that they must defend with evidence, and communicating their results to broader audiences (Buck et al., 2008). In some CUREs, students even pose and investigate their own mini-research questions within the overarching research question addressed by the CURE.

How will the research learning tasks (i.e., what students do to learn AND make progress in research) be structured to focus beyond the development of project-specific knowledge and skills to foster students' development as scientists? Research indicates that tasks engender more motivation if they are challenging but not overwhelming (Ryan and Deci, 2000). Thus, CUREs should be structured to be challenging to students while providing support for them to be successful (Tanner, 2013). Instruction should move beyond helping students develop knowledge and skills particular to the project to developing a deeper understanding of scientific inquiry, the nature of science, and disciplinary norms and practices. For example, an insufficiently challenging graphing assignment might provide specific instructions about what graphs should look like and how they should be constructed (e.g., independent variable on the X axis, dependent variable on the Y axis). An assignment like this would also be limiting because it focuses students' attention on the operations rather than the purpose of graphing. An insufficiently structured assignment would be for students to construct a graph without any guidance. An appropriately challenging and structured graphing assignment might ask students to generate ideas of how to make a visual argument about their findings, draft visuals based on their ideas, present their drafts, get feedback on their drafts, and then revise based on feedback. Students should also have regular opportunities to reflect on their work, communicate about their progress (or lack thereof) and results, and get feedback from peers and instructors in order to maximize their learning (Corwin et al., 2015a, 2015b).

How will students' progress be assessed? Because CUREs engage students in work with unpredictable outcomes, it is likely that students will experience failure in the form of technical problems, negative results, and the like. Assessments must be designed to document and inform the progress of *students*, rather than relying on the success of experiments. Students will need reassurance that their success in the course (i.e., their grades) do not depend on obtaining positive results. Commonly used formative assessments include lab notebooks and periodic research updates, either orally in "group meeting" style or in the form of brief research reports. Posters, journal-style papers, annotated database entries, and oral presentations are common as summative assessments. These types of "authentic assessments" (Hart, 1994) benefit from the use of rubrics, both as a source of guidance about expectations and tool for equitable grading (Allen and Tanner, 2006).

What are the roles of instructional staff? Some CUREs are taught by a single faculty member whose responsibilities seem obvious: teach the course and help move the research forward. As explained in the section on mentoring, however, CURE instructors may benefit from rethinking their role to include mentoring functions. CURE instructors should also give thought to whether they or the students should be responsible for each aspect of the research (Buck et al., 2008). Some CUREs involve graduate teaching assistants or other instructional staff who may not be familiar with the research. In these instances, explicit attention should be given to bringing instructional staff up to speed on both the research and how to interact with students in ways that are consistent with the goals for the CURE. Yet other CUREs involve undergraduates as learning assistants or mentors who may have participated in previous iterations of the CURE. Involving experienced undergraduates can help maximize benefits to students because they are often perceived as more approachable than instructors or GTAs and have a more recent recollection of what it was like to learn the material, struggle to make progress, and overcome their struggles. However, peers may encounter difficulties in this role, such as whether to be an authority or a friend (Terrion and Leonard, 2007a). Peer mentors may also generate conflict by disagreeing with the guidance offered by the instructor or doing work for the students instead of letting students do it themselves. Thought should be given to how to prepare undergraduates for their roles and how to proceed if and when conflicts arise (e.g., Handelsman, 2005).

How will research learning tasks change as discoveries are made and initial research questions are answered? As with any research, the research in CUREs evolves as discoveries are made, conclusions are drawn, and new hypotheses and questions emerge. Given that CUREs have only recently been the focus of study, there has been little if any investigation of how CUREs evolve scientifically, including strategies for shepherding CUREs through scientific transitions. Thought should be given as to when and how research learning tasks should evolve in order for the research to progress and for new cohorts of students to have opportunities to make discoveries.

Challenges of CUREs

There has been little systematic study of the challenges associated with developing, implementing, and sustaining CUREs. Lopatto and colleagues (2014) surveyed a national group of faculty from diverse institutions about the challenges they experienced in implementing GEP. Faculty who persisted in implementing the program reported that the most significant challenges were making the experience fit in the undergraduate curriculum of their institution, concerns about teaching assistantship support, and concerns about class sizes being too large to implement the project well. These same faculty reported that the central support system offered by GEP, including follow-up professional development, a central website with information and resources, supportive colleagues, and staff support for computing, troubleshooting, and instruction, helped mitigate the challenges. The concerns about curriculum fit could be attributable to the content of the CURE (genomics / bioinformatics, which is not a standard course in all undergraduate life science curricula), rather than the research experience itself.

Shortlidge and colleagues (2016) interviewed 38 faculty representing a diverse set of CUREs and institutions about the challenges they experienced developing and teaching CUREs. These faculty reported that they found the logistics, workload, time, and costs associated with CURE instruction to be challenging. About 30% of them also expressed concern about the risks and ambiguity inherent to doing research and how that not only made them uncomfortable as instructors but also could result in student resistance. These faculty believed that instructors who are comfortable with uncertainty, have expertise in the research area, and are willing to invest extra time and effort, especially to get the project launched, are best positioned for success in teaching a CURE. Spell and colleagues (2014) focused more narrowly on understanding the barriers to CURE implementation in introductory biology. However, the national group of faculty they surveyed reported similar barriers to CURE instruction, including the time needed to develop a CURE, issues related to class size (i.e., introductory biology serves many students), and cost. This group of faculty also believed that introductory students were not well prepared to engage in research, that their colleagues would be resistant, and that their administrators would not be supportive. One study of the implementation of an introductory biology CURE examined this directly by preparing faculty at a two-year college and a research university (Wolkow et al., 2014). They found that unique issues arose at the two-year college that were addressable with additional preparation and scaffolding for both faculty and students, and reduction of the scope of work to allow more time to learn to do the work.

CURE Adoption and Sustainability

There are no published reports or studies of the processes by which CUREs have been adapted, scaled up, or sustained. Qualitative research that allows for systematic documentation and analyses of the natural histories of CUREs are needed to yield insight into (1) how to engender buy-in among faculty, students, and administrators, (2) how to continue research over time with new cohorts of students and the generation of new knowledge that affects the research direction, (3) how to sustain CUREs in terms of finances and curricular integration, and (4) when and how to sunset CUREs based on the needs of students, faculty, institutions, and the science.

Although a handful of studies reported costs per student or indicated that cost was a consideration in selecting the research focus and methods, no reports of cost/benefit analyses related to CUREs could be found in the literature at this time. Large-scale, experimental or quasi-experimental studies using direct measures of student outcomes will likely be necessary before cost/benefit analyses are possible.

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