Preparing Teaching Assistants to Facilitate Course-based Undergraduate Research Experiences (CUREs) in the Biological Sciences: A Call to Action

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ABSTRACT
Course-based undergraduate research experiences (CUREs) offer an expanding avenue to engage students in real-world scientific practices. Increasingly, CUREs are instructed by graduate teaching assistants (TAs), yet TAs may be underprepared to facilitate and face unique barriers when teaching CUREs. Consequently, unless TAs are provided professional development (PD) and resources to teach CUREs effectively, they and their students may not reap the assumed benefits of CURE instruction. Here, we describe three perspectives – that of the CURE TA, the CURE designer/facilitator, and the CURE student – that are collectively intended to inform the development of tentative components of CURE TA PD. We compare these perspectives to previous studies in the literature in an effort to identify commonalities across all sources and offer potential insights for advancing CURE TA PD efforts across a diversity of institutional environments. We propose that the most effective CURE TA PD programs will promote the use of CURE-specific instructional strategies as benchmarks for guiding change in teaching practices and should focus on three major elements: 1) enhancement of research and teaching acumen, 2) development of effective and inclusive mentoring practices, and 3) identification and understanding of the factors that make CUREs a unique learning experience.

INTRODUCTION
Undergraduate Research

The 1983 report, *A Nation at Risk*, brought widespread attention to low and inequitable rates of achievement in mathematics and science, insisting that biology faculty, in particular, develop coordinated plans to improve instruction (American Association for the Advancement of Science [AAAS], 2010; Chen, 2013). Since the report, national calls for education reform have escalated. Notably, science faculty have been tasked with bridging the gap between research and teaching in order to attract more undergraduates to science, technology, engineering, and mathematics (STEM) fields (National Research Council [NRC], 2003). The common goal of these reform efforts has been to develop and implement science instruction that better reflects what scientists actually do rather than a contrived version of the scientific method (Spell *et al.*, 2014).

One means to address this aim is to involve students in undergraduate research experiences (UREs). Prior studies indicate that students who participate in UREs advance in their analytical and critical thinking skills (Seymour *et al.*, 2004; Lopatto and Tobias, 2010), display increased academic achievement (Russell *et al.*, 2007; Cole and Espinoza, 2008), are retained at higher rates within the STEM disciplines (Russell *et al.*, 2007), and are more likely to engage in graduate studies (Lopatto, 2004; Seymour *et al.*, 2004; Russell *et al.*, 2007) than their peers who did not engage in

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UREs. UREs that are specifically centered on faculty-mentored research projects impact a student's ability to "think like a scientist," resulting in reported gains in collaboration and communication, as well as improvements in student affective outcomes such as interest in science and development of a science identity (Seymour *et al.*, 2004; Hunter *et al.*, 2007; Thiry *et al.*, 2011). For these reasons, participants of UREs are often better prepared to advance in science fields than their counterparts (Thiry *et al.*, 2011).

Despite strong evidence supporting the need to engage more students in research, there are numerous challenges to achieving that goal, including limits on faculty time, funding, and the resources needed to offer UREs (National Academies of Sciences, Engineering, and Medicine [NASEM], 2017). Because UREs traditionally engage students through one-on-one apprenticeships, opportunities are frequently confined by a finite number of research faculty at a given institution and limited space within each researcher's laboratory (PCAST, 2012; Rodenbusch *et al.*, 2016). Thus, there is inequitable access to opportunities for undergraduates to participate in UREs, as certain groups of students may be more likely to seek out research apprenticeships or to be handpicked by faculty to join their labs (Auchincloss *et al.*, 2014; Bangera and Brownell, 2014). Furthermore, some faculty may be hesitant to take on undergraduate students because training them may result in lower research productivity than the training of a graduate student (Chopin, 2002; Prunuske *et al.*, 2013; Morales *et al.*, 2017). Similarly, recent studies highlight that, in a mentored research experience, students can have negative interactions with their research mentors, be those faculty or other trainees (Cooper *et al.*, 2019; Limeri *et al.*, 2019; Tuma *et al.*, 2021). Although undergraduate research is largely appreciated as a high-impact practice in most STEM disciplines (Lopatto, 2010; Russell *et al.*, 2010; O'Donnell *et al.*, 2015; Lanning and Brown, 2019), there are clearly questions regarding access to and quality of UREs.

Course-based Undergraduate Research Experiences

A potential solution to some of the drawbacks and limitations of apprenticeship-style UREs is course-based undergraduate research experiences (CUREs). A CURE is a course that is generally integrated into a laboratory curriculum, where students address a research question or problem that is of interest to the broader community with outcomes that are unknown both to the students and to the instructor (Domin, 1999; Weaver *et al*,. 2008; Auchincloss *et al.*, 2014). Similar to many inquiry-based courses, CUREs engage students in essential research elements such as using scientific practices, collaboration, and iteration. However, CUREs are distinct from inquiry courses in that they are not only designed to induce the aforementioned outcomes, but they additionally provide the opportunity for broadly relevant and novel discovery – occasionally even resulting in student authorship on scientific publications (Auchincloss *et al.*, 2014; Turner *et al.*, 2021). This critical design element of CUREs is not missed by students. Indeed, students have reported perceiving that their CURE experiences are akin to what it would be like to conduct research in faculty run labs (Rowland *et al.*, 2016; Goodwin *et al.*, 2021b). However, in order to truly engage students in scientific research in the course setting, it is important that CURE instructors actively foster the premise of students as legitimate participants in scientific research and ensure their actions are contributing to achieving research goals (Corwin *et al.*, 2015a).

Like students who partake in UREs, students who have participated in CUREs have demonstrated numerous cognitive and affective gains (Corwin *et al.*, 2015a; Shapiro *et al.*, 2015). These include an increased interest in scientific research as well as gains in research skills, scientific literacy, science identity, emotional ownership, self-efficacy, and persistence in the sciences (Harrison *et al.*, 2011; Brownell *et al.*, 2015; Olimpo *et al.*, 2016; Indorf *et al.*, 2019; Cooper *et al.*, 2020; Esparza *et al.*, 2020; Ramírez-Lugo *et al.*, 2021). Participating in CUREs in introductory biology courses, in particular, can result in an increased likelihood of students graduating on time and engaging in apprenticeship-based research experiences later in their academic careers, as compared with a matched comparison group consisting of students enrolled in traditional introductory biology laboratory courses (Rodenbusch *et al.*, 2016; Indorf *et al.*, 2019). Further, CUREs may be especially impactful for students traditionally underrepresented in STEM fields (Ing *et al.*, 2021) and for students who enter a CURE with lower academic preparedness than their peers (Shapiro *et al.*, 2015; Ing *et al.*, 2021). With their vast potential, CUREs present a viable answer to the national call for widespread involvement of undergraduate students in research (AAAS, 2010; Bangera and Brownell, 2014) and are being broadly promoted as essential to the undergraduate experience (NASEM, 2015).

CURE Instruction

The CURE model can be embedded into classrooms in a countless number of ways. Implementation of CUREs, like any evidence-based pedagogy, is highly context dependent, and CUREs vary across universities, departments, and instructors (see Science Education Research Center, 2021, for examples; Olimpo and Kern, 2021). There are two major categories of CUREs – the "network" CURE and the "independent" CURE (Shortlidge *et al.*, 2016). In a network CURE, faculty often attend a training along with individuals at other institutions to implement a CURE based on an already-established structure (e.g., the Genomics Education Project [Hark *et al.*, 2011]; SEA-PHAGES [Jordan *et al.*, 2014]; Tiny Earth [Hurley *et al.*, 2021]). In contrast, independent CUREs typically emerge from a faculty member's research interests or program (e.g., Fisher *et al.*, 2018; D'Arcy *et al.*, 2019; D'Arcy *et al.*, 2023). To date, CUREs have been integrated into biology curricula at both the introductory and advanced levels, in lab-based courses as well as field courses, and across a multitude of subdisciplines ranging from Microbiology and Genetics to Marine Ecophysiology and Urban Plant Ecology (e.g., Olimpo *et al.*, 2016; Thompson *et al.*, 2016; Fisher *et al.*, 2018; Shortlidge *et al.*, 2021; Stanfield *et al.*, 2022).

The extant literature on CUREs has largely focused on student outcomes and descriptions of CURE curricula (e.g., Olimpo *et al.*, 2016; Rodenbusch *et al.*, 2016; McDonald *et al.*, 2019), with less attention paid to the central characteristics of CURE instruction (see, as an exception, Esparza *et al.*, 2020). Although there is an assumption that the CURE model is facilitated by "senior researchers" (Auchincloss *et al.*, 2014; Rodenbusch *et al.*, 2016), this task has increasingly fallen to graduate teaching assistants (TAs) and other instructional faculty as the inclusion of CUREs in STEM laboratory curricula has continued to grow. Faculty CURE instructors of both network and independent CUREs have reported that effective CURE instruction necessitates sufficient and relevant research experience on the part of the instructor (Shortlidge *et al.*, 2016, 2017). Consequently, it may be challenging for novice researchers to facilitate CUREs due to the dynamic and unpredictable nature of a CURE learning environment (Shortlidge *et al.*, 2016; Heim and Holt, 2019; Moy *et al.*, 2019). As the goal of engaging students in CUREs continues to become more mainstream in undergraduate STEM education, ensuring the preparedness of individuals to facilitate such courses becomes increasingly more relevant.

While the specific design and context of each CURE will inherently lead to variance in student outcomes, such outcomes will also inevitably be impacted by instructor quality and effectiveness. This could be particularly true at the introductory level, where laboratory classes are frequently taught by multiple instructors, who likely vary widely in their capacity to effectively teach a CURE and/or their buy-in to the CURE model (Esparza *et al.*, 2020; Goodwin *et al.*, 2021b).

Graduate TAs

The majority of CURE research and advocacy to date neglects the salient and prevalent reality that graduate student TAs are often the primary instructors of the introductory laboratory sections where many CUREs are or will be embedded. Data collected from 65 institutions demonstrate that TAs are responsible for teaching the bulk of the introductory biology labs at 71% of comprehensive universities and at 91% of research universities (Sundberg *et al.*, 2005). Graduate students are undeniably a key factor in undergraduate science education, yet the prominent role of TAs, in particular in undergraduate biology education, is rarely addressed or acknowledged (Gardner and Jones, 2011).

Many practitioners and researchers have advocated for more holistic and robust professional development (PD) for TAs than what currently exists (Schussler *et al.*, 2015; Connolly *et al.*, 2016; Reeves *et al.*, 2016; Feldon *et al.*, 2017; Connolly *et al.*, 2018; Kern and Olimpo, 2023). Brief trainings, such as the common graduate student PD "boot camp" (i.e., a single- or multiday experience that effectively serves to provide graduate students with a crash course on pedagogy and, consequently, often only discusses said pedagogy in a superficial manner with limited opportunities for practice and feedback) are not particularly effective (Feldon *et al.*, 2017). It is well documented that, in many cases, TAs receive minimal pedagogical support and/or training during their graduate tenure (Rushin *et al.*, 1997; Austin, 2002; Luft *et al.*, 2004; Tanner and Allen, 2006; Gardner and Jones, 2011; Kendall and Schussler, 2012; Schussler *et al.*, 2015; Goodwin *et al.*, 2018). Thus, it is not surprising that nearly 85% of TAs feel inadequately prepared for their teaching assignments (Russell, 2009). Compounding the impact of having underprepared TAs is the fact that the majority of biology TAs (88%) are assigned to teach introductory laboratory courses (Schussler *et al.*, 2015). We know that the majority of students (60% or more) leave STEM majors after introductory courses (PCAST, 2012); therefore, these courses may be the first and last science laboratory experience undergraduates have during their time in the academy. It is therefore of critical importance that these courses are taught by prepared instructors (Reeves *et al.*, 2016). In this context, specific attention to TA PD is especially warranted, as it could have a powerful impact on undergraduate student learning at many colleges and universities, especially within the context of CUREs (Ryker and McConnell, 2014; Reeves *et al.*, 2016; Zehnder, 2016; Esparza *et al.*, 2020; Goodwin *et al.*, 2021b).

Broadly speaking, it is important to recognize that instruction (whether in CUREs or elsewhere) is a complex, multifaceted phenomenon (Cohen and Ball, 1999). Instructor capacity is widely viewed as a critical element of good teaching and is imperative to providing quality education with "the capacity to produce worthwhile and substantial learning" (Cohen and Ball, 1999). Cohen and Ball (1999) argue that instructional reform requires considering all interactions that take place between the instructional materials, the instructor, and the students. A review of the K–12 literature suggests that instructors with deep understanding of subject matter content, who are also proficient in pedagogical content knowledge, were more successful in promoting student engagement and improving student learning than their counterparts who lacked such understanding and knowledge (Darling-Hammond and Bransford, 2007). As stated previously, faculty often choose to teach CUREs based on their personal research and/or pedagogical interests (Shortlidge *et al.*, 2016, 2017). Thus, faculty teaching CUREs may possess deep subject matter knowledge (i.e., knowledge of and about the research topic), pedagogical content knowledge, and interest in CUREs as a teaching strategy, all of which can result in suitable instructor capacity to teach a CURE. However, if CUREs are taught by TAs, it is likely that said TAs are not yet experts in research, may lack deep knowledge of the CURE research topic, may not have experience in evidence-based teaching, and/or may not even have an interest in teaching (Goodwin *et al.*, 2022; Goodwin *et al.*, 2023). In some cases, teaching may simply present a financial means by which TAs can pursue graduate research (Golde and Dore, 2001; Austin, 2002). Further, the ways TAs are assigned to teach various course types (e.g., CUREs vs. traditional laboratories) can vary extensively across institutions, even between departments within a single institution (e.g., Reeves *et al.*, 2016; Esparza *et al.*, 2020; Goodwin *et al.*, 2021b; Goodwin *et al.*, 2022; Goodwin *et al.*, 2023). Collectively, these cooccurring factors – TA content knowledge, pedagogical experience, and TA choice in what they teach – will directly impact both TA and undergraduate experiences in a CURE.

CURE-specific Challenges

CUREs introduce an added complication to any conversation of effective instruction in that their focus is not just to convey content, but rather to provide a research experience. Even for Ph.D.-level instructors, incorporating research into a course can be challenging if their research experience is not similar to that of the CURE, they have little formal teaching experience, and/or they have not engaged in evidence-based teaching practices (Shortlidge *et al.*, 2016).

A documented challenge for TAs who have taught discovery-based chemistry and biology labs is empowering students to take control of their own learning – TAs tend to have difficulty permitting students to have autonomy in figuring out answers on their own and tend to intervene and control the situation rather than allowing their students to experience failure (Kurdziel *et al.*, 2003; Luft *et al.*, 2004; Gormally *et al.*, 2016). This is potentially problematic for TAs, given that faculty who teach CUREs believe one must "have the ability to deal with uncertainty" and have a "background in research" in order to deal with the unpredictability of science and to troubleshoot unexpected issues (Shortlidge *et al.*, 2016). This idea was directly reflected in a study on one institution's TA-taught CUREs, in that TAs reported that their lack of expertise in the research topic was a challenge (Heim and Holt, 2019). The same study reported that TAs felt that the most prevalent issue with CUREs was the unpreparedness of undergraduates to participate in a research-based curriculum. This preconception, alongside the desire of TAs to demonstrate their knowledge to students and to avoid receiving negative evaluations from frustrated students (e.g., Kurdziel *et al.*, 2003; Gormally *et al.*, 2016), all present salient barriers to TAs teaching CUREs. Further, if a TA is not fully prepared or onboard with teaching the CURE and creates a negative or complacent classroom climate as a result, it could impact student outcomes (O'neal *et al.*, 2007; Goodwin *et al.*, 2023). Undergraduates see TAs as less knowledgeable than faculty in traditional (cookbook) lab settings (Kendall and Schussler, 2012), and this perception could be exacerbated if a TA is challenged by the level of research and teaching expertise necessary to facilitate a CURE.

Finally, undergraduates in CUREs are expected to collaborate with the instructor and their peers (Auchincloss *et al.*, 2014). Thus, the interactions in a CURE should be intentionally facilitated and may require more of a mentor–mentee relationship than a traditional teacher–student relationship. For faculty, this can be a benefit of teaching CUREs (Shortlidge *et al.*, 2016). While graduate students can be effective mentors to undergraduate researchers in individual lab settings (e.g., Aikens *et al.*, 2016), to our knowledge, their capacity to serve as CURE research mentors has only recently begun to be investigated (Goodwin *et al.* 2021b; Santillan *et al.*, 2022).

Professional Development (PD)

To address the barriers to scaffolding research experiences within the structure of a course, instructors need time to engage in PD (Spell *et al.*, 2014). As previously described, most TA PD initiatives have little formal discussion of effective pedagogical practices or feedback regarding these practices (Luft *et al.*, 2004; DeChenne *et al.*, 2015; Goodwin *et al.*, 2018; Kern and Olimpo, 2023). The skills necessary for teaching are not simply intuitive and need to be acquired through more structured training and educational programs (Foley, 1974). Research has demonstrated that participation in such PD initiatives (e.g., a pedagogy course) can positively influence TAs' learning and attitudes toward teaching (Zehnder, 2016; Kern and Olimpo, 2023). While researchers have offered a few suggestions for successful program characteristics, prior studies have largely failed to identify the central tenets of effective CURE TA PD (Spell *et al.*, 2014; Rodenbusch *et al.*, 2016; McDonald *et al.*, 2019; Moy *et al.*, 2019). In keeping with the literature on teacher education, we assert that the structure of such PD should be content focused, promote active learning, be provided for a sustained time period, highlight diversity, and utilize collective participation (Desimone and Garet, 2015; Zehnder, 2016).

Relatedly, Reeves *et al.* (2016) put forth a framework that outlines desirable TA PD outcomes: cognition (includes knowledge, attitudes, and beliefs about teaching); teaching practices (i.e., instructional practices); and undergraduate student outcomes. Facilitators of CURE TA PD initiatives would do well to attend to these outcomes as a means to assist TAs in engaging with students around CURE instructional activities in a manner that fosters student learning and success (Shulman, 1986; Avery and Reeve, 2013). To these ends, the most effective CURE TA PD programs will promote the use of CURE-specific instructional strategies as benchmarks for guiding change in teaching practices (Avery and Reeve, 2013).

Graduate training is frequently focused on the graduate student journey from novice to expert researcher, although many other aspects of scholarship are paramount to becoming a successful academic (Austin, 2002). CUREs, in particular, may present an unparalleled opportunity for graduate students to gain exposure to multiple aspects of faculty positions. Many graduate students may be relatively novice researchers and/or teachers, but prior studies indicate that graduate student investment into both activities can be mutually synergistic (Feldon *et al.*, 2011; Shortlidge and Eddy, 2018; Reid and Gardner, 2020). Having the chance to teach CUREs can be a valuable and timely opportunity for TAs to develop both research and teaching skills. Reflecting this idea, the chemistry education research community has recently advocated for "CURE leadership as a training platform for future faculty" (Cascella and Jez, 2018).

PERSPECTIVES REGARDING THE NECESSARY COMPONENTS OF CURE TA PD

As STEM education continues to integrate the CURE model into undergraduate curricula, the critical, systems-level issues discussed above must be considered when heeding calls for developing CUREs, especially when faculty are not the course lead. Despite the relative dearth of literature on CURE TA PD, recent studies have begun to highlight the perspectives of CURE TAs, their students, and CURE designers/facilitators with respect to possible foci for inclusion in such PD. In this section, we review those studies, with the intent of supporting the proposed future directions made at the end of this essay. Collectively, our aim is to increase readers' awareness of the value and importance of CURE TA PD and to encourage conversation among CURE TA PD facilitators.

CURE TA Perspectives

Existing research on the perceptions of CURE TAs has largely been limited to single instructional contexts (Heim and Holt, 2019; Moy *et al.*, 2019; Goodwin *et al.*, 2021b). As alluded to earlier in this article, these studies have demonstrated that, in general, TAs find value in mentoring undergraduates and believe that leading a CURE has the potential to enhance their own professional skillset (e.g., communication and research skills). However, there are some TAs that believe that CUREs are neither beneficial for introductory biology students, nor do they provide a valuable PD experience for themselves (Goodwin *et al.*, 2021b, 2023). One study reported several prevalent barriers and challenges that TAs believe impinge upon their ability to effectively facilitate CUREs. These include: low self-efficacy with respect to serving in a supervisory role, logistical and time constraints, a lack of specific research expertise, and added cognitive demand imposed by the open-ended structure of a CURE (Heim and Holt, 2019). These reported TA benefits and obstacles are akin to those cited by CURE faculty instructors

(Shortlidge *et al.*, 2016), suggesting that targeted PD designed to address one or more of those areas may be of utility to all CURE facilitators. Further, the perceived costs of teaching a CURE can vary widely by TA, indicating that some TAs may need more support than others (Goodwin *et al.*, 2021b).

Seeking to expand upon this body of work, Shortlidge and Goodwin (described in Kern [2022]) conducted a qualitative study across a diversity of institutions nationwide to capture a more representative account of TA perspectives on facilitating CUREs. Findings of this study largely echo the above observations. Specifically, semistructured interview data obtained from 22 CURE TAs revealed that many of them believed that facilitating a CURE helped them hone their own skills in one or multiple areas including research, mentorship, communication, and evidence-based teaching – all of which could be important as they move forward in their careers. Like faculty (Shortlidge *et al.*, 2016), TAs also described developing a better relationship with their students in CUREs as compared with traditional laboratory courses, and many reported increased overall excitement around teaching a CURE. While most TAs in the study had generally positive views of CUREs as a whole, several recognized that they struggled with the unpredictability of research and (less frequently) explained that this was particularly challenging given their own lack of research expertise.

Student Perspectives on CURE TAs

Recently, Goodwin and colleagues (2022, 2023) explored how biology students perceive their CURE TAs, as this critical perspective is commonly uncaptured. As part of their prior work at one institution, Goodwin *et al.* (2021b) documented that TAs largely reported feeling confident in teaching a CURE and did not believe that more training would improve their teaching. Yet, those TAs' students reported wide variation in how they perceived their TAs' competence in creating a student-supportive CURE learning environment (see also Goodwin *et al.*, 2022). Collectively, these data indicate that, even when TAs are confident in their CURE instruction, further teaching PD may be needed, and triangulating student experiences with instructor actions is critical to understanding course outcomes (Goddard *et al.*, 2000).

Relatedly, Goodwin *et al.* (2023) found that TAs can influence how students experience central research elements in a CURE (e.g., discovery and broader relevance). For instance, students with higher motivation to engage in a CURE were more likely to describe their TAs as supporting their autonomy and competence in the key research elements comprising the CURE than their peers with lower levels of motivation. These same students were also more likely to express that their TA facilitated social belonging in the CURE classroom, a critical factor known to impact student success (Strayhorn, 2018). These findings raise a concern with respect to one of the main purposes of a CURE – to make access to research experiences more inclusive (Bangera and Brownell, 2014). If TA-facilitated CUREs disproportionately benefit those students who are already scientifically motivated, the intention of equitable outcomes is not being achieved.

Of similar concern is the observation that, although the CURE model places emphasis on scaffolding opportunities for broadly relevant and novel research, students in the study conducted by Goodwin *et al.* (2023) generally perceived that their TAs' priority was to teach students scientific practices and scientific content – elements that are emphasized in traditional biology labs and that are not unique to CUREs. Additionally, student perspectives regarding the purpose of engaging in a CURE occasionally varied as a function of who was assigned as their CURE TA. Some students felt that CUREs are offered primarily to support students, while others indicated that CUREs exist to enhance the research productivity and prestige of an institution (Goodwin *et al.*, 2023). These findings suggest that how CURE TAs communicate with their students (e.g., through mentoring, informal conversation) and what they choose to emphasize during those interactions may directly shape the way students perceive and engage with the CURE. Additional studies on CUREs taught by TAs across institution type and CURE format will enable us to better understand the bidirectional relationship between TA and student perceptions of CUREs.

CURE Facilitator Perspectives on TA PD

To the best of our knowledge, only one study has asked faculty instructors of CUREs what they believe to be the key potential elements of CURE TA PD (Kern, 2022). As part of their dissertation work, Kern (2022) employed purposeful sampling to recruit CURE facilitators (i.e., non-TA instructors; $N = 49$) in attendance at the 2019 Association for Biology Laboratory Education (ABLE) and Society for the Advancement of Biology Education Research (SABER) annual meetings. Participants were asked to complete a brief survey in which they indicated whether 26 items related to teaching and learning should be included as part of PD for: 1) all TAs facilitating CUREs, 2) some TAs facilitating CUREs, or 3) no TAs facilitating CUREs. Inclusion of the second option, "some TAs facilitating CUREs," was intentional given the wide range of potentially unique conventions for any specific CURE. For example, Olimpo *et al.* (2019) reported on a CURE that required students to obtain human subjects research certification to conduct independent projects on health disparities in the El Paso border region, yet human subjects research certification is unlikely to be a requirement for the majority of CURE students or CURE TAs. Results of Kern's study indicated that a diverse suite of elements ranging from more generalized laboratory and pedagogical practices (e.g., lab safety, inclusive teaching) to more contextualized instructional elements of CUREs (e.g., facilitating collaboration, iteration) were viewed as being necessary for all CURE TAs. Other items – such as developing students' metacognitive abilities and aiding TAs in adopting strategies for discussing with students the broader implications of discovery-based investigations for science and society – were believed to be less essential. Furthermore, items related to the professional growth of the CURE TAs themselves (rather than their students; e.g., planning and designing lessons, translating CURE teaching experience to a CV or teaching statement) were frequently ranked as being essential for only some CURE TAs rather than all CURE TAs, suggesting an area for future discussion and investigation.

After the initial evaluation described above, participants were asked to select the three most important components that they felt should be included in CURE TA PD. The majority of participants indicated strategies for troubleshooting and addressing challenges that arise during the research process. This was followed by strategies for teaching experimental design and/or facilitating students' development of scientific process skills. To a lesser degree, respondents also selected strategies for discussing with students the broader relevancy of their work, strategies for facilitating student communication of their findings, specific teaching techniques, and strategies for improving students' ability to "think like a scientist" as being among their top three choices.

Collectively, these findings corroborate earlier work in the field (e.g., Heim and Holt, 2019) and closely mirror the perspectives provided by CURE TAs. Notably, however, the element that the literature argues is unique to CUREs (broader relevance; Auchincloss *et al.*, 2014) is less emphasized than elements that are typically found in most laboratory courses (e.g., skill building).

IDENTIFYING CORE ELEMENTS OF CURE TA PD

In consideration of the above findings and the previously-reported outcomes summarized herein, we propose that CURE TA PD initiatives could encompass three major elements: 1) enhancement of research and teaching acumen, 2) development of effective and inclusive mentoring practices, and 3) identification and understanding of the factors that make CUREs a unique laboratory experience. Each of these elements are described below.

Research and Teaching Acumen

Previous studies suggest that CUREs should be facilitated by instructors who have spent time conducting research themselves (Auchincloss *et al.*, 2014; Shortlidge *et al.*, 2016), as this may alleviate expressed challenges with teaching CUREs. Reflective of the central tenets of CUREs (e.g., student engagement in scientific practices, discovery, and iteration), facilitators should also possess an adequate understanding of experimental design principles in order to guide students through the process of creating and/or executing independent investigations (Heim and Holt, 2019). This might be accomplished by using microteaching approaches in which TAs are tasked with modeling the experimentation process, involving TAs in outlining and discussing central elements of that process (e.g., *sensu* Harwood, 2004), and/or facilitating open conversation about how the TAs themselves engage in research (and how this might translate, practically, into the CURE environment). While arguably less realistic, it might also be possible for CURE facilitators to intentionally recruit TAs who are more advanced in their program of study – for instance, those individuals who have already successfully defended their thesis/dissertation proposal and, therefore, have more intimate familiarity with the research process.

A TA's research training and expertise could be anywhere along the novice to expert continuum; therefore, it would be wise to engage all CURE instructors in some version of the CURE research itself before teaching the CURE. This would allow for TAs to gain knowledge on the focal study system, context and methodology, and, ideally, prior or related literature. This is likely particularly crucial if a TA is both a novice researcher and a novice teacher. One suggestion would be to pair novice TAs with a more senior TA and/or to structure TA PD such that novice TAs can shadow more experienced TAs or faculty instructors, thereby gaining relevant knowledge on the research project and how to execute pedagogical practices that are specific to the CURE.

More broadly, recognition of and attentiveness to the situational factors governing one's classroom are crucial in optimizing the learning experience. Respondents in the studies described by Kern (2022) – which included CURE facilitators in the biological sciences subdisciplines – valued the importance of "considering the classroom environment." When specifically asked to describe why they valued this tenet as a potential component of CURE TA PD, participants noted the importance of understanding and incorporating students' experiences into one's teaching, being mindful of how to structure the learning environment to be responsive to the needs of diverse students, and remaining cognizant of how individuals in the classroom interact to achieve common goals. Relatedly, in the work conducted by Goodwin *et al.* (2022), CURE students reported significant variation in the ability of their TAs to create a student-supportive learning environment. These findings corroborate previous studies that have emphasized instructor capacity as a critical element of good teaching (Cohen and Ball, 1999). PD that includes giving graduate students a chance to practice relevant evidence-based and inclusive teaching practices could have a powerful impact on TAs' teaching self-efficacy, attitudes toward teaching, and continued use of evidence-based practices (DeChenne *et al.*, 2015; Connolly *et al.*, 2016; Reeves *et al.*, 2016; Goodwin *et al.*, 2018).

Some faculty who develop their own CUREs see those courses as a means to highlight and embody their identity as a teacher–researcher (Shortlidge *et al.*, 2016). Similarly, PD for CURE TAs should offer opportunities for the TAs to reflect on the intersection between research and teaching, so as to normalize and create an integrated framework for facilitating CUREs. Given that TAs report that CUREs offer opportunities for them to improve their teaching, research, and mentorship skills (Goodwin *et al.*, 2021b; Shortlidge and Goodwin (see Kern [2022]), CUREs may be a unique mechanism for training future faculty to embody a more holistic scholarship (e.g., Boyer, 1990), which has been advocated for over the recent decades (Austin, 2002; Gardner and Jones, 2011).

We further contend that TAs could benefit from CURE PD intentionally designed to curate a mindset that embraces the uncertain nature of research. If CURE TAs are expecting that not everything will inherently go according to plan, and that those experiences can be turned into teaching opportunities, then they will be better equipped to practice this skill in real time. Teaching the need for patience throughout the scientific process and normalizing failure as a part of scientific research are important aspects of CURE instruction that can potentially increase undergraduate student buy-in to the authenticity of the CURE (Corwin *et al.*, 2015a; Gin *et al.*, 2018; Goodwin *et al.*, 2021a). Providing TAs with the pedagogical skills necessary to effectively aid students in iteration/troubleshooting and educating TAs about how to troubleshoot themselves is arguably critical in advancing the established research agenda for the course (Corwin *et al.*, 2018; Gin *et al.*, 2018).

Effective and Inclusive Mentoring

Comments pertaining to mentoring and mentorship were replete throughout the studies that we reviewed (e.g., Shortlidge *et al.*, 2016; Heim and Holt, 2019; Goodwin *et al.*, 2021b; Kern and Olimpo, 2023), highlighting the belief that instructors in CURE contexts have a more substantial role than solely that of a deliverer of information and lab moderator. However, TAs differ in their perceptions of what their mentorship role in the CURE classroom should be: some focus on providing emotional support in the classroom, while others prioritize developing students' competence as a researcher. Conversely, some may simply struggle to adopt clear mentorship roles (Goodwin *et al.*, 2021b). The need to adopt multiple roles can be intimidating to TAs, and informal conversations with CURE facilitators (data not shown) suggest that CURE TA PD should address components of effective mentorship and project management, much like how a principal investigator might lead their own lab group and manage different projects (Dolan, 2016). In addition to identifying and demonstrating effective mentoring strategies (e.g., through roleplay), CURE TA PD facilitators might make use of existing instruments (e.g., Mentoring Competency Assessment [Fleming *et al.*, 2013]) to engage TAs in exploring their own perceived strengths and weaknesses in this area. There are a number of resources within the Entering Mentoring curriculum (Center for the Improvement of Mentored Experiences in Research, 2021) that provide realistic case studies that could likewise be used in CURE TA PD. Further, developing in-house case studies for TAs to engage with that are rooted in the institution's context and, perhaps, the CURE content could give TAs practice in handing situations before they arise.

Given that an explicit goal of CUREs is to make research experiences more accessible and equitable for undergraduates (Bangera and Brownell, 2014), intentional TA PD in inclusive pedagogy will be critical for all students to feel like they are "doing science." Part of this effort will be making this aspect of why we do CUREs explicit to TAs (more below) and by reinforcing this intentionality by integrating practical inclusive teaching skills into the PD (e.g., Dewsbury and Brame, 2019).

Knowledge of What Makes a CURE Unique

CUREs offer students a unique platform to engage in research that addresses real-world biological problems. As noted previously, the opportunity for students to engage in novel research that has relevance extending beyond the classroom is what distinguishes a CURE from other forms of laboratory instruction (e.g., traditional labs, inquiry-based labs; Auchincloss *et al.,* 2014). However, we found that when TAs had trouble recognizing the opportunities for broadly relevant, novel discovery in the CURE curriculum, students did not perceive that doing novel research in the CURE was a high priority (Goodwin *et al.*, 2022). Consequently, for those TAs with limited (or no) experience teaching CUREs, PD facilitators may consider explicitly discussing the unique research opportunities provided to students via CUREs and the role TAs can have in supporting students' understanding of the advantages of engaging in such a curriculum. This might be accomplished by first informing TAs that they are responsible for a research-driven course and asking them to discuss what they feel this opportunity entails, relative to the laboratory experiences that they likely engaged in as a student. TAs might also be prompted to consider how CUREs mirror (or not) apprenticeship-style research training. With this framing in mind, PD facilitators could then more formally introduce the dimensions of CUREs (Auchincloss *et al.*, 2014) and lead TAs into a discussion of how they anticipate facilitating such a course. As a training or assessment exercise, TA PD could include TAs completing a modified Laboratory Course Assessment Survey for instructors (Corwin *et al.*, 2015b) or, at minimum, reading the survey items as a group to gain an idea of the specific actions that they could be taking in the classroom to facilitate CURE elements. CURE TAs might be expected to read journal articles from the literature regarding why CUREs are being implemented nationally and to learn about some of the potential outcomes from CUREs. Therefore, those facilitating CURE TA PD should also be relatively familiar with the CURE literature base in order to lead a journal club or similar opportunities for CURE TAs. Lastly, PD facilitators may wish to take advantage of published tools (e.g., Olimpo and Kern, 2021) to aid the TAs in articulating the research and pedagogical goals of the CURE as well as documenting the course activities and assessments that align to each of the five dimensions of CUREs (Auchincloss *et al.*, 2014).

SUPPORTING CURE TA PD FACILITATORS

In addition to focusing on the content of the PD, care must be taken to provide appropriate support to those individuals tasked with PD facilitation. Prior research (e.g., Diaz-Martinez *et al.*, 2021; Miller *et al.*, 2022) suggests that this can best be achieved through creation of a community of practice focused on CURE TA PD that serves a dual function in collating and cataloging CURE TA PD resources. With generous support from the National Science Foundation's Research Coordination Network – Undergraduate Biology Education (RCN-UBE) program, authors Olimpo and Shortlidge (in collaboration with Co-PIs M. Aikens [University of New Hampshire] and A. Schuchardt [University of Minnesota, Twin Cities]) will direct the CURE TA PD to Enhance Scientific Teaching, Research, and Mentoring Capacity (CURE TAPESTRy) initiative (NSF-DBI 2217147). This effort will leverage the infrastructure and successes of previous networks, such as BioTAP (Biology Teaching Assistant Project, 2023) and CUREnet (Science Education Research Center, 2023), to 1) characterize the current CURE TA PD landscape; 2) create, implement, and assess a one-year fellowship experience for CURE TA PD facilitators, who will be tasked with generating novel CURE TA PD materials; and 3) develop and evaluate a "train-the-trainer" edX massively open online course designed to effectively prepare CURE TA PD facilitators for their role in providing PD to CURE TAs.

As a complement to large-scale efforts, such as CURE TAPESTRy, regional and national workshops – such as those conducted by Kern and Olimpo at the 2019 ABLE and SABER meetings – can offer CURE TA PD facilitators dedicated time to begin considering how they might shape a CURE TA PD program while simultaneously expanding the community of practice around CURE TA PD. These individuals, much like the CURE TAPESTRy fellows, could serve as CURE TA PD "champions," thereby broadening the network of educators and scholars committed to this cause. Additionally, the infrastructure of network CUREs may provide an ideal platform for expanding instructor PD to include TA-specific PD.

Regardless, any effort to support CURE TA PD facilitators must be accessible and inclusive, practical (i.e., result in the generation of a product that the facilitator can make use of to further CURE TA PD), promote dialogue around the topic, and be sustainable beyond a funding lifecycle.

CONCLUDING REMARKS

Since their advent, CUREs have increasingly been incorporated into STEM curricula nationwide. While there are now countless studies documenting the impact of CUREs on students' academic and professional growth (e.g., Olimpo *et al.*, 2016; Peteroy-Kelly *et al.*, 2017; Connors *et al.*, 2021), substantially less attention has been given to instructors in this same context. This is especially true for TAs, who are largely responsible for facilitating laboratory coursework, including at both the introductory and advanced levels (Sundberg *et al.*, 2005; Schussler *et al.*, 2015). Accordingly, this essay reflects our strong advocacy for the development and implementation of intentional CURE TA PD opportunities and likewise offers guidance for those interested in meeting this need.

We recognize that CURE TA PD efforts will not emerge as "one-size-fits-all" solutions to preparing graduate TAs, nor do we believe that they should be. The studies reviewed in this article highlight that, even in a small sample, CUREs are implemented in a variety of contexts and that each context will require nuanced PD. However, we encourage creators, facilitators, and evaluators of CURE TA PD initiatives to consider the following: 1) What level of training and experience do the TAs facilitating the CURE have with respect to research, teaching, and mentoring?; 2) What facets of TA PD are essential to include for the particular CURE, and which have a supporting role?; 3) What makes those facets essential (i.e., why are they necessary and valuable)?; and 4) What form will the PD require, and when will it be implemented?

Establishing targeted goals and feasible PD activities will ideally mitigate reported concerns regarding the time constraints of developing CUREs and the expanded role of the CURE instructor (Shortlidge *et al.*, 2016). Furthermore, soliciting routine formative feedback from both the TAs and their students can serve to enhance PD quality and provide constructive commentary on TA praxis. There are a number of ways to collect such feedback (e.g., minute papers, metacognitive prompts administered to TAs during prep meetings), and the methods used should reflect the intention. There are likewise mechanisms by which one can intentionally and systematically assess the outcomes of their CURE (for more, see Corwin *et al.*, 2015a; Shortlidge and Brownell, 2016), which may or may not be a goal for the institution or faculty member leading the initiative.

Although CURE TA PD approaches will inherently reflect the context in which they were created, a concerted and explicit effort among members of the community to attend to this element of CURE implementation will enable said approaches to be adaptable for use across institutions. Establishing partnerships with shareholders in Centers for Teaching and Learning and graduate schools can expedite this process, ostensibly leading to the genesis of new knowledge and techniques for promoting TAs' effectiveness in the CURE classroom. Creating a community of practice and culture around CURE TA PD will likewise foster sustainable advances for all parties involved beyond the immediate environment of the PD itself.

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