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| Perspective

Faculty rewards from course-based undergraduate research experiences (CURE) in biochemistry

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ABSTRACT In recent years, there has been an increase in the number of course-based undergraduate research experience (CURE) courses. These courses provide research opportunities for many more students than are typically exposed to traditional independent research experiences, including women, historically underrepresented groups in science, and non-traditional students. However, the benefits for faculty who teach CURE courses have been less well documented, potentially discouraging faculty from offering such courses. Reports describing the benefits faculty can accrue from developing and teaching CURE courses could incentivize more faculty to develop CURE courses. In this perspective article, we summarize the implementation of three biochemistry CURE courses, highlighting some of the benefits faculty may experience. We also propose some points to consider when designing CURE courses with realistic expectations for a semester-long research experience to provide a framework for instructors who are considering their own CURE development.

KEYWORDS faculty reward, CURE, biochemistry

Course-based undergraduate research experience (CURE) courses are courses where a whole class (led by a faculty member) evaluates a research question with the goal of discovering something important for the scientific community (1). Over the last few years, there has been an increase in the number of CURE courses offered at numerous institutions catalyzed by reports highlighting the benefits of undergraduate research experiences (2–6) and by the fact that more students can participate in CURE courses compared to traditional apprentice-style research experiences (1, 7, 8). Students who participate in CURE courses report increased communication skills (9), confidence, persistence, and interest in science (1), and studies have found that participation in CURE courses increases the probability of graduating with a STEM degree, the probability of graduating within 6 years (10), and leads to learning gains in lower and higher levels of Bloom's Taxonomy (9). Moreover, the availability of CURE courses has the potential to increase diversity in the scientific community by offering research opportunities to a broader population of students, including women, historically underrepresented groups in science, and non-traditional students (11). The possibility of creating a more inclusive environment for undergraduate students has been the main motivator for converting many traditional lab courses into CURE courses at our institution. The benefits for faculty offering CURE courses have been less well documented (10, 12, 13) and most of the CURE literature focuses on the benefits for students (2–6). We believe that an unintended consequence of a student-centered emphasis is a lack of encouragement for faculty. For instance, a report examining what contributes to faculty decisions to adopt new pedagogical strategies suggests that, among many other factors, a sense that an effort would be successful and result in a valuable reward contributes to a motivation to adopt a given strategy (14). Another report suggests that engaging faculty in professional development can contribute to the adoption of specific pedagogical strategies

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(15). Faculty may view numerous barriers, both real and perceived, for implementing CURE courses (12, 16, 17). However, faculty offering CURE courses report tangible and intangible benefits, including the acquisition of data, presentations, publications, intellectual stimulation, and professional fulfillment (12, 13). A study aiming to understand the challenges and motivations of faculty who develop their own CURE courses found that faculty enjoyed teaching these courses more than traditional labs, broadened their research interests, published peer-reviewed articles in basic science and science education, and were viewed favorably in promotion and grant activities (12). Another study (13) found that faculty who developed their own CUREs reported more tangible benefits than faculty who implemented a network CURE developed by other faculty but all faculty reported benefits (13) and enjoyed providing a research opportunity for students (12, 13). Although the number of articles highlighting the benefits for faculty is increasing (13, 18), additional examples of CURE courses that highlight faculty outcomes could help inspire more faculty to develop CURE courses. In our opinion, a fulfilling experience for faculty is likely to be enhanced when faculty expectations are aligned with realistic outcomes. In this perspective article, we summarize the implementation of three biochemistry CURE courses, highlight some of the benefits we experienced, and propose some points to consider to help set realistic expectations for CURE courses.

COURSE DESCRIPTIONS

The biochemistry laboratory at Towson University is an upper-level laboratory class offered once a year in the Spring semester. This class was taught as a traditional laboratory class for many years (30+ years) and was redesigned as a CURE course with the support of the Towson University Research Enhancement Program (TU-REP), a program funded by the Howard Hughes Medical Institute's Inclusive Excellence initiative. Each of us, the three regular instructors of the biochemistry lab, designed a CURE course derived from our research programs, and we offered these courses sequentially, over the courses of 3 years. Prior to teaching our CURE classes, we each attended monthly professional development sessions for one academic year where we learned about the nature of CURE courses, course design, and best practices to promote fairness, diversity, and inclusion in the classroom (19). Professional Development (PD) sessions provided faculty the opportunity to begin to develop aspects of their specific CURE and culminated with a course design presentation, which included feedback from faculty who had developed previous CURE courses. Courses were implemented in the academic year following PD sessions and mentorship from previous developers was available throughout our course implementation. In our courses, students worked in groups to test a hypothesis derived from our research programs. Students designed, conducted, and analyzed experiments to draw conclusions and propose new experiments to support their findings or to test a new hypothesis. Thus, our courses contain the elements that characterize CURE courses (scientific process, discovery, relevance to science, collaboration, and iteration) (1). Table 1 summarizes the biochemistry laboratory transition from a traditional lab to a CURE course.

The first CURE class, developed by J.W., centered around engineering a protein for improved thermodynamic stability. Various aspects of this CURE were piloted in 2015, 2017, and 2019, but full implementation occurred in Spring 2022. An overall strategy was employed to (i) design, (ii) produce, and (iii) test mutant proteins predicted to be more thermodynamically stable than the wild type. Student groups were presented with the overall task and asked to select and test different point mutations using a web-based stability prediction algorithm (20). Genes for the best theoretical candidates of each group were created using site-directed mutagenesis. Proteins were recombinantly expressed in *Escherichia coli* with a hexahistidine tag and purified using nickel affinity chromatography on an AKTA FPLC. Thermodynamic stability was evaluated with circular dichroism spectroscopy using a concentration gradient of guanidine. An activity assay to ensure that the protein remained functional was planned, but time constraints prevented its execution. Traditional biochemistry laboratory techniques (Table 1) were

TABLE 1 Summary of biochemistry laboratory (CHEM 356) class offerings over the last 20 years[a]

Enrollment	Years	Model	Techniques	Instructor	Weekly hours
79 (5 sections) *1 section/year* *16 students/year*	2004–2008	Traditional	Electrophoresis, chromatography, UV-Vis spectroscopy, circular dichroism, enzyme kinetics, pH titrations, macromolecular folding, macromolecular concentration	Various	4
191 (12 sections) *2 sections/year* *32 students/year*	2009–2014	Traditional	(Same as 2004–2008)	Soto	4
102 (6 sections) *2 sections/year* *34 students/year*	2015, 2017, 2019	Pilot CURE	Design and express mutant proteins, SDS-PAGE, chromatography, spectroscopy, buffer preparation, pH titration, and others	Weldon	4
90 (5 sections) *2.5 sections/year* *45 students/year*	2016, 2018	Traditional	(Same as 2004–2008)	Soto	4
36 (2 sections) *2 sections/year* *36 students/year*	2020	Pilot CURE	Structural modeling, structure prediction, plasmid design, express and purify protein constructs, generate DNA fragments, binding assays	Hancock	6
36 (2 sections) *2 sections/year* *36 students/year*	2021	Pilot CURE	Bioinformatics search, template and primer design, PCR, Urea-PAGE, electroelution, centrifugation, sample preparation, UV and circular dichroism spectroscopy, RNA folding, ligand binding assays	Soto	6
31 (2 sections) *2 sections/year* *31 students/year*	2022	CURE	(Same as 2015)	Weldon	6
24 (2 sections) *2 sections/year* *24 students/year*	2023	CURE	(Same as 2020)	Hancock	6
27 (2 sections) *2 sections/year* *27 students/year*	2024	CURE	(Same as 2021)	Soto	5

[a]This course has not changed name since its creation in 1981 and it is offered in the Spring semester. Students enrolled are typically junior and senior biology, chemistry, forensic chemistry, and MBBB (molecular biology, biochemistry, and bioinformatics) majors.

covered within the context of the project, allowing students to directly connect these techniques to their practical application. For the CURE project, we utilized the catalytic domain of *Pseudomonas* exotoxin A, but the strategy could be employed on any protein that is easily expressed and purified. Course assessments included both individual assignments, such as periodic lab notebook evaluations and quizzes, as well as group assignments, such as lab reports, a research proposal, and a final poster presentation to the Towson University community at a student research symposium. Student responses to the course in course evaluations and personal communications were generally positive. They appreciated the level of involvement and control over the project, and they were excited to be included in novel scientific research. They also appreciated the ability to work in groups, the introduction of experimental techniques as a natural part of the research process, and the freedom to make mistakes or fail at a lab activity without grade penalties. Students also requested improvements in course organization and expressed a desire for more direct communication. While much student discomfort can be explained by the less rigid learning environment of a CURE class relative to other laboratory classes, future implementation of the CURE will use the lessons learned to improve student engagement and streamline the project workflow.

The second of three biochemistry CUREs was implemented in Spring 2023 by S.H., wherein undergraduate students examined the DNA-binding properties of an essential, but uncharacterized, protein encoded by a mycobacteriophage (21). The overall goal of the CURE was to characterize protein-DNA binding profiles and identify specific amino acid residues and DNA binding motifs that drive the interaction. Specific student learning outcomes related to all aspects of the scientific process and included improving scientific

literacy, engagement in the scientific process, experimental proficiency in protein biochemistry and molecular biology, and specific content knowledge in biochemistry, bioinformatics, structural, and molecular biology. Because the DNA-binding protein used as the subject of our CURE was uncharacterized and encoded by mycobacteriophages, students were provided an opportunity to make novel discoveries that are of interest to the ever-growing field of mycobacteriophage functional genomics and complement undergraduate educational initiatives in phage discovery (22).

To conduct their CURE research projects, students used a multidisciplinary approach to model the structure of a protein-DNA complex using protein structure prediction and molecular graphics applications (23, 24). Using this model, students identified amino acid residues at the protein-DNA interface and constructed plasmids that express proteins with amino acid substitutions at these critical residues. Students also generated DNA fragments with variable sequences for DNA-binding experiments, expressed and purified variant protein constructs, and measured DNA binding profiles of cognate and variant proteins to DNA fragments to test hypotheses about the molecular basis for the binding reaction. Through this work, students employed many of the classical biochemistry lab procedures as would be conducted in a traditional laboratory but used these to drive original research. Course assessment included short in-class workshops in protein structure prediction, primer design, and protein-DNA binding measurements, exercises in experimental design and data analysis, scaffolded writing assignments addressing all aspects of the scientific process, and writing and presenting a final poster describing their work.

Work from the CURE directly demonstrates that our protein cooperatively binds DNA through its C-terminal DNA binding motif to assemble high-order nucleoprotein complexes on 100–500 base pair double-stranded DNA fragments with little sequence discrimination. These observations were validated and are described in a published research article from the instructor's lab (21). Student responses to course evaluations indicate that they made perceived learning gains in both affective and cognitive learning domains, similar to benefits traditionally attributed to undergraduate research experiences (2–6). These include confidence in performing lab techniques, elevated sense of belonging, gains in writing confidence and proficiency, elevated ability to align experiments with theory, and increased confidence in presenting their work to peers and professors. Student's ability to confidently communicate their projects was evident during their poster presentations to the college community at the end of the semester.

The third course was piloted in Spring 2021 and fully implemented in Spring 2024 by AMS. In this course, students investigated the conformation and binding profiles of related RNA riboswitches (25, 26) with the goal of finding differentiating features in the riboswitches from pathogenic organisms that could be used to develop inhibitor drugs (27). In Spring 2021, students used bioinformatics tools (28, 29) to obtain the sequences of the target riboswitch from various organisms, designed PCR primers to amplify a DNA template containing the selected RNA sequence, and optimized the conditions for *in vitro* expression and purification of the RNA molecules. In Spring 2024, students used the optimized conditions from 2021 to express, purify (30, 31), and test the conformation and binding profiles of the selected riboswitches (26, 32). Considerable troubleshooting was needed as students investigated the best conditions for transcription, correct RNA folding, and ligand binding, allowing students to test various hypotheses and interpret the results of their experiments. As with the previous two courses, students were able to use many common biochemistry techniques (Table 1). Course assessments included quizzes about research articles, oral presentations, laboratory reports, laboratory notebooks, class participation, and a final poster presentation. Although this project is ongoing, the results from the CURE classes provided optimized protocols for RNA expression and purification and clear directions for optimizing RNA folding and binding assays. Finally, students indicated (in course evaluations and personal communications) that they gained several laboratory skills, experience with several biochemistry techniques, and training in in-depth analysis of

biochemistry topics. Anecdotal observations of the final poster presentations indicate that students successfully engaged in the process of science by summarizing the experimental design, analyzing the results, and making appropriate conclusions from the data obtained.

PERSONAL OUTCOMES (NON-QUANTIFIABLE EXPERIENTIAL OUTCOMES)

From our combined experience, we can describe non-quantifiable outcomes from our CURE courses. First, as others have reported (12, 13), we experienced a sense of fulfillment when observing students excel in the laboratory. The excitement of students was invigorating and we experienced feelings of accomplishment about the work completed by the students. A second outcome was a feeling of clarity in our research agenda. Paying close attention to experimental details while preparing experiments was helpful for thinking about future experiments and new research directions. Thus, offering a CURE course facilitated the generation of research ideas for grant proposals, which may be particularly important for new faculty members who are establishing their labs. Finally, as reported by others (12, 13), CURE courses are stimulating, fun to teach, and provide a sense of rejuvenation to the faculty member, which ultimately enhances teaching and other aspects of faculty workloads. The rotation model we established provides an opportunity for various faculty members to enjoy the benefits of designing and implementing a CURE course. Our rotation schedule is planned and revised at our yearly coordination meeting, where all faculty who teach biochemistry courses are invited. This rotation model could also provide instructional (non-tenure track) faculty the opportunity to develop a research program.

PROFESSIONAL OUTCOMES (CONCRETE QUANTIFIABLE PRODUCTS)

Even though our CURE course projects are ongoing, we can report a few concrete products. At the end of our CURE courses, students summarize the results as a final assignment (e.g., internal poster presentation or final report). The organized results are helpful for our research laboratories and provide preliminary results that more traditional research can develop. For example, the purified molecules can continue to be used in our laboratories. Similarly, troubleshooting during the semester resulted in suggestions that helped us optimize our experimental protocols. For example, we found that the input in one of our purification steps could be doubled, potentially duplicating the yield of our standard purification protocol. A third concrete outcome, reported in other studies as well (12), was the identification and recruitment of motivated students to join faculty research programs. For instance, of the 82 students who enrolled in the biochemistry CURE courses, three students became productive lab members in the corresponding PI's lab, contributing data for research publications resulting from work done during the CURE (21) or being hired as full-time postbaccalaureate research technicians. Although this 4% yield may seem small, three students represent a significant fraction of the number of students we accept in our labs each semester (usually 1 to 6 students per faculty) and it highlights the fact that CURE courses can provide more opportunities for students than individual faculty can. It is also important to note that independent research experiences are not required for our students (although they provide credits toward their majors). Thus, a decision to join our laboratories suggests that students were inspired to engage more deeply in a research project, which is a very encouraging outcome for an instructor. Ultimately, research conducted in CURE courses can produce presentations, publications, and preliminary data for grant submissions (12). Although these latter outcomes may require many semesters of students' work, a preliminary count suggests that our CURE courses have increased our productivity. Our CURE courses have provided preliminary data included in recent grant proposals, and 27 out of the 61 poster presentations delivered by our mentored students over the last 3 years.

ADJUSTING EXPECTATIONS

CURE courses are intellectually stimulating but also time-consuming for faculty (12). Although CURE courses are derived from faculty's research programs, there are important differences from a research laboratory to consider. In our experience, being aware of the differences helps set realistic expectations which ultimately promotes feelings of success and fulfillment when students are able to reach their set goals. Here, we describe some of the differences we observed when developing our courses and Table 2 contrasts some of our initial expectations with our actual experience.

Time investment and time frame

The design of CURE courses requires several hours to build an experimental plan that tolerates changes, selects relevant literature, and gathers starting resources for students. CURE courses also require significant technical preparations (12, 33) (solutions, calibrations, specialized supply acquisition) that require faculty input even with the support of a teaching assistant. Students have limited time to finish an experiment (class time) and there are many students working at the same time. Having instruments and consumables ready prior to class allows faculty to assist students during the experiment but requires extensive preparation before class (one to several hours, depending on the experiment). These preparations make it more likely that experiments are successful and produce usable data to continue the project, and that faculty have time to supervise the use of expensive equipment that is often used in biochemistry experiments. When setting goals for a CURE course, it is worth keeping in mind that a CURE course lasts one semester. Depending on the course design, this is typically 50 to 90 hours of laboratory work per group of students.

Rapport and grading

Similar to interacting with research students, interacting with students in CURE courses is very enjoyable and energizing. Ideally, faculty and students collaborate and work toward the common objective of testing a hypothesis. One difference in this interaction is that CURE courses are graded in a different way than research courses. Independent research students are typically self-motivated and choose to conduct research because they are interested in learning. These students spend many hours working in the laboratory and are often graded on their effort rather than the outcome. Our CURE courses are graded like standard courses, which alters the relationship dynamic between students and faculty and can seem more judgmental to students. However, a clear grading scheme that specifically rewards effort as well as knowledge can promote interest in learning (34) and help create rapport between faculty and students. Crediting effort is important because CURE students vary in their level of motivation and interest in the project. It is encouraging for students to feel that their effort is valued (34) and credited to their grades. From our experience, we recommend that feedback in the effort is given frequently (biweekly or more often) to maintain student engagement and to allow less interested students the opportunity to improve.

TABLE 2 Examples of expectations we needed to change as we developed our CURE courses

Initial expectation	Actual experience
This course will be easy to design because it is related to my research project	Creating a course that introduces students to the project, fits into a weekly semester schedule, and tolerates changes is very time-consuming
Weekly preparations will be quick because they are similar to the preparation I do for my own experiments	Additional preparations are needed. Many materials need to be ready to use because students have a limited amount of time in the classroom
It will be easy to help students during the lab because these are the types of experiments students do in my lab	Students in a CURE class have less experience than research students and need more help
All students will be just as motivated as my research students	Students need encouragement and grading schemes need to be planned carefully to reward effort as well as knowledge

Constraints

It is helpful to recognize that CURE courses have some limitations inherent to the classroom design. The implementation of our research projects required significant adjustments to account for the limited lab time period, student's expertise, and available funds, as has been reported by others (12). For example, to fit RNA purification in the lab period, students cast and load large gels during lab, the gel runs overnight and the instructor dedicates 3 hours to complete the extractions the next morning. The experience in the classroom is also different since there are more novice students than in a typical research laboratory, and each student gets less of the instructor's attention compared to independent research students. Students who need more help draw more attention than other students in the same class, which can lead to resentment from the students who receive minimal faculty interaction. Since students typically work in groups, not all students get direct experience in all techniques. Group work can also result in an uneven distribution of effort among the group members, which can lead to dissatisfaction among the more diligent and motivated students. These limitations may not affect the outcome of a CURE course but can affect the students' experience. Frequent feedback on students' performance can help students share the work more evenly and pre-laboratory assignments can help students be more prepared for the experiment.

FUTURE STEPS

More reports describing the benefits faculty can obtain from CURE courses could incentivize faculty to develop CURE courses. We are hopeful that reports of faculty benefits will become more common given the number of CURE courses recently developed. We also want to emphasize the important role of institutions in developing such courses (17, 35). For instance, the TU-REP program provided funding to support the development of CURE classes in a variety of disciplines taught by tenured, tenure-track, and instructional faculty members. These include CURE courses in biochemistry, biomedical genetics, computer programming, computational chemistry, environmental geochemistry, experimental mathematics, field ecology, forensic science, cell and molecular biology, molecular ecology, physiology, and speciation. Many of these courses would not have been developed as traditional classes but arose from institutional recognition of the importance of undergraduate research experiences. While institutions may face different expectations and challenges for implementing CURE classes, support from the administration can dramatically decrease the effort required for CURE courses to succeed and persist. The TU-Rep program provided funding, professional development, and mentorship to successfully establish courses that can be maintained and provide opportunities to many students, including students from historically underrepresented groups (19). A support system (providing faculty training, curricular materials, technical assistance, and community interactions) was found to be essential to help faculty overcome the barriers associated with establishing and maintaining CURE classes (17), and the perception of institutional support was found to increase faculty participation as undergraduate research mentors, especially for underrepresented minority (African American/Black, Hispanic/Latinx, and Native American) faculty (35). CURE classes offer instructors the opportunity to incorporate their research interests into authentic research experiences for students, enriching faculty, students, and their entire institution in the process.

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