FEMS Microbiology Letters, 368, 2021, fnab036

doi: 10.1093/femsle/fnab036
Advance Access Publication Date: 31 March 2021
Commentary

COMMENTARY – Professional Development

Classroom undergraduate research experiences are a "CURE" that increases engagement by students and teachers

Kathleen M. Scott*,†

Department of Integrative Biology, University of South Florida, Tampa, FL 33620 USA

*Corresponding author: Department of Integrative Biology, University of South Florida, 4202 East Fowler Avenue, Tampa, FL 33620, USA. Tel: +813 974 5173; Fax: +813 974 3263; E-mail: kmscott@usf.edu

One sentence summary: Classroom undergraduate research experiences can promote engagement of students via ownership of course materials, and of teachers by providing a mechanism to link their teaching responsibilities to their research goals.

Editor: Beatrix Fahnert

†Kathleen M. Scott, http://orcid.org/0000-0002-9407-518X

ABSTRACT

It is widely acknowledged that having experience conducting research is invaluable for undergraduate science students. Most undergraduate research is undertaken by students in a mentor's laboratory, but this limits the number of opportunities for students, as each laboratory can only take on a certain number of undergraduate researchers each semester. Additionally, it is also widely acknowledged that it is difficult for teachers to meet research goals while providing the best possible coursework for undergraduate students. Both of these bottlenecks can be circumvented via Classroom Undergraduate Research Experiences (CUREs), which integrate research into the curricula of structured undergraduate classes. Students enrolled in classes that include CUREs conduct research to address open-ended questions as part of their coursework. In this commentary, I describe the many ways in which CUREs are helpful for students and teachers, as well as considerations for designing successful CUREs. I provide several examples of CUREs from Microbial Physiology laboratory classes and Genomics classes that I have taught. Results from these CUREs have been successfully integrated into many peer-reviewed publications in which the students are co-authors, which has been a boon both to students' post-baccalaureate opportunities, as well as my research agenda.

Keywords: CURE; Classroom Undergraduate Research Experience; undergraduate research; undergraduate publication; undergraduate authorship; research in structured classes

INTRODUCTION

At the college/university level, science students and teachers can suffer from having diminished opportunities to 'do science'. Students are fed huge volumes of information in their classes, and it can be difficult to integrate opportunities for reflection and synthesis into the semester. As a result, their understanding of science risks being stunted at the lower levels of Bloom's taxonomy (Bloom *et al.* 1956)—memorizing facts and providing descriptions of ideas, without grasping how these facts and ideas converge into meaning and could be used to form predictions. Teachers can also suffer, in that their dual roles as educators and researchers are difficult to fulfill simultaneously, and research productivity or curriculum quality is sometimes sacrificed. Classroom Undergraduate Research Experiences (CUREs), in which students conduct research within the context of structured coursework, can substantially improve science education, both from the students' and teachers' perspectives.

Received: 30 December 2020; **Accepted:** 29 March 2021

CUREs provide a myriad of benefits for students. CUREs give students the opportunity to addresses open-ended questions, quite distinct from the 'canned experiments' conventionally comprising the laboratory portions of their classes. Students in CUREs are required to apply, integrate and explore ideas (higher levels of Bloom's taxonomy). Unsurprisingly, I have noticed that including CUREs dramatically increases student engagement with the material. CUREs also have a favorable impact on students' understanding of the nature of science (Brownell *et al.* 2015; Mader *et al.* 2017). Most obviously, students gain a better understanding of the process of science by 'doing actual science': conducting novel experiments with unknown outcomes and analyzing the resulting datasets. Further, having undergraduate students as authors of the resulting manuscripts includes them in correspondences as the manuscript is reviewed, providing them with an insider's perspective on the peer review process. CUREs have also been found to improve retention in science majors (Rodenbusch *et al.* 2016; Mader *et al.* 2017), similar to what is measured when students join research laboratories individually (Mader *et al.* 2017). For students from underserved groups, which are less likely to join research labs individually, CUREs can provide a mechanism for obtaining research experience (Bangera and Brownell 2014).

Likewise, I have found that teaching via CUREs provide a myriad of benefits for myself. When I incorporate my own research into curricula, my enthusiasm for the research results in greater enthusiasm for the curricula. Incorporating the latest advances in the field into the curriculum is straightforward, as I am already deeply familiar with such, from writing the grant proposals that fund the research projects. It has also allowed me to meld my education and research goals, with great benefit to both. The classes are far more thought-provoking for the students, and my research benefits from the added clarity that I gain by explaining ideas to novice researchers, the added brainpower of fresh minds and the added publications resulting from their efforts.

CONSIDERATIONS WHEN DESIGNING AND IMPLEMENTING CUREs

My motivation in designing my first CURE was that I was convinced it would make the class more enjoyable for myself and the students, which did indeed turn out to be true. Subsequently, I have developed a more helpful thought process for deciding whether and how to integrate CUREs into curricula. The first consideration is whether it is possible to align student learning outcomes for the class with research objectives for a project. Several examples of CUREs that align learning and research objectives are described below. A second consideration is whether there is room in the semester for real-time improvization. Novel experiments with unknown outcomes often result in a need to change plans mid-semester. For example, students in my Microbial Physiology Laboratory class isolated novel microorganisms from a submerged Florida cave system and amplified their 16S genes to place them on the tree of life. When the sequences of these 16S genes suggested that these now organisms were novel species (and perhaps genera!), I asked the students if they would prefer to clear our plans for the semester, and instead spend our time characterizing the physiology of these novel organisms. They quite enthusiastically voted to focus the rest of the semester on characterizing the 'cave critters'. While such course-corrections can be exhilarating for all concerned, it is good to build a few 'buffer days' into the semester's schedule to provide the leeway necessary to adjust the nature and timing of the experiments. Thirdly, it is good to consider whether one year's CURE can inform the design of CUREs for subsequent years. I have found that multi-year CUREs are more the norm than the exception. Experiments often need to be replicated or redesigned, and sometimes a research objective is too large to fulfill in a single semester. Building multi-year CUREs can improve the quality of the results, and decrease the burden on the teacher to come up with novel CUREs each year. This was the case for annotating genomes in Genomics class (see below); it took two years to work through each of the genomes we studied to create a complete picture of the predicted metabolisms of each organism. The fourth consideration is building in a mechanism for quality control for the results, which is particularly important if the results will be incorporated into a manuscript to be submitted. Typically, I view the research results from CUREs as interesting leads, and take the time to repeat any experiments with key or unexpected outcomes once the semester is finished. The fifth and final consideration, if I am not sure a CURE is a good fit for a particular class, is to try a semester with a short project, and see how it goes.

EXAMPLES OF CURES

I have designed CUREs for an undergraduate Genomics class, as well as a Microbial Physiology Lab. These classes are geared toward juniors and seniors majoring in biological sciences. For both classes, student learning outcomes are presented below, followed by CUREs that have been implemented in the classes and publications resulting from these CUREs.

For Genomics class, student learning outcomes (SLO) include the following. Over the semester, students:

A. Use query tools such as text searches and BLAST searches to retrieve data from large databases of genome data (e.g. NCBI and IMG), and also to understand the theory behind the tools (especially BLAST, which is based on molecular evolution), which is necessary to assess the quality of the output.
B. Apply concepts from molecular evolution, physiology and biochemistry to 'ground truth' predictions of gene function based on automated genome annotations.
C. Utilize gene comparison tools (e.g. pairwise and multiple sequence alignments, and phylogenetic analysis) to evaluate hypotheses for the evolutionary history of genes and genomes.

It has been possible to design a variety of semester-long CUREs whose research objectives address all of these SLOs. One type of CURE that has been a good fit for this class is to annotate microbial genomes and predict their metabolic activities based on their genome sequences (Scott *et al.* 2006, 2008, 2018, 2020). I also designed a comparative genomics-based CURE to predict pathways for central carbon metabolism from microbial genome data (Quasem *et al.* 2017), and a CURE to use databases of all publically available microbial genomes to design degenerate primers for genes encoding enzymes that metabolize nitrogenous compounds (Keeley *et al.* 2020). Each of these large projects was subdivided into smaller projects for students to complete over the course of the semester. For example, for the nitrogen project, each student was assigned a particular enzyme (e.g. nitrous oxide reductase) to study.

The SLOs for Microbial Physiology Laboratory include the following. Over the semester, students:

A. Use time-tested tools such as batch and chemostat cultivation to describe the basic aspects of physiology, including use of different redox, C and N substrates and elucidation of optimal temperatures, pH and salinities.
B. Use contemporary tools such as genetic engineering and transcript analysis to decipher mechanisms undergirding basic aspects of physiology of a variety of microorganisms.
C. Apply all of the steps of the process of science: experimental design, hypothesis testing, data analysis, identification of follow-up experiments.

CUREs for this class have included the physiological characterization of two novel strains of bacteria isolated from deep-sea hydrothermal vents (Scott *et al.* 2018), qRT-PCR to track expression of genes relevant to CO_2 uptake and fixation (Menning *et al.* 2016; Scott *et al.* 2019), and random and site-directed mutagenesis to identify genes relevant to CO_2 uptake and fixation (Mangiapia *et al.* 2017).

CONCLUSION

The CUREs I have designed have been very successful for the students, by increasing the numbers of undergraduate students involved in research. Over 200 have been authors on publications, including 96 women, nine African Americans, 28 Latinx and a blind student. In addition to conducting the experiments and writing up the results over the semester, they are also invited to continue their involvement once the semester is finished, by reviewing the completed manuscript before submission, and suggesting responses to reviewers' comments. Involvement in these research projects results in increases in student interest in science, and understanding of the process of science, based on pre- and post-semester implementation of the Classroom Undergraduate Research Survey (Lopatto 2008). These projects, though often quite complex, are enormously popular among the students; many of them volunteer to continue them once the semester ends. If a teacher is ready to incorporate the uncertainties of a genuine research experience into their curriculum, I have found that the students are quite ready to rise to the challenge.

ACKNOWLEDGMENTS

I am deeply grateful to the students in my classes for their enthusiasm for exploring the unknown, to my department for providing me with the liberty to design my curricula, and to Dr Luanna Prevost and students in her Science Pedagogy class for discussing many of the ideas presented in this manuscript. I also appreciate the comments from the reviewers of this manuscript, and the improvements that resulted from addressing these comments.

FUNDING

This work was supported by the National Science Foundation [grant numbers NSF-MCB-0643713, MCB-1952676 and EE-1511439], the United States Department of Agriculture Education Challenge Grant [MOE-2008–02036], the United States Department of Energy Community Sequencing Program [2003 and 2009] and the University of South Florida [College of Arts and Sciences Pilot Studies Award 2017 and Innovative Teaching Grant 2004].

Conflicts of Interest. None declared.

REFERENCES

Bangera G, Brownell SE. Course-based undergraduate research experiences can make scientific research more inclusive. *CBE Life Sci Educ* 2014;**13**:602–6.

Bloom BS, Engelhart MD, Furst EJ *et al*. *Taxonomy of Educational Objectives: The Classification of Educational Goals. Handbook I: Cognitive Domain*. David McKay Company, New York, 1956.

Brownell SE, Hekmat-Scafe DS, Singla V *et al*. A high-enrollment course-based undergraduate research experience improves student conceptions of scientific thinking and ability to interpret data. *CBE Life Sci Educ* 2015;**14**:ar21.

Keeley RF, Class UG, Briggs GE *et al*. Degenerate PCR primers for assays to track steps of nitrogen metabolism by taxonomically diverse microorganisms in a variety of environments. *J Microbiol Methods* 2020;**175**:105990.

Lopatto D. Clasroom Undergraduate Research Experiences Survey (CURE), 2008. https://www.grinell.edu/academics/areas/psychology/assessments/cure-sruvey.

Mader CM, Beck CW, Grillo WH *et al*. Multi-Institutional, Multidisciplinary Study of the Impact of Course-Based Research Experiences. *J Microbiol Biol Educ* 2017;**18**. DOI: 10.1128/jmbe.v18i2.1317.

Mangiapia M, MicrobialPhysiology U, Brown T-RW *et al*. Proteomic and mutant analysis of the CO_2 concentrating mechanism of hydrothermal vent chemolithoautotroph*Thiomicrospira crunogena*. *J Bacteriol* 2017;**199**:e00871–00816.

Menning KJ, Menon BB, Fox G *et al*. Dissolved inorganic carbon uptake in *Thiomicrospira crunogena* XCL-2 is Dp- and ATP-sensitive and enhances RubisCO-mediated carbon fixation. *Arch Microbiol* 2016;**198**:149–59.

Quasem I, Achille AN, Caddick BA *et al*. Peculiar citric acid cycle of hydrothermal vent chemolithoautotroph *Hydrogenovibrio crunogenus,* and insights into carbon metabolism by obligate autotrophs. *FEMS Microbiol Lett* 2017;**364**:fnx148.

Rodenbusch SE, Hernandez PR, Simmons SL *et al*. Early engagement in course-based research increases graduation rates and completion of science, engineering, and mathematics degrees. *CBE Life Sci Educ* 2016;**15**:ar20.

Scott KM, Harmer TL, Gemmell BJ *et al*. Ubiquity and functional uniformity in CO_2 concentrating mechanisms in multiple phyla of Bacteria is suggested by a diversity and prevalence of genes encoding candidate dissolved inorganic carbon transporters. *FEMS Microbiol Lett* 2020;**367**:fnaa106.

Scott KM, Leonard J, Boden R *et al*. Diversity in CO_2 concentrating mechanisms among chemolithoautotrophs from the genera *Hydrogenovibrio, Thiomicrorhabdus*, and *Thiomicrospira*, ubiquitous in sulfidic habitats worldwide. *Appl Environ Microbiol* 2019;**85**:e02096–02018.

Scott KM, Sievert SM, Abril FN *et al*. The genome of deep-sea vent chemolithoautotroph *Thiomicrospira crunogena*. *PLoS Biol* 2006;**4**:1–17.

Scott KM, Sievert SM, Klotz MG *et al*. Genome of the epsilonproteobacterial chemolithoautotroph *Sulfurimonas denitrificans*. *Appl Environ Microb* 2008;**74**:1145–56.

Scott KM, Williams J, Porter CMB *et al*. Genomes of ubiquitous marine and hypersaline *Hydrogenovibrio, Thiomicrorhabdus*, and *Thiomicrospira* spp. encode a diversity of mechanisms to sustain chemolithoautotrophy in heterogeneous environments. *Environ Microbiol* 2018;**20**:2686–708.