A practical guide to course-based undergraduate research experiences

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In November 2015, project leaders and invited guests with expertise in course-based undergraduate research experiences met to discuss the state of CUREs in biochemistry and molecular biology. The following participated in this meeting:

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The meeting catalyzed the development of this guide, which was written by a subset of the aforementioned group. In addition, the following people also contributed:

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INTRODUCTION

J. Ellis Bell

The Vision and Change final report [1] recommends, among other things, the integration of core concepts and competencies throughout the undergraduate curriculum; the introduction of the scientific process to students early and integration of it into all undergraduate biology courses; and the incorporation of research experiences as an integral component of biology education for all students, regardless of their majors. Vision and Change was supported by the NSF, the Howard Hughes Medical Institute, the American Association for the Advancement of Science and the National Institutes of Health, among other groups.

A NSF RCN-UBE grant supported topical meetings focusing on important aspects of Vision and Change for the biochemistry and molecular biology community. This guide is the outcome of one of the meetings and focuses on the incorporation of course-based undergraduate research experiences into the curriculum for all students.

CHAPTER 1 | WHAT IS A CURE?

Joachim Latzer, Tamara Mans and Joseph Provost

In addition to the Vision and Change report [1], several other reports [2–7] also have called for integration of core concepts and skills throughout the curriculum; a focus on student-centered learning environments; and the use of validated high-impact practices, such as research experiences, as integral components of biology education for all students.

Research experiences have a major effect on persistence in science [8–11] and result in positive outcomes in conceptual understanding and skills development, which are essential for effective workforce development [12–17]. The Council on Undergraduate Research defines undergraduate research as "an inquiry or investigation conducted by an undergraduate student that makes an original intellectual or creative contribution to the discipline" [18a]. Such work is a high-impact practice[18b] that provides strong service learning for students, increases retention, enhances student learning though mentorship by faculty and develops a deeper critical thinking ability and intellectual independence.

To date, apprenticeship is the major model for undergraduate research [14, 19–21]. While successful on the individual level, this model is difficult to scale up to include all students, which has led to calls for the integration of research into laboratory classroom activities.

One pathway to reach more students is use of the inquiry model [7, 22–24] in the teaching laboratory. Using known, predictable experimental outcomes provides students with a research-like experience but is limited in potential impact, and it does not meet the CUR definition of undergraduate research.

True research with an unknown experimental outcome is more difficult to achieve. However, in recent years, course-based undergraduate research experiences have emerged as one broadly applicable solution.

The NSF-funded CURE network hypothesizes that the key elements of a CURE include [25a & b]:

- The use of scientific practices
- Discovery
- Broadly relevant or important work
- Collaboration
- Iteration (building on prior knowledge, repeating experiments and using multiple approaches to address the research question)

David Lopatto and others also described seven components of authentic research [26–30]:

- Novel questions
- Student-generated questions
- Development of a hypothesis
- Experimental design
- Data collection

- Data analysis
- Presentation or publication of the research

In addition to these elements, using a CURE for an authentic research experience also includes:

- A minimized role of the instructor
- An unknown scientific outcome
- A project where students are responsible for the design and most of the work

While these elements are important in the design of a CURE they also provide a framework for assessing the impact of different individual aspects of CUREs on desired outcomes (25a & b)

The benefits of CUREs are outlined in Chapter 2, and several successful examples of CUREs are outlined in Chapter 3. Here, we will highlight the HHMI-funded SEA-PHAGES program as an example of the aforementioned elements. SEA-PHAGES offers an authentic research experience to a large number of first-year biology students and has yielded publication-quality work. Since SEA-PHAGES was implemented, research-based discovery was brought to more than 4,800 students at 73 institutions, including community colleges, four-year private schools and large public research-intensive universities.

Through SEA-PHAGES, faculty members have integrated research into the classroom and published the discovery of new viruses and annotated bacteriophage genomes, while enhancing student learning gains and retention and increasing a positive attitude for science [31–35]. The SEA-PHAGES project provides a model to increase access to a range of schools. It reduces barriers to implementing research by providing expertise to faculty members not experienced in teaching this type of course or without the scientific background for bacteriophage research. Other barriers to implementing CUREs and possible solutions are described in Chapter 4.

The remainder of this guide will show you how CUREs have affected students, faculty members and administrators; the different types of CUREs that have been developed to date; and how you can incorporate a CURE into your own teaching.

CHAPTER 2 | WHY CUREs?

Erica A. Siebrasse and Joseph Provost

Selections from this article were published in the April issue of ASBMB Today, the society's member magazine.

For many scientists, working in the lab as an undergraduate and experiencing the joys and frustrations of research alongside more senior scientists were powerful factors in their career choices. Undergraduate research experiences often offer the first taste of the excitement of discovery and the satisfaction of working on a challenging problem.

The apprentice model is a time-tested approach for involving budding scientists in research. However, the demand for undergraduate research positions exceeds their availability. Furthermore, underserved and underrepresented students are less likely to seek out and secure apprenticeships.

One solution to these problems is CUREs, which are a growing mechanism for making research broadly accessible to students. The influence and integration of CUREs have been increasing for years. There are several very successful models (see Chapter 3) and a growing body of scholarly research into their effectiveness at improving students' persistence and success in science.

Students who participate in CUREs report similar positive outcomes to students conducting research through the apprenticeship model (10-12). CUREs participants report gains in their ability to think like scientists, increased excitement about science and increased intentions to pursue science careers.

We encourage you to review the literature on CUREs (References, particularly 1, 25–27 and 36–37), which contains specific data supporting their positive outcomes. For a more personal and practical perspective, we spoke with 12 faculty members, students and administrators from two- and four-year institutions about their experiences with CUREs. We then distilled their thoughts into four reasons why you should consider teaching a CURE.

1. CUREs allow more students to engage in original research than traditional lab courses.

The Freshman Research Initiative (FRI) at the University of Texas at Austin "involves students in doing STEM research from their first moments on campus. It has been a critical mechanism for making research available to many students early enough in their education to make a difference. [The program] involves 900+ students in doing STEM research annually. We simply would not be able to offer research experiences at the scale we need…without FRI." –Erin Dolan, executive director, Texas Institute for Discovery Education in Science at the University of Texas at Austin

"My institution, Oxford College, is a two-year undergraduate division of Emory University, located on a separate campus. My motivation to design a CURE came from my intrinsic desire to build research partnerships with my students at any level. A full teaching load and lack of supporting resources limited by abilities to mentor more than one to two undergraduate students in research every year. I decided to pursue the integration of a research project into my curriculum as a means to work with students in the way I would engage them in a research laboratory." –Nitya Jacob, associate professor, Oxford College

"I used [my CURE] as a pilot program to impact more students. I realized [it] really impacted the way students think, the way they write and the way they do things. I was getting feedback from the other faculty in the department saying, 'Wow, we really like your students.' I realized that I need to get this in my course load and broaden it out to a bigger group of students. The CURE model hit me as the way to do this." –Paul Ulrich, senior lecturer and Undergraduate Research Center coordinator, Georgia State University

2. CUREs are beneficial to faculty members and contribute to their professional development.

"Seeing the quality of work that freshmen and sophomores can produce when presented with a challenge and an accompanying supporting environment has been truly inspirational. Working on CUREs gave me a new perspective about student learning and my own professional development." –Nitya Jacob

"At a community college, faculty are asked to maintain very high teaching loads. In addition, students are limited with respect to their financial aid and credit limits on their degree programs. The CURE was a perfect solution to both of these problems. The integration of the research experience through CUREs was a perfect fit." – James Hewlett, professor of biology, Finger Lakes Community College

"[My CURE] allows me to continue doing primary research. At the same time, I'm training students and having a lot of joy really being involved in and seeing them move from simple theoretical, factual knowledge of the systems to becoming very well-qualified for the job market or moving into graduate education soon thereafter." –Paul Ulrich

"Faculty get to teach in a way they really enjoy--through research--and they identify interested students to work on their research." –Erin Dolan

3. CUREs are beneficial to students--the faculty perspective.

"Preliminary data from Spelman [College] biology CUREs show increases in the number of students persisting in the biology major and identifying interest in earning biology Ph.Ds. Prior to taking the CURE, only 24 percent of students expressed an interest in earning a Ph.D. in biology. After participating in the CURE, student interest increased to 76 percent." – Mark Lee, associate professor and chairman of the biology department, Spelman College

"Students get to try research early and decide whether it is something they want to pursue further in their education and careers." –Erin Dolan

“Students develop a sense of pride when their original ideas take form in a product. They remember the ups and downs of the process—frustration and failure followed by ‘aha’ moments—as a rite of passage that distinguishes their time at Oxford.” –Nitya Jacob

CUREs are beneficial to students--the student perspective.

“[The CURE course] helped me realize that I wanted to become a research scientist, and I am now pursuing a Ph.D. in developmental biology at Stanford [University]. Probably the most valuable lesson I learned from this course stems from the fact that the outcomes of our experiments were unknown. This taught me the data are the data, and you cannot make data fit a hypothesis you like if they do not.” –Susanna Brantley, graduate student at Stanford University and former CURE undergraduate student at Oxford College

“I learned how to navigate and troubleshoot a research project from beginning to end and developed my scientific writing and communication skills by proposing and presenting a project. This [CURE] course has prepared me for an exciting and challenging career in molecular biology and proteomics, setting me apart from many other students.” –Baylye Boxall, master’s student at the College of Charleston and former CURE undergraduate student at Georgia State University

“Instead of being handed a topic, we were free to develop our own question, hypothesis and procedure. While this approach was challenging, it was also highly motivating because I was not only doing a class project but also discovering entirely new information. Going through the entire scientific process with this project piqued my interest in research. I am still doing independent research with [my instructor] on this same topic.” –Nolan Graham, junior at Emory University and former CURE student at Oxford College

“I realize the need for textbook knowledge coming out of college, but the ability to produce knowledge instead of just taking it in was the best educational experience of my college career. The CURE course I completed dramatically altered my career path, making me passionate about computational biology. I also think the ability as an undergraduate to discuss a rich research experience made me much more marketable as a researcher and certainly helped me transition into a highly competitive graduate program.” – Sarah Spencer, graduate student at the Massachusetts Institute of Technology and former CURE undergraduate student at Washington University in St. Louis

“[The CURE course] was unique in that it incorporated research as a teaching tool. I loved having the opportunity to practice research in a classroom setting because it helped me understand the topics we covered in class by applying my knowledge in a hands-on way.” –Nitya Murthy, master’s student at the University of South Florida and former CURE undergraduate student at Oxford College

"This [CURE] course was different from other lab courses in that I was applying critical thinking skills and laboratory techniques I learned in my upper biology courses. This course has helped prepare me for a future career in pharmaceutical research." –Melanie Washington, pharmacy student at Wingate University and former CURE undergraduate student at Georgia State University

"[The CURE course] taught me the value of inquiry and how important questioning what you know is to furthering your knowledge. I had not participated in research before [this course] because I had seen it as something way past my abilities. The lab setup helped me grow as a scientist." –Surina Odhav, senior at Emory University and former CURE student at Oxford College

4. CUREs are beneficial to institutions.

"As a community college, our research culture was limited prior to the development of CUREs. We have seen a transformation in our students with respect to their confidence and an additional identity for our faculty and our department. Engaging in research as part of our CUREs has energized our faculty and given students opportunities for scholarships and internships. In addition, students have seen greater opportunities to share their work and to transfer into STEM programs." – James Hewlett

"In 2009, the biology department began offering CUREs…and we observed a marked increase in the number of students gaining research experiences without an equivalent influx of financial or human resources. We consider the increased research output from students and fundable/publishable work from faculty very meaningful gains" –Mark Lee

"Our biology program has thrived and grown. The use of inquiry and CUREs increased the number of freshmen and sophomores who were accepted to competitive summer research programs across the country. Several of our students have won top prizes in summer REU programs. These successes are often used for student recruitment. Although not directly correlated to the implementation of CUREs in our science curriculum, we have observed a great retention rate of underrepresented minority students who start at Oxford College in STEM fields compared with URM students who start the first two years at Emory College, the four-year undergraduate division of the university." –Nitya Jacob

"Students take [their knowledge], they move on, and I have tried to track their progress over time. [My CURE] has been quite successful in terms of what [students] achieve after completion of the course. Because my CURE students are so effectively recruited into our graduate program at GSU, my department decided to offer a second section of the CURE as part of my regular workload." –Paul Ulrich

CHAPTER 3 | WHAT CAN CURES LOOK LIKE?

David Hecht, Patrick J. Killion, Joachim Latzer and Todd T. Eckdahl

There is no single best approach to basic or applied scientific research in STEM disciplines. Differences in goals, availability of resources and disciplinary practices cause research approaches to vary widely among investigators and institutions. Similarly, there is no single best approach to the implementation of CUREs, which should be tailored to the needs, goals, availability of resources and disciplinary practices of individual instructors, academic departments and institutions. The possibilities under the CURE umbrella (Figure) include modules, courses and programs, which are described below. However, we would first like to address three common misconceptions about CUREs.

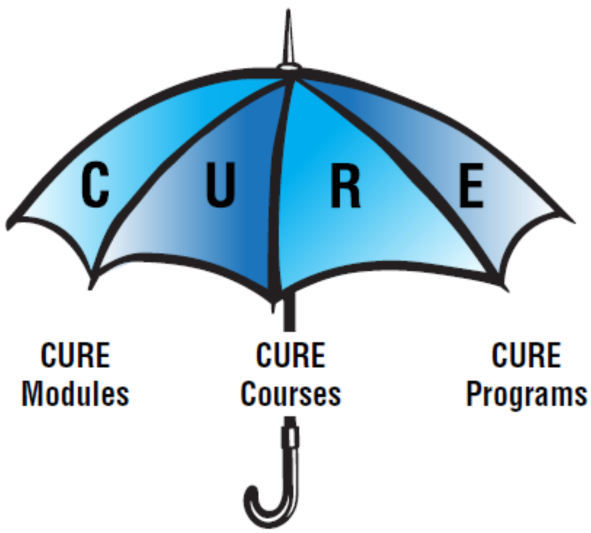


Figure. Examples of ways to incorporate CUREs. Graphic courtesy of Kendy Jones.

Misconception no. 1: CUREs are only for senior students. The design and implementation of CUREs can be varied to serve both early-matriculation and more senior undergraduate student populations. CUREs that serve freshmen and sophomores often are challenged by the necessity to engage both fundamental background material and advanced research methods. It is key to recognize that CUREs of this type need not dedicate a significant percentage of the front-end of the course to fundamentals before the more advanced concepts and methods intrinsic to the research process begin.

In this manner, these CUREs are designed to get inexperienced students immersed in the research process quickly, while they build an understanding of core background material. Conversely, CUREs designed for more experienced student populations often can assume prerequisite course completions that enable the courses to quickly engage advanced concepts and methods.

Misconception no. 2: CUREs are for only STEM majors. CUREs can be designed for majors and non-majors in both STEM and non-STEM disciplines. For example, the University of Maryland recently included CUREs in the reform of its general education program through the creation of required scholarship-in-practice courses. These reinforce and enhance learning in the humanities, natural sciences, history and social sciences through immediate practice of research. Scholarship in practice brings research experiences into courses to meet the mission of engaging students in work authentic to all academic disciplines.

Misconception no. 3: Community colleges cannot implement CUREs. CUREs at the community-college level provide transformative opportunities for diverse student populations to engage in undergraduate research. CUREs at community colleges can be built around faculty research interests or collaborations with other institutions or local industries. CUREs involving collaborations with transfer institutions have provided valuable bridge experiences for students. CUREs in certificate and technical programs provide students with relevant and marketable skills as well as potential employment opportunities with local businesses and industries.

CURE modules

CURE modules provide short-term research experiences for students that can be incorporated into existing courses. They usually involve between two and six laboratory meetings, can be implemented affordably and do not require extensive instructor training.

An example of a CURE module is the pClone system, which gives students the opportunity to study the function of promoters, develop their own hypotheses about the effects of mutations or regulatory proteins on transcription, and test these hypotheses by cloning their own promoters. The pClone system uses a method called Golden Gate Assembly that makes cloning promoters in classroom laboratory settings practical. It has been described in the Cell Biology Education-Life Sciences Education journal and Course Source and is available as a kit from Carolina Biological Supply Company (38–40).

Students who are enrolled in a course overlay, such as a class designated as honors, could have the option to conduct independent research with faculty members. The students and faculty would meet regularly during the semester to discuss the progress on the research projects. In addition to successful completion of the project, student need to earn a grade of B or higher in the class in order to get an "H" designated on their transcripts.

These course overlays provide maximum flexibility for designing CUREs, especially at a community college, where there often is not much flexibility in curriculum modification due to articulation agreements with transfer institutions.

Another flexible option for offering CUREs at community colleges is through independent study. At Southwestern College, students can enroll for one to three credits each semester, depending upon the scope of the projects. In recent years, students have worked on collaborative research projects with faculty members from nearby San Diego State University. As roughly 30 percent of Southwestern College transfer students attend San Diego State University, these projects provide valuable bridge experiences for the participating students.

CURE courses

CURE courses are standalone research experiences that allow students to conduct semester long projects. CURE courses are a good way to draw attention to research experiences within a curriculum. They also provide opportunities for students to work collaboratively on a research project that can be presented or published.

The Genomics Education Partnership enables faculty members at diverse institutions to develop and implement CURE courses. Led by Sally Elgin at Washington University in St. Louis, GEP provides faculty training in eukaryotic genome sequencing and annotation as well as access to original *Drosophila* genomic sequence data (41).

The GEP model is a nationally distributed research project in which undergraduates finish the DNA sequencing of *Drosophila* species genomes and annotate the data to address large questions about the evolution of chromatin structure (42). The first GEP CURE course at Washington University has been adapted at other institutions.

Another example of a CURE course is a two-semester laboratory series developed by Joseph Provost and Mark Wallert (43). Students are empowered to design, execute and analyze their own experiments on a series of wild-type and mutant clones of malate dehydrogenase. The common research theme of a biologically relevant system motivated students to ask novel questions and engaged the students in the course material, which resulted in improved biochemistry and molecular biology laboratory skills and better performance in advanced courses.

CUREs also can be implemented in entry-level classes. Ellis Bell (44) offers one approach to effectively integrating a CURE into the first-year biology program. Freshmen are introduced to research through interdisciplinary courses, where they learn critical skills needed throughout their college careers.

There are many other examples of single-semester CUREs at all levels, including modular approaches for a six-week program (45) and a course for non-majors using plant peroxidases to bring research to a broader audience (46). Many others are found in journals--such as Biochemistry and Molecular Biology Education, Cell Biology Education Life Sciences and the Journal of Chemical Education-- and on the CUREnet website.

CURE programs

CURE courses can be implemented as stand-alone, department-specific offerings, as part of the general education portfolio of courses across all departments and colleges, or as part of a student's curricular involvement in a research-focused program.

The Freshman Research Initiative (FRI) (https://cns.utexas.edu/fri) is a hybrid research and education program hosted by the College of Natural Sciences at the University of Texas at Austin. Since its creation in 2005, FRI has served more than 6,000 students. It annually reaches more than one-third of each CNS freshman class with 40 percent of each cohort coming from underrepresented STEM groups.

Since its inception, FRI has focused on increasing persistence in STEM through transformational research experiences integrated into students' freshmen year. The FRI experience is integrated into the curriculum and allows students to earn degree credit for program participation. Students engage directly with faculty members in authentic research, where the focus is a facet of the faculty member's overall research agenda.

The University of Maryland initiated a major new program in the 2014–2015 academic year to provide authentic faculty-led research experiences, mentorship and accelerated opportunities for first-year freshmen from a wide range of academic backgrounds and disciplines. The UMD First-Year Innovation & Research Experience (http://fire.umd.edu) adapts the UT FRI model and provides first-year students authentic research experiences, broad mentorship and institutional connections that positively influence academic success, personal resilience and professional development.

As part of a $1.1 million grant from the Howard Hughes Medical Institute, Hamline University partnered with Century College and North Hennepin Community College to develop the Engaging Science Students through Investigative Research program. Through this partnership, biology, biochemistry, chemistry, physics, premed and pre-health science majors have opportunities to participate in research projects under the direction of faculty mentors. These projects are integrated as short two- to four-week modules into existing chemistry and anatomy classes with equipment, reagents and supplies paid for with the grant. There are plans to expand these CUREs to additional classes.

CURE opportunities

Although the examples described above illustrate the different forms that exist under the CURE umbrella, they are only a fraction of what is possible. Opportunities exist for the development of new CUREs for individual instructors, collaborative teams and institutions. Another way to increase the number of available CUREs is to rebrand appropriate existing practices as CUREs. If developers of such existing modules, courses and programs are willing to rebrand them as CUREs, they would be likely to find adopters and collaborators. New and rebranded CURE modules, courses and programs can be shared via CUREnet and Course Source.

It is imperative that academic institutions develop additional CURE-like mechanisms that allow early-matriculation students to simultaneously fulfill degree requirements and gain authentic research experiences. Early undergraduate research courses and programs serving students during their first year of college provide an opportunity for universities to identify students with an interest in research early. They also have been associated with a number of positive student and institutional outcomes, including increased STEM retention, student satisfaction, confidence and resilience.

CHAPTER 4 | MAKING IT HAPPEN: HOW DO I START?

Jessica Bell and John Rakus

How do I start?

Convinced? Ready to start? The most important question you need to answer is, "What are my goals?" People implement CUREs with a variety of possible goals. To get you started thinking about your goals, here are possible goals that you might consider once you have decided that you want to implement a CURE in your course. Check off each answer that is yes:

1. Am I going to use a Stand Alone CURE in my own course/department?
2. Do I want to revise the department curriculum to implement wide spread, coordinated CUREs in the major?
3. Do I want to explore unanswered questions in pedagogical research about the impact of various components of CUREs?
4. Am I going to join [4A] or start [4B] a consortium of faculty between institutions to implement a coordinated CURE?

If you plan to join a consortium, logistics may already be in place. If you are planning to start a consortium or work on a stand alone CURE, the checklist can guide you to consider essential aspects of developing your CURE.

Enumerate Outcomes: While the instructional outcomes are self-evident, it is a good idea to think about institutional goals up front in the process. We list potential institutional goals that implementation of a CURE might impact.

Identify Pilot: As with any experiment you might perform in the research lab, it is a good idea to start with a pilot to allow you to work on the logistics and establish a proof of principle. It's not going to be perfect the first time. The pilot course provides practical experience before you fully implement or try to convince your colleagues to adopt/join your CURE approach. If it's just you, be sure to let your department chair know what you are doing, and why! Getting their support will help if students or colleagues are wary of your pedagogical experiments. If it's a group of faculty within a department, be sure to build a consensus of shared goals.

Engage Stakeholders: Whenever you do something new and different in the classroom, it's a good idea to fully explain to your students why you are doing it. Briefly outline your goals and the evidence that supports why you think this approach will be beneficial to them. Include ways that you plan to listen to them to get feedback to improve the student experience in the class. If you are planning to explore the overall efficacy of some aspect of your CURE for pedagogical research, be sure to explain this, too, and get appropriate IRB approval. In terms of your colleagues/department chair/administrators, etc., be open about discussing your goals, focusing on student outcomes, as well as institutional outcomes. In many departments, it may be important for tenure/promotion consideration that your colleagues understand what you are doing and why, especially if you are the first in the department/program to implement such approaches. Make sure that you fully document your goals and outcomes with appropriate quantitative evidence in your annual report!

Funding and Scale-Up: Implementing a CURE in your own lab class doesn't have to be any more expensive than a regular lab course, but…. If it's going to be more expensive, you need to plan. Many departments have fixed budgets for courses. If you need to increase that budget for your course, there are several strategies. If the proposed CURE is centered on your own research, it can be a good investment of your own research funds (institutional or grant) to augment the course budget to make sure that you have the supplies, reagents, etc. you need to implement the CURE. After all, you are collecting preliminary data via the CURE that will benefit your longer term research goals. If you are implementing a CURE as part of a consortium, the consortium may well have budget set aside to help offset the costs to your department. If you are planning to write a grant (either lab science or pedagogical research), be sure to incorporate the appropriate budgets. Remember, with many NSF grants, incorporating a CURE into your application contributes significantly to the broader impact and should be reflected in your budget.

Community of Expertise: As you get ready to implement a CURE, there are many useful resources. In this booklet, we have discussed and referenced a number of examples of CUREs, as well as some of the pedagogical research on the impact of CUREs. Many national organizations such as CUR (Council on Undergraduate Research), HHMI and professional societies such as ASBMB (American Society for Biochemistry and Molecular Biology), APS (American Physiology Society) and ASM (American Society for Microbiology) organize workshops on such topics. Join CUREnet, an NSF funded group of investigators and resources for people interested in CUREs.

While the above discusses aspects of implementing a CURE that are relevant to all faculty, there are two other aspects to be considered if you are engaged in wider aspects of the use and development of CUREs.

Develop Cohorts of Faculty: To sustain and expand to other courses/departments the benefits of CURE implementation, it is often necessary to develop a cohort of faculty at the department or institutional level. This can be done in a number of ways including discussing the successes and refinements of your CURE at the department level. Many departments have regular "pedagogy" discussions at department meetings. If your department does not, suggest to the chair that you would be willing to give a brief presentation on your CURE. A summer faculty development workshop where you can present your “rational and data” for your CURE can provide another forum for dissemination. Such presentations can also become the basis for presentations at National Academic Society meetings and publications in peer reviewed journals such as Biochemical and Molecular Biology Education (BAMBED) or CourseSource.

Iterative Assessment and Modification of Goals: Particularly if you are using your CURE for pedagogical research, it is critical to incorporate replication, iterative assessment and modification of your goals, which are often informed by preliminary outcomes, feedback from stakeholders and refinements of overall goals. These aspects are particularly important if one of your goals is to publish either pedagogical research on the effectiveness of aspects of CUREs or to write a grant for such research.

1. The checklist

- [ ] **Enumerate outcomes**

Institutional

1) Increase graduation rates
2) Increase student retention
3) Increase value of higher education
4) Increase research

Instructional

1) Increase discipline-specific retention
2) Embed foundational concepts & skills into curriculum
3) Increase research

- [ ] **Identify pilot**

1) Implement low-risk, high-payoff pilot
2) Select stakeholder group to complete *proof of principle*
3) Define learning objectives & outcomes to demonstrate efficacy

Stand-alone CURE

- [ ] **Garner administrative support (dean or chair)**
- [ ] **Determine size & scope of CURE**
- [ ] **Align objectives & outcomes to concepts**
- [ ] **Identify best practices in literature**
- [ ] **Determine assessment tool**
- [ ] **Complete logistics-- space & materials**

- [ ] **Engage stakeholders**

1) Engage students, faculty, staff and administration for consensus building
2) Recognize and award faculty members for CURE implementation to incentivize

- [ ] **Funding for scale-up**

1) Grant writing and/or university, college or department budget considerations

- [ ] **Community of expertise in practice**

1) Train through peer mentorship or regional/national workshops

- [ ] **Expand implementation of CUREs**

1) Call for internal CURE implementation proposals
2) Set criteria for participation (training, etc.)

- [ ] **Develop cohorts of faculty to sustain**

1) Develop course (e.g. general chemistry), major (e.g. biochemistry) or discipline (e.g. STEM) level cohorts
2) Implement cohort workshops to review, refine and develop CUREs for curriculum

- [ ] **Iterative assessment & modification of goals**

2. Resources

CUREnet
curenet.cns.utexas.edu

1) NSF-supported access to biology-related CUREs
2) CURE assessments
3) Project descriptions, contacts, project websites

Course Source
www.coursesource.org

1) Open-access, peer-reviewed online journal for student-centered learning

ASBMB
www.asbmb.org/education

1) Foundational concept & skills inventory
2) Assessment instruments
3) Course design tools

Barriers to Implementing CUREs

While some of the barriers and associated strategies to overcome them have been indicated earlier, we felt it might be useful to make specific comments about some of the more commonly encountered barriers.

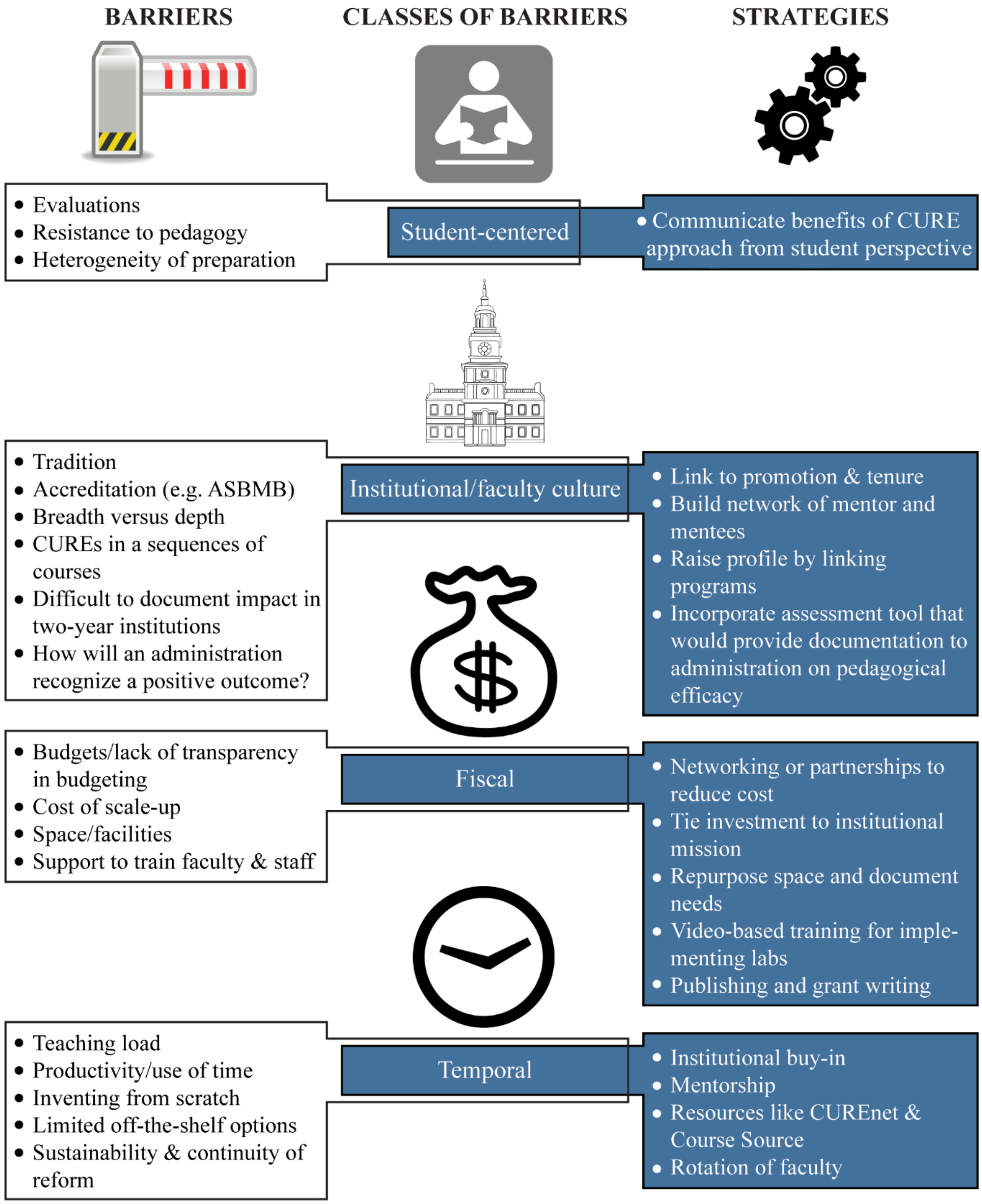
Student-Centered Barriers: Students often like the comfort of a lab book with protocols they can follow and outcomes of experiments they can look up. Deviation from this approach could lead to less than stellar student evaluations of teaching. This potential barrier is, in reality, an opportunity to excite students and let them see the process of science firsthand. What you have to avoid is the student feeling that their grades reflects whether or not they identified the "right" answer, rather than understanding the scientific process. In addition to clearly explaining the overall benefits of using a CURE in the lab, it is important to clearly enunciate your grading rubric, not just for the overall course, but for specific components of the course. This can be particularly important if your CURE contains technique focused components where it is important for the students to master a technique for a subsequent course.

Institutional/Faculty Culture Barriers: Working directly with colleagues whose classes may be impacted by your CURE can overcome resistance to CURE implementation. To address these concerns, identify particular techniques, skills or content that your colleagues feel are critical outcomes from your course that prepare students for subsequent courses. Such discussions may also benefit from detailed departmental discussion of the "breadth versus depth" issue. CUREs do not lend themselves to lengthy laundry lists of techniques and concepts (breadth), but may be beneficial for detailed understanding (depth). Assessing overall outcomes of a CURE can be difficult, particularly with 2 year colleges where students often progress to 4 year schools, but it is well worth the effort, particularly if one of your goals is pedagogical research. The key to administrative recognition of positive outcomes is data. This is critical when a goal is to change institutional culture with regard to this type of student-centered pedagogy and making the argument for recognition of this pedagogical implementation in promotion and tenure considerations.

Fiscal Barriers: We have discussed earlier fiscal barriers in terms of materials and supplies. Other important considerations are space and equipment. The apprenticeship model of research does not put undue pressure on space and equipment outside the normal debate of *"How do I acquire the equipment I need to do the types of experiments I want to do?"* Implementing a CURE can put significant pressure on equipment availability and space creating a potential barrier to implementation. Other than adapting to what you have available, one way to ramp up the scientific value of the CURE (and incorporate potentially significant factors in effectiveness of a CURE) is to develop a collaborative CURE. Amongst different courses (in the same institution or in different institutions), each CURE could tackle related scientific problems, but with different experimental approaches and share data. This extends the impact of the work done by allowing students to propose collaborations and reap the benefits of additional data. This mimics the “real world” approach to research. Perhaps the biggest fiscal barrier to CUREs is the need to scale up to engage all students in CUREs, since this often requires additional lab space, faculty and support staff. Usually, the solution to this barrier involves promoting institutional investment, which is tied to demonstrating successful outcomes with regard to the institutional mission. Once a proof of principle CURE has been evaluated, it is sometimes possible to facilitate scale up and reduce costs of scale up by repurposing space and creating video tutorials on various technical aspects of the research to minimize faculty time for such activities.

Temporal Barriers: How many boxes did you check at the start of this section? Starting a CURE from scratch is time consuming, particularly the first time around. The more boxes you checked, the more time consuming starting the CURE is likely to be, unless you checked box 4A, in which case a lot of the up-front work has been done! However, the long term payoff in terms of student outcomes and your own research productivity is likely to be worth the time investment up-front.

3. Barriers to CUREs & strategies to overcome



Essential reading

We recommend reading references 24, 30, 47 and 48.

CHAPTER 5 | AFTER CURE IMPLEMENTATION: WHAT ARE MY NEXT STEPS?

Joseph Provost

Looking forward, how can the biochemistry and molecular biology community build and sustain the CUREs teaching practice? While expanding the incorporation of authentic research experiences into teaching laboratories is critical, the following are a few additional ideas.

Build faculty networks. As individual, stand-alone CURE developers and implementers, faculty members are silos working independent of others to create a sustainable, collaborative project. As emphasized by David Lopatto, there is a need to create collaborative communities for long-term sustainability. Communities of biochemists and molecular biologists who take a careful, scholarly approach to student outcomes while creating a sustainable CURE are still in demand and short supply.

Contribute to the research on understanding the outcomes and impact of CUREs. If you checked box 3 at the start of the previous chapter you need to empirically examine the critical impact of the various CURE elements discussed earlier. Implementing a CURE is more than designing a research project in a classroom setting. As in any scholarly approach, identifying key elements of a CURE to incorporate is critical to achieving desired institutional and student outcomes. However, these elements have not been extensively studied, creating a barrier to designing effective CUREs.

Assessment of CUREs mostly has focused on the entire experience, without assessing the importance of its individual components. Which aspects of CUREs are important for short- and long-term student gains have, for the most part, have not been established. Two notable exceptions are the assessment of student ownership (25, 28) and networking (49). Addressing the importance of other components, such as the role of collaboration and the length of an effective CURE, as well as which aspects of the process of scientific investigation (25,50) will help improve and advance CUREs to a mature and validated teaching practice.

REFERENCES

1. http://visionandchange.org/files/2011/03/Revised-Vision-and-Change-Final-Report.pdf
2. Dolan, E.L., *Next steps for Vision and Change: moving from setting the vision to change.* CBE Life Sci Educ, 2012. 11(3): p. 201-2.
3. *Vision and Change in Undergraduate Biology Education:A View for the 21st Century*, Science, Editor 2009, AAAS.
4. Benvenuto, M.,., *Educational reform: why the academy doesn't change. THE NEA HIGHER EDUCATION JOURNAL Thought and Action Fall.* 2002: p. 63-74.
5. Bell, E., *The future of education in the molecular life sciences.* Nat Rev Mol Cell Biol, 2001. **2**(3): p. 221-5.
6. in *Bio2010: Transforming Undergraduate Education for Future Research Biologists*. 2003: Washington (DC).
7. Wood, W.B., *Inquiry-based undergraduate teaching in the life sciences at large research universities: a perspective on the Boyer Commission Report.* Cell Biol Educ, 2003. **2**(2): p. 112-6.
8. Graham, M.J., et al., *Science education. Increasing persistence of college students in STEM.* Science, 2013. **341**(6153): p. 1455-6.
9. Russell, S.H., M.P. Hancock, and J. McCullough, *The pipeline. Benefits of undergraduate research experiences.* Science, 2007. **316**(5824): p. 548-9.
10. Seymour. E., H.A.B., Laursen. S.L., Deantoni. T., *Establishing the benefits of research experiences for undergraduates in the sciences: first findings from a three-year study.* Sci Educ, 2004. **88**: p. 493-534.
11. Eagan, M.K., Jr., et al., *Making a Difference in Science Education: The Impact of Undergraduate Research Programs.* Am Educ Res J, 2013. **50**(4): p. 683-713.
12. Crowe, M.a.B.D., CUR Quart, 2008. **28**: p. 43-50.
13. Lopatto, D., *Undergraduate research as a catalyst for liberal learning.* Peer Rev, 2006. **8**: p. 22-25.
14. Lopatto, D., *Science in Solution: The Impact of Undergraduate Research on Student Learning.* Research Corp, 2009.
15. Luckie, D.B., et al., *Infusion of collaborative inquiry throughout a biology curriculum increases student learning: a four-year study of "Teams and Streams".* Adv Physiol Educ, 2004. **28**(1-4): p. 199-209.
16. Myers, M.J. and A.B. Burgess, *Inquiry-based laboratory course improves students' ability to design experiments and interpret data.* Adv Physiol Educ, 2003. **27**(1-4): p. 26-33.
17. Rissing, S.W. and J.G. Cogan, *Can an inquiry approach improve college student learning in a teaching laboratory?* CBE Life Sci Educ, 2009. **8**(1): p. 55-61.

18a. Hensel, N., *Characteristics of Excellence in Undergraduate Research (COEUR)*. 2012, Washington DC: Council on Undergraduate Research. 72.

18b. Kuh GD. Assessing what really matters to student learning: inside the National Survey of Student Engagement. Change. 2001;33:10–17.

19. Sadler TD, B.S., McKinney L, Ponjuan L *Learning science through research apprenticeships: a critical review of the literature.* J Res Sci Teach, 2010. **47**: p. 235-256.
20. Thiry, H., Laursen, L.L.,., *The role of student-advisor interactions in apprenticing undergraduate resarchers into a scientific community of practice.* J Sci Educ Technol, 2011. **20**: p. 771-784.
21. Wei, C.A. and T. Woodin, *Undergraduate research experiences in biology: alternatives to the apprenticeship model.* CBE Life Sci Educ, 2011. **10**(2): p. 123-31.
22. Buck LB, B.S., and Towns MH, *Characterizing the level of inquiry in the undergraduate laboratory.* J Coll Sci Teach, 2008. **38**: p. 52-58.
23. Weaver GC, R.C., Wink DJ *Inquiry-based and research-based laboratory pedagogies in undergraduate science.* Nat Chem Biol, 2008. **4**: p. 577-580.
24. Halme, D.G., et al., *A small-scale concept-based laboratory component: the best of both worlds.* CBE Life Sci Educ, 2006. **5**(1): p. 41-51.

25a. Auchincloss, L.C., et al., *Assessment of course-based undergraduate research experiences: a meeting report.* CBE Life Sci Educ, 2014. **13**(1): p. 29-40.

25b. Corwin, L.A., Runyon, C., Robinson, A., and Dolan, E.L. (2015). The Laboratory Course Assessment Survey: A Tool to Measure Three Dimensions of Research-Course Design. CBE Life Sci Educ *14*, a r37

26. Spell, R.M., et al., *Redefining authentic research experiences in introductory biology laboratories and barriers to their implementation.* CBE Life Sci Educ, 2014. **13**(1): p. 102-10.
27. Campbell, A.M., et al., *The essential features of undergraduate research.* CUR Quart, 2003. **24**: p. 139-142.

28. Hanauer, D.I. and E.L. Dolan, *The project ownership survey: measuring differences in scientific inquiry experiences.* CBE Life Sci Educ, 2014. **13**(1): p. 149-58.
29. Rahm. J., M.H.C., Hartley. L., and Moore J.C., *The vlue of an emergent notion of authenticity: examples from two student/teacher scientist partnership programs.* J Res Sci Teach, 2003. **40**: p. 737-756.
30. Brownell, S.E.a.K., M. J., *Toward a conceptual framework for measuring the effectiveness of course-based undergraduate research experiences in undergraduate biology.* 2015, 2015: p. e525-544.
31. Campbell, A.M., et al., *Genome Consortium for Active Teaching: meeting the goals of BIO2010.* CBE Life Sci Educ, 2007. **6**(2): p. 109-18.
32. Hatfull, G.F., *Innovations in Undergraduate Science Education: Going Viral.* J Virol, 2015. **89**(16): p. 8111-3.
33. Jordan, T.C., et al., *A broadly implementable research course in phage discovery and genomics for first-year undergraduate students.* MBio, 2014. **5**(1): p. e01051-13.
34. Elwess. N.L., L.S.M., *Inducing mutations in paramecium:an inquiry-based approach. .* Bioscene, 2004. **30**: p. 25-35.
35. Hingamp P, B.C., Talla E, Gautheret D, Thieffry D, Herrmann C *Metagenome annotation using a distributed grid of undergraduate students.* PLoS Biol, 2008. **6**: p. e296.
36. Lopatto, D., et al., *A central support system can facilitate implementation and sustainability of a Classroom-based Undergraduate Research Experience (CURE) in Genomics.* CBE Life Sci Educ, 2014. **13**(4): p. 711-23.
37. Shaffer, C.D., et al., *A course-based research experience: how benefits change with increased investment in instructional time.* CBE Life Sci Educ, 2014. **13**(1): p. 111-30.
38. Campbell, A.M., et al., *pClone Intro Biology Lesson*. Course Source, 2015.
39. Eckdahl, T.T., et al. *pClone Genetics Lesson*. Course Source, 2015.
40. Cambell, A.M., et al., *pClone: Synthetic Biology Tool Makes Promoter Research Accessible to Beginning Biology Students.* CBE Life Sci Educ. 2014 Summer:13(2):285-96.
41. Lopatto, D., et al. *Genomics Education Partnership*. Science. 2008: Vol. 322, Issue 5902, pp. 684-685.
42. Leung, W., et al. *Drosophila muller F elements maintain a distinct set of genomic properties over 40 million years of evolution*. G3 (Bethesda), 2015 Mar 4;5(5):719-40.
43. Knutson, K., et al. *Bringing the excitement and motivation of research to students: Using inquiry and research-based learning in a year-long biochemistry laboratory*. Biochem Mol Biol Educ. 2010 Sep:38(5):324-9.
44. Bell, E., et al. *Using research to teach an "introduction to biological thinking*. BAMBED Vol 39, No 1 pp 10-16. 2011.
45. Colabroy, K. *A writing-intensive, methods-based laboratory course for undergraduates.* BAMBED Vol 39, No 3 pp 196-203 2011
46. Kleinschmidt, A. *Class III Heme Plant Peroxidase Protein Analysis.* CUREnet, 2013.
47. Brownell, S.E., et al. *A high-enrollment CURE improves student conceptions of scientific thinking and ability to interpret data*. CBE Life Sci Educ. 2015 Summer;14(2):14:ar21.
48. Corwin, et al. *Modeling CUREs: An agenda for future research and evaluation.* CBE Life Sci Educ. 2015 Mar 2;14(1):es1.
49. Hanauer, D.I. and G. Hatfull, *Measuring Networking as an Outcome Variable in Undergraduate Research Experiences.* CBE Life Sci Educ, 2015. **14**(4): p. ar38.
50. White HB, Benore MA, Sumter TF, Caldwell BD, **Bell** E., *What **skills** should students of undergraduate biochemistry and molecular biology programs have upon graduation?* BAMBED Vol 41, No 5 pp 297-301 2013

SELECTED BAMBED ARTICLES ON CURES

1. Bell, E., et al. *Using research to teach an "introduction to biological thinking.* BAMBED Vol 39, No 1 pp 10-16. 2011.

2. Boltax, A.L., et al. *Connecting Biology and Organic Chemistry Introductory Laboratory Courses Through a Collaborative Research Project*. BAMBED Vol 43, No 4 pp 233-244. 2015.

3. Brown, A.M., et al. *Development of a structured undergraduate research experience: Framework and implications.* BAMBED 2016.

4. Farnham, K.R., et al. *A semester-long project-oriented biochemistry laboratory based on Helicobacter pylori urease.* BAMBED Vol 43, No 5 pp 333-340. 2015.

5. Gray, C., et al. *Known structure, unknown function: An inquiry-based undergraduate biochemistry laboratory course.* BAMBED Vol 43, No 4 pp 245-262. 2015.

6. Knutson, K., et al., *Bringing the excitement and motivation of research to students; Using inquiry and research-based learning in a year-long biochemistry laboratory: Part I-guided inquiry-purification and characterization of a fusion protein: Histidine tag, malate dehydrogenase, and green fluorescent protein.* BAMBED Vol 38, No 5 pp 317-23. 2010.

7. Knutson, K., et al., *Bringing the excitement and motivation of research to students; Using inquiry and research-based learning in a year-long biochemistry laboratory : Part II-research-based laboratory-a semester-long research approach using malate dehydrogenase as a research model.* BAMBED Vol 38, No 5 pp 324-329. 2010.

8. Pontrello, J.K. *Bringing Research into a First Semester Organic Chemistry Laboratory with the Multistep Synthesis of Carbohydrate-Based HIV Inhibitor Mimics.* BAMBED Vol 43, No 6 pp 417-427. 2015.

9. Rodenbusch, S., et al. *Early Engagement in Course-based Research Increases Graduation Rates and Completion of Science, Engineering, and Mathematics Degrees.* BAMBED 2016.

10. Shanle, E.K., et al. *A Course-Based Undergraduate Research Experience Investigating p300 Bromodomain Mutations.* Vol 44, No 1 pp 68-74. 2016.