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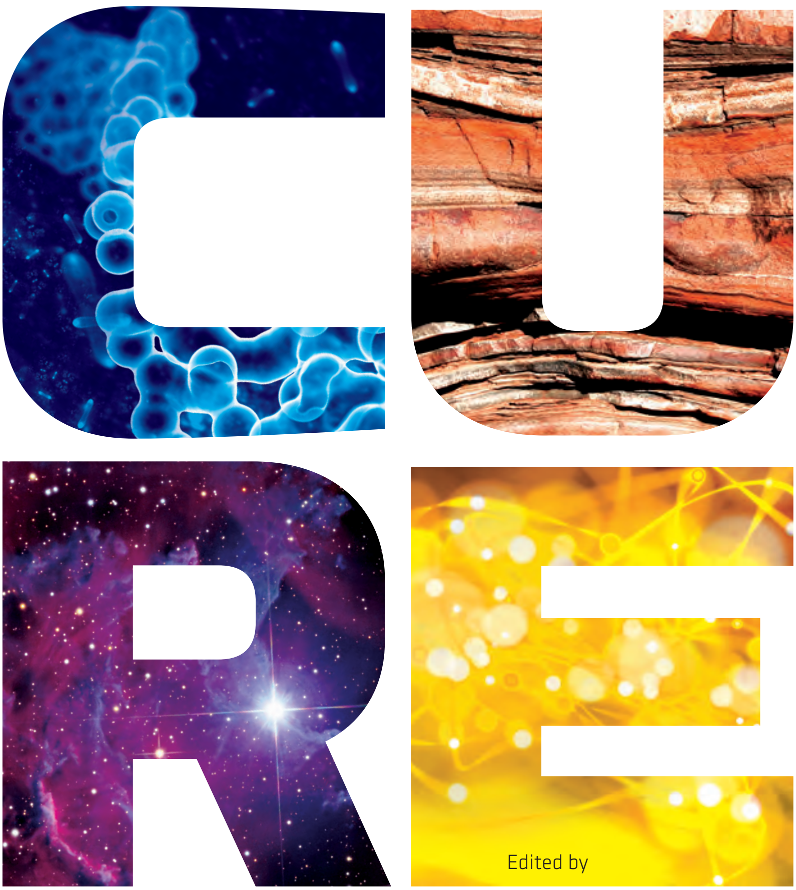
Expanding the CURE Model:
Course-Based Undergraduate Research Experience



Edited by
Rory Waterman
Jen Heemstra

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RESEARCH CORPORATION
for SCIENCE ADVANCEMENT
A foundation dedicated to science since 1912.

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Contents

Foreword

The greatest teacher, failure is.
Yoda

I became a member of the Research Corporation "family" in 1994 when I was selected to be among the first class of Cottrell Scholars. My proposal to the foundation included finding ways to engage undergraduate students in my research in solid-state f-element chemistry. Undergraduate research was an incredible game-changer for me personally, and I recognized the value in engaging emerging scientists in the search for new knowledge. Nearly 10 years later, I was invited to join the Board of Directors for Research Corporation, and I have been engaged with the evolution of its critical programs, including the development of the Cottrell Scholars Collaborative, ever since.

The connection between research and learning in the sciences is indelible. In my experience, chemists learn in the lab—I had already mastered failure in the classroom, and research enabled me to excel. More than the mechanics of a synthesis, collecting a spectrum, or starting a computation, students learn the most when they are asking their own questions—tinkering for themselves—rather than simply following a procedure. Empirically, we understand that this tinkering and the personal investment that leads to intellectual growth comes from research.

Our empirical observation has been justified by study of the learning outcomes of research, and research has been rightly identified as a high impact practice. The cornerstone of our research enterprise, as an educational experience, has been mentored research within faculty-led and peer-supported research groups. I and countless others benefitted from this arrangement and, like many, continue to pay it forward, mentoring new researchers in the academy and throughout industry and government laboratories as well.

As our tech-centered and global economy continues to grow, and our need for a diverse STEM-educated workforce grows with it, there are strains in the mentored research model. Providing traditional research experiences for all students is impractical if not impossible at many institutions. So, how can we furnish students with the opportunity to learn how to test a hypothesis and fail in a comfortable and structured environment? How can we create a STEM-savvy populace who appreciates that wandering lost in the wilderness leads to the excitement of discovery that may change our views on everything or reveals the solution to a global challenge?

One key development has been the model of including a research experience as part of the undergraduate curriculum, and the CURE (Course-based Undergraduate Research Experience) model is one pedagogy that provides a research experience to more students. Infusing research in the curriculum, like CUREs, is an opportunity. Not only can we include and serve more students, but we can expand the passion for science that so many of us developed while practicing science.

The "Secret Sauce" for the success of CUREs and related practices is that they provide the same benefits to students that a mentored research experience does. The added advantages of the practice are that more students participate, they can participate earlier in their careers, and they can use multiple CURE experiences to shop for their passions within their discipline. All this while we know that those students are realizing the same benefits in their development—not to mention the possibility for more discoveries!

A group of Cottrell Scholars identified a problem. The development and uptake of CUREs appears to be faster and greater in the life sciences as compared to the physical sciences. They pulled together a group of experts in the field, fellow practitioners, and leaders to identify the challenges and lay out a set of solutions. They tested hypotheses, some failed, but the lessons-learned captured in this report are a treasure-trove of information. The report outlines the steps that an individual faculty member or department may undertake to advance this practice and open up opportunities for the future practitioners of science.

I look forward to seeing the benefits of this critical new resource.

Dr. Peter K. Dorhout
Professor of Chemistry
Vice President for Research
Kansas State University
2018 President of the American Chemical Society

Preface

Course-based Undergraduate Research Experiences (CUREs) transform traditional coursework into a research environment that meets both educational and research objectives. This pedagogical approach has been adopted by many Cottrell Scholars, who noted that CUREs are much more widely utilized in the life sciences compared the physical sciences, particularly astronomy, chemistry, and physics. Additionally, as these individuals recounted their own challenges in adopting the practice, the barriers that faculty face in developing, implementing, and sustaining CUREs in the physical sciences have become more apparent. Having identified this deficiency, the group of Scholars sought actionable items to facilitate the adoption of CUREs by physical sciences faculty. It was identified that better knowledge of the practice and support mechanisms, along with practical resources such as sample research projects, could be leveraged to promote increased uptake of CUREs.

The Cottrell Scholars are far from alone in this interest. While many groups seek to broadly improve STEM education practices, there are two specific groups that have been advocating for greater research incorporation in the curriculum. Center for the Integration of Research, Teaching and Learning (CIRTL) has promoted the practice Teaching-as-Research ("TAR" *https://www.cirtl.net/p/core-ideas-teaching-as-research*), and the CURE Network ("CUREnet" *https://curenet.cns.utexas.edu/*) has been advancing CUREs by providing resources to practitioners, primarily in the life sciences. Both groups have or will host workshops and conferences (e.g., *https://www.cte.cornell.edu/programs-services/Peer-Institutions/teaching-as-research.html and https://curenet.cns.utexas.edu/resource-by-category/other-resources*). These activities are on top of consistent promotion of undergraduate research activities in the respective disciplines and by cross-disciplinary groups such as the Council on Undergraduate Research or the Association of American Universities. Indeed, this year saw the release of a National Academies report investigating the evolving practices of undergraduate research and advocating for greater adoption of course-based research experiences that leverage best practices in pedagogy and can improve access and inclusion in the academic research enterprise.

The group of Cottrell Scholars did see room for providing additional translation between policy and practice, primarily through equipping and empowering faculty at their institutions and outlining the arguments that can effectively motivate both faculty and administrators to support integration of research into the curriculum. At the core, the group viewed its primary goal as enabling the practitioners. Research Corporation for Science Advancement agreed with this thinking and provided funds to support a workshop on the topic of expanding adoption of CUREs in the physical sciences. The organizing committee anticipated that the workshop would produce a report on the design and implementation of CUREs and inquiry-based labs in the physical sciences, a simple reference guide for starting a CURE, and an on-line environment to provide support by connecting experienced practitioners with new and prospective adopters of research-based curricula.

The group of Cottrell Scholars, along with several key stakeholders from academia and professional societies, assembled in Chicago in December 2016 for an intensive day-and-a-half dive into the barriers that might discourage physical sciences faculty from the adoption of CUREs in their respective curricula. This report is the final anticipated product of that group and details the challenges, solutions, and opportunities associated with broader adoption of CUREs in physical science curricula.

The organizing committee of Cottrell Scholars represented the core group of attendees. Practitioners, discipline-based educational researchers (particularly individuals involved in CUREs), administrators, and representatives from funding agencies were invited as well. These individuals were intended to represent the range of constituencies impacting faculty implementation of CUREs. The organizers had an initial structure for the workshop that included specific working groups tasked to flesh out general ideas that have been identified as challenges and opportunities associated with the practice (Table 1). The organizing committee also identified a broader task in its own charge, investigating both research- and inquiry/discovery-based practices. However, on site, participants focused more on research-based practices (i.e., CUREs) and worked primarily in that area.

Table 1. Working groups populated by workshop participants.
These topics formed the basis of the chapters in this report.

Topic	Leader
Assessment of CUREs and inquiry-based labs	Andrew Feig, Wayne State University
CUREs—Research problem selection and curriculum design	Penny Beuning, Northeastern University
CUREs—Resources and scalability	Amelia Fuller, Santa Clara University
Pre-CUREs	Rory Waterman, University of Vermont
Inquiry-Based Laboratory Curricula	Jenny Ross, University of Massachusetts Amherst
Institutional Opportunities and Challenges Associated with CUREs/Inquiry-Based Laboratories	Jen Heemstra, Emory University

The workshop event was lively and productive. The groups dove into their work, and despite a somewhat grueling schedule, participants remained energetic and upbeat for the duration. The working groups provided excellent content that gave rise to insightful and animated discussion from all participants (below).

CURE Workshop Notes

Example of notes arising from meeting discussion. In this example, the discussion related to the development of the 'quick-start' guide.

At the time of this report, a tri-fold brochure has been produced and disseminated in print to new faculty members at professional development activities, through programing at meetings, and on the Web in several locations, most prominently via the Research Corporation for Science Advancement Web page, in the section for the Cottrell Scholars Collaborative (*http://rescorp.org/cottrell-scholars/cottrell-scholars-collaborative*). The team implemented a discussion group via Facebook (Adding Research to a Class, *https://www.facebook.com/groups/1744026378960195*) as an easy-to-maintain method of promoting interaction and support among practitioners, and a standing site for distribution and archiving of resources. The group has >150 members at time of writing, and while protected, any interested individual can join. This report provides a catalog of the workshop discussion and products, which is presented as a reference for practitioners and administrators seeking to support greater adoption of this practice.

As noted above, financial support from Research Corporation for Science Advancement (RCSA) made the workshop and resultant products possible. The organizers and participants are tremendously grateful for the opportunities that the funding availed and RCSA's unwavering support for the integration of research and teaching. We also thank the participants, who are listed below, for their efforts and insights.

Workshop Participants

Penny Beuning, *Northeastern University*
Scott Bur, *Gustavus Aldolphus College*
Lisa Corwin, *University of Colorado, Boulder*
Ogilvie Craig, *Iowa State University*
Erin Dolan, *University of Georgia*
Leslie Elliott, *Boise State University*
Andrew Feig, *Wayne State University*
Amelia Fuller, *Santa Clara University*
Jim Gentile, *Hope College*
Jordan Gerton, *University of Utah*
John Gilberson, *Western Washington University*
Jason Gillmore, *Hope College*
Jen Heemstra, *Emory University*
Florencio Hernandez, *University of Central Florida*
Robert Hilborn, *American Association of Physics Teachers*
Dmytro Kosenkov, *Monmouth College*
Casey Londergan, *Haverford College*
Will Pomerantz, *University of Minnesota*
Stacia Rodenbusch, *University of Texas, Austin*
Silvia Ronco, *Research Corporation*
Jenny Ross, *University of Massachusetts*
Sammye Sigmann, *Appalachian State University*
Toby Smith, *American Association of Universities*
Levi Stanley, I*owa State University*
Laura Trouille, *Adler Planetarium*
Mark Tuominen, *University of Massachusetts*
Joi Walker, *Eastern Carolina University*
Gabriela Weaver, *University of Massachusetts*
Rory Waterman, *University of Vermont*
Jodi Wesseman, *American Chemical Society*
Kraig Wheeler, *Whitworth University*
Lee Zia, *National Science Foundation*

Participants' contribution to this report represent their own opinions and not those of their respective employers.

Jen Heemstra
Emory University

Rory Waterman
University of Vermont

Part I: Before

1

Development of a 'Quick-Start' Guide

Session Leader: Rory Waterman, University of Vermont

One objective of this workshop was to produce tangible products that facilitate the consideration and adoption of CUREs and related discovery-based practices in undergraduate education, particularly for the physical sciences.

Approach

Workshop participant brainstormed about the nature of products that may stimulate great adoption of CUREs among physical science faculty. Participants agreed that several types of resource are important including additional examples practices in sufficient detail to allow for replication and emulation, a support network that has been developed through Facebook (the "adding research to a class" group, *https://www.facebook.com/groups/1744026378960195/*), and introductory materials that serve as an immediate reference were priorities among the participants. The group set about to producing a short manual that would provide information about the practice for those unfamiliar as well as giving a new practitioner some guidance during their initial design. The workshop participants identified key areas of information to include in such a guide that was drafted and edited by the participants. A final tri-fold brochure was produced by a graphic designer (Figure 1) and printed. A high-resolution copy is available online. (*http://rescorp.org/cottrell-scholars/cottrell-scholars-collaborative*).

Adding Research to a Class Brochure

Tri-fold brochure, developed in early 2017 and deployed on line via the Cottrell Scholars Collaborative Web page (http://rescorp.org/cottrell-scholars/cottrell-scholars-collaborative) and in print.

The workshop participants developed, as one might anticipate, too much content for a tri-fold brochure. What follows is the majority of that content.

Undergraduate research is a high impact practice, and adding a research component to an undergraduate class may help provide better access to research experiences for those students or help meet other learning objectives. Implementing research in coursework can be difficult, but often the biggest challenge is getting started. This document is a brief guide to some of the critical issues you may encounter in exploring this option, and some initial resources to help navigate those issues.

Ask yourself some questions

1 What do you want to accomplish?
Do you want to engage students in a research experience, or is the research a means to meet other learning objectives? Are there other outcomes you would like to see occur like persistence in the discipline or self-efficacy? There are different ways to approach adding some amount of a research experience to a course, and those possibilities are detailed in the course types section.

2 Who is this for?
A research activity is appropriate for any level, but the degree to which that activity is structured and scaffolded changes with developmental stage. A few

examples of research in coursework are presented for different levels in the course types section.

3 What will the students actually do?
It is important to consider both what the students will be attempting in the lab as well as what you expect them to produce or be assessed upon. Students will make more or less research progress based on the amount of structure and their prior knowledge of techniques, but research progress may not be as important as skills acquisition or research design. Those critical choices inform what you need to evaluate in your course.

4 What do you need?
Research costs money and time. A 400-seat general chemistry course cannot get synchrotron time for each student, but those students can have infinite Spec-20 time, for example. Most CUREs require instructional support, which may be the faculty member and/or teaching assistants, appropriate space, supplies, and access to necessary equipment. These needs may be met by converting a pre-existing course that has the requisite resources. At the same time, resources you have may determine the choice of project.

5 Do you have the time?
Converting all of the E&M laboratories for 1000+ students to a CURE is a tremendous operation. However, converting a single experiment is a more manageable step toward a larger goal for a course. Additionally, a shift from traditional experiments to inquiry, for example, may be another way to make larger changes more manageable.

6 Will the research element introduce greater hazards in a lab course?
More consideration may need to be given to additional hazards and increased risk when adding discovery elements into experiments. Complexity and novice workers, combined with agents, chemicals, equipment, and processes having greater hazards can all increase risk in any laboratory.

Research in coursework

Course-based undergraduate research experiences (CUREs) and teaching as research (TAR) are two of several names for the inclusion of research in a class setting rather than as traditional mentored research. Integration of research in coursework can be highly variable from students fully active on a project to students learning about research methods. CUREs are defined by students engaging in genuine research, which can be characterized by five critical features: 1. Use of scientific practices, discovery, broad relevance, collaboration, and iteration (Corwin et al., 2014). The degree to which students pursue any combination of activities represents a continuum from a traditional prescriptive laboratory course, where few of those five features are addressed, to inquiry, where many of the five features could be addressed but the outcomes are known (i.e., genuine discovery is not possible). The critical distinction in research activities, like CUREs, is regardless of other practices present, the students are investigating areas with unknown outcomes. It may be important to prepare students for research more than the activity of research itself in a pre-CURE format where student are engaged in some of the five features to prepare for either research in coursework, a traditional mentored research setting, or other activity like internship.

The problems that students investigate

If students are to engage in research, then the activity of research must be considered first. Defining a set of research objectives for the course paves the way for listing what technical skills students need, safety considerations, and the scope of the investigation. By defining the research objectives early, if not first, the learning outcomes flow naturally from the research and there is less risk of compromising the research or student gains in the course itself.

The scope of the problem is determined by the interest of the instructor as will be the set of skills and techniques needed. If the research problem is relatively simple, a component of a larger question, then the process is easier to scale to younger students, while older students are often more developmentally ready for more intellectually challenging research questions. By definition CUREs are research, and there are now many examples of student teams in courses collecting and analyzing publishable data as stand-alone studies or integrated in larger bodies of work.

What students learn

Like all courses, have specific learning objectives. Therefore, when students are focused on research, this will allow for intellectual growth in specific areas. If the learning objectives are skills based, then research objectives of may be of lower importance than students employing a series of techniques. In converting an existing course to a CURE, there is the risk that specific content or skills may be lost in the conversion. However, carefully designed problems can include any desired content or skills. Incidentally, problems may have high overlap with the faculty member's research interest. In any CURE, it is critical to have instruction on research as part of the course. Students are not being mentored, and questions of processes should be addressed early to ensure that students understand what their role is to promote their success.

Tips for assessment

1 Articulate your objectives

Who are you teaching? Why have you opted to teach a CURE? Who will benefit and how? Focus on collecting and analyzing data most relevant to your objectives. You can collect different data in the future—evolving the assessment as the course evolves.

2 Know your audience
Who will use the data and for what purposes? What data do they care about? Focus on collecting and analyzing data that are most salient to your audience rather than collecting all of the data that are possible to collect.

3 Start small and avoid reinventing the wheel
Are there ways that assessment data are already being collected, such as student assignments from the class itself or course enrollments from the registrar? Start with what you are already doing or identify existing data sources and assessment tools.

4 Ask for help
You don’t have to do this all yourself. There may be people right on your own campus who can help, such as individuals in institutional research, in education, psychology, or other social science departments, or in centers of teaching and learning or evaluation and assessment.

5 Assessment is iterative—just like your research
Once you have answered one assessment question, move on to a new one. You can evolve your data collection and analysis plans as you make progress with the course and learn from the assessment.

Research means *genuine* research

The importance of research as a high-impact practice is well documented, and individuals reading this guide can likely point to research experiences as key points in their own professional development. Despite the premium we place on research and the degree to which research results are vital to society, the activity of research itself is not sexy. Research is often monotonous, repetitive (i.e., “iteration” from[1]), frustrating, and sometime dull. Students should be aware that researchers fail, and that failure in research is much better tolerated than it is in an educational setting. Importantly, students should be informed from the outset of the course that their grade will be based on effort and comprehension, rather than success in achieving the research goal.

Another reality of research is the uncertainty, which breeds risk. Teaching and performing risk assessment should be included in coursework to ensure that hazards are determined and risk mitigated to an acceptable level for a teaching lab.[2] Emergency preparation should be active—not passive. Students should test eyewashes, review spill kit contents, or use a fire extinguisher. They should note near misses in their lab notebooks and report out at group meetings. Students should demonstrate competency to the instructor when training on new equipment with physical hazards.

As researchers, we have a responsibility to disseminate our results, and this is also a critical part of the CURE experience. Some studies in CUREs produce publishable results, and there should be some advanced thought on authorship. Involving the students in discussions of authorship and how credit is assigned are important development points for responsible researchers. Regardless of publications, the students should be acclimated to the idea the fruits of their investigation are useful whether they are positive, negative, or inconclusive during the course itself. Thus, communicating results in written and verbal form are important skills in a research laboratory, but the choice of how that communication is done is the purview of the instructor.

These components enrich the real research experience for CURE participants.

What is being graded?

As with any course, grades must be assigned. The instructor must assess students on learning objectives, which can be accomplished with traditional devices including tests, quizzes, laboratory reports, presentations, practica, etc. Research progress is, naturally, a poor metric by which students can be assessed. As with mentored research progress, progress is influenced by too many factors to accurately reflect on a student's learning.

Supporting a CURE

Executing a successful CURE requires resources. The most immediate resource is your time. To be successful, you need to invest thought and effort into the planning and execution. Additionally, research activities require resources, be it consumable materials, time on research-grade instrumentation, or training for users. The degree to which a CURE can be run within the budget of a traditional laboratory experience is based on the nature of the work and ingenuity of the instructor. As with all endeavors, a cost-benefit analysis aids in developing support for activities that require additional resources. CUREs have the potential to meet pre-existing learning objectives *and* developmental objectives such as persistence or self-efficacy that are sought after but difficult to address by other means. CUREs can also help departments to meet the strategic goal of providing each undergraduate major with a genuine research experience, which can be difficult to accomplish solely through traditional research internships.

Learn from your peers

There are now many iterations of research-inclusive courses across disciplines. While there are a myriad of routes to develop these courses, one common pathway follows. There is a linearity to these tasks but they can be executed in the order that suits you best.

Initial stages

1 Select research objectives and develop learning objectives from these.
2 Identify the course (new or converted) that will be used.
3 Select problem(s) to be investigated and techniques to be employed.
4 Plan the scope and scale of the course.

Administrative work

1 Solicit buy-in from appropriate administrator (e.g., department chair).
2 Identify needs, if any, beyond a conventional course and make the ask.
3 Assemble the necessary resources for the course (space, TAs, instrument time, etc.).
4 Assemble the necessary personnel (trained TAs, stockroom, faculty, etc.).
5 Devise any non-learning metrics of success.

Educational work

1 Using your objectives, design the course details (activities, assessment, etc.).
2 Develop an explicit plan to instruct students on research as an activity.
3 Include features that ensure the work is research (iteration, discovery, risk assessment, etc.).
4 Test the plan with a smaller group of students to ensure they are engaged in the targeted activities.

Execution

1 Be flexible in running the course; let the learning outcomes drive the curriculum.
2 Solicit feedback from students and/or faculty.
3 Evaluate against your learning objectives and any metrics of success.
4 Be prepared to make choices between research progress and student learning with attention to both.
5 Iterate the course and run again.

Tips from adopters

1 Get help! Help may come from a colleague with similar ambitions, an administrator who supports your plans, or an off-campus peer who has executed similar coursework (e.g., CUREnet), among others.
2 Plan…and then plan some more. Research is open ended, but students need instruction on how it is done. Instructors need be ready to make choices about research and learning goals, particularly if these become conflicting.
3 Start small. Practicing with research students, a smaller section of students, or a smaller part of a course is an excellent way to hone the CURE model in your own hands.
4 Be cognizant of time and timing. We are often overly ambitious in our own research, and teaching students in that format will both slow any progress and potentially take more of your time.

5 Acclimate students. Research means failure, so students need to know that success in the course is not attached to success in their project.
6 Iterate. Like all changes to your teaching, adding a research component will be most successful after some trial and error.

Resources

These are a few starting points to get documents and help for your planned course.

CUREnet is a network dedicated to this practice: *https://curenet.cns.utexas.edu/*

CIRTL supports development of new practices: *https://www.cirtl.net/*

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2

Getting a Leg Up on Research: The Pre-CURE Model

Session Leader: Rory Waterman, University of Vermont
Contributors: Jordan M. Gerton, University of Utah; Holly S. Godsey, University of Utah; Florencio E. Hernandez, University of Central Florida; Laura Trouille, The Adler Planetarium; and Kraig A. Wheeler, Whitmore University

Introduction

The motivation for students to engage in high impact practices such as research and/or inquiry comes with the risk of limited benefits to participant students if they are ill prepared or unguided in their work.[1] This potential issue is exacerbated by the scalability that CUREs (Course-based Undergraduate Research Experiences) have relative to traditional, mentored research. Therefore, a structured introduction to the practice of science can help ensure success for students that participate in either course-based or mentored undergraduate research experiences. Such an introduction would also provide a context for students involved in other high impact practices, like inquiry, to maximize their learning. Finally, a firm understanding of the practice of science would promote stronger outcomes for students in internships and co-ops, where academic outcomes may not be as evident to students.

We introduce the term “pre-CURE” to describe an adaptable introductory or preparatory program focused on scientific research. The main goal of pre-CURE is to present a holistic and realistic picture of scientific research to students of all majors and academic level. The pre-CURE, in providing preparation for research, also addresses scientific literacy by outlining how knowledge is acquired through research and that there are multiple ways to investigate a problem under the broad umbrella of scientific research. This unique experience is anticipated to accompany students through their careers and beyond.

The pre-CURE model has four specific aims:

1. Offer all students a first academic exposure to authentic scientific research practices.
2. Present the benefits and challenges associated with scientific investigation.
3. Provide a unique, "signature" science literacy experience.
4. Prepare for future inquiry, CURE, mentored research, or internship.

Because a CURE offers an avenue to a research experience, such course-based activities must meet five critical components that define research, namely scientific practices, relevance, discovery, collaboration, and iteration.[2] In principle, a pre-CURE may simply address content and skills that prepare students to undertake all of those activities in a mentored research experience or a CURE. Because any research experience often utilizes a single method of inquiry (observational vs. hypothesis-driven vs. curiosity, etc.) and often has a single mode of investigation (theoretical vs. experimental, etc.), a broader view on the process of science is often absent from these experiences. The specific value of pre-CURE is that the understanding of the practice of science is greater than the understanding garnered from a single experience as a practitioner.

Additionally, pre-CURE provides a stronger science literacy experience than traditional coursework. With that feature, development and expansion of pre-CURE offerings, particularly for non-science majors, would provide science literacy absent from even many college graduates.[3,4] Indeed, some studies indicate that science literacy does not improve for students upon completing a traditional college-level science course.[5] This improved science literacy is itself science advocacy: Students who understand science better are both more able to make informed decisions on those topics but also provide a more informed and authoritative voice in conversations with peers over science-related issues. Additionally, science majors have a unique opportunity to educate and instill basic science principles that could serve further advocacy for science within their immediate surroundings when they can better articulate the process of science as well as understand findings.

Implementation

The intrinsic flexibility and adaptability of pre-CURE allows for its relatively easy implementation by teachers, instructors, lecturers, professors, and TAs, in virtually any academic setting and educational level (K–16). Because more experienced instructors are familiar with program content as well as course pedagogy, these individuals can offer an important resource for identifying key areas to develop *and* deliver pre-CURE instruction. Those with less experience in the classroom are also uniquely positioned to implement pre-CURE activities. For instance, newer instructors often provide a fresh outlook at curricular issues coupled with less-rooted instructional plans that can provide ample opportunities to engage students with practical and realistic viewpoints of the scientific research process. Ideally, curricular changes that implement pre-CURE activities will occur at the departmental/divisional level where the entire cohort of instructors can contribute to the ownership of the pre-CURE model(s).

Pre-CURE is designed to prepare students of all majors to understand, from a realistic point-of-view, the benefits and unique challenges of scientific investigation. What students can gain in these courses is a much better understanding of how knowledge is developed through the practice of science. The pre-CURE also provides an early venue to connect classroom concepts with practice. That is, the deeper connection to research can provide both context and value to students in the pre-CURE as well as other courses. Finally, the pre-CURE model contains many, if not all, of the parts of research, which means that these courses provide aspects that are critical parts of what makes research a high-impact experience.

Pre-CURE can be implemented in various course modalities. It is easy to add the requisite components to lecture-based courses, seminar programs, field trips, pre-labs and traditional laboratory courses, among others. Additionally, the format that is utilized is not prescribed. Pre-CURE courses or pre-CURE content within a course can be delivered as anecdotes, case studies, invited speakers, CRAP Test, literature-based research, and so on. This chapter explores some readily implemented pre-CURE models with examples of existing programs that exercise this unique practice. In this forum, we present potential design options as a stand-alone course, distributed content throughout, or in a pre-college setting, though copious other variants are possible.

1. Stand alone course

Context: A department has an existing “freshman seminar” course to introduce majors (and prospective majors) to the discipline. The course runs two consecutive semesters and is required for graduation. The course meets once per week for 1 hour (1 credit), and a pass/fail grade is assigned based on attendance. Historically, the freshman seminar has been used to introduce undergraduates to the range of research activities in the department, so each week a new professor presents their research in a way that is (hopefully) accessible to early undergraduates.

The proposition: An enthusiastic professor wants to reform this existing course to better prepare students for research in a variety of sub-disciplines and contexts.

Program or curriculum development: The specific goals and desired outcomes should be articulated early in the planning process. For example, it might be desirable for students to be able to demonstrate understanding of specific aspects of the scientific enterprise, such as the nature of scientific inquiry and research, various scientific practices, specific skill sets, etc. Another desired outcome might be that students gain an ability to connect existing and future disciplinary knowledge to specific scientific practices and processes. Perhaps students will be expected to be able to analyze the validity of publicly accessible data or scientific claims (e.g., climate data). Given that the freshman seminar course is already a departmental initiative in that it represents the interests of the entire department and the desire to have this course better prepare students for future research experiences, these goals should be developed in collaboration with other members of the department and should specifically include departmental leadership. Additionally, given that research, and undergraduate research specifically, is a primary institutional goal, it might also be useful to seek input and collaboration from other institutional entities such as an office for undergraduate research, a STEM center, a center for teaching and learning, dean, the vice president for research office, etc.

Once the course/project goals are articulated, a commensurate assessment strategy can be developed. It should be acknowledged that assessment plays a key motivational and accountability role for students, so it may be necessary to move away from the existing low-stakes assessment strategy. However, it is appropriate to start small/minimal and build a more robust assessment plan as the project matures. It is also appropriate to have some course goals that are not easily evaluated. Evaluating the impact of the course on students over time can help improve the course and generate resources to sustain the course over time. Furthermore, there are assessment tools that many faculty may not be aware of that collaborations on campus may reveal.[6]

Once the goals and assessment strategy are in place, a series of activities that help students develop the competencies articulated by the learning goals can be developed. These activities could include faculty research seminars, but these activities would also presumably include other elements such as reflective writing, development and application of rubrics for effective communication, manipulating and analyzing research-based datasets, hands-on activities, etc. There are various models for instruction in the basic practices of research.[7]

Early in the planning process, it is important to evaluate what resources are needed to achieve the goals of the course and to take stock of the available local resources. Resources may include actual funding, faculty buy-out time for course development, appropriate space, materials, and (importantly) collaborators and champions among colleagues and institutional leadership. The availability of appropriate resources will ultimately determine the possible scope of the project. It is essential to recognize that a faculty member's time/effort is a limited resource, perhaps especially so for early-career faculty. Therefore, it is critical to evaluate the availability of one's own time/effort to help properly scope the project. To sustain the course over time, it is also important to identify colleagues who could teach the course, where the earlier these colleagues are engaged in the planning process the better.

Some possible outcomes:

> **Relatively minimal/easy course modifications:** The instructor decides to co-opt every other (or every *n*th) week/seminar to interject explicit instruction relevant to the research presented in the seminars. Depending on the lineup of faculty/seminars for the semester, this could include lectures/exercises/activities on the nature of science, statistics and uncertainty in the context of scientific data, measurement and observation, foundational principles and/or methods underlying the research presentations, scientific communication, etc. Another possibility would be to have students produce reflective writing pieces regarding the research presentations, and ideally this would be accompanied by a rubric and/or template for those pieces. Reflective writing is a good way to develop analysis and metacognitive skills in addition to communication skills. Furthermore, writing pieces could be evaluated in part or in total by other students, which has a cognitive value but also helps students begin to appreciate the nature of peer review (not to mention potentially easing the grading load on instructors!). Students could also be asked to score/grade each seminar using a rubric, which could either be provided by the instructor or co-developed with the students as part of their learning outcomes. Students could be assigned a grade based on a combination of work products (e.g., reflective writing pieces), participation/attendance, and some measure of engagement in external research-oriented activities.
>
> **Intermediate course modifications:** In addition to or instead of above, the instructor incorporates hands-on activities associated with the research seminars. For example, the instructor might solicit data or projects/problems from the faculty members giving the seminars, and help the students perform analyses of the data, or design strategies to address the projects/problems. An example would be a lab-sourced data set that could be statistically evaluated and compared to various physical/mathematical models. This activity would require explicit instruction on the relevant types of analyses and coordination/collaboration with the faculty members presenting their research. It might also require more resources, both in terms of development time/effort and potentially funds for materials, space (e.g., for computation/analysis), logistical/administrative support, etc. Another possibility is to incorporate in-class activities or homework that allow students to explore foundational concepts in different aspects of measurement (e.g., a group activity for measuring the oscillation period of a pendulum and determining the physical attributes it depends on), communication, or some other scientific practice.
>
> **Major/difficult modifications:** The instructor could institute major or whole-cloth reforms, including adding an explicit laboratory component, short rotations through research laboratories, team/group projects, etc. While such major changes will essentially be equivalent to creating a whole new course, the advantage of starting with the freshman seminar is that it would effectively replace an existing course, rather than add an additional course(s) to the majors' curriculum.

Example: Research seminar as a pre-CURE

The increasingly strong chemistry curriculum at the high school level including general chemistry, AP chemistry, and in some instances, organic chemistry coupled with extensive preparation in calculus have led to many students placing out of the first-year curriculum for majors at the University of Vermont. At the same time, these students are not often sufficiently prepared for sophomore-level organic chemistry as first-year students and spend their first year not engaged in the major. The department had a replacement for general chemistry, Introduction to Research, that placed students with AP credit in rotations through research laboratories. Students in this course, however, lacked both disciplinary background as well as research understanding, and the course met with mixed success.

To address the needs of high performing first year students, the department chair, Prof. Christopher Landry, developed a one-credit course titled Chemistry Scholars Workshop. A core activity of the course is brief research presentations to the students by faculty, who also supply a copy of the presentation slides to Prof. Landry. In the subsequent meetings, Prof. Landry helps students unpack the research presentations. In many instances, there are fundamental concepts that can be highlighted. That is, students can be reminded that they already have tools to understand current research. More important, the students see and develop an understanding of the process of research and how faculty can arrive at their conclusions.

The end goal of the course is for students to identify a research advisor and begin mentored research in their second semester.

They are also guaranteed at least one summer of funded research, paid for by the department. The students are provided with an overview of the department's research programs, an overview discussion of each area, and a brief introduction to the faculty members in the class session. These various pieces—with Prof. Landry's encouragement—prepare the students well to seek positions in various laboratories. As a result, the first offering of the course led to successful second-semester research projects for most students, and two participants stayed for summer research after their first year.

Example: Nature of science as a pre-CURE to support non-science majors

The University of Utah is offering a course titled Nature of Scientific Inquiry that provides students with an introduction to the scientific endeavor as both a body of knowledge and as a process. The course distinguishes scientific inquiry as a unique way of knowing that employs a specific set of norms and practices. Students perform simple scientific inquiries to explore foundational principles and engage in their own open-ended discovery activities. The framework for the course is built around the scientific "understandings" about the nature of science that can be taught using a variety of scientific examples ranging from the concepts specific to describing science such as "scientific investigations use a variety of methods" to the features that distinguish science from pseudoscience such as "scientific knowledge assumes an order and consistency in natural systems." This framework makes it possible for the instructor to tailor the course to their expertise, a theme, or current events. For example, the course might use the history of the earth, evolution, or plate tectonics as a central theme to explore the various characteristics of the nature of science. Alternatively, an instructor might have students investigate the evidence for relativity and quantum mechanics and how new evidence caused a significant paradigm shift from classic mechanics to address how science is revised. Yet another option is to use the framework to teach about current events. For example, in fall of 2017, students learned a variety of scientific tools and practices by modeling the 2017 solar eclipse, gathering and analyzing meteorological data to make predictions about Hurricane Harvey, and investigating the properties of wildfires in the west.

Explorations are also carried out within the context of their historical development; for example, students might investigate the basics of pendulum motion while learning how Galileo's work on pendula revolutionized navigation. Students also grapple with ethical scientific dilemmas and explore how science interacts with society. Findings are communicated through writing, discussion, and oral and poster presentations. This course is intended to provide a foundation for *non-science* majors to become part of a scientifically-literate society, and context for science majors as they progress through future coursework and scientific careers.

Part of an existing course(s): Another approach for implementing a pre-CURE program could include a distributed model where students are introduced to the basic principles of the research process across several existing courses. These associated courses could be department/discipline specific, but could easily be adapted to accommodate institutional wide instructional initiatives such as those associated with general education requirements. This distributed model would ideally involve a cohort of faculty committed to the mutual goal of preparing students for future research experiences, potentially including CUREs. The implementation of pre-CURE content would follow a variety of possible instructional strategies. These may include merging pre-CURE activities with existing course topics or the implementation of new course modules based on pre-CURE specific objectives. Depending on whether the institution implementing these changes has a large transfer student population, care should be taken to provide these students equitable opportunities to benefit from the pre-CURE experience since their pre-transfer curriculum may not have incorporated the same elements. Some practical examples of this may include:

Historical perspectives: Because the research process demands an understanding of what has gone on before, providing students access to historical perspectives is an entry point for pre-CURE programs. Previous discipline specific investigations may provide opportunities to discuss early discoveries of fundamental importance or examples of notable disputes/controversies that have since been explained (e.g., polywater). Integrating historical perspectives into existing coursework also provides an opportunity to specifically highlight work done by under-recognized researchers as a way to develop a more inclusive perspective on science.

Current reviews: Offering well-placed vignettes that describe the societal importance of current research efforts encourages research literacy and appreciation. Such activities can inspire and invite students to make important connections between discipline specific outcomes and the world around them. The depth of content may be adapted to a particular student demographic and anticipated instructional outcome.

The research process: Though applying CURE principals to a variety of laboratory settings and experiments is covered extensively in this report, exploring the research process should not be disregarded in pre-CURE programs. By exploring the details and procedural aspects of research agendas, students are offered important viewpoints of the research method. These discussions could easily stem from the outcomes of historical and current research efforts as reported in the literature, but could also take a turn where student participants gain insight to the research process via guided inquiry activities

Developing research proposals: The process of writing even a short research proposal provides significant benefits to the student, and it is a critical aspect of the research enterprise that is often absent from undergraduate research experiences. Many institutions offer fellowships of some sort for undergraduate research, and most require applicants to develop a research proposal independently or in collaboration with a mentor. Thus, a capstone project that involves writing and submitting a research proposal to the institution for funding (if available) could be an excellent way to integrate pre-CURE elements into an existing course.

Because the goal of pre-CURE is to provide students with a realistic view of scientific research experiences, it stands to reason that exposing students to several smaller purposed activities may outweigh models that target singular, but substantial activities. It should also be noted that additional flexibility exists with the pre-CURE approach for learning communities to adopt common themes across associated courses or by providing students with unique views of the research process involving these same courses. Both paths offer valid entry points for student engagement with course content directed at Pre-CURE activities/discussions. As such, emphasis should be placed on leveraging local resources and current momentum to most effectively help students explore the various aspects of the research process.

2. Distribution across several courses

Context: The core components of a pre-CURE can be delivered in more than one course. Thus, all four aims of a pre-CURE experience can be addressed. Distributing any core knowledge across multiple offerings risks transfer students losing key content or skill. In this regard, using distributed content to reinforce key components of the pre-CURE model both meet objectives, support retention, and prevent transfer students from slipping through the cracks. Many introductory courses present the nature of science, but those experiences are often focused more on the scientific method than on how the activity of research helps to generate new knowledge. One of the largest gains that can be made across multiple courses is to better establish the foundations for future research activity (specific aim 4). Meeting specific aim 4 lays the academic ground work for success in a research endeavor. However, multiple interventions allow departments to better address two of the critical challenges identified by Branchaw and coworkers for students entering research, namely the transition from classroom-based learning to that in a research environment and integration of students in the social structure of a research community.[8] Addressing these two challenges within this (or any pre-CURE) structure would promote student success. More importantly, it provides a particular benefit to students who would be unfamiliar with research, like first-generation students, as well as for students underrepresented in science who have been documented to experience isolation or intimidation within a research environment.[9,10]

The proposition: A department can more easily add the components of a pre-CURE experience by deploying modules in several courses to lower the burden of adding a new course or significantly modifying any one course.

Program or curriculum development: If the specific aims of a pre-CURE experience are rephrased as nature of science, nature of research, research preparation, and research activities, the timing and implementation become highly flexible. One can imagine that activities of those four aims can be distributed across any multi-semester sequence. Nature of science can still be included in a first-semester course. In this model, it may be more appropriate to include aspects of the nature of research in that content. Revisiting the nature of science again with a greater emphasis on the actual activities that generate the data and knowledge would be appropriate. Indeed, much of the way in which the nature of science is presented ("here's the structure of the atom; now, here is how we learned what the structure of the atom is.") can give the impression that science proceeds to foregone conclusions or the 'right' answer. The experience that a data set does not scream a conclusion is a critical component in understanding how research works.

Research activities are themselves highly variable, but activities in which students collect information and provide some analysis and justification are a good point of initiation. These practices can be encouraged by displacing some traditional classroom practices with those that better emulate a research process such as case studies, concept mapping, or simulations.[11] At the same time, students can begin to be supported in developing the shared goal driven aspects of research by developing more collaborative experiences in the classroom such as group work in the aforementioned examples as well as simply group problem sets, writing and peer review, and peer instruction. Developing a sense of collaboration in the classroom will allow students to better transition to the research environment. The other benefit of adopting practices that may support research success is that many are already known to both enhance student learning as well as provide better support for students from diverse groups.[12-14]

An introduction to the research activities available in the department is a useful step in developing a pre-CURE experience. Thus, presentations on the various areas of research available to students can provide this instruction, and if those presentations are made by near peers (e.g., more senior undergraduate students), then these students can also provide some comment on adapting to the lab and other informal mentoring that would support the transition to a research environment.

Naturally, time for formal presentations on department research may be limited in the curriculum. Thus, instructors can solicit examples of key course concepts illustrated by department research. If these examples provide both a currency to the research and illustrate communal aspects of research, then these may also help to contribute to retention in STEM fields.[15] In these examples, inviting students to discuss those examples or the research that has developed since, provides the same connection to current activities as well as potential for near-peer mentoring that further would support the transition to a research lab.

Finally, some formal discussion on the mechanics of research including safety in a research lab, ethics, expectations from research advisors, structure of research groups, and career outcomes provide students with critical preparation for the actual work.

Example: Writing seminar with pre-CURE content

As part of a revision to the majors' curriculum, the Department of Chemistry at the University of Vermont introduced a one-credit writing seminar in the fall of the second year. The course has an overall focus on discipline-specific writing with a secondary goal of searching, reading, and analyzing primary literature. Despite the specificity of the task, using literature provides a platform to explicitly discuss the nature of science as well as issues of scientific integrity. Furthermore, sampling literature from across disciplines provides an opportunity to discuss the various approaches to research (e.g., experimental vs. theoretical), kinds of data collected, and methods of analysis used. In this way, this one course addresses aims 2–4 (vida supra), but these are not the sole focus of the course and these aims are supported in other areas of the curriculum as well.

3. High school and pre-college preparation

Context: College preparatory coursework is a useful route for recruiting, and many institutions are engaging students with weaker preparation in college preparatory (bootcamp) work in the summer prior to matriculation. If these activities are conducted in the context of research skills, then yet better persistence in the discipline and self-efficacy may be achieved. Indeed, such a strategy places a better context for academic success (i.e., good first-year performance fast tracks students to laboratories for research opportunities). Alternatively, high performing students can be recruited to the institution through a pre-CURE experience and are given a better entry point to productive research experiences earlier in the curriculum.

The proposition: A department seeks to improve high school students' transition into their program by either recruitment or improved retention.

Program or curriculum development: High school engagement meant to serve the institution often addresses two significant goals: Engage and serve prepared students or improve under-prepared students' success and outcomes. Students with good preparation can be provide with a pre-CURE experience as a recruitment tool. A well-developed program can take strong academic preparation and sets a path to productive research experiences. Because a program of this type has a strong focus accelerating students into the laboratory, it naturally contains nature-of-science and investigation content as well as hard skills relevant to the discipline.

Students with limited preparation can be provided with the content and skills that lead to improved outcomes in the degree. In this instance, a connection of that content within a pre-CURE can be leveraged to further improve student success as well as retention. For example, providing a context for remedial mathematics support can help aid motivation. Students who recognize that not only strengthening their mathematics preparation is valuable, but that those mathematics skills have a direct connection to research in the department (e.g., math skill A is used to understand research type X or is needed for research activity Y).

Execution of these kinds of programs is variable. A model that can accommodate either the accelerated or supportive experience as well as models that mix these outcomes is a summer pre-matriculation event. Part-day, day-long, or multi-day programs are possible. The nature of the event determines the funding. Programs that support students coming into a program would likely be supported by the institution, but programs that offer a leg-up on a science degree are likely to be supported by admission fees paid by the student. The latter program, however, can admit a deeper pool with some scholarship support by the institution or pooled from admission.

Academic year, non-credit bearing programming is also possible. Events in which participants are targeted based on personally relevant content can yield high attendance without academic credit. Workshops on the activities that support research such as communication skills, collaboration, and discipline-specific information literacy, among others, are possible. Very early in the semester, before students experience demands from coursework, is an ideal time for these interventions.

As an external outreach program, the pre-CURE model provides the opportunity to develop a better connection of students to research. Departments can develop collaborations in which content and materials to support pre-CURE objectives can be provided to high schools that may significantly benefit or routinely matriculate students into that institutions' program. Such a collaboration may be best facilitated by an education professional who can align department goals in the pre-CURE with standards at the school. The on-going effort to successfully adopt Next Generation Science Standards[16] represents an excellent opportunity for college science departments to provide input on how to aid preparation for college and serve an on-going professional development need among teachers.

Some possible outcomes:

> **Stand-alone programming:** Bootcamp models represent stand-alone programing that departments can undertake or partner in design with collaborators such as colleagues in K–12 education, campus outreach offices, or student support offices. Overhead costs for week-long (or longer) programming can be high, and the purpose of the activity, be it better student outcomes or stronger recruiting, will likely govern the source of support for the programming.
>
> **Summer mentored research:** There is a significant cost in time to mentor students, but some support structured for this kind of activity exist (e.g., Project SEED administered by the American Chemical Society). The critical component is to invest time in an early summer program that provides the key understanding of the process that develops knowledge from the activity of research.
>
> **Academic-year research experience:** Local partners may provide students with a variety of research experiences. While there are some examples of mentored research programs, there is the also the possibility of engaging entire classes in, for example, data collection as a vehicle to understand the process of research.

Example: Pre-CURE in a chemistry summer camp for high schoolers

Dr. Jones was contacted by Madeline White, a high school student who participated in one of her outreach activities two summers earlier. Miss White was looking for research opportunities in her laboratory. With great empathy for the student Dr. Jones accepted Miss White with no hesitation. During the next six months the student visited Dr. Jones' laboratory two times a week to work under the direct supervision of a graduate student. During this time Miss White was involved in an interesting project related to a problem of national interest,[17] the analysis of contaminants in drinking water and the development of reliable remediation approaches to ensure the safety of the nation's vital fluid. During that period Miss White was able to develop, independently, part of the project. She learned how to do a literature search, how to design and test experiments, how to use different analytical techniques, and even more importantly she learned that scientists need to be patient and persistent. Dr. Jones' experience with Miss White was so rewarding and constructive that she decided to take this initiative to the next level to generate a greater impact in her community.

In pursuit of this goal, Dr. Jones developed an intensive, one week chemistry summer camp (CSC) with an independent scientific research component.[18] Using this approach she expected to have a better opportunity to teach students the fundamentals and applications of chemistry in a more relaxed environment, and to present students a more realistic picture of what it means to perform scientific investigation in the lab.

To implement the proposed CSC, Dr. Jones had to think about the logistics and the mission of CSC. To become more inclusive, Dr. Jones sent an open invitation to all 36 rural schools in the region six month ahead. Because of the obvious constraints of space and funding, Dr. Jones had to limit the number of campers to a maximum of 12. To make a fair selection of campers, she first invited teachers to postulate their corresponding top two chemistry sophomore and/or senior students. Then, she evaluated the students' performance as well as their attitude towards sciences. All nominated students were invited to write a personal statement to describe their motivation to be part of this initiative. After receiving 29 nominations from 31 schools Dr. Jones made a final selection based on the students GPAs, grade in high school chemistry, and personal statement. Because this program was directed to students with economic limitations, during the first year Dr. Jones applied for external funding through the ACS-IPG program to cover all the expenses, including educational and research materials, lunches and snacks, and a Camp T-shirt. This final item was of great importance to create a sense of belonging and pride among students. Finally, to launch the camp Dr. Jones recruited a group of enthusiastic graduate students from her program to assist as teachers and mentors of the campers. This was a very successful approach for both graduate students and campers.

By having students working in small groups, in different independent research projects under the supervision of a graduate student, Dr. Jones was able to spark the scientific curiosity in most campers while showing them the beauty of sciences, the excitement of achieving new discoveries, and the typically undisclosed tedious aspects of investigation in a research laboratory (literature search, calibration, pretesting, repetition, misinterpretation of false positives, and frustration, among others). Dr. Jones would like to expand the impact of CSC to all southern states.

Add-on programming: Given the cost and complexity of mounting multi-day programming for transitioning students, it may be both economic and efficient to seek partnerships for student orientation sessions to mount sessions or half-day programs that can meet the pre-CURE objectives. Admissions offices provide complete programming for admitted students, but the clear benefits with respect to competitive admission of increased engagement with departments and faculty is attractive to most institutions. Thus, reallocating some orientation time or providing time before or after scheduled activities is more likely if the mutual benefit of engaged programming is conveyed.

Workshop models: Most programs have at least a week-long delay for the start of fall laboratory sections. This is usually unscheduled time for undergraduate majors who also have not fully engaged their course material and developed effective time management and study skills. Intervention in the context of research preparation can provide all students with skills important to early successful engagement in research (e.g., information literacy) but those interventions can also provide access to academic support early before students encounter problems in their coursework, or as is so common, adapting to college-level study. The workshop model does not need to be limited to students early in their college career and can be an important step for students annually to prepare for deeper and more meaningful research experiences.

Concluding remarks

The success of expanding research experiences through integration of research in traditional classroom or laboratory coursework invites further leveraging of this technique for the benefits of students and workforce development. A pre-CURE model would better prepare students for research experiences of any kind. The focus of a pre-CURE experience on a practical understanding of how science works, as described herein, can achieve better student preparation but also provide other long-term benefits

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Part II:
During

3

Continuum of Labs

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Why should you update your labs?

Cookbook labs: we all have them, we all complain about them. This is a name for labs where students follow an experimental procedure presented as a "recipe" to illustrate a principle or assay, but the students do not seem to learn very much. The experiment culminates in a "worksheet" where calculations are performed and some sort of uninspired conclusion is presented. Faculty often lament that these labs are terrible, and continue on to present a myriad of excuses as to why these labs still exist in this form.

The point of this chapter is to give you concrete examples and short-term activities to help take your lab from cookbook to CURE (or anything in between). Before we do that, we will give you a brief introduction as to why you should consider changing your courses. Numerous studies have demonstrated that students learn best when they are actively engaged in the work they are studying.[1] Cookbook experiments are, by default, "active," but encourage completion of the task rather than learning. Laboratory work should be teaching students to become critical thinkers—not how to fill out forms. By participating in experiences that truly excite and engage the students in the concepts and ideas, they will learn the material better and be able to apply it to new situations.[2]

Finally, we want to encourage you to teach this way because it is just more fun for you. Watching students perform rote assays, which you have seen performed dozens of times, is not professionally stimulating for you either. This chapter will help you to go from flat to fabulous in your laboratory classes. We understand that full CURE courses might not work for every school, set of students, or faculty member, but even small improvements in a laboratory curriculum can offer big rewards for the students and the faculty. In this chapter, we discuss courses where more engaging aspects of learning have been implemented enabling students to learn how to be scientists through a continuum of approaches altering cookbook into CUREs.

What is the continuum?

Just like there is not one way you can teach a course, there is also not just one way to offer a laboratory experience that engages students in scientific practices and has lasting benefits to the student's learning gains. In this chapter, we hope to offer a variety of solutions for taking an already existing laboratory course, which might be of the cookbook variety, and morphing it into a better, more engaging, and active experience for the students.

CURE elements

Before we can discuss examples of how to enhance laboratory courses, we want to spend a little time explaining the previously identified pedagogical elements that are characteristic of "CURE" courses,[3] since these aspects are what we are ultimately striving to embody (as detailed elsewhere in this book). In moving towards a CURE lab, not all of these components may be engaged fully. And even specific components may not be implemented in pure form. In this chapter, we think of each component as a continuum where the pure implementation defines one end of the continuum and a traditional cookbook lab defines the other end.

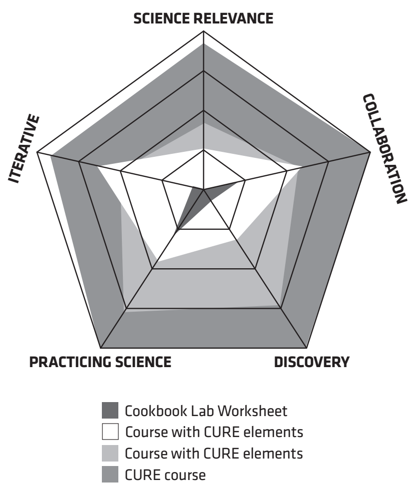
Practicing science: Practicing science involves a variety of activities, such as literature searches, coming up with questions, and building apparati, not just collecting and plotting data. The more activities the students in a course engage with, the more authentic the experience will be. Something as simple as not pre-assembling the equipment for the students can be a step toward more engagement. Adding more of these activities means that experiments may take more time, and inevitably increases the level of chaos in a lab, which can call for increased attention to safety issues. Is it worth it to make better, more informed, and thoughtful citizens? We think so.

Iterative approaches: Science is inherently iterative, self-building, and self-referential. Getting across that experiments in a laboratory are connected and build off each other—instead of being one-shot tasks to be completed—is a way to train students in the nature of science as well as revisit concepts, ideas, and even skills so that students can have multiple opportunities to learn, practice, and see multiple sides of these concepts. Even cookie-cutter lab courses can build in iterative processes at a low level, for instance learning a technical skill (e.g. pipetting or titrating), and using that throughout the laboratory course for the entire semester. In this chapter, we give examples of more involved ways to build a lab curriculum that allows students to take knowledge or concepts and uses them throughout a course, giving them multiple opportunities to try, fail, and try again.

Discovery/inquiry: Discovery is the ephemeral holy grail of science that is glorified in the movies as an “a-ha” moment. Although truly important, fundamental discoveries are rare in science, discovering mechanisms and relationships in nature is actually something you can recreate and do in a laboratory. Taking a cookie-cutter laboratory class and changing how the question is asked can take a boring lab of filling in a worksheet and change it into a revelatory experience where the student and/or the instructor can discover fundamental principles for themselves, such as how a pendulum depends on mass and length or how the protein yield changes as a function of the inducer added to the bacterial cell culture. Most importantly, students can be the authors of their own ideas. They can decide which parameter to change, and different groups can change different parameters, allowing for an exciting and interesting sweep of the conditions of an experiment. Adding discovery or inquiry aspects into a laboratory, even if you, the instructor, already know the answer, can be powerful for student engagement, interest, and ultimately learning gains.

Collaboration: Despite the stereotypes, science is not done by solitary people working alone in their basements. More so than many human endeavors, science is a collaborative endeavor. Indeed, some of the biggest projects on the planet (super colliders like CERN, the LIGO gravitational wave observatory) involve hundreds of people to conceive, design, and construct scientific equipment to make new fundamental discoveries. In our own labs we have students who might have their own projects, but are never working in isolation (at least for safety reasons!). If collaboration is so fundamental to science, why do many labs have every student working on and handing in separate worksheets? Because the way we do labs is driven by grades (even for faculty) and not true learning gains. Adding truly collaborative aspects and projects into lab courses will teach the nature of science to students. Doing it well will also lessen the resentment that some students have for “group work.”

Broad relevance to science (aka doing something new): Perhaps the hardest aspect to add to a course that serves hundreds of students is the aspect that what you are doing is actually relevant to science. We even recognize that our own research is sometimes deemed “low impact” by reviewers, so this is a pretty high bar in some fields. Yet, this aspect of CURE courses is part of the excitement for students, and perhaps even the payoff for faculty. What if you could get hundreds of students making new data from a class? Just think of the papers! CURE courses are able to do this. Of course, adding something new does not require publication of a paper. Students can work out new protocols or assays, develop novel representations, create a new compound, or express and purify a protein for the first time. Such products are attainable, if not publishable on their own, and will ultimately move the field forward.



Radar plot of 4 different courses with varying amounts of each of the 5 elements of a CURE course. The cookbook course has no new science and very litter discovery. The CURE course has high levels of all CURE aspects. The courses we describe here are intermediate like the courses with CURE elements.

Not all of these aspects will be doable or appropriate for every laboratory experience because it will ultimately depend on the course, the students, your resources, and time. And that is okay! Taking a course that is already a workhorse course, a required laboratory class, and changing it all at once is not feasible, advisable, nor fun. In this chapter, we offer concrete examples and methods for taking an existing lab and morphing it into a better experience. We also hope that for those of you who are getting the opportunity to design a new course from scratch, you will also consider baby-steps toward CURE as a way to ease into the deep end of the pool. This is especially important if you or your colleagues are not entirely comfortable with the concept or practice of CURE courses. For more on curriculum design for truly CURE courses, we encourage you to read the chapters on CURE course design and assessment (Chapters 4 & 5).

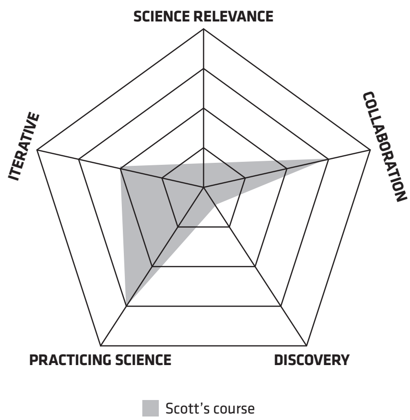
To keep track of these different desirable aspects that can be included into lab experiences, we decided to plot them (Figure 1). This is a radar plot, and it is good for capturing snapshots of degrees to which a multi-aspect system (like personality) has each aspect. We like the ability to characterize different types of classes with a snapshot graphical method. Remember that the ability to represent concepts in graphical form is an important skill of science.

For each of the five elements of enhanced laboratory experiences, you can have varying degrees of practicing science aspects or collaboration. On this plot, the closer to the edge on each of these aspects you are, the larger the amount of that aspect you are including. Further, the rating for each aspect is a number between zero and one. Zero is at the origin (middle) of the pentagon; one is at the edge. You are striving for all ones, but most classes will be in between. To make a CURE course, the goal is to maximize the area encapsulated in the plot. Cookbook courses that include few aspects of engaging laboratory experiences sit right at the middle origin. For each case study or example class we describe, we will give a rating for each aspect.

Specific examples of evolving cookbook into more

We are assuming that you picked up this book because you are interested in offering exciting and engaging courses and laboratories for students to enhance their learning and have a bit more fun yourself. Maybe you were assigned a course that had not changed in 30 years, and you want to give it some updating. Maybe the administration is telling you that your labs are low-rated. Or perhaps, you just like to do something a little different. The advice we are offering is through anecdata, use cases, and examples. After these examples, we also have a series of short topics to give concrete advice about how to go about making these changes to curriculum and overcoming obstacles that might pop-up as you are trying to make changes. Our most important piece of advice: include other faculty and support staff (lab, administrative, and safety staff) right from the beginning. You might be the driver making this happen, but what happens when you go on sabbatical? Will your class die or go back to the old way when someone else takes it over? Making these changes as part of a team is essential for sustaining this change, but you have to do this right from the beginning because bringing someone on later does not provide the buy-in or incentive to continue (that is, they will not feel ownership).

Scott's example from chemistry: When I started teaching at Gustavus, I inherited a solid, confirmation-based laboratory curriculum that focused on learning lab techniques such as how to use a separatory funnel. Though it had served our department well for quite some time, I wasn't vested in it, and I looked for ways bring some "current best practices" into the experiments. One specific example is the classic Grignard experiment wherein students make a Grignard reagent (butyl magnesium chloride), add it to a carbonyl compound (students could select from various ketones and aldehydes), and isolate the resulting alcohol by distillation. I changed the lab by having students select from alkyl (1°, 2°, and 3°), aryl, and benzyl halides (Cl, Br, and I). Students then followed the basic procedure outlined in the existing coursepack to form the Grignard reagent. I asked them to pay attention the relative rates of formation (as assessed by disappearance of solid magnesium). The addition of a carbonyl compound and the isolation were the same as before. The next week, I used prelab lecture time to have students collate their qualitative kinetic data and discuss what trends they observed. With some guidance (in the form of leading questions), students were able to identify the bond-dissociation energy of the C-X bond as the important variable. By analyzing the products (did they actually get the product they expected?), some were even able to talk about the effect of increasing substitution on the success of the reaction.



The radar plot of Scott's chemistry course.

Of particular importance to me was that several students attempted the same reaction, which gave us repeats and different conditions to compare. If a reaction didn't work, we could discuss if it was because of student error or if the substrate simply doesn't work under those conditions. It sparked discussion about reproducibility. In addition, one of the substrates does not work, so students experience failure in the context of finding out the scope and limitations of the reaction. This helps reframe failure—*it's only failure if you didn't learn anything from it.* Also, opening up variability in the starting materials made the data noisier, so students get to experience the messiness that often goes with research. From simple perception-based assessment of this altered lab compared with the traditional lab, students were much more engaged and felt more invested in the outcome of the reactions.

Over a number of years, I modified many of the labs in similar ways. These aren't ground-breaking changes, and they aren't even particularly large changes in any experiment. Yet, they made a large difference for the course and student attitudes. Observing the change in student outcomes was personally satisfying, and it gave me the confidence to embark on strategic planning for employing CUREs to transform departmental curriculum.

Samuella's example for an embedded inorganic laboratory project: At Appalachian State University an independent synthesis research project is embedded in the Inorganic lab. Students have three weeks (9 total class hours) to synthesize a metal-acetylacetone (acac) complex. Lab time is parsed into the final three labs periods, but preparatory work begins early in the term. Ideally, the compounds can be synthesized and characterized in two weeks. Should the synthesis fail to produce product, an additional lab period is available. Each student requests a specific transition metal starting compound and the instructor approves. By design, no two students in the same section will have the same starting compound. This promotes ownership of the project. The departmental Chemical Hygiene Officer (CHO) collaborates with the instructor for the risk assessment piece. The instructor provides students with a starting material, IR and NMR spectra for acetylacetone, and students characterize their own product in the same way. While the synthesis of acac compounds is well defined, the course has the following aspects to hit on CURE elements:

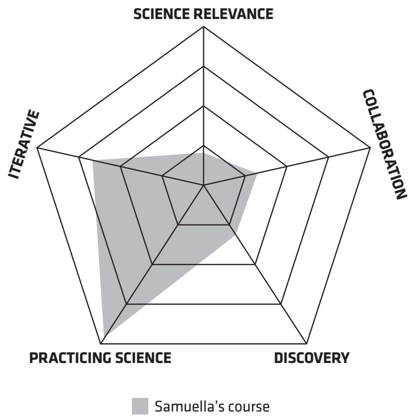
Library assignment using Scifinder: Students must research aceylacetonate, including the structure, IUPAC name, CAS#, homoleptic definition, and sources which describe the synthesis of any metal complex with this ligand. This assignment is due about a month into the semester. Students must reference primary literature, not lab manuals they may find online.

Approved reagent form: Students must next complete the approved reagent form. The purpose of this form is to ensure that the synthesis will produce enough compound to characterize, but not an excess to minimize waste. The form also ensures that the reagents needed are available in the laboratory. Students must navigate the university inventory system to determine availability of the chemicals. This requires the following information: the compound to synthesize, the expected, theoretical yield (1-5 g), all reagents needed and estimated amounts (from literature).

Research proposal outline: Due about a month after the library assignment, this document requires a title page, abstract, introduction, experimental section, expected results, and references. This helps the students learn what is required in a proposal, and helps to orient them to the research project.

Risk assessment: Although often overlooked, preparing a risk assessment is an important task for both the professor and student in a laboratory. Using the Job Hazard Analysis (JHA) tool, students perform a RAMP analysis where they must break their process into steps where they, **recognize** or identify hazards, **assess** and estimate risk, implement controls to **minimize** risk, and indicate how they would **prepare** for emergency.[4] The tool is evaluated by the CHO who meets with each student to discuss the "holes". Students must have their JHA approved by the CHO prior to starting the project.

Reporting: At the end of the module, the students report on their work. They report in two ways: a formal research paper and an oral presentation to the instructor. Reporting your results is an important final step of real scientific research.

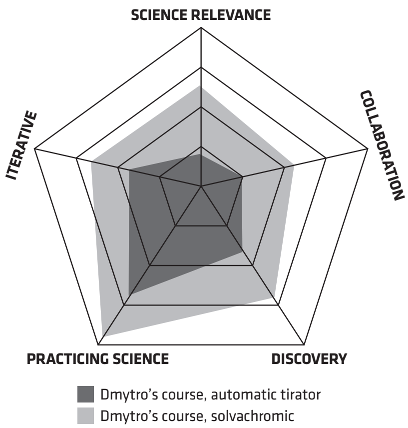


The radar plot of Samuella's inorganic chemistry course.

Dmytro's example from physical chemistry: At Monmouth University an interactive approach was applied to revise the physical chemistry laboratory courses replacing traditional "cookbook" labs with research-based projects. Each semester students start by working on guided one-week projects to learn basic physical chemistry techniques (e.g. electronic/vibrational spectroscopy, molecular modeling) and then they were given opportunities to choose a multi-week research project of mutual interest to students and faculty. This provides opportunities for students to practicing science and help faculty to reach their research goals. It is not uncommon that after taking the physical chemistry course students continue working on their projects in the faculty member's research lab. Below are provided two examples of the recently implemented laboratory projects:

Building and experimenting with an automatic titrator: Students are provided with the basic information on automatic titration then students build, calibrate, and program an automatic titrator using an open-source microcontroller platform and standard pH probes. While the laboratory does not focus on generating new knowledge, the students are building laboratory instrumentation from scratch, which is an important research skill. The laboratory also requires students to troubleshoot their autotitrators, allowing for iteration, failure, and retrial. Students naturally learn concepts of calibration, precision, and accuracy of measurements in the course of the laboratory. This project has been described in detail elsewhere.[5]

Investigation of solvent effects on the electronic transitions in organic chromophores: The purpose of this laboratory is to study fundamental intermolecular interactions between organic chromophores (e.g. pyridinium N-phenolate betaine dyes) and common solvents (i.e., water, methanol, anisole, and dimethyl sulfoxide). The pyridinium N-phenolate betaine $E_T(30)$ dye is a highly sensitive molecular probe that is used to determine solvent polarity based on its solvatochromic behavior, its ability to absorb light in the UV to visible range depends on the solvent polarity. Students prepare samples in various solvents. They record and analyze UV-Vis absorption spectra of the dye in each solvent. They employ quantum chemical calculations (e.g., time-dependent density functional theory combined with various solvent models) to examine the excited states experimentally observed in UV-Vis absorption spectra. The project is primarily discovery-based as details of the mechanism of intermolecular interactions of $E_T(30)$ dye and some of the solvents are not known to students or the instructor. The project relies on collaboration among faculty and students as students produce scientifically significant results.



The radar plot of Dmytro's physical chemistry course

A significant component of the revisions made to the physical chemistry sequence is to provide opportunity for students to communicate their results to the broader community at various levels. Based on results obtained in the course students prepare the posters to present their work at undergraduate research and professional conferences. Students have also co-authored several publications.[5-7]

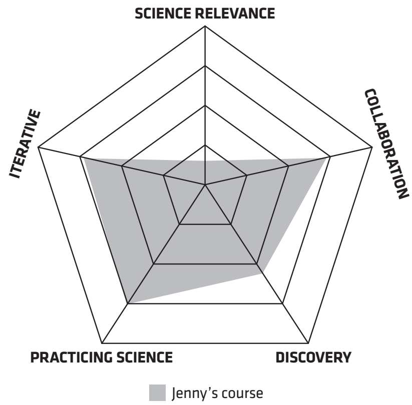
Jenny's example from physics: My second year at the University of Massachusetts Amherst, I was assigned to teach optics, a 500-level specialty course for majors. This was challenging for me because, although I use, practice, build, and understand a lot of optics in my research, I had never had a formal course in optics. So, I did what most new faculty who are given a course to teach do. I got the notes of the last guy who taught it, and I did the same thing. Same notes. Same lectures. Same homework assignments. Same exams. This was terrible for the following reasons:

1 **I didn't own it.** It wasn't really my class. It is true, I needed some help getting to know the topics of the curriculum, and I had very little time (the course was assigned only a few months before I had to teach it), but I really didn't feel comfortable.

2 **The course was a 4-credit lab.** It was structured as 2, 2-hour slots every week. But, the course I was given was a lecture course. That meant that I was talking for 2 hours straight each course. Yuck!

3 **The lab was a joke.** There were only 3-4 labs, and there was *some* equipment for them, but only enough for one group to use at a time. And the equipment was archaic, in some cases broken, and (worse yet) repetitive of some sophomore-level labs, even though this was supposed to be a senior/graduate course!

Honestly, the students didn't even hate the class, but I hated the class. I didn't feel that the students could really do optics after leaving that course. Optics is not a theoretical field, in my opinion. It is applied and hands-on and you learn it by getting in there. I decided to change it for the next year to try to give the students more opportunity to really build and work with optics. Since I had learned how to build optics by working on microscopes, I thought it would be fun to have students build a light microscope throughout the semester. The problem for year 2: I had no resources to make this change. I needed about $3000 of equipment for a single set-up of actual optical equipment. I got it together for less by scrounging from my own lab, begging the department, and using some of my own NSF grant funds, figuring this counted as broader impacts. I also needed a space for the lab, so I convinced the chemistry department to let me have a little space in a new teaching lab area in a new teaching building (physics had no space in the entire building, which was devoted to chemistry, biochemistry, and biology). So, I had secured a space where students could safely leave the equipment, and I got the equipment for a single set-up.



The radar plot of Jenny's physics course.

In year two, I made only a few changes to the structure and the hands-on lab portion. This iteration was sub-optimal for the following reasons. There was still a terrible set of lectures delivered to the students in terrible two-hour sessions (yes, I gave them a break in the middle). The lab, although new and hands-on and allowing students to trial and error with microscope designs, had only one system of equipment. Thus, each lab group (of three students) had to come in separately to do the lab. They would tinker, trouble-shoot, and finally get a design that performed as a microscope should. At the end of the session, they would take pictures of it, and tear it all apart, so the next group could do the same thing. Tearing down something you work hard to get right is a bit demoralizing, but they knew it was for the greater good.

In year three, I was able to upgrade the lab thanks to funding from RCSA Cottrell Scholars. I purchased three additional set-ups, so I could have 12 students in the course. I also got a different lab room owned by biology. The room had a projector, white boards, and lab benches. Using this room, I was able to teach lecture and lab in the same place, allowing me to offer short lectures punctuated with hands-on activities that demonstrated directly the concepts of optics I was deriving immediately after I spoke them. I also opened the course to biology students in year 3, which allowed me to make interdisciplinary lab groups.

Because we had more access to equipment, I integrated the microscope building along the semester more frequently, and allowed more tinkering time for each step of the microscope project. The project was scaffolded and divided into bite-size chunks to have them design the condenser (part that controls the light going onto the sample using apertures and field stops), design the imaging path (they imaged to a camera, since putting your face into an optical path, particularly if there could be lasers, is a safety hazard), and then test the system's magnification and resolution comparing to theory. At the end of each of these steps toward having a microscope, the students reported on their designs and features at a class-wide poster session. I invited faculty and staff from multiple departments to the poster sessions, and they evaluated the students' results, poster displays, and presentations. The final poster reported on an individual additional feature they would build onto the microscope specifically designed to test a biological question. The students had to come up with a biological question to probe, build the additional optical apparatus onto the microscope (such as epi-fluorescence, or an optical tweezer), and test the system.

I loved this class. The students loved this class. In May, three students went with me to the New England Society for Microscopy meeting at the Marine Biological Laboratory in Woods Hole, MA, to present their posters and show off their microscopes (yes, we drove one set-up to Cape Cod). Everyone loved it, and one group won the poster prize that year.

In year four, I was reasonably happy with the overall class, but felt that the last missing component was the student assessment. My original goal was to assess if the students could actually "do" optics, but was the written midterm and final actually assessing that? Doing optics is more than being able to solve multi-step theoretical problems. It really means being given a new optical problem and being able to come up with an answer that works. I love optics because there are infinitely many right answers. I endeavored to alter my final assessment to test student understanding and learning directly. I threw out the written exam and gave a hands-on practical. The exam consisted of students coming in and being handed a paper that read, "You are an optical engineer, and I am a customer. I need a system that can do..." The thing I (the customer) needed was not described in optics terms. It was described in words. For instance, "I have a laser with a 2 mm diameter, but I need it to have an 8 mm diameter." The students had one hour to design, build, and test the system while I sat and watched what they did. It was illuminating and gratifying to understand that most of my students were capable of building a new optical system that performed as I requested! The students were also happy with this exam. One student told me, "This is the most realistic exam I had in all of college."

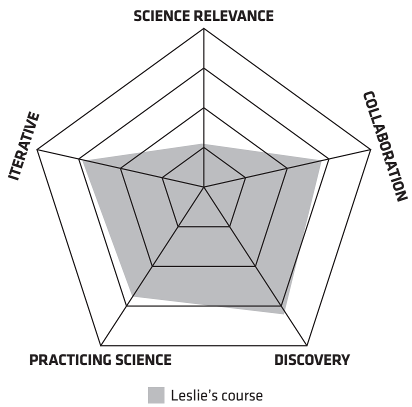
This example is both an example of how you can make changes, but also an example of what and what not to do. One major failing was that I did not include any other faculty members. I became a champion for this course, but my department (as many physics departments do) rotated me out of the course after year 4. I tried to convince a colleague to do what I did, but she had the same issue I had in my first year of not owning the course. Happily, she kept the advanced lab emphasis, and had students work on more quantummechanical aspects of optics (lasers, detection, etc.). I am working with another junior faculty member to try to convince him to request the course when I rotate off again in a few years.

I have been able to use this course in novel ways I did not anticipate at first. After my students presented at the MBL, researchers there who run and facilitate their short courses on microscopy asked for the equipment list so they could train their students in basic optics using hands-on microscope-building work. The equipment is currently used in three courses worldwide: Analytical and Quantitative Light Microscopy (MBL in Spring), Optical Microscopy (MBL in Fall), and the Bangalore Microscopy Workshop (National Centre for Biological Science, Bangalore, India). I personally teach at two of these (AQLM and Bangalore), and these courses have raised my prominence in my subfield of research, since many faculty from all over the world teach and send students to these courses. Further, the main students enrolling in these courses are biology graduate students, allowing more impact of teaching optical concepts to students in the life sciences.

After three years away, I have now rotated back into teaching optics again. And, I am at it again. I changed the course again to allow students more self-assessment, so they can trial and error on calculations and theory for optics as well as tinkering in the lab. I got rid of the written midterm and replaced it with a series of 10 competency exams that are shorter and more focused on specific topics. In order to make the course more like practicing a sport—try, self-assess, error, correct—the students were able to grade themselves on these exams using a rubric. They were also able to retake the assessment as many times as they wanted (different questions) to get a passing grade. Most students retook the assessments 2–5 times, and in so doing, they mastered the topic and actually learned the material much deeper than they would have studying and taking a single, high-stakes exam. I will likely make minor tweaks again next year, but I believe that the self-assessments worked well, and the students liked it and felt that they learned the material better (attitudinal assessment). Much like practicing a sport, if students can self-correct, they can progress more quickly. Further, it had the added bonus that I was a seen as more of a “coach” who enables students and less of an ”adversary” who tests students in a cruel way.

A description of this course can be found in an article on the Physics arXiv: *http://arxiv.org/abs/1606.03052.*

Leslie’s example from a non-majors class: With the new set of science standards that most states have adopted—the Next Generation Science Standards—teachers are called to engage students in scientific practices as they develop scientific understandings. Our students—future elementary teachers—have few models to draw from in their own experiences as students. Our course is designed to engage students deeply in scientific practices. The course (a 24-student lab-based course) has no textbooks or lab manuals, but begins with a puzzle or question that students then pursue in lab groups, share with the whole class, and develop and refine models iteratively over many weeks. We have elected to study topics that are easily investigated and relatively "everyday" phenomena: light, color, the eye, sound, and observational astronomy. As much as possible, we use everyday materials, stored in the classroom, so that students can easily construct experiments and observations.



The radar plot of Leslie's chemistry course.

Our university, like many schools that prepare a large number of teachers, has dedicated science courses for future teachers, and this course would be added to the list of options. We discussed our plans with the College of Education and our own department chairs and curriculum committees to explain our goals and rationale for the course. We decided to begin with just one section, and, based on student evaluations and feedback, consider increasing the number of sections over time.

With plans in place, we applied for NSF Transforming Undergraduate Education in STEM: TUES (now Improving Undergraduate STEM education: IUSE) funding; this provided the resources for faculty release time to develop and assess the class, funding to co-teach the course with physics and biology faculty, and funds for simple materials that could be kept in our classroom (so as not to run back and forth to the stockroom for every new idea). We advertised the course to the elementary education majors and began with 24 students, in a foreign language classroom, using a rolling cart of materials.

Students were disoriented at first, but quickly adjusted to the structure of the course and embraced it. Comments like this one from our end of course survey are common:

> "This is the first science class that has ever made me feel like a scientist. Even in other classes when I had to do experiments, everything was so structured that I felt it was more of just an assignment. I have never just been given a topic, like the eye, and then let loose to try to figure out how it works. I am really glad that I took this class because it gave me a whole new outlook on science. Before, even though this is my last year, I never knew what it was like to be a scientist. At times I felt extremely frustrated and like I was going nowhere in finding out new information. But then when I finally did figure out a piece of information and had that 'ah-ha!' moment, the frustration was well worth it. I felt a sense of accomplishment and excitement every time that myself or my group discovered something new. I began to realize that the feelings I was experiencing are probably an everyday thing for actual scientists."

One thing we did not anticipate was the amount and variety of materials we would need. By the third iteration of the course, we had a set of materials, a dedicated classroom, a set of rolling whiteboards, and waitlists for the course. We have tried out new topics from time to time, collaborated with a range of faculty, co-taught and then solo-taught the course.

In this course, the students are the authors of their own ideas. We have found that, at times, those ideas may be truly novel, as when a group of physics teachers constructed a representation of energy (Atkins & Frank). At other times, they develop unique language or their own jargon, such as when a group defined the point spread function of a focal point as a "Seurat spot reunification point" (Atkins Elliott, Jaxon & Salter).

Sometimes, the students make novel predictions, for example they made interesting hypotheses about the colors of a thin film interference under fluorescent lights (Atkins & Elliott). In all of these examples, these students were acting as scientists, and they felt like they were doing science, even if what they were "discovering" was already known. In this course, the "relevance" is that students feel like they have something to say and someone to say it to. You can accomplish this in many ways: connecting students' work to a broader scientific community's questions, connecting their work to local concerns and needs, or creating a culture in your classroom in which they are the audience for one another's findings and claims.

This course has been described in more detail in a publication,[8] and information on how to incorporate writing into the class is described here.[9] Online resources for this course can be found here: *http://www.composingscience.com/*, and a video of this course can be found here: *http://studentsdoingscience.tufts.edu/case-studies/seconds/view-the-case/*.

John's example from advanced inorganic chemistry: I was a newly hired visiting assistant professor at a small liberal arts school with little research infrastructure. I wanted to continue my research program, but was only afforded 10 weeks in the summer with maybe one funded student.

Therefore, I took the opportunity to use the Advanced Inorganic Lab that I was scheduled to teach to introduce students to research and also to accomplish some scholarship. The course had about 10 students as well as some funds for supplies and reagents. The original lab format required that students perform four labs (from a list of ten) over the course of the semester. I replaced one of these labs with a research component focused on my own research topic. The students were paired up and given a set of unique ligands to synthesize that I thought would be good targets for my research program. I had not had time to make them myself, so each pair was charged with devising a process to make these components. Here is how I organized the section of the course that was research-based:

> **1st lab meeting: Scifinder Search.** I sat down with the students and showed them how to use Scifinder to search for variations of the compounds (since they had not been synthesized before) and also potential reactions to make the ligands. They were then tasked with looking up the prices and MSDS of the chemicals required to attempt the synthesis.
>
> **2nd lab meeting**: **Proposal.** Next, the students had to propose a synthesis and order chemicals (maybe in between lab meeting #1 and #2). We sat down together and reviewed their proposed syntheses and revised/submitted their chemical lists for order.
>
> **2nd/3rd/4th/5th lab meeting**: **Synthesis and Characterization**. Three to four class periods were spent on attempting the synthesis and characterizing the products, if any. During these days, the students would perform experiments, share their data with me, and discuss what steps should be explored, repeated, or altered.
>
> **6th lab meeting: Reporting.** An essential aspect of science research is reporting your results. We have many mechanisms for reporting in science including written publications, oral presentations or poster presentations.

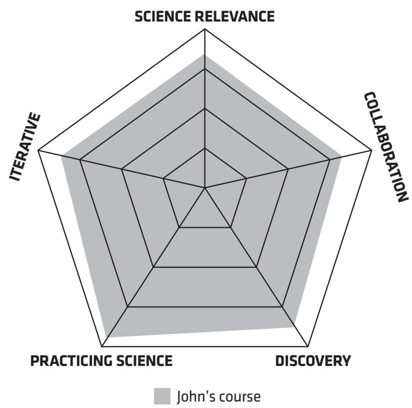
None of the students' syntheses were "successful" in a sense that the proposed ligands were not able to be synthesized. That being said, failure and knowing which paths do not "work" is as important as knowing which do. The course was a success, despite the failure of the synthesis.

If I had stayed at that institution the next year (I moved to another institution), I would have increased the number of labs in the Advanced Inorganic curriculum dedicated to research. We also would have designed a new ligand scaffold, as the students basically proved that my original ligand scaffold was a dud (thanks students!). In that sense, the course was a success for science and for my own research. Based on the students' results in class, I ultimately redesigned that ligand scaffold to a completely new one. Since moving to my new institution, I published many papers on the new scaffold, but none of that work would have been possible without the students' hard work in this laboratory course.

Further, the class was also a success for the students. They reported that they enjoyed the class: "it was exciting to not do recipe-type chemistry" and "it was interesting to try to make new compounds not known before."

Despite most of the course being a more cookie-cutter class, this one module had most of the elements of a CURE course, including:

> **Practicing science:** The students learned and practiced scientific literacy, risk assessment, defining problems, communication, and failure.
>
> **Iterative approaches:** The students had several course days to try, fail, iterate, troubleshoot, and retry the synthesis. Thus, the project built on itself, as many projects do.
>
> **Collaboration:** Students worked together on their science and presentations. Further, the students worked with me, through our individual conversations.
>
> **Discovery and science relevance:** As I described above, neither the students nor the professor knew if the synthesis would work. It turned out it did not, and that enabled future discoveries of more promising strategies.



The radar plot of John's inorganic chemistry module.

More examples of CURE elements you can incorporate into your laboratory courses

Above, we went through a number of specific examples from our own departments or courses where we incorporated elements of CURE courses into boring laboratory courses in order to give the students a more authentic research and learning experience. Here, we list many more examples of items that can be added to courses to increase the research authenticity of a standard laboratory course.

Practicing science

Risk analysis: Creating a risk assessment tool is an excellent way to teach students an understanding of chemical hazards beyond the SDS. Students must learn to find primary sources of information as they would in a research laboratory, think critically about conflicting data, and perform iterative processes to reduce risk. For example, a student who must work with a flammable solvent might want to know the boiling point and flash point of the solvent to decide what the safe working parameters are. If students find different numerical values in the literature they will need to evaluate the validity of the data to make the correct decision about mitigating the risk.

Literacy: It can seem like reading "the answers" is antithetical to inquiry, but, of course, drawing on the literature is a core scientific practice. Facilitating the ability to find peer-reviewed publications that are relevant, careful reading from the literature, and using that reading to inform and advance your own ideas are not taught in lecture courses, where the faculty and a textbook typically provide all the information that students need.

Because we are an interdisciplinary team, we have noticed that different disciplines teach this to greater or lesser extent innately. Life science students appear to be ingrained with the ability to search and read the literature from undergraduate courses, perhaps because the field is younger with fewer foundational principles, so the textbooks often have incorrect data upon printing. Physical science students are from fields with textbooks that have concepts verified for hundreds of years, so they are used to looking to texts for information that is accurate. Unfortunately, that doesn't give them access to the concepts or results from the most recent and exciting fields and experiments that they will need to do cutting edge science. A useful online resource we recommend is found here: *http://www.composingscience.com/reading-together/*.

Reporting results: One of the most important facets of science is the reporting out of the results. Without reporting the results, you might as well have not even done the experiment, since it will not help the field. Young students especially underestimate the importance of reporting their results. In the above examples, the students are trained to report their results in a professional manner through oral presentations, poster presentations, peer-reviewed articles, final reports, and even written proposals for the next steps or future experiments. In some courses, we have added the process of peer-review into the writing of publication-style manuscripts. In this case, the peer review requires a cover letter to the editor, which is a summary of the results in a different format than the manuscript itself. The peer review can include student peer-reviewers, giving an opportunity for collaboration with peers (see below). Further, the revision process allows for iteration on the writing and reporting (see below). Finally, you can also require that the student authors compose a response to reviewers, which is essential in manuscript writing, but is yet another platform for scholarly debate with educated reviewers and "experts" on your research. We would also like to point out that grading a presentation, with an appropriate rubric, is much easier and faster than grading a long-format written exam, making it a faster asse*ssment tool as well.*

Defining problems and designing appropriate experiments: One of the most challenging parts of science is defining a well-posed scientific problem and designing appropriate experiments with control experiments to test the problem. Even students in graduate school often miss the opportunity to define and design their own problems, if their advisor doesn't give them the opportunity. Designing scaffolded laboratories that give the students the chance to make models and predictions to define the next problem and the required experiments.

Failing and trying again: Many of the research-like additions lend themselves to allow for student failure. This is also important to the iterative element of CURE courses (see below), but it also normalizes an important aspect of science, which is that failure is not only an option, it is a requirement to progress. This can be one of the most discouraging, disappointing, and frustrating parts of research. It is important that students experience it early and get used to it. Just as importantly, students need to realize that science is full of failure, and they might not enjoy it if they cannot handle this aspect.

Iterative approaches

Reflective work: One way that students can reflect upon their work is to be given the opportunity to improve a written product based on constructive comments from the instructor or peer reviewers. For instance, the first time students are required to create a risk assessment tool, they will not recognize all the hazards, understand which hazards present the highest risk, know how to mitigate risk, or understand how to prepare for emergencies.[4] If the tool is evaluated and discussed with the students, they begin to shift to a more "active" thinking mode and will begin more introspection on what they are doing. One student remarked, "I never thought about the fact that plugging in the hotplate with an open bottle of solvent in the hood might be a problem."

Building project: In several of the examples above, the project was to build a scientific instrument. This is not necessarily new to science, but the ability to tinker, try, test, and troubleshoot makes these approaches inherently iterative. Further, most instruments can always be refined, made more user friendly, or made more automated, which allowed for infinite iterations.

Variable approaches, failure modes, and imperfect data: The challenge is providing meaningful science experiences that provide sufficient opportunity for variation in method or outcomes while still leading to understanding of a scientific concept. Counterintuitively, in order to engender authentic science experiences, especially to develop argumentation skills, students need "bad data"—that is, data that will lead them to think about what they have measured and how they have gone about measuring it. This can be facilitated if we present an appropriate context, and support students' investigative natures. Students will then begin to participate in the practices of science during laboratory courses fully realizing the potential of the course. In a few of the examples above, multiple groups and conversations generated data or discussions with enough variability that discussion amongst students often felt more like group meeting rather than pre-lab.

Discovery/inquiry

When the instructor knows the answer and the students are discovering: Many of the curricula for inquiry-based labs (e.g. PSET, PET, PBI, LSET, POGIL...) take this approach. In these curricula, students might not develop their own questions and investigative procedures, but they are led to author their own conclusions. With guidance from faculty and through conversations with peers, they are led towards canonical ideas. In the example above where an independent project is embedded in an inorganic lab course, one student commented at the end of the semester that it was the first time in their academic career where they had felt true "ownership" of an experiment.

When you and the students don't know the answer, but you are pretty sure you know how it will work: In an introductory physics lab[10] that emphasizes the role of uncertainty in their data, students are tasked with creating a "target" where a launched ball will land 50% of the time. The particular approach students will take in determining the location and size of the target should draw on the physics they have learned and the uncertainty measurements they have taken, but there is enough variability between groups that each group's particular answer and approach may be slightly different.

When nobody knows the answer: In the course for future teachers, we begin one unit by dissecting cow eyes and developing questions in each lab group to examine. One group was curious about how pupil shape affects what an animal will see. Aside from a vague idea that pupil shape matters very little for standard lenses and geometric optics—all that should vary is the brightness of the image—the faculty themselves had no idea why goats, say, have horizontal lenses. Students primarily made progress on ruling out ideas and theorizing possibilities, rather than making any experimental verifications of these ideas.

Collaboration

Peer evaluation: Assigning groups is essential for staving off student grumbles during group work and collaborative labs. Another beneficial method for helping group dynamics and getting everyone to participate is to require peer evaluation within the groups. To implement this, we start at the beginning of the formation of the group. The students are asked to talk for 10 minutes about what their expectations for group members are. How much should each contribute to ideas, conducting the work, analysis, writing, or reporting out? After the conversation, they are told to create a document, like a memorandum of understanding, about the responsibilities of group members and what is expected. In a sense, they are creating the rubric on which they will grade each other at the end of the collaboration. At the end of their time as a group, the students are asked to evaluate each other. The resulting evaluation translates into real points that affect their final grade in the course. In addition, having these conversations with collaborators should be a best practice of responsible research at all levels (even in your own group!). Conducting these conversations early in the collaboration process can reduce issues that can arise down the road regarding credit on papers, contributions, and author order.

"Jigsaw" collaboration: An easy method to take a cookbook experiment to turn it into something bigger and collaborative between groups of students. This is essentially done in Scott's example above. Another example is from introductory physics: testing how the mass and length of a pendulum affect the period of oscillation. You can easily turn this into something more collaborative by having each group test a slightly different mass and length from every other group in the course. After they have measured the period for several masses and lengths, they report out to the class about their results. The instructor or a designated group collects all the results, and plots them all together to determine the fundamental rules that govern the motion of the pendulum. Although this is a fairly low-level way to get inter-group collaboration, we find it is effective, especially when paired with a discussion of the nature of how science works via collaborations, and treat the students as individual collaborative teams.

Conversations: Many of our collaborations as scientists happen in lab meetings or at the bench, as we share ideas and get feedback on our work. Having frequent opportunities in lab for students to share ideas—through informal conversations in their groups to more structured conversations between groups—is one way in which students can share, vet and debate ideas. Prior to beginning an investigation, you might have students discuss and share ideas; as they develop experimental methods or techniques, these can be critiqued and improved upon in the whole class discussion.

Model collaboration—pull in "faculty experts": You can demonstrate the collaborative nature of science in your classroom by bringing in experts on different aspects of the class to demonstrate or teach those aspects. This also demonstrates that you don't have to know everything yourself, and that asking for help when you require true expertise outside of your training is normal in science. As an example from above, if you want to integrate specific assignments where you may not have the expertise (such as a risk assessment or information literacy), you can reach out to the chemical hygiene officer and research librarian.[11]

Broad relevance to science
In the examples above, we had several illustrations of how you can actually get new data that has relevance to real science in a class—even in a single module of a semester-long course. For more examples and ideas, we recommend going to the problem design section (Chapter 4). Such CURE classes can be modified to be pre-CURE courses (Chapter 2) to make a module that is truly novel and relevant to creating new science.

Concrete advice

In this section, we have specific short articles on concrete advice that will help you to implement and change a course to be more engaging and active to enhance student-learning gains. Many of these suggestions can be applied to anything in your teaching, including lecture courses.

Low hanging fruit—easy changes that make your classes more engaged:
How do you decide what to change? In order to make it easier to get started and make a change, we suggest you find an easy target to start. Start with updating a single lab in a course, altering it from recipe to more open-ended where you give them access to the equipment, but do not tell the students how to acquire or analyze the data. Another easy contribution could be to add a student-led reflection period to the end of a lab to get students to think a bit more about what they did and learned. You could add more information and highlights on the nature of science in order to connect what students are doing in the lab with how science really works. Whatever changes you want to make, don't go crazy! If you start talking about revamping the entire curriculum, it might be good to reflect and make sure that you are not biting off more than you can chew. Think about altering courses where you have more content control such as an honors section, majors section, or non-majors section.

Making 20% changes—you don't have to do everything in the first year:
This chapter is all about making changes, but change can be scary. The bigger the change, the more intimidating it can be. We recommend starting with small changes and iterating each semester or year with additional changes based on program assessment. This is good advice for any teaching assignment—not just for modifying a lab course. The rule of thumb when making course changes is to only revise the 20% of the course that is least desirable at one time. Following this rule of thumb allows changes to be made a little at a time and makes the process much less daunting. For example, from year 1 to year 2 of teaching a particular course for physics

majors, Jenny changed her office hours to evening homework sections, added small group work, and started doing more computer demos as examples in class. She did not overhaul her lectures or completely change from a lecture style to an inverted classroom. For the following year, she made more changes to the course that included more student participation and active learning during class. If she could have continued to teach this course, she could have eventually completely overhauled the course into a flipped classroom. Though more resources may be required, this methodology is also true for changing laboratory courses. This is clear from the vignettes included in this chapter.

Sustaining the changes you make through faculty cohorts: In some departments you might be the only person teaching a particular course and you can teach it for as long as you want. If so, great! You can be the champion for change in a particular course and make it as exciting and creatively engaging as you want. But, what happens the semester you go on sabbatical? What happens to your special class? What if you are in a department where the teaching assignments rotate? For any of these situations, the best way to sustain the implementation of an innovative course is to have another faculty member cover or take it over. Our advice for sustaining innovative teaching is to create the changes initially with a group of faculty, staff, and lecturers. This way, all these people have buy-in to ensure the work you are doing is maintained even during the semester you spend cranking out papers in your lab or from a beach in France.

Planning processes: Most of us approach change by engaging in some sort of planning process, whether it is discrete or just in our heads. The more complicated the changes to be made, the more significant the planning process should probably be. “Strategic Planning” is a loaded term for some people, but using some of the principles of strategic planning is very useful for effecting change.

A variety of tools exist for helping formalize strategic thinking, from SWOT (Strength, Weaknesses, Opportunities, and Threats) analyses to logic models. Almost all processes start at the end and try to work backwards.

Try to ask yourself the following:

Question: What long-term outcomes do you want to see?

Think about: These could be student learning outcomes and gains, attitudinal outcomes, or even getting some research done.

Question: What kinds of things do people need to be doing to make that long-term outcome happen?

Think about: These could be the kinds of habits that lead to successful outcomes - like pre-lab planning, better communication, or teaching assistant training.

Question: How are you going to change what people do?

Think about: Which groups of people need to be changed? Students, faculty, staff? How will you incentivize each group?

Question: What resources do you need to support what you're going to do?

Think about: These can be human, fiscal, equipment, space, or skills that students are expected to have coming in.

Question: What resources do you already have?

Think about: These could include willing faculty, funding, time, instrumentation, and space.

Once you lay things out in a backwards order, it becomes simple to write an action plan by looking at it in the normal order—"If I make this assignment, students will show these outcomes."

While "working backwards" is not comfortable for many people, having a process that focuses on the goals is really helpful. In reality, people often start in the middle, and bounce around from thinking backwards on some things, but forward on other things. Don't get caught up in how it "should" be done, just jump in and use it as the tool it is—a hammer still works even if it doesn't hit the nail precisely on the head.

Finding resources: One of the most important aspects of planning and executing change in your lab (or course or department) is to have resources for the change. There is an entire chapter about securing resources elsewhere in this work (Chapter 6), but we wanted to touch on it here, as well, focusing on particular solutions for securing resources that we have found successful.

Information: Remember that you aren't alone. Other people have tried (and even been successful) in implementing something like what you are thinking. Sometimes finding resources is as easy as looking at disciplinary education journals (*American Journal of Physics, Physics Teacher, Journal of Chemical Education*, and *Cell Biology Education*, to name a few).

There are a variety of Internet resources, some of which are referenced elsewhere in this document. Talking to people at conferences and calling people who have authored papers/blog entries can provide information about how to adapt something interesting to your context. Most professional society meetings have educational sections/divisions and sessions at the meetings, and those are good places to find people to talk to. For physics, there is the American Association of Physics Teachers, which has two conferences each year.

Money: Approaching administration for funding can be useful, but you are less likely to be successful if you approach them with a posture of privilege: "We deserve money to do something like this because it's obviously a good thing." Try a negotiating stance: "If you give us money for [this project], we'll give you a course that does [something specific] for the college." Remember that administrators, including chairs and deans, are working from a limited budget. They have a mission and agenda. The more your vision matches their mission, the more likely you are to be funded.

Most deans have a strategic plan or mission statement online. Use that to craft your proposal.

People: As we have said above, if you want to sustain the changes you are making, we recommend working in a group. If you are the initiator of the ideas for the change, that means becoming a leader, of sorts. The best way to encourage and motivate people to work with you is to appeal to their ideas for what a good class should look like. Further, make sure you include staff, teaching faculty, and tenure-stream faculty in the group of people working on making the change. People who are worried it will take too much time or don't want to devote the energy are not good partners for the change, but you should still spend time convincing them what you are doing is good for the students, class, and department. As described above, the group you are working with to create the change needs to have some ownership, which means brainstorming the ideas, and accepting their input and ideas. These are all part of good leadership in general. For more information on a great leadership course, check out the Academic Leadership Training Workshop (American Chemical Society and Research Corporation for Science Advancement).

Time: You know what they say about teaching? It's like a gas: it expands to fill all the available space. You could spend a lot of time working on a new, exciting class, but it is best if you partition the time out. In many of the examples above, changes were made through a weekly meeting with the group to work on the changes. Again, we recommend making the simplest changes first, which will also make it so that you are getting the biggest bang for the amount of time you can afford.

How do you grade this stuff (assessment)? One of the lamentable parts of cookbook labs is the "worksheet" that students fill out. We all know the history of the worksheet. Students used to do long reports, but more students combined with fewer TAs/faculty hours means you need a faster way to assess your students' work, and the conclusion is to have them fill in the blanks. In this area, we discuss novel, beneficial, and time-efficient assessment methods to help you to make sure students are meeting learning gains in the lab. Methods include lab practicum, posters, oral presentations, written reports and manuscripts, and notebooks. We will discuss these work products means and some best practices for assessing them. See Chapter 5 for more complete details.

Lab practicum: At the end of a lab course, we often want students to be able to apply these lab techniques and practices in novel ways, not simply repeat the labs they have done. We use "lab practicum" as lab-based exams that ask students to demonstrate what they have learned in a lab setting. This might be similar to an oral exam—where a single student meets with the professor to discuss and solve problems—but in the lab setting. Or it may be done in groups of students, looking not too dissimilar from any other day in the lab. As described in the example above, students at the end of an optics course are asked to actually build a novel optical system. This requires that the students have mastered the required skills for the optics lab, and also can identify appropriate contexts of their use. Another approach is to have students individually work on a problem before coming together as a lab group.

Posters: Having students present their results from a lab in poster format is a nice, time-efficient way to determine if your students understand their lab work and results. It is easiest to make a grading rubric that is shared with the students, so they know what will be graded. The students set up all their posters into a "poster session," as might be at the end of a summer research experience. During the poster session, you can walk around, with the rubric and literally grade at the poster—on the spot. Positive aspects include:

1. You can probe students' knowledge about what they know by asking them to explain their work directly.
2. Posters are inexpensive, and can be printed cheaply as individual pages and taped together.
3. Students learn presentation skills including poster design, data representation and figure design, and oral presentation skills.
4. You can invite other faculty, students, and administrators to help you grade. If you have a 2-hour poster session, you can grade numerous students quickly.

Oral presentations: Having students prepare and present a set of slides about their results has similar positives as poster presentations. For oral presentations that use slideshows, you would need to reserve a space that has a projector. Grading rubrics should be developed and shared with students. Students can be used to peer evaluate using the rubrics. There are a number of different types of oral presentations. For instance, the American Physical Society "March Meeting" has 10-minute talks. These are challenging, but good practice for students. You can also add a bit more of the "practicing science" aspect by having students wear a name badge which emulates a conference feel.

Written reports, manuscripts: These have been described above in a few places along with the best practices for making them more authentic and iterative and less just a homework assignment. Coupling manuscript writing with literacy and manuscript review helps students understand format and style better. Initially you may get a lot of "fancy language" because students will want to sound "smart" or "sophisticated" by using a lot of jargon. Worse yet, they will use a lot of weird sentence structure that does not flow well or is down-right confusing! They will get the hang of writing through the peer-review of each others' work, which we highly recommend.

Notebooks: Keeping a laboratory notebook is an important research skill. Many students in the lab undervalue this task until they run into trouble—needing important information that they neglected to include at the time. Grading of classroom laboratory notebooks can be difficult. We recommend using a rubric. Even better, students can develop their own rubrics and self-assess or peer-assess each others' notebooks. Like with the manuscripts, that can enhance collaboration, communication, and lead to faster improvements based on what they like or don't like from the work of their peers. An online resource can be found here: *http://www.composingscience.com/notebooks*

Risk analysis tools: Risk analysis tools are easy to use for assessing student learning in chemical safety concepts. After you create the tool, a grading rubric to assess the tool is easily prepared. Example questions/required components include: What hazards should students have uncovered? What controls were specified? Were risk levels assigned correctly? Because risk assessment is vital where discovery research is happening, we recommend that you set a criterion for minimum achievement before students are able to move onto the laboratory. For instance, if 70% of the students in a group must complete a Job Hazard Analysis with a competent score and then the group can move onto the laboratory. If students score poorly, you can use the rubric and analyze where the students are weak and talk with them about what to improve.

Making student groups that work: Students often dread "group work." Somehow students have been burned many times in high school, and they voice their dislike of working in groups. Students who are high achievers (or at least those who think they are) often gripe that other students will steal their work or slow them down. Many of these criticisms can be mitigated through carefully explaining the purpose of groups, and creating groups that are functional.

A best practice for creating groups is to have groups of three with one high achieving, one middle, and one challenged student in each group. Further, in courses where there are few women, students of color, or foreign students, it is best to put them in groups together so that they can amplify each others' ideas. There are online tools that help you to form groups based on a variety of inputs that the students can enter themselves, such as *www.catme.org*.

> **Other online resources include**:
>
> *http://www.crlt.umich.edu/tstrategies/tsgwcl*
>
> *https://ocw.mit.edu/courses/mathematics/18-821-project-laboratory-in-mathematics-spring-2013/teamwork/forming-teams/*
>
> *https://web.stanford.edu/dept/CTL/cgi-bin/docs/newsletter/cooperative.pdf*

Of course, even these groups may not work out, so it might be good to rotate the groups periodically in class. In advanced labs with students performing individual lab modules, the groups can change for each multi-week module. For laboratories where the students have a different lab each week, it makes sense to rotate them 1-2 times per semester. This also helps them meet more of their fellow students in class.

Group ethics: There are a number of ways to mitigate negative feelings about students working in groups. The most important way, which is true for any working group, is to have an agreed upon set of goals and moral code. Students can directly work and decide about these on the first day of class after a short, getting-acquainted exercise. Using leading questions or statements, students work together to decide what is important to them about the class, about the group, and about their goals. For instance, having the students discuss the following prompts: 1. Our goals for this group are..., 2. A good group member will..., 3. It is important to us that... The students work together to fill in these prompts and come to a consensus about the important aspects of group work. Using these prompts, students can also create a rubric with which they will evaluate each other at the end of the semester (see peer evaluation, below).

Credit, assessment: One issue many students have with group work is concern that poor group effort will bring down the individual's grade. In particular, they worry that if the group answer is wrong, then the individual group member who knew the correct answer will suffer. As the instructor, you can reassure students that the wisdom of three people is always better than one, though that isn't always comforting to many students. You can create mechanisms to mitigate these feelings such as having both individual and group grades. Should the group score be lower than the individual's score, assure students that they will get the higher score. Again, this is very rarely needed.

Peer evaluation: If working well together in a group is truly important to you in the laboratory course, it is important to value it with points for the grade. Although you can grade the students on their group work, it works very well if they grade each other. Using the rubric or ethical guidelines from the first day in the group, the students can evaluate the performance of themselves (self-reflection) and others in the group. Those evaluations can be put together to create a group grade that can have some significant fraction of the points. Thus, their final peer-evaluation has real consequences, and they are encouraged to work together better.

Documentation and self-reflection—what's working? There is an entire chapter on assessment here (see Chapter 5), but we want to give some concrete tips on how to go about self-assessing and most importantly documenting what did and did not work in the class for yourself, so that you can make changes that make sense. The chapter on assessment is more about learning gains, but there are always those small things that are wrong, easily fixed, and changeable. For instance, note that typo in that pre-lab assignment that completely altered the meaning of the paragraph. Update your syllabus, so it actually includes your contact information. Did you figure out a good analogy to describe entropy when you were having discussions with students in the lab? In order to make your life easier, we recommend making corrections when you see them and documenting parts that worked and did not work along the way during the course. At the end of the course, you should set aside some time to read through your notes, reflect, and make changes to improve the documents, website, and other documents of the course. In 9 months, when it is time to pick up the class again, you won't have to make these changes, because you already did that work.

Don't worry about stoplight thinkers—shut down curmudgeons: We all have people in our departments who are curmudgeons who *poo-poo* new ideas and change. Sometimes they say it won't work or it was tried before and failed. You might come into contact with people like this in your endeavors to implement change, and our advice is to ignore them. Like learning, change is hard but worth it to make things better. Counteract nay-sayers by having a good team locally and positive mentors near and far. Also remember that doing nothing may be easier, but it certainly is not the goal of science research, and it should not be the goal for science teaching, either. If one of the nay-sayers is your own department chair, this could be a big problem. Departmental leaders should have the mission to make the department better for both students and faculty. Try convincing them using the tactics from above, listed under "Money" to argue that your changes are in line with making the department better. For more information on how to engage nay-sayers see "Selling this approach" below. Positive publicity for your class can also help to move leadership if the positive praise comes back to them. Include a strong assessment plan to show how learning objectives will be met in the course design. Positive assessment results can go a long way to silence the nay-sayers.

Selling this approach to others in your department and administration: Messaging and framing are important both for building support and for mitigating criticism. When you announce that you are trying to update a course, and the person who designed the course is still in the department, for example, it's easy for your colleague to hear, "That course you developed is crappy, and I'm going to fix it." What you want them to hear is, "The course you developed served our students well, and the students are successful because of the work you did. Imagine how much more they can do if we build upon what you have already done." Find some people you trust and try out some different ways to talk about it. Different colleagues will need to be convinced in different ways, but at the end of the day, the changes you want to make need to be grounded in helping the students achieve. Positive arguments for skeptical colleagues can be found online here: *https://www.physport.org/recommendations/Entry.cfm?ID=93342*

Publicity: So, you are making a great class, and putting in a lot of effort to really upgrade your class. But how can you make sure that your department or college notice? If you have an annual review, you can discuss your course changes there and elaborate on the rationale for the change, what you did, and how effective it is. Another way is to go after some publicity. In courses where you have poster or oral presentations, you can invite your colleagues to watch the presentations. Some of us also invite the upper administration including the chair, dean, and provost to see the poster presentations. Even if the invitees do not attend, getting the email invitation informs them that you are going above and beyond in teaching your students. If you are doing something truly innovative, you can even invite the media! I know it sounds crazy, but the alumni magazine is often looking for stories they can write about what current students and faculty are doing. Talking to the alumni magazine, your college media office, media relations, or the school newspaper or radio is a good strategy for getting your awesomeness out there!

Resources:

https://www.physport.org/methods/

https://www.physport.org/recommendations/Entry.cfm?ID=93342

http://www.composingscience.com/

http://www.composingscience.com/reading-together/

http://www.composingscience.com/notebooks/

http://studentsdoingscience.tufts.edu/case-studies/seconds/view-the-case/

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4

Research Problem Selection and Curriculum Design

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This section addresses issues of choosing an appropriate research problem for a CURE. The choice of research problem depends on many factors, including time, personnel, and financial resources. Research problem selection also depends on specific research and learning goals. This section will discuss issues to consider as well as give multiple examples of CUREs at a number of different time and size scales.

The elements of CUREs

The characteristics of a CURE are that students use scientific practices, such as generating and testing hypotheses, generating and using models, selecting appropriate methods, and generating and analyzing data; that the work involve discovery or generating new knowledge, and thus the outcome must be unknown; and that the work is relevant. In addition, CUREs should involve collaboration among students and a process of iteration. Thus, selection of problems for a CURE should take these characteristics into account.

What is the value proposition inherent in running a CURE? What are your research and learning goals?

Research education cultivates a different type of cognitive development than the typical classroom experience can accommodate. The open-ended, project-based nature of research-based learning develops creativity, resourcefulness, observation, communication, critical and analytical thinking, and collaboration skills in ways that translate directly into real-world relevance more than traditional "cook-book" laboratory or classroom experiences. Research-based learning helps students learn to "think for themselves," that is, to develop greater agency in the context of relevant, real-life experiences. Typically, students engaged in research make many choices in the face of uncertainty and learn how to use preliminary results to continuously improve upon an initial idea. Students learn new skills in the context of new cognitive associations about the scientific topic at hand. Like learning to ride a bike, it is difficult to learn this without actually doing it. That is the point: to learn by doing. If the research topic is timely, compelling, or socially impactful, the students' motivation greatly increases. There may be a compromise made when deciding to offer a CURE-type course in that one cannot typically introduce the same amount of "content" as in a traditional course. A CURE typically has more intrinsic engagement and builds other skills through real-world problem solving. This is not an "either-or, which is best" situation, but rather a "both-and" situation.

Skills vs process: Learning goals of CUREs include specific skills, student experience in the scientific process, or both, and note that skills are often best learned via a process-based design. Again, this is usually answered in a "both-and" way. Experience in specific skills can often be built into CUREs. Problem selection is a key consideration for building in experience in specific skills.

For an example of learning and research goals, the Integrated Concentration in Science (iCons) courses at UMass-Amherst provide student-led, interdisciplinary team research on real-world issues. A particular junior-level iCons course on renewable energy has learning goals that include a) integrative understanding of theory and practice, b) development of core experimental skills, c) leadership in framing, planning and conducting research investigations, d) multidisciplinary communication, and e) synergistic collaboration and project management. For the iCons program as a whole, the research goals are to advance renewable energy, sustainability, and biosystems. Interdisciplinarity is essential to the program; almost every real-world problem is solved by an interdisciplinary group, and multidisciplinary teams are the rule, not the exception, in industry. The iCons program course at UMass focuses on both skills and the research process, but with a primary emphasis on the scientific process, in common with most CUREs.

Another example of learning and research goals comes from the Chemical Biology course at Northeastern University. The learning goals are, in part, to use molecular modeling to develop testable hypotheses related to protein function, to build skills in biotechnology methods, and to communicate research findings effectively. The laboratory section involves several research projects: the main one involves using molecular modeling to choose mutations to construct in a protein of interest to test a specific hypothesis about protein function. The students carry out site-directed mutagenesis and assays of protein function to test their hypotheses; they then describe their reasoning in in-depth written reports.

Structure (e.g., project within a course, entire course, across multiple courses): There are multiple structural ways to implement CUREs, ranging from spanning all four years of an undergraduate career to a smaller part of a single course. Many current CUREs are stand-alone courses that provide research experiences, sometimes integrative and building upon prerequisites, but typically within one semester. Enrollments and the number of students involved vary widely. Some programs, like the UMass Amherst iCons program, span the four years of an undergraduate program in a coherent, scaffolded, and cumulative way.

How will you assess your project? Is doing the project a learning goal in itself?: As described in Chapter 5, assessments should evaluate the learning and research goals of the specific course or program. Attitudinal surveys, formative/summative assessments, research outcomes, and other evaluative tools can help to provide the necessary feedback to improve each course along the way and/or to help construct the next version or subsequent semester as research moves ahead. Longitudinal information from alumni can be used to evaluate the impact on their professional development.

Where does your research/CURE idea come from? Who is the champion?: Project selection is highly dependent on overall learning goals, research objectives, and available resources. Selected projects should maximize the buy-in of everyone involved (Chapters 6 & 7). A research area that is immediately connected to a specific PI's area of expertise, or an interstitial area that connects multiple PI's research interests, is ideal because it provides a clear context and perhaps a set of clearly defined research goals. PIs interested in setting up CUREs are strongly encouraged to use their ongoing work to generate ideas that might adapt particularly well to a broad and inexperienced group of researchers. In research, PIs and their research groups are typically continuously coming up with new ideas or spin-off projects that might work well in this context. CUREs tend to proliferate and thrive when everyone, from PIs to students, collaborators, TAs, and lab staff, can contribute research ideas for new work or new modules.

The "idea environment" for new CUREs should be as broad as possible. Built-in local partners, like other institutions, industrial contacts, or K-12 teachers, can provide ideas or clear CURE-ready research questions. It is also quite possible to find existing research projects to join, including some massive CUREs running across many institutional consortia (Santa Clara, for example) and "open-source" research questions. For example, a recent Haverford Superlab was motivated by synthesizing and characterizing new malarial drug leads that were posted on an open-source repository by Indian scientists. CUREs that involve students synthesizing novel compounds can take advantage of industrial connections such as open innovation platforms (e.g., Eli Lilly *https://openinnovation.lilly.com/dd/what-we-offer/compound-acquisition.html*) that can provide an opportunity to have the students' compounds have broader use, and also provide a cash return for the CURE. Keep your eyes and ears open broadly! There are many possible partners, and participation with external partners can be a particularly powerful source of student motivation during the CURE itself.

Questions that are best answered through many similar experiments, rather than through one single person's ongoing work, can form especially good CUREs. A CURE can explore (i.e., trying new conditions or functional groups associated with a particular reaction or lead compound), but it can also optimize or more clearly define a specific problem area (i.e., defining optimal synthetic conditions for an important reaction, or finding the most sensitive reporter group for a specific kind of imaging experiment). Standardization of equipment and lab space is often desired, but it is important that a feedback loop be built so that CUREs don't get stale, because then they are not really CUREs anymore.

A project with built in work redundancy allows for students to master a technique through repetition, while creating new knowledge. Chemistry projects that systematically determine structure-property relationships can fit well into this mold. The end result need not be biological activity, but could easily be some materials-related outcome. Having an activity or property that is readily measured via quantitative results is ideal, allowing the class to generate large data sets that can be analyzed together in a meaningful way.

The University of Minnesota has formulated a CURE to replace a second semester organic chemistry lab. The CURE was designed around the synthesis of low molecular weight, low complexity organic "fragment" molecules and studying their interaction with a protein of biomedical interest by nuclear magnetic resonance spectroscopy (NMR). Although the methods and protein target are selected by the faculty member, we elected to engage the students initially by asking them to choose their own molecule to make. In this case, this is a faculty-guided CURE with student input. A practical consideration when implementing open-ended student problem selection criteria, is to limit the number and range of variables for student choice, as the size of chemical space is vast and the available resources are limited. In the Minnesota example, after developing a short three to four multi-step synthesis of a parent compound, students learn a basic sequence of synthetic and characterization techniques and choose from a set list of 40 different building blocks to introduce a diversity step in the first part of the synthesis. This CURE focuses on a class of proteins for which there are many homologs (bromodomains, both human and malarial), which have distinct biological function. Because the techniques to study them will be similar, and the protein isolation similar, this is a way to set up the CURE for long-term sustainability once the chemical space has been sufficiently explored with new fragment scaffolds for the first bromodomain of interest.

A successful CURE almost always involves trying something relatively new every semester or year, and that discovery process is something that teachers, TAs, etc. can share with, and model for, their students. An advantage of structuring a CURE around your own research is that you (the PI and instructor) become the immediate champion of the project. Having a champion is important as it can demonstrate to the students that there is a consumer who is interested in the end product, thus giving it value for helping science move forward and establishing a personal connection. Your own research program may also benefit.

It is important that there always be a few really invested parties, such as the PI, some key TAs, a graduate student whose work benefits from the CURE results, etc., involved in the CURE idea, the design, and the follow-up/feedback loop between iterations of the experience. Choosing a project that someone really wants to follow up, which can often include some students from the CURE or from a previous iteration of the CURE as undergraduate researchers, and that has publishable outcomes is an important part of project selection and CURE design. Building in some follow-up or a clear feedback loop is essential to maintaining the “freshness” of the CURE (see below) but also to making things publishable. CUREs often generate exciting results: someone still has to wrap them up and write them up, and knowing who that might be ahead of time is very important. Of the most recently published Superlab results from Haverford, all were “finished” by senior thesis students and/or the faculty who ran the Superlab experience. This is also the case with the advanced organic lab at Utah, where the publication was enabled by a group of engaged students who worked during the following semester to “clean up and finish off” the CURE’s results.

Although in principle results from such a CURE could lead to novel findings, and ultimately publication-worthy data, anticipate that the pace and reproducibility of such experiments could be slow as the students both learn and conduct research at the same time. The scope of interdisciplinary projects such as a medicinal chemistry study can be broad, so although a complete publishable research story may not result from the CURE itself, consider whether you could structure your CURE so the results might be used in the context of a broader story or otherwise establish a new research direction. Exploratory CURE work could initiate a new direction of research for your own lab, while still achieving the same learning goals for your students. In this case, the publication could come further down the road.

Instituting a clear cleanup and regeneration loop between successive CURE experiences is necessary, because CUREs are research and research takes careful and reflective attention to detail. CUREs can be somewhat more bandwidth-intensive than for conventional labs, which one can often just “put back in the box" for the next semester or group of students. Involving students and teaching staff in the feedback loop is an excellent opportunity for integration of a PI's own research and research team with a CURE, is a key part of making a CURE into publishable research, and is also necessary to make the next iteration of a CURE current rather than something that goes over the same, already-trod ground. CUREs will have different natural cycles depending on many factors: there are several Haverford Superlab modules that come back in a new form every 2–3 years after gestating further in PIs' research labs.

Collaborative projects, or projects that can be run by multiple instructors with different background expertise, can be very successful with the caveat that there be clear ownership and division of labor. Team teaching can broaden the scope of a CURE. In the Minnesota case, having faculty assist with the protein and NMR-based experiments or additional biophysical measurements can provide valuable human resources to augment the synthetic training of the students in the organic chemistry laboratory. Haverford Superlab also provides some examples of this: sometimes 14 weeks are split evenly between two seven-week projects, but sometimes a 14-week project with two instructors is implemented when the two instructors are both invested in a common question or research area that requires the expertise of both. In another example, in some semesters, the Northeastern Chemical Biology CURE has used the results of research projects from a Molecular Modeling class as the basis for design and construction of mutations in proteins to test the predictions from the modeling experiments.

Throughout a CURE, building context for the students is essential in providing a genuine experience of research. They shouldn't just feel like a cog in a wheel, and they should be empowered to ask questions and propose their own directions when possible. Motivation for different projects comes from different places, but providing some clear introductory information is always important so that the research question is clear. The learning goals of the CURE should be explicitly advertised to the students up front, especially regarding the differences between a CURE and other labs so that it is clear that there is an expectation that all participants, including the instructors, will learn something new (not just skills) and that failure is possible, if not likely, because it is an intrinsic part of trying new things. Failure, with clear documentation, is a centrally important part of the scientific process and students should be clearly reassured that scientific failure does not necessarily equal a failing grade, especially if students demonstrate high-quality thinking about possible causes of failure and how to address them.

If a project is based on primary literature, then that literature should be introduced and time should be spent using the literature to motivate the experiments that the CURE will attempt. Having students follow your own publications is one way to introduce them to reading scientific manuscripts. Assignments to find specific information or proposing new organic synthesis routes using online resources such as SciFinder is another way to introduce them to this process. The CREATE (Consider-Read-Elucidate the Hypothesis-Analyze-Think of the next Experiment) model is one way to structure introducing the literature (see Hoskins, et al.)

If a project is collaborative or based on a contact's work (either a collaborator at another institution, an industrial partner, or another PI elsewhere who has published in the same area) then those people can directly be mobilized to provide what can be a very effective context beyond what the local instructor can provide. Outside collaborators and contacts can visit the class or meet individually with students to explain why the project is important. Haverford Superlab modules usually include some sort of external contact, either by email, Skype conversations, or on-site visits to talk to the students.

A recent example of this type of collaboration is the 14-week spring 2017 Superlab project, that included a visit from a nearby professor from the University of Delaware, a Skype class session with a spectroscopic expert from the University of Nevada, and email consultations with another expert from Franklin and Marshall College: all three of these external consultants provided invaluable advice, expertise, and ideas that helped the CURE to proceed in unexpected and productive directions. The Minnesota CURE is a collaborative project with Gustavus Adolphus College. The undergraduate laboratory is held at Gustavus Adolphus College, and the visiting scientist, or consulting stakeholder, in the project is the professor at the University of Minnesota whose research directly benefits from Gustavus students' work. Early engagement with the students from the visiting professor at the beginning of the semester lays out the research problem, as well as periodic visits and feedback sessions throughout the semester as the CURE progresses and the students begin making and testing molecules. As with most research, unanticipated connections can emerge between CUREs and other courses and curricular pieces. At Minnesota, site-directed mutagenesis is needed to help assign the protein resonances. The students make a site mutant in the protein to eliminate a side-chain that will receive an NMR active nucleus, and observe what resonance disappears in the NMR spectrum. This type of make and measure project and the data it generates fits very well into Gustavus Adolphus College's Proteins course.

When and how do students get control of their own learning? In CUREs, Students should have the opportunity to exercise individual choices and creativity. Developing undergraduate student self-leadership in research benefits significantly from a clear pedagogical scaffolding. Ultimate goals for students include identifying an interesting and relevant research project, designing it, carrying it out (with the requisite need to quickly iterate and improve the research design), and managing effective communication with colleagues and advisors along the way. However, growing such independence can be a challenge for students with little to no experience in research thinking and practice. Venturing into new territory feels risky to most students; the fear of failure and the "tyranny of choice" can hinder some students from diving in, so it is vital that the instructor(s) engender some psychological safety for the students. Essentially this means conveying that research outcomes are uncertain. For many students, this uncertainty in research is a wholly new paradigm. In an environment of relative safety where it is clear that failure will not lead to penalties, students can adopt a new mindset of proactivity and resourcefulness.

Research thinking is closely related to both design thinking and rapid prototyping, in which "design-build-test-iterate" is a route to higher quality outcomes. This loop cultivates creativity within students. Providing inexperienced students with a limited menu of possible "bite-sized" research topics can serve as one form of scaffolding, as well as providing direct support, training, and mentoring. Training along the lines of "tell-me, show-me, let-me-try" and later, "see one, do one, teach one," can be effective. New students in research can benefit greatly from near-peer mentoring, sometimes by assisting more experienced students in a research project. As students progress through an undergraduate program, they can assume responsibility for a greater degree of research scope and creative responsibility, provided that they have had prior, appropriately scaffolded, research experiences. Reading the research literature, performing web and literature searches, consulting with experts and collaborators, and finding resources to perform the research are all part of the research resourcefulness fostered by CUREs. This resourcefulness is distinctly different from textbook learning and is immediately relevant to real-world careers. Synthesizing ideas and pursuing them in research also helps students develop agency and full ownership of their capabilities.

Most universities have not yet adopted scaffolded research coursework experiences for their undergraduates that span multiple years in a coordinated way; it is more common for a few students to be involved in their own research labs across multiple years and grow in that context. It is logistically and financially easier to constrain the scope of possible research, usually within a one-off course. Some universities are beginning to integrate and coordinate the undergraduate research experience explicitly in the curriculum throughout the four-year undergraduate degree, so that the degree of "self-ownership" can be scaffolded and grown appropriately. The UMass iCons program is one such example. Another approach is a mini-CURE or "pre-CURE" in an otherwise classical lab course in a semester immediately preceding a CURE course to help students get accustomed to the CURE model (Chapter 2).

What student team or collaborative strategy best lends itself to your project? Research almost always happens in groups, and designing groups effectively is a centrally important part of a successful CURE. While the entire

CURE often constitutes a group for data analysis and comparison purposes, work can happen in groups of varying sizes. Lab work with variations on the same procedure (i.e., different genes/mutants, proteins, synthetic conditions) should necessarily be replicated by multiple pairs of hands, so the minimum group size for CURE labs is usually two students. Groups of 3-4 tend to have more independent ideas and mutual creativity and can have clear role assignments when needed, and groups larger than four tend to exclude one or more of their members from the most important intellectual formation parts of the experience. Diversity within groups might initially make students uncomfortable, but extensive research indicates (and anecdotal experience with CUREs also suggests) that more diverse groups lead to both better outcomes for all students and more productivity on the part of the diverse teams.

The UMass iCons program has groups of 3–5 members. A considerable amount of time is spent developing each team culture so that students can have an environment of psychological safety. This is important for empowering the students to pursue a topic of real-world relevance, knowing that best-case research outcomes are not guaranteed but that, in any case, they will make a research contribution and have a valuable experience. Each course typically has more than one team selection process during the semester. For example, one research project may have assigned teams and the subsequent project may have teams formed by topical affinity and voting. One iCons course on renewable energy research runs as though the class membership were a small start-up research and development company—a “team of teams”, one might say. In assigning teams, it is important to pay attention to the research on diversity in teams, for example, to have a least two women on a team in environments in which women are underrepresented. Haverford Superlab tends to run in pairs, while other CURE labs typically have groups of 2–4 students.

Establishing both group and individual goals is a critical design feature when working in groups. Coordination of responsibilities in the team should be established with some instructor oversight, as students do not necessarily know how to do this or do it efficiently themselves at first. One feature that makes these team management issues civil is a culture of creative innovation and the accepted natural uncertainty that accompanies such a culture.

What resources are necessary for your project to be feasible?

Curriculum considerations: It will be easier to get buy-in for your project if it satisfies a requirement or fills a gap in the curriculum, especially in majors that have very structured and crowded curricula, such as chemistry and physics. CURES or inquiry labs can satisfy capstone requirements, requirements for instruction in ethics, critical thinking, using the primary literature, research experience, or disciplinary or technical writing. You may be able to leverage your project to satisfy a requirement for instruction in a specific topic or area. CUREs are especially appropriate for discussions of scientific ethics, and questions will arise about data handling, credit and attribution, and appropriate authorship and publication practices, providing timely material for such discussions.

The American Chemical Society has recently introduced a new macromolecular chemistry component to its degree requirement. One way to address this is through a distributed approach throughout the curriculum. Development of a CURE that evaluates small molecule-protein interactions is another way to address this need covering important principles in both organic chemistry and biochemistry.

Facilities and infrastructure: In terms of resources, parallel projects can simplify your investment and that of the institution. In the University of Minnesota example above, an SAR analysis with limited synthetic options might provide the parallel aspect. In biochemistry-related fields, site-directed mutagenesis projects that involve making different mutations in the same protein work well. In biological fields, phenotypic screening with the same set of bacterial strains is a parallel experiment but still allows students to make choices that they will have to justify. Environmental, analytical, or physical chemistry experiments can utilize the same or similar tests on different samples. These types of projects can still provide the experience of having the student justify with scientific thinking, for example, choice of mutation, choice of sample, or choice of sampling site.

A challenge in designing such a laboratory is that a suitable protein should be chosen that expresses in high yield to support the demands of the class and has reasonable long-term stability to minimize the frequency of protein production. Both protein expression and purification facilities are thus necessary. In a synthetic fragment laboratory that would involve binding to a protein, a variety of biophysical methods should be available. Differential scanning fluorimetry (thermofluor) can be carried out to measure protein stabilization by a small molecule binding event based on an increase in thermal melting temperature. Such an experiment can be conducted in a 96 or 384 well plate with a qPCR instrument. Alternatively, the Minnesota approach uses a protein-based ^{19}F NMR method, which necessitates both having a medium strength magnet (400-600 MHz) and a probe that tunes to the ^{19}F Nucleus. Alternative NMR methods analyze the small molecule in the presence of protein, and can be carried out with significantly less protein, on standard NMR probes. Resource demands for CUREs can also spark innovation in research. The Minnesota researchers have published on using paramagnetic metal additives to increase the speed of NMR data acquisition. Using 20 mM solutions of Ni(II), data acquisition time can be reduced to 30 minutes on a 400 MHz NMR instrument with a standard room temperature probe.

It is best to avoid relying on equipment and facilities in individual faculty research laboratories. The level of oversight needed for an entire class of students using research-grade equipment is likely to be challenging. In addition, research equipment is for the use of the research laboratory and use by CURE students will interfere with research and can generate conflicts. One possible exception to this is the type of experiment students can set up almost entirely in the teaching lab and the research instrument is used only for the actual data acquisition, such as differential scanning fluorimetry, in which all reactions can be set up separately and only the actual data acquisition occurs with a qPCR instrument once the plate of reactions is assembled.

Funding: In general, CUREs and inquiry-based lab experiments are more resource-intensive than more typical labs. This might prompt resistance, so it is worth spending time identifying available resources to help implement your project. Many institutions offer curriculum innovation funds, student research project funding, research project seed funding, and/or diversity and inclusion grant funds. If you are writing an NSF proposal, and the project is related to your proposal, you can describe this as part of your broader impacts and include funding for your CURE in the budget. Start with your curriculum coordinator, laboratory staff, and/or chair or dean, depending on the structure and culture of your institution. Do your homework to determine what the current laboratory costs are, if a lab already exists for your course; if a standard laboratory is being converted to a CURE, the increase in cost could be minimal. Parallel projects can be designed specifically with cost in mind. If the projects are completely open-ended, a budget or cost evaluation step can be built into the workflow to raise awareness of costs among students and provide an opportunity for oversight of costs.

Staffing and professional development: From the beginning of project design, assess the staffing needs of your project. Also consider new opportunities that will be available to personnel and students. From a practical perspective, lab preparation work is likely to be somewhat more demanding for personnel who do this work at your institution. The more streamlined and fewer variables in your project will make the prep less complicated.

On the other hand, the prep work for a CURE is likely to be more interesting and can provide an opportunity for greater engagement of laboratory staff.

If a minimal set of techniques are used, TAs can be trained after immediately completing the course or as the semester progresses. By focusing on a few sets of variables to change in any given CURE, training can be made to be more manageable. In the case of the Minnesota CURE on fragment screening, as new organic syntheses are developed, TAs need to be familiarized with the reactions being performed. This is anticipated to change frequently, due to the nature of the research, which should be accounted for. Adequate prep time and workload credit should be allocated to TAs for inquiry labs. Undergraduate TAs can be trained as near-peer mentors. A key consideration is to train the TAs and other instructional staff to act as coaches to prompt students to think about how to answer their own questions, rather than as a source of answers (e.g., BIOTAP, part of NSF grant for TA training, *https://biotap.utk.edu/*). Similarly, instructors should view themselves as coaches and mentors, akin to their roles in research laboratories. Instructors have an obvious role in evaluation of students, but they are also critical role models and coaches and mentors in research and should strive to strike an effective balance.

A key incentive for TAs associated with CUREs is to relate the research project to their thesis research. At the most basic level, they will gain additional experience relating their project goals to less experienced researchers. They may also use the CURE to recruit talented, motivated researchers and to generate preliminary data for their research project. If TAs are interested in careers in teaching, the opportunity to create a CURE or to be engaged with teaching one can be a positive addition to their teaching portfolios.

Feasibility and robustness: While inquiry-based labs can be a source of (very) preliminary data for your own research, don't do a CURE project that is critical for your research to move forward. If you are expecting the CURE to help advance your own research, think of it as being on an exceptionally long time horizon, with plenty of time built in for iteration and troubleshooting. You can determine robustness by having relatively inexperienced undergraduate researchers or TAs run pilot experiments. Another way to enhance robustness is by requiring student proposals that have to be approved by faculty and/or TAs before projects move forward.

Success will depend on many factors, including the clarity with which the project is developed, and the technical skill of the students. Complicated, multi-step protocols will require far more oversight, and possibly student experience and engagement, for success. Building in time for troubleshooting and repetition of failed experiments will increase the likelihood of success. Also, simply telling students that you expect the work to succeed can help move more projects into success. For many students, this is the first experience with experiments without a known answer, so they may not know what to expect. Having not experienced much failure before, they may not even consider that their work will not be successful. This is a delicate balance, so consider the backgrounds of your students and the culture of your institution as you craft your message. Remember to emphasize to students that the quality of their evaluation of their failures in the research project will be an important indicator of their grade, not whether the project succeeded. If projects involve multiple steps, it is useful to have points at which materials from steps that worked can be shared with students whose projects didn't work, so that everyone can still move forward in parallel; another approach is to have materials from previous semesters or research laboratories that can be inserted into appropriate points of the CURE as needed. A willingness to be flexible so that all students can move their projects forward will decrease frustration and make the experience more rewarding.

Iteration is also likely to improve project outcomes, and will help students develop independence and critical thinking. In the case of the possibility of outright failure, building in time for repeating experiments will increase the likelihood of success. The importance of good notes and detailed observations should be conveyed to students and they should be held to this standard, which will help improve their troubleshooting and thus outcomes of research. The instructors and student assistants should also take good notes about what worked and problem areas to help move projects forward in future iterations.

Scalability encompasses several features, including scaling the project to be available to more students as well as scaling the project to higher levels of student choices and more variables or more aspects of the project. Our recommendation is to start small and build as your comfort grows. Engagement of other instructors or other partners can provide a natural scaling factor as their interests become incorporated in the CURE.

Safety: Safety must always be a top consideration. This issue can quickly become very complicated when students have complete freedom to choose their projects. Projects can be parallelized or limited to specific parameters to minimize safety risks. A safety assessment can, and should, be part of every project, and is especially important for those that involve a wide range of student choice. See also the separate section on Safety.

Deliverables: A student project proposal, student-generated protocol, and/or safety assessment can be a good first assignment to get students to think like researchers. Depending on the goals and length of your CURE, you might also want to design a mid-point check-in to assess student progress. Depending on your expected end product, additional periodic check-ins may be warranted. You might want to determine both material progress as well as progress in terms of understanding, record-keeping, using the literature, and troubleshooting. Notebook checks are commonly used as a periodic assessment. Effective data management and record keeping is often a challenge for beginning researchers, so providing a model of a good notebook and setting and maintaining clear expectations for record keeping are essential. The ultimate product of the CURE might be a final paper, oral presentation, poster session, specific experimental results, or even a working prototype. Engaging students in peer review of presentations can also be effective.

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Examples

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ACS Symposium Series chapter: *http://icons.cns.umass.edu/* (iCons program at UMass Amherst), *http://www.olin.edu/projects-research/whole-new-engineer/* (Olin College approach), *https://cns.utexas.edu/fri, http://serc.carleton.edu/index*.html, *http://pubs.acs.org/doi/abs/10.1021/acs.jchemed.5b00547?journalCode=jceda8 http://pubs.acs.org/doi/abs/10.1021/acs.jchemed.5b00875, http://www.asbmb.org/asbmbtoday/201604/Education/CUREs/*

5

Assessment of CUREs

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Contributors: Lisa Corwin, University of Colorado, Boulder; Erin Dolan, University of Georgia; Joi Walker, East Carolina University

So, you want to try teaching a CURE—how will you know it "worked?" Assessment is an everyday way of referring to the idea of evaluation, which involves judging the merit, worth, value, or impact of something, like a course or a program.[1] Assessment of your CURE will involve systematic collection and analysis of educational data that can help you determine whether and for whom it was effective. There are several factors to consider when developing an assessment plan to determine the effectiveness of your CURE. Is it your first time teaching a CURE and are you still working out the kinks? Or, is this the fifth pass that now operates like a well-oiled machine? Who are your students and what are their motivations and goals? For whom are you doing this assessment—yourself, colleagues, administrators, potential funders? Is your goal to publish the assessment data? Considering all of these factors can seem daunting, and it can be challenging to sort through them to generate and implement an assessment plan. This chapter is designed to guide instructors in assessing their CUREs by considering four factors that determine the scope of assessment:

1. Offering

How many times have you taught this CURE? Assessment of a CURE must align with its level of development to yield useful data.[2] As with any new endeavor, we gain skill and expertise incrementally. We wouldn't expect a child to be able to ride a bike perfectly the first time, and we should not expect ourselves—as new CURE instructor—to implement a flawless model of our course the first time. Design your assessment to inform the productive development and evolution of your CURE and allow assessment to evolve with the CURE. For example, assessment for a new CURE should evaluate the successful completion of goals for the semester, and whether the course aims are reasonable in scope and difficulty:

> Did students complete the tasks I wanted them to complete? Can I document progress toward student learning goals using the existing assignments and student assessments, or do these goals need to be changed?

In later offerings of the course, aim to determine course effectiveness more broadly and publicly. For example, you may need to convince colleagues or administrators of the course's value or demonstrate the effectiveness of your CURE across multiple implementations or contexts.

2. Stakeholders

Who cares about the assessment and who will see the assessment results? In some cases, only the instructor will view the assessment. At other times, colleagues, administrators, and funding agencies may have a vested interest in the outcomes of the CURE. Definitions of "success" may vary among stakeholders and individuals in different professional roles care about CURE success for different reasons. An instructor may hope that students develop scientific curiosity and skills that allow them to examine the world critically. Colleagues may hope that the CURE allows students to develop knowledge of laboratory techniques that will prepare them for future coursework or undergraduate research internships. Administrators may be most interested in whether the CURE increases persistence in the major, resulting in increased institutional retention rates. Each stakeholder has a vested interest in the success of the CURE, and they can influence whether it can be sustained. When designing assessments, consider which constituencies have a stake in the CURE's success and which data and analyses will be most informative to them.

3. Student educational background

What are the prior educational experiences, backgrounds, and motivations of your students? The ways students benefit (or not) from CUREs and the extent of these benefits will differ based on differences among students.[3,4] Assessment should consider both what students are hoping to get from the experience and the magnitude of change that is likely to occur given their backgrounds and interests. For example, unlike STEM majors, non-majors typically do not aspire to enter research careers—therefore assessing whether they have developed specific laboratory skills or continue to take STEM courses may not be relevant. Instead, assessment might focus on general education outcomes for non-majors, such as building information literacy or teamwork skills.[5,6] Similarly, we might expect seniors to master material more rapidly or produce higher quality products than freshmen. Just as we would not use a yardstick to measure a microbe, we should not use assessments that are either too narrow or too broad to capture student achievement. To ensure your assessments are meaningful and useful, tailor which outcomes you choose to measure and scale your assessment to your student population.

4. Dosage

How much time are students involved in the CURE? How much time and effort students invest in the experience will influence the outcomes they realize.[7,8] For example, students who participate in a CURE for two hours per week for one month will realize different outcomes that students who spend four hours per week for two semesters.

In addition to the four factors above, two primary aims drive CURE assessment: 1) to **inform** future CURE design, or **formative assessment**, and 2) to **document** the impacts of the CURE for stakeholders (e.g., CURE students and/or the institutions they attend), or **summative assessment**. You can address both of these assessment aims simultaneously throughout development and refinement of a CURE. For example, surveying CURE students about their intentions to persist in STEM and conducting focus groups with these students to elucidate reasoning behind their choices to persist can generate predictions of future retention (a summative assessment), while also identifying "what worked" and what needs improvement (formative assessment).

In the scenarios below, we describe the assessment of four hypothetical CUREs and how it can be used to inform different stakeholders about course effectiveness[9] and inform improvements to the CURE design. Several references offer more in-depth advice and describe various ways of measuring key variables in greater detail.[2,10,11]

Scenario 1: Data for the instructor

Professor Nancy James is planning to teach a new CURE course in the fall. For this initial course offering, she wants to focus on the implementation of the course and not be overburdened by the assessment plan. She wants to ensure that the course assignments serve multiple purposes—supporting students in making progress on their research, determining student grades, and helping her to assess how well the CURE is working. She is most interested in students' developing scientific communication skills, both oral and written. She is contemplating lab notebook entries, multiple one-page project updates, and a final project report. She is also considering oral communication tasks such as informal group meeting presentations and discussions and a final poster presentation, but must be careful not to overburden the students with too much work. She is excited to invite the whole department to the end-of-course poster session to see what students have accomplished and thus opts to use the poster presentation as the students' final project as it provides aspects of both oral and written communication and the opportunity to share work publicly. These assignments vary in their complexity and workload, can be graded, and should collectively reveal how students' thinking about research and communication skills have matured over the semester. She plans to develop simple, low stakes, holistic rubrics for assessing group meeting presentations and participation, notebook entries, and project updates, and a more complex analytic rubric for the poster presentations.[12] Finally, to get holistic feedback on the course, she will ask students to complete a five-minute post-course reflection, in which they respond to three prompts: What are two things you got out of the course? What elements of the course helped you get those things? What are two suggestions you have for improving the course? These reflections are used informally to improve the course for next year and as part of a debrief discussion with other teams implementing CUREs on campus.

Implementation advice

Why: The purpose of assessment during the first offering of a CURE is to inform your offering of the course, to smooth operational road bumps, and to collect data on students' experiences that could inform future the design of a more robust assessment. For example, it may be that your students are realizing highly beneficial but unanticipated outcomes, or it could be that only a small tweak is needed to help them realize the intended outcomes of the course.

Who: In the initial offering of your CURE, you, your instructional team and your students are the primary audience for the assessment results.

What: The main assessment data are student assignments and feedback. In early CURE offerings, it is important to review the students' assignments and give them feedback. Are students making lab notebook entries according to specifications? If not, how can you revise the instructions, rubrics, or other interactions with your students to better guide the students toward the desired performance? End-of-course reflections can help you decide which aspects of the course should remain as is (i.e., the elements of the course that students found helpful) and in what ways the course might be improved (formative assessment aims). For blank rubric frameworks and simple introduction and sample rubrics and templates, see those shared by Dannelle Stevens and Antonia Levi, *http://www.introductiontorubrics.com/overview.html*, as well as Jon Mueller's Authentic Assessment Toolbox: *http://jfmueller.faculty.noctrl.edu/toolbox/*

When: For a new course, collect direct feedback from your students mid-semester as well as at the end of the course. This allows you to make mid-course corrections to improve the experience for current students.[13,14] Various formative assessments should be distributed throughout the experience (weekly such as lab notebook entries and monthly such as group meetings and project updates) so that you can gain regular insight into where students are experiencing success (the CURE is "working") and where students are struggling (the CURE needs to be improved).

Scenario 2: Data for colleagues

Professor Anne Rossi has offered a CURE to a small group of students once as a pilot and worked out some of the instructional kinks through formative assessment. The CURE focused on characterizing metal binding to proteins and peptides. Students in the CURE used a variety of techniques to quantitate the Keq of metal binding as well as characterize the structural changes that occur upon binding. Given the emphasis on equilibrium in general chemistry, she now wants to scale-up the CURE to replace a section of second semester General Chemistry Laboratory, but her colleagues have expressed concern that students may not develop proficiency with the standard laboratory practices expected for upper-division courses, such as graphical analysis, titration, and pipetting. Despite her colleagues' hesitations, Rossi suspects that her course accomplishes departmental goals for general chemistry laboratory. She knows that her pilot group of students was successful in titration and pipetting because they performed research that required these skills. Also, in response to formative assessment performed during the first offering, Rossi adjusted the course so that students had sufficient time to generate detailed lab reports, which included constructing and revising their graphs to accurately represent their data. Despite this anecdotal analysis, she expects that she will need to demonstrate to her colleagues that the CURE students develop these skills definitively and quantitatively. Prof. Rossi plans to review her course to determine when students perform these tasks and design skill stations with short practical exercises where students demonstrate their proficiency in front of a teaching assistant. This approach allows her to document students' competencies and quantify the number of students in the course who perform each skill successfully.

Implementation advice

Why: The purpose of the assessment in Scenario 2 was to demonstrate that the CURE version of the course fits within the curriculum and to ensure students realized the desired course-specific outcomes. This kind of assessment is helpful for demonstrating that the course helps students develop specific skills and knowledge that are of value to your department and discipline and match departmental course goals. It helps if your department has a curriculum map that identifies the learning outcomes related to an entire program of study so that you can clearly identify levels of student development at each stage and how the CURE aligns with the broader programmatic objectives.

Who: Your departmental colleagues (e.g., tenure track faculty, fixed-term faculty/ instructors, undergraduate laboratory directors, and laboratory managers) may all be invested in the success of the laboratory curriculum and the CURE and are thus your audience for the assessment.

What: Given this scenario aims to offer a single type of credit for two versions of a course it will be important for you to determine how critical it is for students to learn the same knowledge and/or skills in both versions of the course. Perhaps it is important for students to develop a set of technical skills and gain experience collecting, analyzing, and interpreting data, but it is not so important for them to gain particular conceptual knowledge (they will learn this in a "lecture" course offering). Resolving this issue will be especially important for courses that serve as prerequisites because instructors of upper-division courses will assume students are entering their course with similar levels of preparation. The Undergraduate Program/Curriculum Committee should also be consulted when proposing a CURE to replace an existing course or course section. If the CURE will be offered as a section of the course, then you may need to assess across CURE and non-CURE sections to demonstrate equivalency.

When: Since the CURE section will substitute for a required course, you should consider the role it plays in the larger undergraduate curriculum. For example, does it need to meet ACS accreditation benchmarks? Do skills emphasized in the CURE align with skills taught in the existing course? To demonstrate student proficiency, lab skills can be evaluated at a skill station during the semester, perhaps as a prerequisite to embarking on part of the research (i.e., "you must show that you can pipet with X level of accuracy before you can do this part of the experiment"). In some cases, you may find that a lab skill taught in the current lab course is not addressed in the CURE. If so, explore whether students truly need to learn this skill and consider including it as a small, add-on module in the CURE offering that doesn't need to be integrated into the CURE.

Scenario 3: Data for your department chair or dean

Professor Xavier Hernandez has been teaching his semester-long, introductory biology CURE for the last three years. The course enrolls 40 students per year (20 students per section), all first-term freshman. Students who do not complete his CURE take the standard introductory biology lab course. Prof. Hernandez also teaches the sophomore microbiology class. He noticed that the students from his CURE seemed to register for his micro course every year at a much higher frequency than other biology students. This informal observation prompted him to ask for an institutional report of the enrollment records, GPAs, and graduation data (e.g., continuation in the biology major, completion of a college degree) of his CURE alumni as well as other students who entered as biology majors. He conducted a regression analysis with the data in order to control for any differences in prior achievement and demographics of students who completed the CURE versus the standard offering.[3,4] When he looked at the results, he was shocked. The students who took his CURE had a much higher likelihood of staying in the biology major and even staying at the university relative to the students who took the standard biology laboratory course. Prof. Hernandez wrote up concise brief and created an infographic, which he shared with his Department Head, Dean, and Provost. He is hoping that the results will encourage administrators to provide continued support for his CURE and incentivize other faculty to transform their introductory lab courses into CUREs. Now, the Provost plans to tout the Biology Department at annual meetings with the Alumni Council and University Board of Trustees because it speaks toward the actions the university is taking to improving student outcomes. Two of Prof. Hernandez's students have been invited attend these meetings to share their experience with the CURE and how it influenced their educational and professional trajectories.

Implementation Advice

Why: Telling success stories is important for visibility of your CURE, for engendering collegial buy-in and administrative support, and for ensuring its long-term sustainability. These stories are also particularly important if your aim is to garner support for the CURE model broadly across your department or college or to scale-up your specific CURE. Your job is to make the story easy to tell by providing a clear, data-driven message that aligns with your institution's mission and priorities and testimonials from students that make the message more personal.

Who: Department, College, and University Administrators are the primary stakeholders at this level. Administrators have access to resources (space, money, personnel, etc.) that can either launch a project or sustain it long-term. To garner their support, you need to provide them with the data that make your case effectively and efficiently as well as student stories that illustrate impact on a personal level. Remember that 10 (or more!) other units on campus may be making similar requests. Your program needs to align with departmental and institutional priorities, which often center on retaining and graduating students in a timely fashion. Institutions are always looking to enhance their image and illustrate their worth through communication of success stories. These stories can be about specific students that did well or overall improvement for a group of students. Stories and associated data can be used via social media or institutional and popular press to build reputation both within and beyond campus, support advancement efforts, and communicate the value of higher education to legislators and the public.

What: Most campuses have an Office of Institutional Research or Assessment, which likely reports to the Provost or President. This office should have access to student enrollment and performance data, either directly or through the Registrar and/or the Admissions office. You will need to have a method for identifying your own students as well as a comparison group of students (e.g., students who completed a different non-CURE offering of the same course), which the relevant office can then use to query the institutional data. There are a variety of methods by which student outcomes can be compared (e.g., multiple regression, regression discontinuity analysis, propensity score matching), which vary in their rigor. Consult with a statistician for advice if these techniques are not familiar.

When: A pitch to a Department Head or Dean likely comes at two different stages. The first may come before the project starts, especially if you need funds to initiate your CURE. Such requests are likely to have expectations of future reporting on the influence or outcomes of the initial investment. The second request occurs after you have demonstrated success of a pilot when you need expanded space or resources to reach a broader population of students. A single section of a course that affects 30 students per term may be viewed as important to your department, but as a boutique exercise to your Dean or Provost because it will not have campus-level impact. Make sure that you know the priorities of your administration so that you can design your assessment to yield data that will be valued by administrators. For instance, if your institution is concerned about STEM persistence or the success rates of underrepresented or underserved students, then you will need to collect and analyze data on enrollment in subsequent STEM courses, completion of STEM majors, and student race/ethnicity, gender, ability status, and first generation in college status. Although student testimonials may seem unscientific, they can put a personal face on the impact of a learning experience that appeals to administrators, alumni, and potential donors.

Scenario 4: Data for publication or preliminary studies in a grant proposal

Professor Yichin Xi had been leading her general chemistry CURE in which students assess heavy metal contamination in soil. The first two semesters were spent developing standard operating procedures for studying five different metals, which could be shared between students. Now, they are starting the real environmental survey in collaboration with Professor Carla James, a specialist in urban planning and environmental impact assessments. Xi presented her CURE during an environmental chemistry division session at the ACS meeting. She even brought one of her CURE students who had stayed on in her lab as a research intern to present about his work at the meeting. Her department head and college administration were particularly excited about her course because institutional data indicated that students in her general chemistry offering were much less likely to earn failing grades or withdraw than students who enrolled in other versions of the course.

Xi happened to attend a chemistry education division session during the ACS meeting. While she was there, she spoke with Dr. Jeff Mitchell, a chemistry education researcher specializing in studying teaching and learning in chemistry. Mitchell thought the course performance data were interesting, but was more interested in understanding what about the course was leading to these outcomes. He posed some thought-provoking questions. Were students more motivated because the work was relevant to their daily lives? Did the CURE help students become more confident in their ability to do science and develop their identities as scientists? Was the peer mentoring structure of the course providing an opportunity for students to see successful students in action and get help from them? Was the fact that students tackled a difficult problem through teamwork helping to build a sense of community that encouraged them to persist in the face of difficulty? Each of these hypotheses could explain the effects Xi was observing, but she had no idea how to measure abstractions like “sense of community” and “motivation.” Conveniently, Mitchell was part of a larger team working to understand factors that influenced the persistence and success of undergraduate students from backgrounds underrepresented in the sciences. He encouraged Xi to join the monthly conference call with his team and discuss her course and observations with the group.

Their initial conversations led to Xi’s course and students being included in a larger, ongoing study, which helped to address her concerns about having a sufficiently large sample (number of students) to draw meaningful conclusions from the assessment data. Working with a team of experts in the learning sciences also afforded Xi an opportunity to learn about how to design education studies, including how to navigate the IRB review process and how to select to right assessment tools and methods. She also learned about the broader body of research on chemistry education that allowed her to identify knowledge gaps that her work could help address. Finally, Xi was able to tap connections she developed to identify an external evaluator for an NSF proposal she was writing with other STEM colleagues to integrate research experiences throughout the introductory STEM curriculum.

Implementation advice

Why: Discipline Based Education Research (DBER) presents a unique opportunity to integrate teaching and research by conducting research ON teaching and learning. This field can help faculty in teaching-intensive positions develop a research program that fits with their professional responsibilities. Work of this type may also appeal to the research mindset and interests of research-intensive faculty. Publishing about educational innovations can help others learn from it and adapt or adopt it for use with their own students. This broadens the impact of the work, which can maximize likelihood for funding from granting agencies (e.g., NSF) that place value on broad impact.

Who: If you are aiming to publish about your CURE, it is important to consider what other instructors could learn from your work. This requires getting to know the body of research on teaching and learning in your field. Remember back to how you learned to read literature in your discipline—there will be terms, methods, concepts, and ways of thinking you will need to learn. Finding an expert in the area, such as a **chemistry or physics education researcher**, whom you can tap for advice, references, and networking can shorten your learning curve and help you find key people and resources more quickly than you can by yourself. It is also important to consider the people who will evaluate your work, such as **journal editors and reviewers and grant panelists**. Consider approaching members of editorial boards or authors who have published in educational journals in your area, such as the *Journal of Chemical Education* (*http://pubs.acs.org/journal/jceda8*), *Chemistry Education Research and Practice* (*http://www.rsc.org/journals-books-databases/about-journals/chemistry-education-research-practice/*), *CBE – Life Sciences Education* (*http://www.lifescied.org/*), and *Physical Review Physics Education Research* (*http://journals.aps.org/prper/*). Search the National Science Foundation grants database for individuals who have received funding for undergraduate STEM education, especially for CUREs or other undergraduate research experiences (e.g., Research Experiences for Undergraduates Sites). Grantees are likely to have collaborators or evaluators with relevant expertise.

What: Be ready to share what you have done with your CURE, how you have designed and implemented it, and any observations you have made or data you have collected to gain insight into potential outcomes. Then be ready to listen and learn. If you are interested in identifying collaborators to evaluate or study your CURE, ask for ideas of key journal articles, websites, or people doing related work. There is publicly available information on CURE assessment on the website of CUREnet (*http://curenet.cns.utexas.edu/*), a network of people and programs related to CURE instruction in the life sciences. Scientific societies are another source for information and networking as most have an education committee, members who are leaders in undergraduate STEM education, and other avenues for sharing teaching resources.

When: The time to think about assessment for publication or a grant proposal is after you have implemented your CURE at least once and ideally a few times so that logistical issues related to teaching the course don't undermine the process of assessment.

Additional Advice on Assessment of CUREs

CUREs offer special challenges for assessment. By their nature, they vary from term to term as the research questions evolve and from section to section since instructors often focus on lines of research that are relevant to their professional interests. The assessment is not about whether the research output of the CURE is going to lead to a Nobel Prize, but rather whether the course is achieving its aim of giving the students an opportunity to conduct authentic research, and in the process, learn about their field.

The four scenarios above hopefully illustrate that assessment is not monolithic. The term continuous improvement implies that every iteration of the course should be better than the last. The course improves because by paying attention to student learning, development, and success, the experience is tuned until the students consistently achieve the expected outcomes. Course assessment evolves as the audience for that assessment changes. The data needed to make an assignment better is very granular and may be of interest to you or the instructor of another CURE, but is not likely what your department chair or Dean wants to see relative to the impact of the course on students. As you plan the assessment strategy for your CURE, the list below hopefully provides advice to help you avoid some pitfalls and focus on the most critical aspects of the data you need to collect.

Flexibility: Some research-related tasks and assignments may not yield the anticipated student products the first time the assignment is given. Building time into the curriculum to provide feedback to students and allow them to revise or redo assignments will help improve their work as well as providing instructors time to edit the assignments and associated assessment tools (e.g., rubrics) without waiting for the second offering of the CURE.

Comparison studies: Beware of comparison studies between CURE and non-CURE sections, as these types of studies are complex and challenging to conduct properly. CURE versus non-CURE offerings will differ in their design in ways that may not be distinguishable using available assessments. Development of valid and reliable measures of desired outcomes requires significant time and expertise. There may be unanticipated differences between students who enroll in CURE versus non-CURE offerings that could affect the results and the sample sizes for CURE versus non-CURE offerings may not be sufficient to control for these differences statistically.

Selection bias: Students who enroll in a CURE may not represent the typical student. For example, they may differ in their standardized test scores (ACT or SAT), gender, race/ethnicity, physical abilities, or first-generation status. They also may differ in their motivation and their interest in research. The statistical methods noted above can help to control for this. CUREs that have an application process may be able to use waitlisted students or students who are selected but do not enroll (e.g., because of scheduling conflicts) as a comparison group in order to control for motivation or interest.

Start-up effects: The CURE itself is likely to differ over the years, especially early on in its development. Thus, the first cohort of students and their experience with the CURE may be substantially different than subsequent cohorts or offerings. Sometimes first cohorts are left out of these kinds of analysis in order to avoid artifacts that result from the changing nature of the CURE.

Conflation with other variables: Does your CURE stand alone or is it part of a broader, multi-part, student success initiative? In some cases, the effects may be part of the whole student success effort and not tied directly to the CURE. There are no straightforward ways to disaggregate effects unless there are students who participate in some but not all of the initiatives. In these cases, the best option may be to acknowledge this limitation[15-17] and assess the initiative as a whole.

Ethics: The review and approval of an assessment plan by an Institutional Review Board (IRB) is not needed for internal evaluation studies aimed at local improvement. It is only required if you plan to publish your results or otherwise present them publicly. For more on this, see the next scenario. However, FERPA restrictions may apply even for internal studies. Be sure to use de-identified data that cannot be tied back to individual students. Note that if student numbers are small, students may be identifiable even if you remove their names and ID numbers. The ultimate goal is to act in ways that protect student privacy and confidentiality, and IRB personnel can advise on how best to do this even if the assessment plan does not need their review (i.e., is determined to be exempt from review).

Collecting the "wrong" data: It is easy for us to make assumptions about how our students are benefiting from research experiences. For example, it may be that a month-long CURE is sufficient to pique students' interest in research, but not enough to build their confidence in their ability to be successful in science ("science self-efficacy"). Measuring the impact of this CURE on students' science self-efficacy may yield negative results (i.e., no change pre to post) and may miss the opportunity to document how students are actually benefiting (e.g., higher interest in doing a research internship). To avoid this pitfall, start by asking three simple, open-ended questions of students (as in the first scenario): (1) what did you get out of this experience? (2) what aspects of the experience helped you get that? And (3) what is at least one suggestion for improvement? Students can respond to these questions at the end of the CURE through an online survey or even on an index card. Students' responses can then guide the development of hypothesis about how and why the CURE is "working" and the design of future studies to test these hypotheses.

Collecting too much data: Sometimes faculty are so focused on not missing an opportunity to collect assessment data that they err on the side of collecting too much data to analyze meaningfully. To avoid this, prioritize one or two questions to tackle at a time and focus data collection and analysis to address these. As questions are answered and new questions emerge, develop new plans for data collection and analysis.

Working with small sample sizes: Lab courses typically have small enrollments, which may limit the number of students from whom assessment data can be collected. There are several ways to work around this issue. One option is to take advantage of the small sample size by collecting qualitative data such as student responses to open ended questions, interviews, or focus groups. These types of data are often too intensive to collect and analyze from large samples and can yield insights into how the CURE might be working (or not) for students. Another option is to collect data over multiple offerings of the CURE. This approach may require collecting other data on students, such as SAT or ACT scores, gender, and race/ethnicity, to help control for differences across years. Yet another option is to collaborate with other instructors to collect and analyze data across courses. Analyzing data collected using this approach may require using statistical models that account for the "nested" nature of the data. In other words, the analysis has to account for the fact that students' responses in one course offering may be more similar to each other than to responses from another course offering (i.e., correlated) and this must be addressed in how the data are analyzed to figure out the unique effects of the CURE per se. Consult a statistician for help if these ideas are not familiar.

Continuing to collect the same data year after year: Once faculty have spent the time and effort to carefully select assessment tools and to put the data collection and analysis methods in place, it can be hard to change plans even when the original assessment question has been answered. Assessment is like science research—it is iterative. New questions should be tackled as original questions are answered, and this will likely require using new assessment tools and methods. Avoid this pitfall by completing analysis and interpretation of assessment data in a timely fashion and using the results to inform next steps (e.g., collecting another round of the same data, writing results up for publication, developing new assessment plans).

Overburdening students with assessment: As more colleges and universities are using data to inform decision-making, students are being surveyed more and more often, leading to survey fatigue. Surveys can be quite informative, so don't discard surveys altogether. Rather, think carefully about whether you need to survey students (for what purposes? what will you do with the data?) and how to minimize the burden for students, for example by asking them to complete surveys during class time and using the minimum number of survey questions needed to address the assessment question.

Working in a vacuum: In recent years, there has been a lot of progress on undergraduate STEM assessment in general and CURE assessment in particular. Consider getting advice from or collaborating with individuals actively assessing CUREs. This approach will save time, energy, and resources and avoid a lot of frustration. When approaching a potential collaborator, remember that the most fruitful collaborations require negotiation and reciprocity. Consider how the project could build capacity and offer benefits from both sides, leading to a better learning experience for your students as well as new understanding of how to make CUREs effective.

Take-home message

Assessment does not have to be a dirty word. For scientists, assessment should be second nature. We would never dream about giving a talk or writing a paper without supporting our claims with data from our experiments. Assessment takes this same thinking into our classrooms—do we have data to determine whether we have answered our educational questions and accomplished our instructional goals? Just as in the lab, if we try to tackle a problem that is ill-defined or too broad, we make little headway. Same too with assessment. Small steps that you actually complete are more useful than grandiose plans that never get enacted. Start small with data for your own consumption on whether and how your students benefited (or not) from the experience. Then, ask for help or initiate collaborations when you need expertise that you don't have in order to move the assessment forward.

Electronic resources

NSF-2010 User Friendly Handbook for Program Evaluation: *https://www.purdue.edu/research/docs/pdf/2010NSFuser-friendlyhandbookforprojectevaluation.pdf*

Designing Performance assessment for Undergraduate Research: *http://pubs.rsc.org/en/content/articlelanding/2016/rp/c6rp00057f#!divAbstract*

Refs to CURE Specific assessments (see table in Erin E. Shortlidge and Sara E. Brownell IRB and Human Subject Page—When is Human subjects required (NIH or NSF Resource Page on when IRB is required): *https://www.nsf.gov/bfa/dias/policy/human.jsp*

CURE Survey: *https://www.grinnell.edu/academics/areas/psychology/assessments/cure-survey*

CUR documents on CUREs

CUREnet site: *http://curenet.cns.utexas.edu*

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Part III:
After

6

Resourcing, Scalability and Sustainability of CUREs

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Introduction

Once equipped with a general plan for your CURE that fits well within your institution's curricula and priorities and matches your research and educational objectives, you will need to think about how to identify and secure a number of resources to get your project started. In this chapter, we highlight five categories of resources new CURE practitioners should consider early in their planning process to position themselves for success. Later in the chapter, we will highlight successful practices from a variety of CUREs in the physical sciences to give new practitioners ideas about how to plan, implement, and sustain a CURE.

When initiating a CURE, we encourage faculty (and administrators) to consider five essential categories of resources, detailed below, and we make recommendations based on successful practices highlighted through examples.

Resource 1: A CURE community
Who can offer experiences and expertise to support you? Identify and talk to CURE "veterans" at your home institution and/or nationally; these individuals offer expertise and experience that qualify them as valuable resources to you. Although each CURE is unique, it is very enabling to recognize that you are not alone in your interest to run a CURE course, nor should you troubleshoot your course in isolation.

Resource 2: Money
This is probably one of the biggest worries for new practitioners, because we all know that research, even in the curriculum, costs money. As you start to

think about the details of your CURE, consider the financial costs. Can you petition for startup funds from internal sources (e.g., your dean or provost, a specific center at your institution, etc.)? Are there external sources that would be interested in funding startup costs, including government or private foundations? What are the ongoing costs as this CURE is sustained for multiple offerings? Will the changes you enact fit within your department's ongoing instructional budget? As will be detailed below, faculty are often successful in securing funding for their initial CURE implementations through various channels. However, it can be more challenging to secure funds for sustaining CURE programs. Consequently, we recommend that new practitioners consider this point carefully as they begin planning a new CURE course or module.

Resource 3: People
Who needs to be involved? What faculty will teach the CURE? Who will pilot the CURE exercises or experiments? Will there be TAs (graduate or undergraduate) for the CURE course/module? Will support staff be needed? What special training will any of these people need, if any?

Resource 4: Time
When will the CURE be offered? For how long? Do you have adequate time for planning, and, importantly, testing, your ideas? Will faculty receive any extra time (e.g., course releases) for CURE planning and testing? How will you allocate time for writing up and disseminating the results of your CURE? Toward the end of this chapter, we offer a potential (albeit, quite flexible) timeline for the development and implementation of a new CURE. An important recommendation here is that faculty new to teaching CUREs should allocate time for testing how the CURE activities planned will work in the hands of students. This important step will facilitate a far smoother first implementation of the CURE.

Resource 5: Facilities and infrastructure
What unusual or new space, instrumentation, or data needs are associated with your CURE? Will you need access to specific equipment or data sets? Can you secure these by agreements within your department, school, or by partnering with Centers or other institutions? How will data collected by the class be managed, checked for quality, analyzed, and shared? As examples below highlight, having more students engaged can benefit a number of research projects, but student data are only useful when they are of reliable quality and are managed carefully. This is a substantial challenge that should be considered early on in the planning stages.

This chapter largely assumes that you have already made the decision to implement a CURE for some or all of your course and now wish to consider successful strategies to get it up and running. The choices you make regarding CURE problem-selection and the amount you want to change at one time will, of course, impact how you identify and secure resources needed. These choices are discussed in other chapters and include:

- Steadily changing one part of course at a time to include CURE module(s).
- Changing an entire course to the CURE model ("whole CURE").
- Adapting CURE templates used at other institutions, including national models, to your course.

Lastly, we will address special considerations about scalability and sustainability of CUREs at the end of this chapter. Again highlighting examples of CUREs, we examine models that run as multiple sections of a given CURE, examples where multiple CUREs are offered throughout a department or campus, and examples of CUREs that leverage multi-institution networks. These larger-scale and often longer-term ideas, naturally, also encompass resource considerations. Although it is a challenge to bear in mind the longer-term view as one is just getting started with CUREs, we encourage new CURE practitioners to think about these issues early.

Resourcing examples

In this section we will look to a wide range of short examples of how faculty and institutions have found initial and sustaining resources of all five types listed above. Rather than a few detailed case studies, we endeavor to supply a broad range of micro-examples that can help you consider how you might meet initial and ongoing resource challenges in a way that fits your context and goals. Again, we are primarily focused on those looking to resource the implementation of a "whole course" CURE, though the lessons these examples give us could be applicable to other approaches as well.

Professional learning community models run the gamut from institutional to national, from tightly focused within a discipline (or even subdiscipline or research topic) to cross-disciplinary, and from highly organized to loose affiliations. What virtually all CURE practitioners have found is that having some connection to others also investing in CUREs as a pedagogy is vital. A community gives you a group of others to learn from, to share experiences with, to draw ideas from, to troubleshoot with, and from whom you can seek or to whom you can give encouragement. Most scientists do this naturally in the form of conferences and symposia, professional networks, even research group meetings! The same can apply to our teaching and research through CUREs.

On campus, Dean level offices and Centers for Teaching and Learning may provide community or at least connections to others in your institution also implementing CUREs or interested in doing so. We encourage faculty to check in with these offices first to identify potential on-campus resources; we find that even on small campuses, it can be hard to keep track of all of the innovations being made across disciplines. A variety of more or less structured affinity groups on campus may already exist, or these offices may be able to provide resources for you to start such a group with the cohort of colleagues they help you identify. At Santa Clara University, the Faculty Collaborative partners faculty development, academic technology, and assessment experts in support of new curricular changes advanced by the pedagogical literature. At Hope College, Division of Natural & Applied Science resources (frequently augmented by systemic change grants, e.g., from HHMI) have funded informal faculty lunch conversations or book discussion groups; such ventures wax and wane with faculty interest. Also at Hope College, poster sessions highlighting the range of on-campus CUREs activities have helped nurture community and give ideas to other faculty considering implementing CUREs. However, such events have generally been ad hoc, and require a faculty champion or the commitments of an external grant to the institution to make them consistent features. At Iowa State University, an ongoing Professional Learning Community of faculty teaching CUREs meets every two weeks to discuss pedagogy and practical issues, upcoming opportunities, and offers support to new CURE practitioners. Keys of the longstanding success of this program have been: 1) To have two facilitators in charge of the group; this redundancy helps when one of the facilitators has an increase in time pressures. 2) To rotate the facilitators every few years. At the two largest Freshman Research Initiatives[1,2] (University of Texas at Austin and University of Maryland at College Park), the research educators in charge of each CURE meet regularly to discuss challenges and good practices. The aforementioned groups of educators all come from a broad range of disciplines. Within a discipline, faculty at the College of New Jersey in department teams have re-worked their major's four-year curriculum to include a sequence of CUREs from freshmen to senior. The faculty who teach these courses regularly meet to coordinate objectives and suggest solutions to course challenges.

Both face-to-face and virtual external communities connect CURE practitioners with like-minded colleagues to brainstorm, collaborate, encourage, empathize, and troubleshoot. Much like we find community within our research, workshops and symposia on CUREs occur within broader professional meetings. In chemistry, these symposia have occurred at the American Chemical Society's national meetings and the Biennial Conference on Chemical Education. In biology, where CUREs are a more established pedagogy, workshops are routinely put on at a range of meetings by members of the Research Experiences in Introductory Laboratory (REIL)[3] Biology network. Thus one can build a professional network around CUREs much like one might build a professional network around organic photochemistry or particle physics. Affinity groups can also originate around small pots of money from foundations. This is exemplified by the Cottrell Scholars Collaborative funded by Research Corporation for Science Advancement, a venue to convene those interested in disseminating CUREs pedagogy more nationally. This grant has led to the creation of this book (among other things). Larger funding sources may include components that convene practitioners for face-to-face meetings. Finally, if you choose to join a large multi-institutional CURE professional community around a national project, the CURE is "ready made." These include such examples as Harry Gray's "Solar Army"[4] (run through Caltech's NSF Center for Chemical Innovation in Solar Fuels)[5], SENCER's Great Lakes Research Initiative[6], HHMI's SEA-PHAGES[7] program, the Distributed Drug Discovery[8] project coordinated by IUPUI, and any of a variety of other citizen science projects. Some of these multi-institutional CUREs build community through annual (or less frequent) gatherings, including SEA-PHAGES, Distributed Drug Discovery, Small Worlds Initiative[9], and the Vertically Integrated Projects program initiated by Georgia Tech.[10]

Online repositories and virtual communities are also rich sources of support for CURE practitioners. Meetings initiated by investigators supported by a grant may in turn spawn online community; this was the case with the cohort of Howard Hughes Medical Institutes "Capstone Grant" recipients. Online communities of CURE practitioners may be limited to those from a specific network of programs or grants or more nationally open. These virtual communities may exist on ubiquitous social or professional media platforms like Facebook or LinkedIn, or on more specifically tailored tools like AAAS's Trellis platform. An additional example in this vein is Zooniverse,[11] an online community for faculty using citizen-science tools within their course. National repositories of information on CUREs can be found in resources like CUREnet[12], dedicated specifically to this pedagogy, or within broader science education repositories like SENCER[13] (Science Education for New Civic Engagements and Responsibilities, an initiative of the National Center for Science and Civic Engagement) or SERC[14] (Science Education Resource Center at Carleton College). Disciplinary or subdisciplinary communities or repositories, while not necessarily revolving around CUREs, may nevertheless be a source of information on CUREs and networking with people within your specific discipline or research focus. Examples of these include nanoHUB[15] or IONiC VIPEr (the Interactive Online Network of Inorganic Chemists' Virtual Inorganic Pedagogical Electronic Resource).[16]

Finally, CUREs themselves provide a professional learning community of sorts for the students, and some programs are very intentional about fostering these communities. The CURE cohort may also take other courses (such as a first year seminar course) together, for example. In certain cases, institutions have gone so far as to institute living-learning communities in which CURE participants intentionally live together, and the CURE team includes dormitory resident assistants as well as faculty, teaching assistants, etc.
The Hope College Day One[17] initiative is but one example of this, and similar initiatives exist at much larger institutions, such as Iowa State.

Money both to *initiate* and *sustain* your CURE can likewise come from a variety of internal and external sources. At least some financial investment is required at the start or early on in a CURE to account for the curricular change. Initial funding may provide the salary/stipend or release time required for planning, designing, testing, and first implementation. There may be instrumentation or other infrastructure required. There may be increased staffing necessary at a variety of levels (faculty, professional/support staff, and or teaching assistants) relative to more traditional courses, either for first implementation or indefinitely. Likewise there may be permanent or temporarily increased consumables costs. All of these need to be considered, and funding sought as necessary.

Funding to *initiate* a CURE can come from within or from outside of the institution. Frequently a dean or department is willing to consent to a time-limited commitment of resources to establish a CURE. These funds may come from discretionary resources or specific resources allocated via an office or administrator for teaching and/or research. An advantage of applying for funding for a CURE is that the investigator can conceivably apply for funds allocated to support *either* advancing scholarship *or* pedagogical development (or both!); there may be multiple funding opportunities for project initiation. The line between internal and external funds blurs a bit when it comes to grants made to an institution for improving STEM pedagogy, such as HHMI's institutional grants, or Council of Undergraduate Research's recently announced CUR Transformations Project[18] (itself in turn funded by NSF). Finally external funds can come in a variety of guises. There are grants specifically for pedagogical change, such as NSF's former TUES or current IUSE grants. These seem most common for CUREs that are most broadly implemented, and often require an institutional commitment to institutionalize (and absorb the ongoing costs associated with) the resulting CUREs. But many practitioners have found initial funding for their CUREs in the form of individual PI research grants, whether with an explicit educational component (e.g., NSF CAREER) or as "broader impacts" activities within standard grants. Such funding may be particularly (but not exclusively) relevant to those CUREs most tied to a single PI's research program. A subset of such individual investigator grants include "supplements" directly or indirectly supporting the CURE (such as a Research Opportunity Award on an NSF grant, which funds a PUI faculty member to collaborate with a Research University faculty member.) Alternatively, sub-awards from a large multi-institution or "center" grant from NSF or other funding agencies are a possible option, including for those joining some national or multi-institutional CUREs.

To support ongoing operational costs of a CURE, a variety of approaches have been successful. Some practitioners have been able to design CUREs such that the net financial costs are comparable to the more traditional courses they replace and thus are inherently and seamlessly absorbed by the institution, e.g. upper-level CUREs at Iowa State University. Sustaining funds are necessary when the CURE requires higher staffing or consumables than the course it replaces (or serves as an alternative to), and can also be important if one is to implement or sustain a local "community of practice" that didn't exist previously. Institutions may be less likely to commit to these ongoing costs from the start, but may be willing to absorb modest cost increases in return for demonstrated benefits of the pedagogical change. This can be a smart investment for a university: enhanced retention and graduation rates,[19,20] both reported outcomes of CURE models, offer the potential to recoup expenditures on CUREs.[21] Although national data support these contentions, there may be nothing as effective as your own assessment data coupled with local anecdotes to convince your administration of the value added by your CURE. Another model that is effective at some institutions to raise sustaining funds is to implement laboratory fees that offset additional costs in a CURE. However, such fees may have a disproportionate, negative impact on some underrepresented populations of students; because these are often students we want to reach with CUREs, this option should be exercised with some degree of caution. Some universities, e.g. Iowa State, have also been able to leverage institutional funds available to pay undergraduate peer mentors to help staff the CUREs. While foundations and funding agencies may be unlikely to fund a CURE indefinitely, there are examples (analogous to how we fund ongoing research endeavors with a succession of grants) where increased staffing for a CURE can be funded as line items within individual faculty research grants as the nature of the CURE is to advance actual research in a classroom setting. To the extent that the research described in a proposal can be advanced in part through a CURE, that grant can contribute to the costs of the CURE, either in consumables or even in staffing. For example, UT Austin's Freshman Research Initiative relies on postdoctoral Research Educators whose salaries are supplied, at least in large part, by individual PI research grants. Partnering with institutional advancement or development offices can also be an effective way to solicit donors specifically to support CUREs and other pedagogies of engagement. Industry partners have provided valuable continuing support to the Vertically Integrated Projects Consortium[10] (led by Georgia Tech and University of Strathclyde) through annual giving or endowment. Hope College's Day One Watershed Project[22] is an example in which particular start-up costs were funded directly, and an endowment for ongoing staffing costs was provided by an industry donor. Likewise community non-profit partners may help sustain ongoing CUREs relevant to their mission.

People are an important resource to consider for your CURE as well. Individual faculty or small teams are required from the start, from visioning to planning to testing to implementation. Senior partners in teaching and learning may be required, either initially or indefinitely. Some STEM faculty have partnered with their faculty colleagues in education, or drawn on Center for Teaching and Learning staff to aid in course design, assessment, etc. It will also likely be necessary to involve "students" (either actual students in a pilot course, or graduate or undergraduate TAs, or research students) in testing the feasibility of your ideas for your CURE. These students may then come to serve as graduate TAs (gTAs) or undergraduate TAs (uTAs) in the actual CURE implementation. A creative faculty member at Smith College used high school girls in a science camp setting to test overall feasibility and specific procedures in a freshman level CURE on biogeochemical cycling planned for the following year!

Like any lab course, graduate (or undergraduate) teaching assistants (gTAs and uTAs) are likely to do a large share of the work before, during, and after the CURE, including supervising students. Example responsibilities of TAs include: determining experimental setups and protocols, prepping solutions, equipment or instrumentation for the experiments, editing and updating lab manuals (including maintaining records during execution for future modifications), coordinating uTAs, curating and integrating CURE research results or data, interfacing with administrators to recruit students for and to promote the CURE, assisting with budgeting and ordering. Because of this long list of potential responsibilities, more highly trained TAs may be required for a CURE. The responsibility for this training may fall to the faculty member, a Center for Teaching and Learning, and/or an institutional TA training program, and this may evolve with time. Another option is to form a professional learning community of the TAs,[23] so that they can share best practices and suggest solutions. Not only may more highly trained TAs be required, but more of them are likely necessary. Closer supervision of students, especially as not everyone in the CURE course is likely to be doing exactly the same thing, is likely important. The more divergent the project(s) within the CURE, the more TA support may be required. Thus even programs with gTAs frequently supplement with uTAs in their CUREs.

Some "lead" TA or other hierarchical structure is frequently employed. Postdoctoral scholars or instructional faculty are employed for this purpose at some institutions. The University of Texas's Freshman Research Initiative and the University of Maryland FIRE programs employ postdoctoral "Research Educators" to keep their large programming running well. Hope College's Day One program employs postbaccalaureate science students who contribute many of the things postdocs do in some research university CUREs—they work in close consultation with faculty to determine experimental details for the CURE, sync CURE-generated results with those from the PI's independent laboratory, coordinate uTAs, and may themselves act as TAs or do some practical lab instruction. One interesting alternative to gTAs or uTAs is to engage more senior students in the course a second (or more) time in a multi-cycle or Vertically Integrated Project approach like that implemented at Georgia Tech and others in their consortium. Following this model, responsibilities increase in each student's subsequent enrollment in the course and more senior students serve as mentors or peer leaders to more junior students. The course ends up being about 20 students each year, albeit built with 3-4 cohorts of students. The model extends traditional research experiences and leverages a single CURE to impact multiple generations of students. This structure parallels that of a traditional independent faculty research laboratory more closely. Finally, several programs note increasing workload for support personnel (e.g., stockroom curators, lab managers, instrumentation technicians, facility managers, lab directors, librarians) related to CUREs. It is important to engage with these key support persons early in the process and regularly during implementation as well.

Lastly, while it may initially seem that the project lead faculty on the CURE is the one constant, eventually you will be faced with succession planning. Whether this is for when you retire, or take a sabbatical, or desire or are needed to teach elsewhere in the curriculum, someone else needs to be able to take over. Your CURE is only truly sustainable when it can outlive your own frequent personal engagement in the course. Depending on how the research question(s) of your CURE are structured, your CURE may also have a fixed end, once the question is answered and the paper published. This may require you to prototype a new research topic for your CURE or extend the previous research.

Time is another important consideration from the outset, as there are time implications to creating, implementing, sustaining, and reporting outcomes from a CURE. Time is also closely linked to project selection.

For the lead faculty member, the time investment in your CURE begins when you first begin to consider moving from a more traditional lab to a CURE. While we have garnered few if any examples of faculty receiving explicit release time for planning, feasibility testing, or first implementation, this is certainly a resourcing conversation you could have with your dean or department chair. Some faculty report using an institution's January Term or May Term to pilot a CURE or test aspects of its implementation planned for a later semester-long course. A related approach that has been successful at Santa Clara University and at Iowa State University is to pilot CURE content with a smaller group of students, for example as an honors laboratory section or a laboratory section aimed only at majors. Successful components have then been scaled to higher enrollment courses. At times, funding has been available for small summer stipends both at Hope College and Santa Clara University for faculty developing new courses—at one point in time this included CUREs, particularly those convergent or interdisciplinary in nature. Funds might also be available for a STEM and/or education graduate student to develop and test the CURE. Similarly there are courses in which team-teaching across departments is counted as the full number of contact hours for participating faculty from each department, rather than splitting the load between them. This is most likely to be allowed in early implementation or when meeting a specific institutional priority; longer term impacts of this model on faculty load and teaching capacity could be prohibitive. But this can nevertheless prove effective, as in subsequent iterations of a long-running CURE it is more feasible for the faculty members to only be present and engaged in the time for which they are specifically given credit.

The College of New Jersey (TCNJ) stands out as a particularly progressive curricular example in the area of CUREs, and both faculty and student time have been addressed accordingly. Courses at TCNJ include more authentic, in-depth work such as CUREs. TCNJ has reduced the number of courses a student takes each semester as well as the number of courses a faculty member teaches. The "load" for faculty also includes mentoring and advising, as well as course development. In parallel, TCNJ added to their promotion and tenure expectations the integration of teaching and scholarship.

Teaching a CURE will frequently require extra time from a faculty member for a variety of reasons: CUREs may not fit as neatly into class periods, there may be more individualized need for student help, there may be increased TA or other staffing to supervise, and more trouble-shooting is generally required of anything approximating authentic research than traditional "cookie-cutter" labs. Nonetheless, there are ways to manage this discussed below. Moreover, many faculty report that the "extra" time is not really zero sum as CUREs enable faculty to leverage their teaching time (and teaching dollars) to advance their research.

When it comes to managing faculty time commitment in the CURE, project choice is important, as is appropriate staffing. Having students work in teams minimizes the number of individual projects, and even having students replicate one another's experiments offers an important lesson in experimental reproducibility as well as other pedagogical benefits. Especially for larger CUREs, the more closely related the projects, the less demanding they can be on faculty/staff time. In particular it can be advantageous to have multiple systems or examples studied by the same techniques or using the same protocols, rather than the same system studied by a variety of techniques or protocols. Participation in a larger multi-institutional CURE has received mixed reports on how this structure impacts faculty time. Some faculty have found that there is decreased time commitment, especially at startup, albeit at the expense of some independence. Others note that participation in the consortia brings new commitments over time.

Faculty teaching CUREs are also encouraged to think about delegating some communications to supporting staff where appropriate to save some time. The Texas FRI program has already given us one model to save faculty time in the lab by paying postdoctoral research educators to maintain "open lab" style drop-in laboratories. Although this has infrastructure implications as well, some traditional labs already employ "open lab" hours, suggesting that this may not be unmanageable. Hope's Day One program uses post-baccalaureate facilitators to insulate the faculty member from some additional workload by tasking the post-baccalaureate with managing some student and TA needs. Iowa State's CUREs meet during regularly scheduled lab meeting times, and trained uTAs are the first point of contact with troubleshooting and requests for help. Also at Iowa State, staff scientists from a large research center provide community, encouragement, judging, and feedback to student CURE participants, rather than faculty. Some faculty report using communication methods such as Moodles, discussion boards, Wikis, etc., to help minimize individual emails and office visits. We note that in addition to saving some of the time demands on faculty who lead a CURE, many of these strategies simultaneously contribute to a rich community of students, TAs, and others in a CURE that has its own advantages.

Despite all best efforts and planning, faculty teaching CUREs should recognize that the nature of research means that unexpected and even urgent needs are likely to arise and demand immediate attention and time. To take an example, a trained instrument technician may be out sick on the day your students were to use that instrument. On the day of the lab, for which you and your students were prepared, you will need to adjust the day's laboratory experience, and likely, your plans for subsequent laboratory meetings. In a short period of time, you'll need to evaluate such questions as: 1) Might other techniques be available and useful? 2) Is this experiment necessary for the progress of the research? For the student learning goals? 3) Could you acquire the data outside of class time either personally or enlisting a TA or similar, then disseminate to the students? 4) How will this impact subsequent experiments planned? We expect these issues to arise in research, and we cope with them regularly. When the research overlaps with a scheduled course time (and syllabus), the challenges of dealing with these urgent issues are amplified, and CURE instructors should be aware that time demands frequently cannot be perfectly estimated.

It is also important for faculty teaching (or planning to teach) CUREs to acknowledge that they will ultimately spend time reporting out the outcomes of their CURE. Certainly any internal or external funding is likely to come with the expectation that results will be reported back to the funder. But it is equally important to publish both the research outcomes and the educational outcomes of the CURE to a broader audience, as appropriate. For example, combinatorial organic chemistry experiments based on the Distributed Drug Discovery program have been published recently in the

Journal of Chemical Education.[24,25] Depending on course design, large sets of data and experimental results, typically first analyzed in the CURE by novice scientists, may need substantial attention from a skilled (i.e., faculty, doctoral, or postdoctoral) researcher to parse into publishable work. That said, there are a number of papers reporting research outcomes from CUREs. For instance the University of Texas, Austin FRI has a web list of several dozen peer-reviewed papers with CURE student coauthors to come from their work.[26] The Hope College Organic Chemistry II Laboratory elective Independent Synthesis Projects have over the past 15 years contributed materials or preliminary results (though not generally at a coauthorship level) to at least 18 peer-reviewed papers and 4 funded grant proposals.[27] Similar examples from both local and national CUREs, at both small colleges and large research universities, abound. Contributions to the science education community about your CURE via publications and/or professional presentations are an essential way to reinvest in the CURE community. We encourage all faculty to report out, locally (on-campus and regionally) and nationally, to share the successes of their CURE implementation as well as the lessons they have learned in the process.

Faculty and staff time are not the only important time consideration. The time of students is also a resource. We all know research can expand indefinitely in ways that traditional laboratory experiments are far less prone to do. While students may be able to put slightly more time and effort into a course that also does double-duty of providing them an undergraduate research experience, and have demonstrated a willingness to do so, you must be mindful of their time. This is especially important to students who must also work outside school (often far more hours than we realize) to support themselves or their families. Expectations must match the credit load of the course, and setting modest or incremental research goals will help. Moreover the course must "count" toward students' major program or degree in a meaningful way. This is best accomplished when the CURE either completely replaces or acts as a direct substitute or alternative to an existing course, rather than as a simple elective. This is also relevant to keeping department staffing loads—by faculty, TAs, and others—as close to net zero sum as possible.

As we seek to diversify STEM with respect to gender, race/ethnicity, socioeconomic status, and first generation college students, these considerations of student time become increasingly important. There are data[28] on the additional outside work first generation and underrepresented minority students commit to and how this poses time and place constraints for uncompensated research experiences, summer bridge programs, or free elective courses, under the (sometimes mistaken) impression that it will lead to increased cost (thus a caveat about using increased lab fees to fund CUREs) or time-to-degree.[29] However there is at least some evidence that participation in at least one specific CURE can lead not only to increased retention and other good pedagogical outcome, but even to shorter overall time-to-degree!

Facilities and infrastructure needs of your CURE can differ from those of "traditional" lab courses, creating special demands, often for space, special equipment, and instrumentation.

We highlight here a few creative solutions identified by some faculty teaching these courses. A common approach used in a number of CUREs relies on students extracting and analyzing data mined from publicly available databases.[30-35] We have listed a wide variety of these below. These databases span a wide variety of subdisciplines across the physical and life sciences. Use of these resources enables the incorporations of authentic, free data into student coursework.

Overview: *http://esa.org/fed/wp-content/uploads/2012/09/FED-Webinar2011-Overview.pdf*

All disciplines: *http://sciencehackday.pbworks.com/w/page/24500475/Datasets*

Zooniverse: *https://www.zooniverse.org/*

Your state's Department of Natural Resources, e.g.: *http://www.iowadnr.gov/Environmental-Protection/Water-Quality/Water-Monitoring/IOWATER,*

Geological surveys, satellite images, ice-mass, sea-levels, earthquakes and other geo-data: *http://serc.carleton.edu/getsi/index.html*

IRIS with earthquake data: https://www.iris.edu/hq/

NOAA view with weather and ocean data: *http://www.nnvl.noaa.gov/view/*

Weather data, based at ISU: *http://mesonet.agron.iastate.edu/*

Geo Data site of USGS: *http://cida.usgs.gov/gdp/*

Google Earth—for landscape/terrain studies: *https://www.google.com/earth/*

Moon and Mars: *http://www.google.com/earth/explore/showcase/mars.html*

http://www.earthscope.org/

Collaborative Drug Discovery (CDD): *https://www.collaborativedrug.com/*

Genetic sequencing data: *http://lycofs01.lycoming.edu/~gcat-seek/curriculum.html*

DNA Subway: *http://dnasubway.iplantcollaborative.org/*

Genome Solver: *http://genomesolver.org/*

Ecology: *https://ecologicaldata.org/find-data*

Ecology on global scale: *http://www.spicynodes.org a/9b01388572f487d53540e53cfdf09c51*

Interdisciplinary Earth Data Alliance: *http://www.iedadata.org/*

Integrated Microbial Genomes-IMG: *http://img.jgi.doe.gov/*

Plant/Eukaryotic and Microbial Systems Resource: *http://www.metnetdb.org/PMR/*

Social science: *http://www.icpsr.umich.edu/icpsrweb/content/ICPSR/partners/index.html*

Other CUREs have found successes (and cost economies) by using a "campus as lab" model.[36,37] A common approach for many CURE laboratories is to gather samples for course-specific analysis from nearby sources. These might be soil samples for evaluation of contaminant concentrations in an analytical chemistry laboratory or geology samples to be studied. Another cost-efficient idea has been to use data generated on campus in student projects. For example, a course at Cal Poly-San Luis Obispo draws data from buildings certified on campus by LEED (Leadership in Energy and Environmental Design). Part of the design of these buildings entails a data-gathering function, and CURE student projects have been designed to use these data to answer specific research questions about building function.

When specialized instrumentation or services are needed to support a CURE, it can be possible to partner with another organization or a faculty member at the same or at a different institution to access this resource remotely rather than develop the expertise and/or absorb this cost "in house." For example, some organic chemistry CUREs engage students in the preparation of novel, potentially biologically active compounds. These synthetic products are evaluated variously for biological activities. These evaluations take place either in the laboratory of the faculty instructor, in the laboratory of another faculty member at the same institution, at a different institution, in the course of a biology CURE, or at an external institution that offers free services. The last of these is showcased by the Community for Open Antimicrobial Drug Discovery (CO-ADD),[38] a project that will receive and evaluate compounds for their ability to inhibit bacterial growth. Another similar model employed in CUREs involves accessing advanced instrumentation remotely. Geology laboratory courses at the University of South Florida and other nearby institutions have probed samples by remotely controlling instrumentation at the Florida Center for Analytical Electron Microscopy housed at Florida International University.[39] Similar remote instrumentation ideas have been implemented at varied programs under the CASPIE (Center for Authentic Science Practice in Education) program umbrella.[29] Lastly, often CUREs will in themselves generate large quantities of experimental data and/or physical products (e.g., compounds, materials, devices), and identifying resources to organize, store, and share these products can be an added challenge for CURE practitioners. For example, combinatorial organic chemistry laboratory experiments under the Distributed Drug Discovery (D3) model at Santa Clara University, IUPUI, and other institutions generate dozens to a hundred or more new compounds in each laboratory iteration. Critical information about chemical reactivity can be gleaned from systematic analyses of students' reaction yields and purities, but this information must be carefully collected, organized, and curated. One strategy to standardize format, share with select constituencies, and to archive data is to have students enter data into forms using learning management software platforms (e.g., Blackboard or similar), Google forms, or similar. Related, physical or virtual outcomes from the course can in some instances be publicly shared. In the D3 project example above, structures of compounds prepared are archived in a publicly accessible database at Collaborative Drug Discovery (CDD)[40]; this in turn could be mined by other researchers for use in their own work. Physical compounds prepared in a CURE can also be shared. Many research universities also maintain compound libraries for high-throughput screening campaigns or similar; partnering with one of these screening centers is another way to disseminate physical CURE products.

Although identifying and securing these many resources to support your CURE likely seems like a daunting task at the outset, we again remind new and aspiring practitioners that there is a wide community of CURE "veterans" who can empathize, and, importantly, share expertise. Most CURE practitioners assert that the time and effort invested is worth it given the many positive outcomes of teaching a CURE for both the student learning and the faculty research project. Even when research projects are unsuccessful, CURE courses and modules are highly effective inquiry exercises. Moreover, there is substantial literature[41] that documents the impact of CUREs: to promote student learning in the physical sciences, to train students in the scientific habits of mind, and strengthen creative problem solving. Given both the effort and the learning experience of teaching CUREs for faculty, students, TAs and others, we reiterate our strong encouragement that faculty disseminate their work on these projects, including the unique resourcing solutions that work for them. Sharing both successes and challenges within the community helps all of us develop and refine CUREs.

Timeline

On the next page is the beginning of a guide to a timeline to consider for several key resource items, in the form of tables sorted by the preparation phases and execution phases of a CURE: early timeframe, including visioning, planning, and feasibility tests (Table 1), the time just before and following the first implementation (Table 2), and long-term considerations (Table 3). There are likely many variations and circumstances that could either accelerate or slow down the timeline outlined below, particularly in the first two tables. For example, considerable time may be spent in visioning and pre-planning before even committing to conduct the first feasibility test or pilot implementation. We also note that this timeline is intentionally "resource" centric.

Many other aspects of setting up a CURE not included in these tables will be occurring at the same time, (e.g., selecting a project, thinking about assessment, etc.). Moreover, CUREs are ideally planned as sustainable endeavors at your institution; these courses can be led by other faculty individually and/or in aggregate and can be supported sustainably in some fashion (Table 3). These considerations are particularly important should your course reach larger scales, as detailed in the next section.

Table 1: Early timeframe planning for CURE resources

	Visioning	**Planning**	**Feasibility test**
Resource	*9-12 months before*	*6-9 months before*	*6 months before*
Community	Identify other CUREs on campus or similar CUREs at other institutions	Get feedback during design phase	
	Other campus resources (teaching centers, etc)		
Finances	Have conversations with Dean Chair: your vision, goals & scale align as far as possible with institution values & leadership vision Identify sources of funds for startup costs & request budget How will this likely be included in curriculum, hence increase the chance operational funding could be sustained	Secure startup funds	Sketch ongoing costs Track the costs of the feasibility test
People Faculty	Build a team or go solo the first time?		
People TA			Lead TA should be involved in pre-student feasibility test
People Staff		Have conversations with staff, get their input	Staff involved in pre-student feasibility test
Time	Negotiate possible time release (for planning/testing)	How will it count for faculty? (Overload? leverage teaching for research?)	Estimate how much faculty/staff time will be required on an ongoing basis
Facilities & Infrastructure	Plan your space needs and identify possible space	Identify instrumentation needs, data source, connect with national models, etc.	

Table 2: Timeframe before and following first implementation

	Quiet before the storm	**1st implementation**	**2nd-3rd implementation**
Resource	*3 months before*		
Community	Get feedback from others after feasibility test	Use community as sounding board, engagement Build a community of TAs	Report back out locally
Finances			Conversations with Dean Chair on ongoing costs
		Track costs Include a curriculum or run as test for first time	Look for efficiencies Include a curriculum
People Faculty			Report back to colleagues, build excitement / potential collaborators or successors
People TA	Identify specific TAs, consider overstaffing on first implementation	JITT TA training, tap into community resources if possible	Add in peer mentors, uTAs
People Staff		Conduct regular meetings of staff, TAs, faculty	
Time		Quantify time required of faculty, TAs, support staff and students Make clear expectations of student time commitment	Search for time efficiencies Reassess student time on task
Facilities & Infrastructure	Revise based on feasibility test		Reassess adequacy of space, instrumentation, data sets

Table 3: Long-term CURE resource planning considerations

Resource	**Long-term**
Community	Report back out nationally
Finances	Move to continuous funding model Assess no net direct cost increase, or else justify additional funding
People Faculty	Explicit succession planning, reserve time for startup process for next faculty
People TA	Self-sustaining training model, contribute back to community
People Staff	Assess no net staff increase, or else justify additional staffing
Time	Assess no net increase or justify either multiple TA or one semester counts for full year Adjust credit load or workload to sustainable level

Scalability: some ideas to consider

To increase the chance of success, most CURE projects start small. This section describes a few possible paths for reaching a larger number of students. The main takeaway of this section is that we encourage new CURE practitioners to consider how to grow or connect with other CUREs during the process of designing the CURE. The advantages of growing in any one of the ways suggested below will allow your course to benefit a larger number of students (and faculty).

Your institution's core values are good guideposts as you plan what scalability directions are more likely to succeed. For example, if your college has a mission of open access, then your scaling plan could focus on providing early opportunities for authentic projects as first year students. If your mission includes preparing for professional and graduate schools then the scaling could focus on CUREs at the sophomore and junior level. Scaling may also be more viable if the topics of CUREs align with the mission (e.g., community service or the Land Grant mission of applying knowledge).

Scaling may manifest differently on different campuses, but there will likely be three main models: 1) CUREs that contain multiple sections in large enrollment courses, 2) multiple CUREs within a department or campus, or 3) templated CUREs that span multiple institutions.

CUREs have been successfully implemented with multiple sections. Two examples include Hope College's Organic II Lab Independent Synthesis Projects and Iowa State University's genetics CURE. These CUREs develop strong community, both for TAs and students. They also bring economies of scale for operational costs. A larger sample of data collected from formative learning assessments will lead to smaller statistical uncertainties in data used to make decisions on how to improve the CURE. Large courses can require a considerable amount of faculty time. As such, it is important to consider delegating tasks. An effective course structure directs faculty expertise toward supporting the TAs and staff, rather than directly working with students. A key challenge with multiple-section CUREs is the importance of project selection. It is critical that students are able to make progress on their research topic, while simultaneously keeping a manageable workload for the instructional and prep staff, including data collection and analysis. In these cases, it is vital that the staff and any other key stakeholders whose work will be impacted are involved in the early design stages and testing of multiple-section CUREs.

The second model of scaling is to connect multiple CUREs within a department or campus. A leading example is the College of New Jersey where extensive discussions and planning have taken place on how students build skills and knowledge by participating in CUREs throughout their time at college. Deliberate planning can address how integrated experiences can make a non-linear impact on students. Students who participate in multiple, integrated CUREs within a department or campus have time to develop their technical competency, their confidence and self-efficacy, and build their identities as scientists. From a practical point of view, multiple CUREs provide the opportunity to build community among both students and faculty. There are also potential economies through shared, centralized assessment, recognition of faculty time inputs, and support for professional development of instructional staff.

The third model for scaling is to be part of templated or multi-institution CUREs. The most direct benefit is the assistance and support you receive during your first implementations. Over time, by participating in these CUREs you strengthen the national community and hence impact education on a scale larger than the students on your campus. There are several multi-institution CUREs including:

SeaPhages: *http://seaphages.org/*

Small World Initiative: *http://www.smallworldinitiative.org/*

The Solar Army: *http://thesolararmy.org/*

Vertically Integrated Project: *http://www.vip.gatech.edu/*

Distributed Drug Discovery (D3): *http://d3.iupui.edu/*

A related option to consider is smaller regional collaboration between institutions; over time these can, in some cases, expand.

Concluding thoughts

We have given you a lot to think about and plan for in this chapter—we recognize that it may seem overwhelming! We all know that it is usually quite helpful to think ahead and do our best to plan. But, CUREs are research, and we know a few fundamental truths about doing research. First, research is unpredictable; even the most careful plans still do not always go the way we think they will. Also, research should be fun (or at least engaging) for most faculty, students, and other staff involved, making the tough parts (including, perhaps, the planning) worthwhile in the end. Lastly, research allows us to be part of an exciting community of scientists, and we find this rewarding. It's equally rewarding to be a part of a new community, the CUREs faculty community, and to introduce students, TAs, and others to it as well. So, even if you can't stomach all the planning and long-term thinking we advocate here, we encourage you to commit to the CURE for at least one "run" and go for it! We look forward to hearing how it goes for you!

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7

Creating and Sustaining Change in Your Institution

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Executive summary

CUREs, inquiry-based laboratories, and other research-related activities are being incorporated into a range of courses, in a variety of programs, at all types of institutions. Knowing who has initiated these curricular changes, why, and what success looks like from various perspectives can position us to better articulate to others why incorporating research and inquiry-based experiences into courses is important and worthy of support. To successfully expand our efforts, we need to consider what conditions are required to foster sustainable change and be able to guide others through the process of thinking about, planning, implementing and assessing things differently. Reflecting on a series of questions can help us to craft value propositions, which foster buy-in at departmental, institutional, and national levels. Understanding the process of change, the steps it entails, and the challenges we will face along the way will prepare us to sustain our efforts and accelerate the momentum toward a research-rich curriculum.

Being part of a bigger picture

There is increasing national pressure being placed on colleges and universities, and specifically on STEM departments, to encourage their faculty to utilize evidence-based teaching practices in the classes they teach.[1] Integrating research into science curricula via CUREs, inquiry-based laboratories, and other related activities offers one effective way to employ such evidence-based practices in your teaching.[2] Whether you are just beginning to consider incorporating research into your curricula, or you are building upon series of previous successes you have had in this arena, you are part of a broader community working to improve student experiences and enhance learning outcomes. While change can begin with a single faculty member choosing to do things differently, knowing the contexts, goals, and motivations of others in your department, across your institution, and at the national level can help you succeed and leverage your investment of time, effort, and resources.

Within an institution, the departmental level is the most immediate context to consider. It is generally at this level that decisions are made regarding teaching assignments and allocation of resources. Aligning your efforts with departmental goals will help build buy-in from departmental leadership and other faculty who are crucial to the design and implementation of research-based curricula. Highlighting related activities in other departments can also motivate change and provide models from which to draw inspiration. Tapping into the expertise of colleagues and leveraging the strengths of your department will also foster your success.

The institutional level encompasses a broader context. Working at this level may provide access to greater resources and enable broader change through coordination of multiple departmental efforts. However, the key stakeholders at this level are greater in number, further increasing the importance of buy-in. Highlighting the connection between your efforts, the overall institutional teaching mission, and other initiatives aimed at improving teaching on your campus can motivate support at the institutional level.

At the national level, your efforts are supported by reports calling for greater undergraduate participation in research, as well as recognition of CUREs and inquiry-based laboratories as a superior alternative to prescriptive lab curricula.[1,2] The recognition that such high-impact educational practices[3] will enhance STEM literacy and the preparation of a diverse STEM workforce can be used to motivate change at all levels within your institution. Several resources are also available at the national level to support faculty in the process of incorporating research into the science curriculum.

Building buy-in

As you incorporate research into the curriculum, you will likely need the support of others. Given the diversity of departmental and institutional contexts and cultures, there is relatively little prescriptive advice that can be applied universally. Thus, the following sections guide you through a series of reflections to determine the most important considerations and most powerful value propositions for your unique setting. Understanding both your perspective regarding the benefits of the changes and the potential value to the stakeholders around you can help build buy-in. Considering other perspectives will also help you to identify challenges that could impede your plans and strategies to overcome these challenges. Thus, we encourage readers to consider the questions in all of the sections below, not just those that most closely align with their current position. If questions and potential responses do not apply, modify or replace them. Each section concludes with a few "tangible tips" that are applicable across many institutional contexts.

Building value propositions for faculty members

Use these questions and potential responses to help think through what must be considered by faculty members and what will motivate and prepare them. The goal is to gain the faculty member perspective, not necessarily to answer all the questions. Modify or replace those that are not appropriate.

What is your context?

- You want to try something new with your teaching
- Your department, college, or university is encouraging this practice
- You want to expand your research productivity
- You want to explore new lines of research or start new collaborations

1 *Where are you on your career path?*

- Assistant professor
- Associate professor
- Full professor
- Lecture track faculty
- Adjunct faculty

2 *How will this fit into departmental or institutional activities?*

- You will be the first person to consider implementing a CURE
- Faculty have talked about CUREs, but your department/institute has yet to implement one
- Several faculty in your department/institute teach CUREs

What are the benefits and challenges of incorporating research into the curriculum?

1 *How could this advance your career or level of job satisfaction?*

- Expand your capacity for research
- Improve your efficacy as an instructor
- Help you establish a reputation as an innovator in education at your institute
- Have fun exploring something new

2 *What are the challenges you might face?*

- Students might not like the ambiguity and failure that comes with research
- The time spent developing the curriculum might detract from

other activities

Cost may be an institutional barrier to implementation

Need to find a research problem that is appropriate to the CURE format

This might impact tenure review

If you want to initiate change, what levers do you have?

1 *With whom do you need to talk?*

Do you have trusted colleagues you can talk to early in the process?

Do you need to talk to colleagues who might oppose your plans?

With whom do you need to talk to secure the resources needed?

2 *Who do you need to have on board?*

Who decides teaching assignments in your department?

Who allocates budget for lab courses?

Who allocates teaching assistant positions?

3 *What is the value proposition to your students?*

What additional skills will they gain compared to the current curriculum?

How will this help prepare them for success in their future careers?

Will this research experience help them secure a job or admission to graduate or professional degree programs?

4 *What is the value proposition to your colleagues and department?*

How will this impact the skill level of students graduating from your department?

How will this impact the teaching reputation of your department?

How will this impact the research reputation of your department?

Will your efforts at curriculum reform make it easier for others to follow?

5 *What is the value proposition to your college and institution?*

How will your course increase the future success of students at your institution?

How will student satisfaction be improved?

Will your course significantly increase capacity for undergraduate research at your institution?

Will your efforts at innovation bring positive publicity to the institution?

Tangible tips

- Get early advice from a trusted colleague.
- Be open with your colleagues about your plans and motivation for curriculum reform.
- Don’t reinvent the wheel—learn what others have done to implement CUREs and don’t be afraid to emulate successful models.

5 On the first day of class, explain to students the nature of the CURE and how they can benefit from the course. Reassure them that experiments often don't work in authentic research and that this will not impact their grade.

Building value propositions for department chairs

Use these questions and potential responses to help think through what must be considered by department chairs and what will motivate and prepare them. The goal is to gain the department chair perspective, not necessarily to answer all the questions. Modify or replace those that are not appropriate.

What is your context?

1 At what type of institution are you?

Research intensive

Primarily undergraduate

Comprehensive

Community college

2 To what degree and in what ways is undergraduate research currently incorporated in your department?

Most undergraduate students find traditional lab internships

Some undergraduate students find lab internships, but demand exceeds availability

There are very few opportunities for lab internships

Students do not think that research is an important part of their undergraduate experience

Faculty do not value or utilize undergraduates as a part of the department's research efforts.

3 How will this fit into departmental or institutional activities?

Your institution has yet to implement CUREs

Other departments in your institution teach CUREs, but your department does not

Several faculty in your department teach CUREs

What are the benefits and challenges of incorporating research into the curriculum?

1 How could this increase student engagement and success?

Students gain critical thinking skills

Students are more engaged when experiments are novel

Students are motivated by a desire to publish

Students can list the research experience on their resume/CV

Does your department have the resources needed to quantitatively assess these outcomes?

2 How could this increase faculty engagement and development?

Allow faculty to expand their research capacity

Increase self-efficacy through implementation of an evidence-based practice

Help faculty to be recognized with teaching or mentoring awards

3 What are the challenges you might face?

Students might not like changes to the curriculum or the ambiguity and failure that comes with research

Faculty may need additional resources (time and money) to develop and implement CUREs

This might impact tenure review for junior faculty

Ensuring the sustainability of the curriculum reform may be a challenge as teaching assignments shift

If you want to initiate change, what levers do you have?

1 With whom do you need to talk?

Will the faculty in your department be enthusiastic to incorporate research into curricula?

Is your department chair, dean and/or provost supportive of your plans?

Are there other faculty within your department to whom you can turn for support?

Should your department survey the students prior to making changes?

2 Who do you need to have on board?

Who will teach the CURE? Are they tenure-track or lecture-track faculty? Are they junior or senior faculty?

How much budget is available for TAs and the materials/supplies/equipment needed to teach the CURE?

Is there anyone in your department or institution who can help with assessment?

3 What is the value proposition to students in your department?

What additional skills will they gain compared to the current curriculum?

How will this help prepare them for success in their future careers?

Will this research experience help them secure a job or admission to graduate or professional degree programs?

4 What is the value proposition to faculty in your department?

Will this increase the recruitment and retention of majors for your department?

How will this impact the teaching reputation of your department?

How will this impact the research reputation of your department?

Will this allow your department to be a catalyst for broader institutional change?

5 *What is the value proposition to your college and institution?*

How will a CURE curriculum increase the future success of your students?

How will student learning be impacted?

Will student satisfaction be enhanced?

Will the CURE curriculum significantly increase capacity for undergraduate research at your institution?

Could your efforts to employ an innovative and new teaching approach bring positive publicity to the institution?

Tangible tips

- Change will be more sustainable if multiple faculty in your department buy in to teaching CUREs.
- Faculty may need reassigned time or other resources for curriculum development.
- Allocating resources for faculty to attend CURE symposia or workshops are strategic investments.
- If faculty members invest the effort to develop CUREs, they should be allowed to teach the courses for multiple consecutive years and have the option to rotate out of the courses at their choosing.
- Faculty need to know that the department chair supports their efforts. This will be especially important if there is student resistance to the CURE format.

Building value propositions for institutional administrators

Use these questions and potential responses to help think through what must be considered by institutional administrators and what will motivate and prepare them. The goal is to gain the administrator perspective, not necessarily to answer all the questions. Modify or replace those that are not appropriate.

What is your context?

1 *Who are your stakeholders?*

Students

Parents

State and federal legislators

Donors

Other faculty

2 *Where do most students matriculate when they leave your institution?*

4-year college or university

Post-secondary education

Professional school

Workforce

3 *What is the primary role of research on your campus?*

Your institution currently has minimal research activity

Faculty conduct research with the primary goal of mentoring undergraduate students

Research is a key activity for faculty

What are the benefits and challenges of incorporating research into the curriculum?

1 *How could this help student outcomes upon graduation?*

Students gain skills that aid with job placement

Students are better prepared for graduate-level research

Increased confidence in reading primary literature leads to lifelong scientific literacy

2 *How does this align with institutional initiatives?*

Has your institution promised each student the opportunity to participate in research?

Can CUREs be leveraged to generate and support diversity?

Does your institution have a goal of increasing research productivity among faculty?

Is your institution aiming to expand the number of degree-granting programs?

3 *What are the challenges you might face?*

Students may have concerns over how the modified curriculum will impact their grades and their future plans (e.g., applying for medical school)

Departments may need additional resources (people and materials) to develop and implement CUREs

Faculty may feel that implementation of CUREs reduces their autonomy in teaching practices

CUREs may not align perfectly with previous course listings, requiring modifications to degree requirements

If you want to initiate change, what levers do you have?

1 *With whom do you need to talk?*

Do you have support from Department Chairs and other key administrators?

Do you need to seek funding from your institution or donors?

Should this change be integrated with an existing or new campus-wide initiative?

2 *Who do you need to have on board?*

Who will teach the CURE? Are they tenure-track or lecture-track faculty? Existing faculty or new faculty?

Will the CURE be interdisciplinary, requiring coordination between departments or colleges?

What are the desired outcomes?

Who will conduct assessment?

3 *What is the value proposition to students in your institution?*

Can your institution promise that every student will have the chance to participate in research?

Will this alter the pass rate in lab courses?

Will this help close the achievement gap for underrepresented or underserved students?

Will students have a chance to engage with the community and work on problems of local relevance?

4 *What is the value proposition to faculty in your institution?*

How can the institution reward faculty who participate in this curriculum reform?

What additional resources and improved infrastructure can be brought to the departments to support CUREs?

Can the CURE curriculum alleviate the over-demand for traditional undergraduate research experiences?

5 *What is the value proposition to your college and institution?*

How will a CURE curriculum increase the graduation rate and future success of students?

Does the CURE curriculum help meet a current strategic goal of the institution?

How will the outcomes of the CURE curriculum be advertised to the Board of Directors/Trustees/Regents, state and federal legislators, donors, and the public?

Tangible tips

- Connections to centers for teaching and learning and institutional research offices can help faculty design and conduct meaningful assessments of CUREs.
- Students involved in CUREs can be powerful advocates for sustaining and expanding efforts to integrate discovery- and research-based activities into the curriculum.
- New faculty hires play critical roles in maintaining momentum.
- Tenure and promotion committees will benefit from guidance regarding the evaluation of portfolios from faculty members involved in CUREs.

Ensuring readiness for change in large-scale efforts

Many CUREs begin with a single faculty member deciding to add authentic research to their curriculum. Given the autonomy found in academia, this type of change can often be made with minimal involvement of colleagues or administrators. However, expanding an individual CURE to a department- or college-wide effort, or launching a large-scale CURE requires significantly more commitment from a larger number of people. While these large-scale efforts introduce challenges and complexity, they carry the benefits of enhancing learning outcomes for greater numbers of students and helping ensure the sustainability of the reform. Fortunately, successful implementation of a small effort can serve as a foundation for expanding the scope and reach, allowing faculty to leverage their initial investments of time and resources.

Before undertaking a large-scale CURE or expansion of a CURE across multiple courses, you will want to position yourself to make these changes successful, scalable, and sustainable. Determining whether you are ready will involve a careful assessment of many factors including available financial resources, faculty member(s) time and workload, professional support, facilities, as well as an assessment of the level of departmental support and institutional commitment for the proposed course changes. An excellent tool to help you to determine the readiness for your large-scale CURE is the "Readiness Survey" developed by Project Kaleidoscope (PKAL) in conjunction with the Association of American Colleges and Universities (Appendix 1).[4] This survey will help you to verify that all the necessary planning, people and institutional support are in place prior to launching a large-scale CURE. Assessing the readiness of your CURE project before proceeding will help align your expectations with the resources available and the level of support you have received.

To ensure success in the long term, it is always best to start small and build upon your successes. Starting with a project that is overly ambitious or which is too large given available resources and support can result in failure. Also critical for the success of your project is your ability to demonstrate that the changes you have made in the course are having positive and impactful benefits such as enhancing student learning. Have an assessment plan that will utilize well-established evaluation tools and metrics in place before you start your CURE. Don't be afraid to ask for help as you develop your plan for evaluation and assessment. Oftentimes, if you have a campus-based teaching and learning center, they can help you to develop an effective evaluation plan and may be able to help you to conduct your assessment. You should also consider talking with others either on your campus or at other institutions who have implemented their own CUREs to understand how they have evaluated the effectiveness of similar course-based reforms.

Determining that the necessary components are in place will ensure the ultimate success of your implementation of large or expanded course-based reforms. The process of examining your readiness will allow you to address required institutional- or departmental-level approvals and other hurdles, make any necessary modifications to your plan, and begin the process of implementing your plan with confidence.

Leading institutional change

Regardless of our positions and formal titles, we each have the capacity to be thought leaders in our institutions, motivating widespread change aimed at incorporating research into the curriculum. However, change can be a complex process, and may appear daunting at the outset. Our efforts must be aligned with the existing cultures, ways of thinking, and political structures of our discipline and institutions.[5] By working with others within and across our organizations and aligning our activities with related efforts, we can act with greater efficiency and increase our collective impact.[6] Although the process of extending the impact of CUREs, inquiry-based laboratories, and other research-related activities will vary among disciplines and institutions, research on change can help guide our efforts in each unique institutional setting. Below we outline two different models for considering the process of change.

Kotter offers the following series of steps for creating and sustaining change:

1 Establish a sense of urgency
2 Create the guiding coalition
3 Develop a vision and strategy
4 Communicate the change vision
5 Empower broad-based action
6 Generate short-term wins
7 Consolidate gains and produce more change
8 Anchor new approaches in the culture

Pursuing these steps with our colleagues, within courses, and across academic units will help address questions, shift perceptions, and change the approaches we use to engage and prepare our students. This process requires listening, communicating, assessing, and celebrating. It also requires being responsive to the disciplinary and institutional contexts in which we are working, considering the history of related efforts, the current climate, and the future goals of our colleagues and organizations. Change is certain to be met with differing opinions from a variety of stakeholders. It is important to see the value in these alternative viewpoints, and to utilize the diversity of ideas to strengthen and refine the plan for change.

The human and organizational aspects of change are also highlighted in the model for institutional change recently mapped out in the Keck/PKAL (Project

Kaleidoscope) Model for Systemic Institutional Change in STEM Education. "Because any change process is dynamic and nonlinear, this model takes the shape of a flow, much like a river where there are multiple points of entry (and exit) as well as obstacles that create eddies along the way."[4] In many ways, the elements of this change model mirror the stages of the scientific method. This may help the process to feel intuitive to STEM faculty who are well-acquainted with the overall arc and iterative nature of scientific research.

The model incorporates practical steps and logistics, along with key phases:

1 Establish vision
2 Examine landscape and conduct capacity analysis
3 Identify and analyze challenges and opportunities
4 Choose strategies
5 Determine readiness for action
6 Begin implementation
7 Measure results
8 Disseminate results and plan next steps

Like a river continues to flow or science progresses, the change process is ongoing. Similar to research experiments, some strategies may fail to achieve their goal, creating a need for iteration, which leads to organizational learning and improved outcomes. Plans must be dynamic and responsive to the individual contexts of the disciplines and organizations. "There is no 'one-size-fits-all' approach for promoting change. Campus contexts, goals, expertise, resources, missions, and leadership structures are different at every institution."[4] However, analogous to the gratification that is found in successful completion and dissemination of a research project, success in curriculum reform can motivate and fuel further efforts and expansion.

Thinking and acting systemically

CUREs, inquiry-based laboratories, and other research-related activities are part of a larger educational ecosystem. Strategies from other university- and national-level educational reform initiatives[7] can help us proceed in ways that will foster the long-term success and sustainability of these curriculum reforms.

Undergraduate research is among the high-impact evidence-based practices that provide substantial educational benefits to students, increasing rates of student retention and student engagement.[3] Recognizing these benefits, the Council on Undergraduate Research has developed programs focused on institutionalizing undergraduate research, working with institutions, state systems, and consortia to integrate research into their curricula.[8] Individuals at all levels who are looking toward incorporating research into their curricula or expanding their efforts in this area are encouraged to take advantage of the resources that are provided by this initiative.

The Undergraduate STEM Education Initiative, launched by the Association of American Universities in 2011, is also taking a systemic approach. "[The AAU Undergraduate STEM Education Initiative] is based on understanding the wider setting in which educational innovations take place—the department, the college, the university, and the national level. Thus, it emphasizes the separate roles of senior university administrators (top-down change), individual faculty members (bottom-up change) and departments (change from the middle out), all of which are necessary for sustained institutional improvement to undergraduate STEM teaching and learning." [9]

Agents of change acting across levels, leading in formal and informal ways, will help obtain resources, build buy-in, and leverage successes. Their effectiveness will be enhanced if they are informed by research on CUREs, the outcomes of individual efforts, and models for large-scale change. It is our hope that this chapter provides a starting resource for gaining this critical information.

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"In recent years, faculty have recognized that the excitement and deeper understanding of science that students experience when they participate in laboratory research can be successfully scaled to a much larger student population by incorporating research into the curriculum. As faculty have learned how to make these course-based undergraduate research experiences most effective, we are very pleased to be able to compile and share their insights through this publication. We expect this how-to guide will be extremely useful for faculty at colleges and universities across the country as they seek to enhance student learning."

Daniel Linzer, *President, Research Corporation for Science Advancement*

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