Chapter 7

Development and Use of CUREs in Biochemistry

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Course-based undergraduate research experience (CURE) is an approach to integrate research into a teaching laboratory. CUREs are a developing pedagogy that broadens access to the high impact practice of research and a novel way to engage students using research as a teaching modality. The creation and use of CUREs are becoming increasingly popular to both engage students and broaden access to research for more students. As the pedagogy of CUREs is relatively young, the definitions and practices defining a CURE and how CUREs are implemented are highly diverse. This chapter will expand on the history and evolution of CUREs, and highlight what we have learned on the student learning gains, discuss assessment. The faculty practitioner is the primary audience for this work; the instructor in the trenches, whether at a two-year community college, a well-funded PUI, an underfunded school, or a sizeable land-grant research institution. We will examine the details necessary to understand the results of educational research and provide a framework to create, adopt, or develop a CURE. This chapter will be a resource for adopters as well as inform educational researchers.

Why Undergraduate Research and CUREs

Can you remember the first time you had an interesting research question or idea ending in an exciting experiment? Is the reason you are passionate about science because the process of science involves bouncing ideas around with a group of colleagues, deeply reading literature to create a hypothesis or the design of an experiment? Are you excited by science because of the joy of getting results from a challenging assay? Was it was holding up that Western blot that finally worked, the PCR reaction that amplified or synthesis of an elusive compound. Do you recall that feeling when, for the first time, you held data in your hands that only you knew and was something of real interest for your scientific community? For most scientists, this is why we do what we do. Reading about science is not as motivating or enriching as is doing science; much like reading about being a concert pianist does not make one able to play Chopin. Providing a practical experience of being a scientist, rather than reading about science for our students makes perfect sense. CUREs are part of a continuum of

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how we integrate research, discovery and other elements of the practice of science into our teaching laboratories and is one way we can help provide this experience for a large group of students.

The impact of research on student learning naturally brings about the memory of working in a mentored research laboratory as an apprentice, now defined as an undergraduate research experience (URE). The influence on undergraduates involved in UREs has been studied with the most significant impact on the motivation and persistence of STEM students (*1*). Weaver et al. described the benefits of integrating research- into courses for undergraduates as similar to those seen with UREs (*2*). More specifically, the involvement of undergraduates in research promotes how students think and act as scientists, bolsters their feelings of belonging, and improves their confidence in STEM (*3*–*6*) Students rated the effectiveness and benefits of an undergraduate research experience using the Survey of Undergraduate Research Experiences (SURE) and reported a higher likelihood of persistence in STEM and independence (*7*, *8*). A longitudinal study of over 2000 students as freshmen and again as seniors show that like the Lopatto work, student involvement in a URE is more likely to plan to pursue graduate or professional degrees in STEM by 14 to 17% (*9*). Another study by Peteroy-Kelly et al. used three validated instruments including the Genetics Concept Assessment in addition to the Classroom Undergraduate Research Experience (CURE) survey to demonstrate increases in the understanding of concepts and attitudinal gains for students involved in a year-long CURE in genetics and cellular and molecular biology laboratory (*10*). Others (*11*, *12*). describe in stronger terms how CUREs help a student realize an increase in interest and motivation for and to continue in science, and increase in cognitive gains, especially for learning the scientific process. Detailed planning and careful analysis of the project found that the CURE enabled both high and poor-performing students to make more significant gains in conceptual understanding. The Course-Based Undergraduate Research Experience (CURE) also supported student increases in understanding, and participation in, the scientific process, including reading literature, analyzing data, communicating results and other activities required for success in STEM. The authors conclude that the work "suggests that CURE experiences do indeed lead to learning gains…" (*10*). At this time, there are only a limited number of robust studies that identify the causal mechanism for URE outcomes. However, there exists a large body of work, some referenced here, that provides ample support for UREs as a means to improve increases in graduation rates, retention and a stronger understanding of scientific processes including data analysis and the scientific process (*6*).

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

Graduate Student and former CURE undergraduate at Oxford College (*13*).

Wei and Woodin (*14*, *15*). describe and encourage the incorporation of an undergraduate research experience outside of the apprentice URE model. Recognizing the need to broaden access for research, Woodin describes a variety of approaches, including CUREs, to meet these needs. Supporting the call from both Vision and Change and President's Council of Advisors on Science and Technology to increase access to research experiences, there is a growing number of faculty who have developed individual CUREs to provide these important research experiences in their courses. Others which will be discussed here, have clustered to create larger-supported systematic CUREs

(GEP, SEA Phages, and others) to meet these needs. However, like UREs, the impact on students has to be carefully examined.

There are many compelling reasons to broaden the URE experience and by extension the CURE accessibility. As suggested in several studies, UREs and CUREs help to increase the STEM workforce. One benefit of a CURE is to provide the motivation, persistence, and other reported positive gains of UREs to more or even all students, including non-science majors. Overall there is low retention in STEM students, and, for at-risk populations this is an even more significant problem. Increasing the retention rate by providing such experiences would have a beneficial impact on the potential STEM workforce. The NSF reports a 33% retention rate for students in STEM undergraduate degrees, yet predict a 20.4% increase in employment in the biological, environmental life sciences, and 12.75% increase in the physical sciences (*16*, *17*). Another study by the U.S, Education Department indicates that of those who started in a STEM degree program only 52% remained and the attrition was worse for those in community college programs where only 30% of those starting a STEM major (*18*, *19*). Such results translate to a national concern about the ability to meet the demand for trained workers in STEM (*20*).

Overall there has been an increase in STEM-related jobs. In the private sector, there is a predicted 34% increase in employment growth compared to past decade (*20*). Over 360,200 new physical and life jobs was forecast to be created between 2014 and 2024. Because of low retention rates and a changing demographic of college-bound students, the current rate of STEM degree growth is likely to create a concerning shortfall to meet the national needs. Causing concern is where the U.S. is situated in the global field of science and technology. Simply put, we are outpaced internationally, which impacts the nation in many ways (*21*).

Further complicating the need to meet STEM workforce demands is whether the demographics of that future workforce will mirror those of society. By 2060 the White Non-Hispanic population is predicted represent 44.3% of the US total population followed by Hispanics at 27.5%, and Black or African Americans will represent 15% of the US population. Asian and American Indian / Alaska Native is predicted to represent 9.1 and 1.4% respectively in 2060. The increase in each population describes a decrease by 9.6% for White Non-Hispanic Americans and a relative increase of 40.6% for African American, 93.2% for Hispanic American, and a 37.3% for American Indian (*22*) Troubling is the proportion of black and other minorities in the physical and life sciences. White students make up 67-68% of these science majors, while Asian students represent 16 and 19% leaving 13-15% of the rest of the majors from the remaining communities.16 The differences of course are amplified when examining the workforce. In 2015, 28% physical sciences and 48% biological science employment were women while Hispanics and Blacks accounted for only 6% and 5% of science and engineering occupations respectively (*19*). Gender is also a concern for STEM careers. While in psychological sciences, biological sciences, and math women represent 77%, 58.7% and 42.9% of degrees awarded in 2015. Women still are behind in computer science (18%) and engineering (20%; 16, 20). Even with the near even ratio of female to male in biological sciences females who are interested in science more often move into non-diagnosing health practitioner fields instead of STEM workforce or other opportunities (*19*).

> *Clearly, there must be an intervention to meet the needs of a changing workforce and to meet the needs of our students. We must recognize and address that many students, who cannot afford a summer internship or are not exposed to research depending on the institution and mentorship, will not be exposed to the gains of UREs.* ***The difficulty of access for many students makes creating and providing CUREs for all students a critical initiative in STEM.***

What Is a CURE?

The most straightforward description of a CURE is the integrating of research into the classroom environment. This is the common theme among many of the early CURE or CURE-like courses. To better understand "research," it is helpful to understand what the STEM community defines as research and how the description of CUREs has evolved. The Council on Undergraduate Research (CUR) defines undergraduate research as "an inquiry or investigation conducted by an undergraduate student that makes an original intellectual or creative contribution to the discipline" (*23*) while the ACS describes undergraduate research in chemistry as "self-directed experimentation work under the guidance and supervision of a mentor or advisor. Students participate in an ongoing research project and investigate phenomena of interest to them and their advisor". See Box 1 for an expanded description (*24*). Historically the driving force for creating CUREs was to broaden access to the positive impact of research (UREs) on students. CUREs are distinct from traditional "cookbook" and inquiry laboratories. Inquiry based experiences have strong support across STEM disciplines and show unique and important student gains. Inquiry-based experiences do share some learning characteristics, including generating their questions, obtaining supportive evidence, and depending on the experience analyzing and connecting the results to the initial scientific question (*25*, *26*). Inquiry shares some features with CUREs. The inquiry cycle includes a process where students are engaged in the scientific process and using literature or prior observations generate a question and hypothesis and then investigate, discuss, and reflect. However, for inquiry-based laboratories, the answer is either known or of limited use to stakeholders outside of the classroom. CUREs programs are distinct from Inquiry laboratories as CURE create opportunities for students to engage in the scientific method on problems where the answer is not known, supporting enhanced student persistence and identity in STEM. Research is the crucial difference between Inquiry and CURE; does anyone know the results of the experiment? Is this project broadly of interest to the scientific community (see Box 2)? If the answer to the first is yes and no to the second, then the activity is an inquiry and not a CURE.

While antidotal, the comments by 2018 ACS President Peter Dorhout supports these findings when he writes "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" (*27*).

Several groups describe the key or minimal components of a CURE. One of the early descriptions came from a poll of faculty engaged in undergraduate research who were asked to define the essential features of a successful undergraduate research project (*28*). This work was summarized and using organizational psychology leadership theory defined as structural items or those that create the structure for the research project and are more measurable. The responses include:

- *Reading literature*,
- Opportunities for students to *design and conduct research* while exploring creativity.
- The ability to work both *independently and collaboratively* (on a team) with peers
- The establishment of student-faculty *mentorship* or partnership
- *Ownership of the project* by students
- Careful *reproducibility* of results combined with mastery of techniques.
- Oral and written *communication*.

Focusing on larger size courses (50-500 students) the Australian funded Authentic Large-scale URE (ALURE) group created a consortium of 39 academics serving over 7000 students in creating

resources to support development and assessment of these class-based UREs (*29*, *30*). In their final report (*31*) the four key elements (and the structure) of each element of an ALURE are:

- *Design and Logistics* – What is the research question, what makes this research authentic, what are the student learning goals and how will they be assessed, and what equipment, training and resources might be needed.
- *Motivation* – Why is the instructor implementing the ALURE, what are the overall outcomes and expected challenges, why would another faculty member be interested in the project and what challenges might another colleague encounter.
- *Support for Students* – Recruiting student to the project, student learning objectives, support for students as they experience cognitive and other challenges, and training for teaching assistants.
- *Evaluation* – Who are the stakeholders and how will they use the data, and how will the data be analyzed?

The Genomic Education Partnership is a large-scale bioinformatics CURE. Using the SURE survey (student self-reported gains), they found that a key feature of their CURE is that gains on several learning benefit items increased with *time spent on the research* aspect of the project (*32*).

Gentile, Brenner and Stephens led a study for the National Academies of Sciences Engineering and Medicine on UREs (*6*). As part of the panel's conclusions, they encourage undergraduate participation in UREs and recognized that CUREs are part of the spectrum of this engagement. They have a more extensive list of characteristics that defined UREs as a whole. These activities must:

- *Engage students* in research practices including the ability to argue from evidence.
- Aim to *generate novel information* with an emphasis on discovery and innovation or to determine whether recent preliminary results can be replicated.
- Focus on *significant relevant problems of interest* to STEM researchers and in some cases a broader (civic) community.
- Emphasize and expect *collaboration and teamwork*, involve iterative refinement of experimental design, experimental questions or data obtained.
- Allow students to *master specific research techniques*.
- Help students *engage in reflection* about the problems being investigated and the work being undertaken to address those problems.
- Require *communication of results* either through publication or presentations in various STEM venues.
- Are *structured and guided by a mentor* with students assuming increasing ownership of some aspects of the project over time.

Of course, these definitions include the recognition that not all URE experiences will have the same intensity and depth.

> Voices of the students: I realize the need for textbook knowledge coming out of college, but the ability to produce knowledge instead of just taking it in was the best educational experience of my college career. The CURE course I completed dramatically altered my career path, making me passionate about computational biology. I also think the ability as an undergraduate to discuss a rich research experience made me much more marketable as

researcher and certainly helped me transition into a highly competitive graduate program. *Undergraduate student at Washington University in St. Louis* (*13*).

BOX 1 – American Chemical Society and Undergraduate Research

What is research at the undergraduate level?

At the undergraduate level, research is self-directed work under the guidance and supervision of a mentor/advisor — usually a university professor. A gradual transition towards independence is encouraged as a student gains confidence and can work with minor supervision. Students usually participate in an ongoing research project and investigate phenomena of interest to them and their advisor. In the chemical sciences, the range of research areas is quite broad. A few groups maintain their research area within a single classical field of analytical, inorganic, organic, physical, chemical education or theoretical chemistry. More commonly, research groups today are interdisciplinary, crossing boundaries across fields and other disciplines, such as physics, biology, materials science, engineering, and medicine.

What are the benefits of being involved in undergraduate research?

There are many benefits to undergraduate research, but the most important are:

- *Learning, learning, learning. Most chemists learn by working in a laboratory setting. Information learned in the classroom is more clearly understood and it is more easily remembered once it has been put into practice. This knowledge expands through experience and further reading. From the learning standpoint, research is an extremely productive cycle.*
- *Experiencing chemistry in a real-world setting. The equipment, instrumentation and materials used in research labs are generally more sophisticated, advanced, and of far better quality than those used in lab courses*
- *Getting the excitement of discovery. If science is truly your vocation, regardless of any negative results, the moment of discovery will be truly exhilarating. Your results are exclusive. No one has ever seen them before.*
- *Preparing for graduate school. A graduate degree in a chemistry-related science is mostly a research degree. Undergraduate research will not only give you an excellent foundation, but working alongside graduate students and post-doctorates will provide you with a unique opportunity to learn what it will be like.*

Taken from ACS: Undergraduate Research in Chemistry (24).

In 2012, Fukami et al. described the divergence from traditional or cookbook laboratories to "authentic research-based courses" where the research was integrated into the curricula (*33*). Here, the inquiry format is extended to include "authentic" research as a teaching motif. Incorporating hallmarks of authentic research as defined by the AAAS and the National Academies, Brownell and colleagues define the factors in a yet to be labeled "CURE" as:

- Development of student-generated *research questions whose answers are currently unknown*
- *Longitudinal focus* on one set of research questions over the length of a course
- Implementation of *experimental designs that are not predetermined*
- *Collaboration* among peers
- *Presentations* by students of results and ideas for future research.

In this study the defining factor for a CURE is authentic research (*34*). Based on the frequency of the responses, authentic research was determined by either novel questions (if only one theme was mentioned) or the collections of themes that add to the process of science. In this study, biology faculty were asked what the essential components of authentic research experiences in introductory

biology classes were. In addition to research, most described elements important for a CURE as experimental design, data collection, and data analysis. Presentation or publication, hypothesis formation, student-generated questions, and new questions were reported at a lower frequency and thus defined as second or third-tier design elements of a CURE.

BOX 2 WHAT IS AUTHENTIC RESEARCH?

"Authentic" as a description of research is loosely defined depending on the discipline and user. In the Brownell description, authentic is used to highlight the differences in traditional labs and is used to describe a research experience that incorporates those found in the apprentice model (33, 34). This is similar to how Wei and Woodin describe the research approach in the classroom (15). The definition of authentic can be defined as authentic as a process or as a product. In the ALURE program, "authentic research" has a more robust definition. In their work, "Do we need to design course-based undergraduate research experiences for authenticity?" A review of the literature identified authentic as required for a CURE, yet they found no conclusive agreed-upon definition for "authentic research". The first theme defined authentic as "what scientists do" or "the practice of how science is conducted". The second central theme defined authentic research as an ownership or something personally relevant to the scientist/student (31). This lack of clear definition will limit the ability to measure the outcome of such work, and become a barrier to acceptance as well as reducing potential implementation of CUREs in general. An example of how 'authentic' can confuse the issue when discussing research integrated in CUREs is how for some authentic means "real research" or "genuine research" which translates to many things depending on the stakeholder including the potential to publish the results (2). Auchincloss et al. describes that to avoid the diverse definition and lack of uniform use of authentic, research in a CURE should have "broader relevance or importance" (35). Like the diversity of what are the essential elements of a CURE, what is "authentic" is also not easily defined. While less fluid, the definition proposed by the Dolan group broader relevance or importance makes a cleaner and more precise approach to defining this activity of a CURE.

Another group of experts in UREs and CUREs led by Erin Dolan and others were gathered as part of the Course-based Undergraduate Research Experiences Network or CUREnet (*35*) and one of their outcomes was to develop a consensus definition for a CURE. Together they created a description of the dimensions that make a CURE unique from other laboratory experiences. These five features (also called dimensions) form both design features and build a framework for a logic model to measure the mechanism of effective learning and outcomes of a CURE. The design features or dimensions include:

- *Use of science practices*: This includes the many activities involved in the scientific process such as researching the literature, designing scientific questions, building a hypothesis, designing approaches to test the hypothesis, creating methods, analyzing data and as done in a research environment ''navigating the messiness of real-world data''. Basically, the design and methods of a research project. The level and depth of incorporation of the practices will depend on the length of the CURE and the audience and instructor although the CUREnet group proposes that several of the practices should be included in a CURE to make it unique from other laboratory experiences.
- *Discovery*: The purpose of a research investigation that is not known is the discovery. The ownership can be either student or faculty directed or collaborative in nature, but the outcome must not be known. This is a key distinguishing feature of CUREs from inquiry and mirrors one of critical elements of research in the apprentice model.
- *Relevant or Important Work to a Broader Community*: As described in Box 2 on authentic research, this is the opportunity for students to contribute new knowledge. Separate from the vague definition of authentic or genuine research, in this design feature of a CURE, students conduct work that others will find important. Such an audience could of course be the traditional scientific community via an eventual publication contributing to the larger

body of knowledge in their discipline or even something "a report of interest to the local community".

- *Collaboration*: In addition to the networking skill that develops as students collaborate via teamwork, it is important to recognize that, just as science is not conducted in a vacuum, modern research involves collaboration both within and outside of a research group's laboratory. Increases in student metacognition takes place when teamwork/collaboration takes place. As described by Auchincloss et. al., collaboration may encourage the students to think and recognize the issues in both their understanding of the project and their reasoning. It would be curious to learn the nature of collaborations that mimic those in today's research between groups of students or a second scientist (assuming a PI role rather than an instructor) might impact the CURE experience outcomes.
- *Iteration*: Similar to the findings by Elgin's Genomic Education Partnership where they believe this dimension increases duration (staying in STEM major), and has an important impact on other student outcomes. Iteration means that a CURE must have time for students to fail or repeat experiments, a key part of the scientific process.

The Dolan group emphasized that each of these features can provide the context to examine the impact of elements of CUREs using theoretical and empirical evidence. While later we will address assessment, defining these key features can be used to assess how each feature is used in a CURE to either determine its difference from other pedagogies to test their impact on student outcomes. Together these features, when taken as a whole, define CUREs separate from inquiry or traditional cookbook laboratories and are what make a CURE like an internship or apprentice research experience.

The simplest definition of a CURE is straight forward as the integration of research into a teaching laboratory. Yet unpacking of the dimensions of a CURE remains frustratingly elusive. Complicating matters is that biology and biochemistry have seemed to embrace and developed many CUREs while other STEM disciplines lag or have a very different approach and definition to integrating research. Terms such as inquiry, discovery, authentic, and others are used which are not delineated from traditional laboratory experiences. As such, we can expect more varied lists of key elements and definitions of CURE as our disciplines continue to evolve.

As scientists, there are many unique developmental experiences from undergraduates, through graduate school and eventually becoming practicing scientists. These diverse pathways explain how various groups of faculty/instructors can come up with distinct lists of what a CURE should contain yet emphasize many of the same characteristics of research. The diversity of lists of dimensions, activities, and outcomes, elicits the question "is a universally accepted definition of a CURE possible?" If a CURE is created for internal use and not publication, the answer is "not exactly." Using evidence-based and peer-reviewed educational research resources to understand the affective dimensions of a CURE is vital in creating a universal definition of a CURE.

For assessment and to build a common framework to develop the instruments critical to measure the causal mechanisms for these CUREs, there must be at least some set of features agreed upon by the community. Building from these, we can ask questions that are both appropriate and transferable. The caveat is that these agreed-upon features form the core of what a CURE must minimally contain. From this common base, there is a place to add the individual needs.

While there are merits to each of the lists of definitions described here the Auchincloss et al. dimensions of a CURE to distinguish a from inquiry and traditional laboratory experiences are influencing many groups and individuals. The evidence is found both in recent literature and

referenced in many poster and oral presentations in biochemistry and biology conferences (*35*). In our earlier review on CUREs in biochemistry, we adopted the same five dimensions in our description of a CURE (*13*). These five key dimensions of a CURE, if commonly accepted, can become the structure or framework by which the broader community can measure how important or useful the dimension in a CURE experience in a way that is broadly usable. As Auchincloss et al. explain, "The five dimensions compromise a framework that can be tested empirically by characterizing how a particular dimension is manifested in a program, developing scales to measure the degree or intensity of each dimension, and determining whether the dimensions in part or as a whole are useful for distinguishing CUREs from laboratory learning experiences" (*35*). We have yet to learn the relative importance for each dimension in achieving student gains. Most CUREs vary in the intensity and approach of how each dimension is employed. Not every CURE will employ every activity of each dimension. Thus, "Using this framework to identify critical elements of CUREs and how they relate (or not) to important student outcomes can inform both the design of CUREs and their placement in a curriculum" (*35*).

There is a gap in our understanding of the relative importance of the CURE dimensions. The CUREnet group recommended gathering empirical evidence to characterize the impact of each dimension and the role various dimensional activities have on CURE outcomes (*35*).

A shining example of a CURE activity lacking empirical evidence to support the impact on student outcomes is hypothesis development. Our opinion is that hypothesis development (one of the activities of the Scientific Practices dimension) is foundational and truly distinguishes a CURE from traditional laboratory experiences, and further has a strong impact on important student outcomes such as identity, ownership, and persistence. How much do the students engage in, and the level of accountability of hypothesis development should be examined for the contribution to the related student outcomes. To address this question, data needs to be collected using suitable validated instruments.

Developing a Hypothesis as Part of "Scientific Practices" Activity

Examining the literature, we see that the accountability or involvement of hypothesis generation greatly varies in importance in many CUREs. In some ways, this level of incorporation of hypothesis generation reflects how we as scientists started our projects in graduate school, where many were given a project to develop with an existing hypothesis. While later in our career as a post-doctorate or newly minted faculty, we were able to create our own project and synthesized a truly independent project from an interesting scientific question. The process leading to hypothesis generation impacts how students understand the scientific question, develop methods, and design experiments to test the hypothesis. Such a process is what we do as scientists and should be reflected in a CURE. Box 3 indicates a model of minimal actions and approach to designing hypothesis in a CURE.

One approach to incorporate hypothesis development as a key dimensional activity is described by Bell et al (*36*). In this work, several outlines of mini-curricula designed to guide students through the steps of hypothesis development CURE as student investigates malate dehydrogenase (MDH) in a range of classes from gateway first year classes, to community college courses to capstone senior level courses (*36*). The focus of the project is one or more his-tagged wild-type MDH to be expressed in bacteria. Students are asked to critically evaluate a feature of MDH using information in the literature and using bioinformatics, develop the hypothesis of the domain's function, using site-directed mutagenesis predict the outcome of an amino acid mutation and design experiments to test that hypothesis:

BOX 3 - Suggested MINIMAL features and workflow to teach student how to generate a hypothesis should contain the following elements:

Identify the Big Picture. Ask why this is important to science or society.
Generate the scientific question upon which the hypothesis will evolve
Investigate Background Information.

Conduct literature search, evaluate preliminary evidence or observations, conduct bioinformatic or structural analysis to determine what is known about the scientific problem/big picture

Create a specific hypothesis from the scientific question

Make predictions arising from the hypothesis including a null-hypothesis

Design experiments to test the hypothesis

The key is to get the students to connect the reading with a question. Students need to understand they are asking an interesting question not "doing and assay or seeing "what happens".

Students will often be more comfortable making simple "guesses" as a hypothesis, not fully informed by the question or the background information. A student may recognize that an amino acid side-chain is positively charged and suggest a mutation leading to an opposite charge. This is easily done by focusing on the function and structure of the protein as well as published bioinformatic input. Thus, guiding students using peer review and other approaches to mature their hypothesis and predictions is the mentor/instructor's critical role.

Project introduction, review and primary literature review: Presentation of big picture of the research project, provide simple review of structure and non-covalent interactions driving enzyme structure and function.

- Group work dissecting key elements of critical/central MDH paper
- Given handout with major points about MDH including enzyme function
- Use think-pair-share to focus on MDH function and reaction
- Students find 5-10 papers on MDH that might be the foundation of an idea/question/hypothesis and use mindmap to detail on publication
- Students generate literature background with feedback

Bioinformatics Tools to Develop a Hypothesis

- Students given presentation on developing questions: big picture to detail – build from background to MDH.
    - Include specifics on what is a good hypothesis
    - Start mindmap on hypothesis development
    - Small group discussion on potential areas of interest and generate ideas for project.
- Introduce to appropriate bioinformatics. i.e. clustal omega, pubmed, or other database/software to compare known structure, features, sequences from literature to the clone they will be working on.

- Students will conduct think-pair-share to decide on big picture question and how they are going to construct their bioinformatics approach.
- Students conduct analysis and further develop scientific question and hypothesis along with mindmap of evolving project
- Students share sample bioinformatics evaluation (e.g. clustal alignment) and discussion of conclusions drawn from it

Molecular Visualization to Refine Hypothesis

- In-class presentation review on what is a good hypothesis emphasizing the fact that it must make testable predictions.
- Hypothesis review leads to a discussion of non-covalent interactions and their roles in protein structure-function and the role they take in enzyme activity
- Students think-pair-share and develop mini-mindmap to identify the amino acid(s) important to their hypothesis
- Students conduct molecular visualization of the structure (Pymol or other software) workshop to make images of residues they are interested in that show what types of interactions the amino acids may engage with (other parts of the protein, substrate, cofactor, etc. …).
- Students are challenged to start developing hypothesis detail – how do they think the residue(s) of interest interact with other parts of the protein, the substrate, etc.

From Hypothesis to Predictions and Experiments

- Student presentation of hypothesis. Must include background, amino acid sequence alignment, 3D structure of active site and cofactor binding site, and reasoning for the proposed mutation.
- Mini-presentation (by faculty) on experimental approaches. Briefly review key aspects of available experimental approaches. The goal is to connect the student's research question/ hypothesis to experimental approaches.
- Small group discussion on proposed mutations, think-pair-share activity to allow students to further develop ideas of experiments to test hypothesis
- Small student group meeting with faculty instructor to discuss planned mutations, the design of primers and provide guidance moving forward with their project

Study Section: Peer Review & Critique of Proposals

- Students participate in a "panel review" session of their draft proposals.
- Student Scribe summarize strong and weak points of all proposal raised during discussions and "panel" rank proposals.

Finalize Proposal

- Students revise their own proposals having reviewed feedback from panel, presentation questions and faculty feedback.
- Open time for students to ask follow-up questions
- Final report submitted.

This is a thorough approach to guide students through the process of creating and designing a hypothesis and develop an experimental design approach based on the input to hypothesis generation. For those conducting non-protein/enzyme CUREs the concepts of active learning, background investigation, and the development of a hypothesis to drive experimental design could be fashioned from this approach. The example provided here requires five-six laboratory sessions to conduct and is an example of a comprehensive approach performed in a semester-long CURE. Depending on time constraints, an abbreviated version could easily be adapted. A complete description of a hypothesis module is integrated into the MCC CUREs community including lesson plans, goals, and key teaching discussion points specific for a variety of institutions including community colleges and large-research intensive universities and shorter examples of hypothesis development can be found on www.coursesource.org.

How Far Along Are We?

Roger's Bell Curve describes the various stages for adopting (or diffusing) new ideas, innovation, or technology (*37*). At the outside leading edge of the bell curve lie those who are the enthusiastic creators and most willing to use new ideas. These are the innovators and represent a small (2.5%) population willing to take risks in their careers. As CUREs are relatively new, those faculty who integrated research or adapted from an inquiry mode only a few years ago are our innovators. Individuals represented by the next 13.5% of the curve are considered early adopters who are also risk-takers and as described by Rogers, are more leadership than innovative oriented. Early adopters tend to be influential and along with the innovators are the people that push out ideas into the broader culture. Early majority individuals make up the middle left portion 34% of the bell curve, are willing to create new and innovative ideas, use more caution and work to convince the rest as they are willing to accept new ideas. The late majority and laggards finish the last 34 and 16% of adopters of innovation. They tend to be more traditional in approach and are not as interested in change. Laggards will find a reason to fight against change and only adjust when forced to do so.

> Voices of the students: [The CURE course] taught me the value of inquiry and how important questing what you know is to furthering your knowledge. I had not participated in research before because I had seen it as something way past my abilities. The lab setup helped me grow as a scientist.
> *Undergraduate student at Oxford College* (*13*).

CUREs are in the mid to late Early Adopter mode of innovation diffusion. Historically the bulk of chemistry and biology laboratories have been traditional laboratory experiences where the problem and answers are not in question. Over the last 5-8 years, a real integration of research into teaching undergraduate biology and biochemistry laboratories has taken hold. This wave of focusing on engaging students in the teaching laboratory follows decades-long research into how we engage students in the classroom with active learning or pedagogies of engagement including process-oriented guided learning, case-based learning, flipped classrooms and others. Groups from the innovators are now creating mature CUREs and encouraging the next focus for CUREs (assessment, adoptive measures, sustainability and large scale implementation). However, as we will discuss later, the growth and maturation of CUREs is leading to a bifurcation of literature on CUREs, separating those with advanced educational research expertise and the practitioners (the faculty without specific and in-depth educational research training).

The Evolution of CURES

An informal analysis of the education literature shows many of the early publications of inquiry started in the mid to late 1990s. In 2001 J.E. Bell called for a close examination of how we integrate interdisciplinary approaches to learning and called for a realistic experience of a research experience in teaching laboratories (*38*). Early descriptions of incorporating shorter elements of research in a curriculum followed several years later. The journal Biochemistry and Molecular Biology Education's (BAMBED) early attention to CUREs include an initial call to incorporate research for undergraduates as the barriers from adopting research in the teaching lab, their benefits addressed, and these innovators suggested strategies to overcome the gap of "research-practice" (*39*). The first BAMBED publication describing the outcome of research and not inquiry in a teaching laboratory was described for a microbiology lab (*40*). In 2010, Parra et al. described bringing faculty research interest into the teaching laboratory as a modality to strengthen the research-teaching nexus (*41*). In 2011 J.E. Bell (*42*) furthered the idea as he described the impact of research on biological thinking and how to develop critical components to adapt the integration of research into the teaching environment.

In the Journal of Chemical Education (JCE), inquiry as a method for simulated research has been described as far back as the 1950s with hundreds of publications using inquiry over the past ten years. While the importance of a research experience is emphasized by the American Chemical Society's Committee on Professional Training (ACS CPT) and described by the ACS CPT's leadership (*43*). Yet, even with this history of engaging students using inquiry and research projects, only a handful of publications specifically describe CUREs in the journal JCE. One interesting example published in JCE describes how instructors adapt the concept of a one-semester CURE/URE fusion taught over a one-month dedicated period (January term) using a formal research introductory course combined with a separate URE experience in a formal research lab course (*44*). It should be noted that the lack of CURE specific, publications in JCE is not entirely reflective how the chemistry community has embraced CURES. One might posit that the lack of ACS JCE publications on CUREs is in part, why the ACS focused literature has not fully embraced the CURE pedagogy in name while some chemists are certainly doing it in practice. Research Corporation for Science Advancement recognized the lack of formally developed CUREs in the physical sciences and created an impressive report of a meeting of experts and Cottrell Scholars. This report highlighted both the barriers to adoption for those in the physical sciences, the definition and assessment for CUREs and described several examples of CUREs being used by the Cottrell Scholars (*27*).

One of the earliest publications on research in the teaching laboratory was published in Cell Biology Education in 2006 (CBE Life Sciences). Here, the impact of summer research in an apprentice model vs. a collaborative learning model where students conducted guided-curricula in a pseudo CURE format was presented (*45*). Another innovative work was published in 2007 that started students using guided inquiry approach and transitioned students to work on a novel research project (*46*). Since that time, CBE Life Sciences has published over 50 research articles, review articles and meeting reports describing both systems incorporating CUREs and individual faculty creating and examining the impact of their CUREs.

One of the current approaches to encourage the adoption of CUREs is the CUREnet project and website. In its second evolution, the NSF funded CUREnet project created a network of faculty to develop, teach and assess CUREs. The website, CUREnet.org, provides a collection of deposited CUREs and supporting documents to design, operate, and assess CUREs. The CUREnet collection

database is searchable with terms of discipline, core competencies, nature of research, state, target audience, duration, and state. Early in its inception, the CUREnet leaders organized a meeting of working group experts to identify and address critical issues in CUREs. The meeting resulted in an influential report (35) helped summarize the current state of CURE assessment and identified gaps in our understanding of CUREs. Much of this work describes the approach and evidence needed to define learning framework and theories needed to understand which elements of CUREs are effective in promoting student gains and provide and advanced pathways by which instructors and design and test their CUREs.

> Voices of the students: This [CURE] course was different from other lab courses in that I was applying critical thinking skills and laboratory techniques I learned in my upper biology courses. This course has helped me prepare for a future career in pharmaceutical science. *Undergraduate student at Georgia State University* (*13*).

Examples of CUREs

There are several examples of established national level CURE programs. These programs support the adoption of CUREs for a diverse range of institutions. Three of the most established programs are the HHMI funded Science Education Alliance – Phage Hunters (SEA-PHAGES) targeting first-year life science students, The Genome Consortium for Active Teaching (GCAT) and Genomic Education Partnership (GEP). These are highly successful because of the inclusive and rich set of resources supporting faculty engaging in CUREs. Each have a proscribed approach and a shared scientific theme. Faculty engaged in these national-level CUREs engage in training workshops, provided teaching materials, and a roadmap to easily adopt and reduce the activation barrier to starting a CURE. While the benefits to these large consortiums are many, the constant challenge is sustainability. Once funding ends, the costs to continue providing training and support are significant. Staff and faculty are needed to maintain stocks, publish new works, maintain websites, provide workshops as well as generate and share physical resources. The GCAT project is no longer active due to funding, limiting further adoption of the CURE and use of their tools. Thus how these effective and important programs are sustained will be a challenge. We will briefly discuss each as an introduction to these projects as they are well published and widely recognized.

SEA-Phages (www.seaphages.org)

This is a centralized, highly structured and well-supported program for first-year students to isolate and analyze the genome of soil bacteriophage to understand the genetic diversity and evolution as they generate data for future publications. Member faculty are provided mentorship and teaching help, access to databases and are encouraged to participate in ongoing symposia and workshops. For their involvement, participating faculty/institutions are expected to follow the guidelines for SEA-Phages CURE (described as authentic discovery-based phage research) curricula that involve a proscribed approach ultimately enriching the GenBank database and potentially cumulating in collaborative research publications. The key to this is the robust support system for adopting faculty. Self-described as a CURE-like, the inclusive Research Education Community (iREC) the participants across over 100 instructions were serving thousands of students. Using the student self-perception of learning gains, first-year students participating in the SEA-Phages program rated as well or better than those who participated in traditional UREs or CUREs (*46*). They also found that students involved in the project had an increased effect on intent to stay in sciences

(persistence) and suggested that this is due in part to project ownership and the agency of identity and community within the project (*47*, *48*).

Genomic Education Partnership (GEP; www.gep.wustl.edu).

GEP is another, inclusive well-supported community of CURE faculty providing opportunities to upper-division students. GEP students analyze raw sequences and annotate the genome of Drosophila with the ultimate goal to publish on the evolution of the model organism. There is a complete and extensive set of curricula designed to train faculty to incorporate the sequence finishing and annotation with a base or minimal package to a much more extensive set of projects. The current focus is continuing on Drosophila but is expanding to studying the evolution of parasitoid wasps. There is a CourseSource publication describing the genomic training in modular form used to prepare students for independent research (*49*). The GEP large-scale bioinformatics approach to CUREs is easily implemented with reduced costs as the research does not require wet-lab space or costs to access the database. Several research publications have resulted from these CUREs which include many undergraduate student co-authors. In addition to the benefits of an inclusive centralized program, the GEP project benefits to students are independent of the type of institution which encourages a wide variety of universities to adopt the program and that there is a benefit to student gains when the duration of the CURE is increased (*12*).

Genomic Consortium for Active Teaching (GCAT; www.bio.davidson.edu/gcat).

The GCAT is a nationally supported CUREs with a more decentralized or directed approach. The three sub GCAT foci provide online resources as well as materials for faculty wishing to incorporate molecular biology into a CURE. GCAT Chip provided chips/microarrays from a range of species for analysis and assessment. While the chips are no longer provided, there remains a support system for those wishing to adopt the project for their own needs. The GCAT pClone and Synthetic Biology project are approaches in which faculty can use the materials to generate a CURE. While the workshops are no longer funded, the resources and training materials along with instructions to obtain plasmids and other materials are still in place. The pClone system gives the students the ability to use the scientific process to design and own projects asking about the effects of mutations or regulatory proteins on transcriptions using the pClone system (*50*).

A newer and developing semi-centralized community of CURES is developing to fill the need for a protein or biochemistry centered approach. Each of the national projects described so far is genetics and molecular biology oriented. While there are plenty of persuasive examples of individual or small clusters of faculty creating a range of CURE research topics, there has been until recently a lack of more extensive programs. Two NSF funded programs Biochemistry Authentic Scientific Inquiry Lab (BASIL) and the Malate Dehydrogenase CUREs Community (MCC) are beginning to fill this need.

Malate Dehydrogenase CUREs Community (MCC; www.mdh-cures-community.squarespace.com/contact)

Another protein-centric CURE project focuses on a single enzyme, malate dehydrogenase (MDH). Building on the experience creating CUREs in their courses and programs (*13*, *51*, *52*) and the research experience the MCC provides structure and support for faculty adopting CUREs in entry and advance courses for a range of institutions including community colleges. The CURE centers on MDH because the protein is stable, the enzyme assay straightforward, and inexpensive. Importantly there are many unanswered exciting research questions. Participants in the MCC have

access to a large range of His-tagged bacterial expression constructs of MDH from organisms ranging from plant and mammalian, to salt or cold-adapted organisms, parasites, and photosynthetic bacterium. Currently being developed are resources to support adopters including training resources, protocols, learning outcomes and rubrics. MCC CUREs conducted in modular form running either half a semester or a full semester and are all based on a hypothesis development and proposal module. Faculty wishing to focus on kinetics, allosteric properties inhibition or evolution and adaption of MDH will find validated protocols, learning goals, guides, and other resources in the mechanism cluster. Two other clusters supporting CUREs include the protein conformation cluster (structure, function, folding and dynamics) and cellular biochemistry cluster (post-translational modifications, protein-protein interactions, and genetic regulation). The MCC involves a consortium of 16 institutions that are asking pedagogical questions on the duration of a CURE and the impact of collaboration between students.

Biochemistry Authentic Scientific Inquiry Lab (BASIL; www.basilbiochem.github.io/basil/index.html)

The BASIL project is intended for biochemistry laboratory adoption, and is amenable to lower-level courses and even for use in outreach activities. A collection of affinity tagged plasmids containing the genes for Protein Data Bank entries described as having an unknown function from the starting point for this project. From this database of over 4000 proteins (*53*) the BASIL group has focused on proteins predicted to be similar in structure or predicted function to a hydrolase. As described, this allows an open-ended research project using an enzyme assay that is reasonable and cost effective. While described as an inquiry lab, BASIL addresses the key dimensions, qualifying the project as a CURE. Using computational tools, students are asked to predict the function and suggest physiological substrates for the selected protein. The scientific process begins with well-defined modules guiding the students through bioinformatics and docking software. Students then use literature and propose a hypothesis and test their CURE. Paul Craig, one of the founders of the BASIL program states "In the CURE setting, we want our students to be fully engaged as scientists, including hypothesis creation, experimental design, data collection and analysis, scientific writing and presentation. To help students move from a "cookbook lab" setting to hypothesis creation, we get them started on the parts of an experiment that are well established, e.g., expression and purification of a protein, then we provide them with tools to explore that protein in the wet lab (molecular weight determination, protein concentration), as well as computational tools and exposure to the literature. We challenge them to identify the things they know and the things they don't know about the protein and then create a hypothesis about the protein, such as its function or potential binding partners. Then they have to design experiments to confirm or deny that hypothesis". Support for BASIL faculty members includes assessment, blog posts, online tutorials for the bioinformatics modules, a community of faculty to support the development and entry is inexpensive with a ten clone starter pack for under $50. As the assessment of this project is transferable to other CURE projects, we will discuss the BASIL assessment approach in the assessment section of this chapter. A description of the development of the project has been published and, along with the website, contains a support system for CUREs that should be self-sustainable (*54*).

Other CURE Examples

The Freshmen Research Initiative (FRI; www.cns.utexas.edu/fri) is a hybrid research and education program hosted by the College of Natural Sciences at the University of Texas at Austin

(55). Since its creation in 2015, Fri has served more than 6,000 students. It annually reaches more than one-third of each natural science freshmen class, including 40% of each cohort coming from underrepresented groups. Faculty create "research streams," which are ongoing projects for students to engage in a research project. A research stream is a three-course research sequence serving 35-40 students. The first course is a research methods class, and the second two courses in the Stream are semester-long CUREs. Faculty Stream mentors are supported by an educational post-doctorate or a PhD-level research educator and funding for the Stream. The program serves between 900 students in 2015 with 27 active research streams. UT Austin Fri advertises over 200 publications have been created with student co-authors in the Fri program. Six different institutions, including Iowa State, University of Maryland and Binghamton University SUNY have replicated the first-year CURE experience. The beauty in this program is the organized approach a university commits to bringing research faculty together with hundreds of freshmen students and supports the organization and structure. Like the outcomes from SEA-Phages, this first-year experience finds that students involved in the CURE program are more likely to graduate with a STEM degree (17% higher 6-year graduation rate in STEM) than those students who do not get the experience in the first year. Also particularly exciting is that the experience has the same impact regardless of race, gender, or first-generation status, indicating that first-year CUREs have the potential to truly broaden the outcomes for all students (*56*).

Another structured, systematic approach to bring the research experience and positive outcomes to a broad audience at research-intensive universities include the Center for Authentic Science Practices at Purdue, the Vertically-Integrated Projects Program at Georgia Tech, and CU Boulder. Other examples of multi-university collaborations integrating research in introductory chemistry courses include the Center for Authentic Science Practice in Education (CASPiE (*57*); and Research Experiences to Enhanced Learning (REEL (*58*); program. Finally, UCLA has created a scalable framework to give students a supported CURE or URE option in their upper-division in the life sciences. The Competency-based research laboratory curriculum (CRLC) has served over 1000 between 2010 and 2016. Students who elect the CURE path (vs. a sponsored URE path) will take two 10-week laboratories (*59*).

In addition to the system supported CUREs in large universities, community colleges also have several key examples. As part of a $1.1 million grant from the Howard Hughes Medical Institute, Hamline University partnered with two community colleges, Century College and North Hennepin Community College to develop the Engaging Science Students through Investigative Research Program. Through this partnership, biology, biochemistry chemistry, physics, premed, and pre-health science majors have opportunities to participate in research projects under the direction of faculty mentors. These projects are integrated as short two- to four- week modules into existing chemistry and anatomy classes with plans to expand the CUREs into additional courses. There is also a network of community colleges (Community College Undergraduate Research Initiative; www.CCURI.org) that supports the development of CUREs within a growing consortium of community college faculty.

Examples of Various CUREs Implemented across Scientific Disciplines

Chemistry

At Emory University, the second semester of physical chemistry was converted to a semester-long CURE experience (*60*). This CURE focuses on the interaction of uremic toxins with the protein human serum albumin. Students were introduced to the research topic and techniques needed for the

CURE over the first four weeks. Students were given the overarching research problem and worked in rotating groups to test and create data that was iterative (repeating data through rotating groups) and worked as a class to analyze and interpret the results. Using the Lopatto CURE survey found similar positive gains across the survey as other CURE experiences. While the authors admit they did not expect these results from an upper-level class when many of the students had already been involved in research, the students reported increased tolerance for obstacles, collaboration, and increased ownership. Gourley and Jones recently published a series of concrete examples of CURE and CURE like activities to "fill the gap between generalized or holistic assessments and individual classroom/laboratory innovations which can serve as models for adoption" an ACS book (*61*). An example is self-defined as "collaborative undergraduate research" in the classroom where over 15 weeks, students conduct structure-function protein research conducted in the department of chemistry, University of Wisconsin-Eau Claire (*61*). This, like much of the other works described by Gourley and Jones, have the essential elements of a CURE. A chemistry CURE reported in JCE utilizes Inorganic Chemistry (*62*). The University of Vermont created an inorganic chemistry laboratory to fill a set of needs in their inorganic discipline and used the opportunity to provide students with a CURE. The research project centered around creating a catalyst for the dehydrogenation of ammonia borane using transition metals. The course was designed to align with the key components of CURE as described by Auchenloss et al. (*35*). Using the CURE survey, showed gains in their understanding of the scientific process, ownership, and research activities.

Biochemistry and Molecular Biology

Familiar to many, lactate dehydrogenase (LDH) is an enzyme that has been used in inquiry labs for many years (*63*). Ayella and Beck converted the experience into a CURE where students generated a hypothesis, learned skills in expression, purification and enzyme assays, performed site-directed mutagenesis based on their hypothesis and performed independent experiments examining their scientific questions (*64*). Collaborating between two institutions, private liberal arts McPherson College and the public Wichita State University, the students self-reported the types of gains seen for other CUREs and some students, who were not exposed to research before, continued this as an independent research project. The Peterson group provides another example of individual biochemistry and molecular biology CUREs that use gene expression as a research question (*65*). This research focuses on a sigma factor, RpoS, which regulates RNA polymerase in Escherichia coli and is itself controlled at many different levels. Three universities, Suffolk University, Wellesley College, and DeSales University, coordinate to create a 9-week or a 5-week CURE. Here, students identify genes regulating RpoS, then generate a hypothesis on how the genes might impact RpoS at the transcription or translation level. Using an overexpression screen with an RpoS′-′LacZ reporter, students discover their candidate genes and develop a hypothesis on how the candidate genes affect RpoS by analyzing the domains of the proteins. Finally, they tested their hypothesis with a series of different LacZ reporters. Using a range of internal assessments of learning outcomes and attitudinal surveys, students each showed an increase in learning of specific concepts and ability to analyze specific data, indicating that for this CURE students were able to learn concepts as well as more generalized outcomes.

Biology

A novel approach is described by Kowalski et.al where three interdisciplinary CUREs from biology, chemical biology, and neurobiology were created around a central research theme (*66*).

Students take one or more of the CURE courses set up in biochemistry, chemical biology or a neurobiology semester-long courses. In the design of this unique CURE, there was an intentional and collaborative element integrated to between each CURE in the various courses. Student learning outcomes of concepts and experimental skills were conducted using an in-house instrument as a pre-post course instrument and used the CURE survey. Five goals were assessed: Generate novel data relating to the common project, develop students' experimental design and data analysis skills, promote positive attitudes about science and perceptions of learning gains, promote student retention in STEM disciplines, and promote faculty research productivity. Overall there was a significant and measurable increase in both new scientific knowledge and increased faculty involvement. Getting new data and keeping faculty involved is critical at a PUI. Several manuscripts have been generated using the data.

In addition to the larger inclusive and system supported CUREs we have provided a list of institutional approaches to broaden access to research and a small sampling of individual-smaller scale CUREs to demonstrate the range of approaches to giving students the critical research experience. A longer list of CURE examples across diverse disciplines can be found in JCE, BAMBED, the Chemical Educator (TCE), Journal of Microbiology and Biology Education, and CBE Life Sci) and a growing list of CURE programs and individual CURE examples can be through the CUREnet website (*67*).

Pedagogical Research: CURE Learning Outcomes and Assessment

> "We operate on the principle that undergraduate research is not only the essential component of good teaching and effective learning, but also that research with undergraduate students is in itself the purest form of teaching."
> *Jim Gentile Past President Research Corporation, Dean Emeritus College Natural and Applied Sciences -Hope College, AAAS Fellow, National Associate-National Academies of Sciences* (*6*).

While there is a collective agreement that UREs and specifically CUREs are important in the development of undergraduates, missing is a robust understanding of the mechanism or connection between specific dimensions and activities to outcomes. Much of the published CURES do not examine which part of a CURE leads to an improvement in a given outcome(s)? Thus proper assessment must be conducted.

Which type and level of assessment best used to evaluate a CURE depends on the final goal of the faculty involved. There are three reasons and depths of assessment. For those who want to locally (for the investigator's own measures, a department or informally to report CURE outcomes within an institution) will be much different than the type of assessment needed for publication or (and possibly not different) from the assessment needed to assess student outcomes adding to the comparable data to effectively evaluate the causal effect of CUREs on student outcomes.

To better understand how to plan and interpret assessment, one should start with a simple primer. First, are the six types of assessment of learning. 1) Diagnostic assessment or pre-assessment is to measure a students' strengths, weaknesses, and knowledge before instruction. Such assessment is particularly important when considering what will be measured for an introductory vs. advanced or capstone CUREs. This type of assessment will inform how you will form a CURE and influence the outcomes. 2) Formative assessment is used to measure outcome progress during a project. The goal is to monitor progress to provide feedback and identify progress and gaps. 3) Summative assessment are aimed at measuring student gains at the end of a CURE. An assessment of the extent that a set of outcomes have been reached or the effectiveness of learning. 4) Confirmative assessment is used

after a CURE has been running and an examination if the instruction is still a success – sort of an extended version of summative assessment. 5) Norm-referenced assessment to compare a student's performance against an average and often a national norm. As the SURE and CURE surveys are now closed, but with permission, can be used as a norm-referenced tool, faculty can assess their student's gains against the national norms. And finally, 6) Criterion-referenced assessment measures a student's performance against a goal or specific standard. Something they are expected to know. For some, this might be the type of assessment used to measure a specific domain of knowledge and skills.

Outcomes – Most simply defined, the benefits of a CURE are the learning outcomes most desired for our students after they complete a CURE. Sometimes the term "learning goal" is used interchangeably with "learning outcomes." Think of an outcome as a statement that describes the knowledge, skills, or behaviors a student should gain. Outcomes are specific and use active verbs making the outcome clear. These are different from learning goals, which are broad descriptions of what the CURE will accomplish, such as expose students to research methodology. Whereas a learning outcome, those benefits of the CURE such as content knowledge, motivation, understanding the process of science, and persistence in science. The source of CURE outcomes originates from the community of scientists. Some are published (*35*, *68–70*), and others come from the experienced and consensus of practitioners of our collective disciplines. An outcome is measurable using verbs that specify the student gain (behavior, skill, concept, ability…), often using active verbs from Bloom's Taxonomy. To create a more valid outcome, one must use multiple lines of analysis to be sure of the outcome. For some, this might be a conversation of faculty and educational experts. Irby et al. propose an exciting approach to moving what they propose as anticipated learning outcomes that are written before and without the feedback of what happens after a CURE or project has been completed (*64*). Using a defined a data-driven approach which involves a close analysis of the process of a proposed outcome, multiple faculty input and review and an alignment check with a review process to mature an outcome to a "verified outcome." While the authors describe the process for a specific type of outcome, their work demonstrates how careful use of multiple inputs can create appropriate, useful, and assessable outcomes.

Following a rigorous evaluation of publications describing CUREs, the Dolan group described a logic model for CURE instruction to organize variables in CUREs. In their model, the Dolan group evaluated outcomes based on the time of participation of CUREs. Early or short-term outcomes (analytical, technical, content skills) that are both more readily assessed with prepared assessment instruments and achieved early in the process of a CURE, medium-term (motivation, collaboration science appreciation sense of belonging to a larger community…) and long-term outcomes (self-authorship, resilience and grit, persistence, science identity…) that may even need assessment after the CURE is completed (*35*, *70*) Another more applied set of outcomes for CUREs is described by Irby et al. where they use a five-step evaluation method to validate CURE leaning outcomes (*71*).

The next step in the assessment of a CURE program is mapping outcomes to CURE activities and dimensions. Aligning CURE activities and dimensions is critical to extending the understanding of the impact of a CURE, how the implementation of a CURE design is useful and leads to student outcomes while supporting the national dialogue on CUREs. To properly accomplish alignment, we must move beyond the approach of assessing only the outcomes. To measure the mechanism or causal elements of a CURE, educational research experts and discipline based-education research (DBER) encourage practitioners to use social learning theories to build a framework in which appropriate assessment and gains can be understood (*6*, *27*, *35*, *72*) Practitioners, defined here, are those "*faculty and instructors in the trenches without specific graduate training in science education*

research". Appropriate theories of student learning and development must be selected to make the connections and then apply existing or create validated assessment instruments to measure the outcome.

Fortunately, a number of models describing pathways of dimensions/activates to specific outcomes aligned with potential assessment instruments have been suggested (*72*). These pathways and assessments apply a range of student and social learning theories, social cognitive theories, and applying epistemological development, several models linking a set of activities from CURE dimensions and outcomes are described for adoption. Learning theories include behaviorism, social learning theory, cognitive learning theory, constructivism, and social constructivism. Starting with various dimensional activities, early, mid- and late outcomes are aligned, and connect the activities to the outcomes. Such analysis helps define what might be done in a CURE, the outcome from that activity, and suggest off the shelf assessment to investigate the mechanism of learning gains.

Choosing the right assessment instruments is critical to measure the appropriateness of the dimension or activity in question. The often-cited CURE and SURE surveys are self-reported assessments of students to measure student experiences in research like courses. Unfortunately, while often used, the surveys have been reported as limiting. A meta-analysis of CUREs and UREs published between 2010 and 2015, identified only a small number of studies used validated assessments beyond self-reported gains to determine the gains in conceptual learning or research highlighting a need to identify ways to best design both UREs and CUREs to promote learning (*72*). Similar results were reported by the National Academies which conclude that research on the efficacy of UREs and CUREs are 1) in the early stages of development, 2) that only a small number of studies have employed research designs that support inferences about causations and 3) call for CUREs to incorporate the types of assessment that move beyond described cases or correlational designs for a single CURE (*6*). After analysis of published CUREs, educational researchers find the theoretical framework (the principles used to explain, predict, and understand the outcomes of learning) important to ascribe learning outcomes missing (*73*, *74*). Thus it is critically important, for the assessment of CUREs to have meaning to use more sophisticated and appropriate validated tools.

Unfortunately only a few validated assessment instruments or "off the shelf" assessments are available. The Laboratory Course Assessment Survey (LCAS (*75*); uses student perception of the dimensions based on inputs from UREs to characterize if the student's CURE experience is distinguished from a traditional laboratory. The four-point scaled (Likert like) instrument can be used to link particular elements of CURE design to activities and outcomes. The Experimental Design Ability Tool (EDAT) and the expanded EDAT are open-ended tools to measure student's ability to design experiments using a simple experimental design prompt in a pre/post-test format (*76*, *77*). The exam is a description and prompts given to students to think about and design a basic experiment. The format is a short essay. For instructor use, can be used as is. For pedagogical use requires training and validation of multiple evaluators to be useful. The EDAT does not measure quantitative skills, and as the content and terminology is general, the instrument works for a range of students. The Extended EDAT (EEDAT) has a more defined set of prompts and grading rubric to measure the same outcomes (*77*). Another survey using a multi-point response survey is the Project Ownership Survey (*78*). This survey asks students to rate the level of agreement of intellectual responsibility on a project. The survey investigates three factors, emotion of the experience of the laboratory course, project ownership, and the type of course in a series of questions. The ownership survey is described to help identify design features of experiences that enhance student ownership and is appropriate for full student/faculty use. An interesting instrument intended to measure the development of intent to persist in STEM throughout a summer URE is the Student Integration

into STEM Careers and Culture (*79*). Highlighting several factors that impact student persistence the instrument, with support from an educational expert should be amenable to a CURE. As an exemplar, the study on discovery, iteration, and collaboration of students in CURES used three of these instruments to measure the gains (*80*). Although many of these instruments are validated, many more are described in the various publications that must be adapted and tested before the instrument can be used for pedagogical research (Box 4).

BOX 4 - A CALL TO ACTION. UNIFYING THE PRACTITIONER WHO WANTS TO PUBLISH AND THE PEDAGOGICAL EXPERT

What we have here is a failure to communicate - Cool Hand Luke 1967. For those practitioners who want to engage in pedagogical research here is the barrier we see and how to address it. The growth of pedagogical engagement as it has moved from the classroom into the laboratory is impressive, exciting, and still growing. Instruction of student learning in the teaching laboratory has long since moved from aligning lectures with labs, and lists of skills to inquiry and CUREs. In the "early days," innovators created and invested themselves in engaging students. It was a time of shared community, and a sense of purpose as meetings about how to improve laboratory teaching was in its infancy. In 1990, Ernest Boyer argued for the scholarship of teaching to be placed on par with basic research discovery (81). And as noted by John Moore, the call did not take hold, and some might say the research of teaching has yet to fully be embraced as an equal to basic science (82). In the 1997 JCE editorial, Moore wrote "It seems to me that we are on the threshold of significant developments in action research in chemical education. A great many teachers of chemistry are interested in experimenting with how they can help students to learn. We are beginning to develop ways to evaluate successful innovations according to our existing epistemology, even though we are far from being able to provide evidence that would convince skeptics". It was at this time that groups like Project Kaleidoscope (PKAL), ASBMB and ACS increased their focus on the scholarship of teaching. In the late 1990s to early 2000s, meetings were focused on research education of teaching. In the late 1990s, satellite meetings of small groups of biochemists met and shared ideas. In 2000s ASBMB moved the content to the main meeting and ran symposia on teaching biochemistry pedagogy (43). Much of this work mirrored activities hosted and coordinated by PKAL. In 2007 CBE-Life Sciences Education began to run a series of articles to help nonexperts become familiar with the science teaching literature as the gap in the educational experts and science faculty was too large to appreciate and use (83-84). These efforts initiated a change of how the science community teach and think about teaching. Paralleling this change was the development of the scholarship of teaching and learning (SoTL; 85), and discipline-based education research (DBER; 86) and the hiring of science-research experts into science departments (87). Whereas SoTL is the practice using pedagogy, assessment, and methodologically sound approaches to teaching DEBR is an interdisciplinary approach bringing social science research that explains learning with and from the scientific discipline's perspective and practice.

Despite the significant growth of empirical research on undergraduate teaching and learning, the communication between practitioners and research experts is more complicated and less accessible. Unfortunately, over time, there has been a widening of the gap between the practitioners and the rigorous approaches described and defined by DBER and other educational research experts. There are many excellent sources to help ask epistemological questions on educational research, but as evidenced by the call for better assessment of CUREs, these are not being used. To address this gap clear communication is needed.

Perhaps it is because there are only a few "shelf-ready" assessment tools. The average faculty struggles to adapt and validate existing tools as often described because of the unfamiliar terminology and literature. Complicating and growing the divide is the need to investigate even more convoluted paths of outcomes, activities, and dimensions using social science research of framework and other the approaches well outside of the scope of our discipline. This, coupled with a lack of experts needed to ask for collaboration or help leave many practitioners unable to meet the call of the National Academies. The question remains: How can we make excellent publications describing the appropriate approach to educational research more reachable by the practitioner? The answer lies in basic research. Considers the explosion of cell signaling research after inexpensive and easy to use, commercial phosphor-antibodies became available. Understanding ERK signaling alone skyrocketed once the ability to test for ERK activation using phosphor-ERK and ERK antibodies reached the market. A similar validated, easy to use for the average faculty will make the goals of what parts of a CURE are effective and how to engage faculty will happen when the tools and communication bring the two groups back together.

Practical Approaches: Organizing Your CURE

There are a number of resources that take different approaches on how to design a CURE including the backward design (*88*, *89*) and a case-by-case approach with examples provided by the Research Corporation (*26*). Using the practice of backward planning, starting with outcomes is the preferred approach to designing a CURE and its assessment. Education has embraced this approach (*88*) to design curricula, courses, activities, and now CUREs (*89*). Another approach to create a CURE is to participate in one of the CUREnet workshops (*67*). Advice on how to start a CURE that includes a helpful checklist and a description of how to overcome barriers has been described by Bell et al. (*13*).

Here are a few important points to consider when organizing and creating your CURE:

- What are the broad goals of your CURE? Will it be an entire course or for a portion of a semester? Is this CURE for entry-level (gateway) courses or an upper-division experience? Are there departmental or institutional goals that need to be considered?
- Identify a pilot CURE. Start with a simple pilot that you want to adopt (with the same experimental plan or your own research idea). Allow yourself to establish a proof of principle and gain some practical experience and allow your CURE to evolve over time, rather than make the one perfect large-scale CURE. Be flexible as the project evolves to adjust for scheduling, troubleshooting and the types of chaos that research will bring.
- Consider the outcomes already defined in the literature described here and engage your stakeholders to create, review and define your outcomes.
- Using one of the models analyzed map the outcome(s) to an activity and dimension. If creating new outcomes use the guidance of Corwin et.al. or work with a DBER or education research specialist (*75*).
- While the effectiveness of hypothesis has yet to be fully examined, inclusion of a hypothesis module.
- Define the research goals (experimental) for the students. What are the resources and time needed to ramp to the CURE or time to complete the CURE. Remember that iteration is one of the key dimensions along with duration that have shown to have positive impact on student gains.
- Ask what are the skills and backgrounds students bring to the CURE. Will some be more capable with a URE experience? How will you balance the diversity of skills and attitudes brought to the CURE?
- Articulate how you will mentor your students through the CURE. Will you have check-points, research milestones, expectations, mini-meetings, scientific and development goals to provide students guidance and grades.
- Research the final output of student work – oral presentation, poster, final paper.
- Define the balance of student responsibilities in the CURE. Hypothesis, method development, decision points, background and literature development.
- Identify the training support will students need? Will students need help with skills such as pipetting, making solutions and buffers, statistical analysis, protocol and instrument support. Knowing what the need and providing the resources before the semester starts is a stress reducer.
- Develop cohorts of faculty. Work with other faculty as you create your CURE. At the department level, discuss with your peers, review your plans with your chair/head, find a

group of like-minded faculty to present your "rational and data" for your CURE. Feedback of this nature is important in the iterative process of backward planning.

- Map your research to the class size and outcomes. Will all students do a unique aspect of the project? Will there be overlap or duplication within the course?
- Design the assessment. If this is a pilot or a CURE that you don't plan to share or publish, use the appropriate assessment. If you plan to grow the CURE beyond your institution for grant, publication or sharing with the scientific community, engage a DBER or research educational specialist to guide through the assessment.

ACS and ASBMB Accreditation and CUREs

One of the motivations to integrate research into the laboratory is to provide a research experience for a broad audience. The ACS and ASBMB each promote research as part of their accreditation; however, neither has a requirement for research in their accreditation evaluation. The ACS requires 400 hours of laboratory experience beyond general chemistry laboratories. If a program does not meet the 400-hour requirement with the traditional laboratory hours (i.e., organic, biochem, physical chemistry … labs) a program seeking accreditation can count up to 180 hours of the 400 hours of laboratory time to meet the minimum requirements. If research is used to count hours, a set of graded research reports must be submitted for evaluation. The ACS Committee of Professional Training (ACS CPT) will not accept laboratory reports for a research write-up. However, in addition to evaluating various aspects of a program, the ACS accreditation process values pedagogical approaches, development of student skills including problem solving, team and communications skills as well as a research experience for the students. A CURE provides evidence of these items for accreditation and renewal. Programs submitting materials with inquiry or CUREs as part of the student experience are viewed favorably. The ASBMB also has a minimum expectation for laboratory hours (400 hours, including general chemistry) and is recommended that at least one of these experiences be research/inquiry-based. The ASBMB accrediting body recognizes that it is difficult for large or small schools to provide all students with a research experience; they do appreciate the experience that CUREs bring to a program and outcomes for students.

Future of CUREs

Two concerns need to be addressed: 1) the issues of persistence, and 2) enhancing the diversity of STEM graduates to sustain future STEM workforce needs. CUREs are important in solving these needs. First, we must continue to mature the appropriate assessment of dimensions and activities of CUREs to make their implementation both more effective and efficient. Second, we must continue to create better ways of lowering the energy barriers needed for faculty and programs to increase the broad and early implementation of CUREs in the curricula.

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