# Transforming Laboratory Education in the Life Sciences

*A scalable framework for designing authentic undergraduate research experience-based courses benefits both students and faculty*

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Throughout college, students encounter experiences that influence their decisions to continue or leave their intended science, technology, engineering, and math (STEM) majors. All STEM faculty share in a responsibility to encourage undergraduates to persist in these studies. Evidence continues to support active learning as an equitable teaching practice that benefits diverse student populations, including women and underrepresented minority students most at risk for leaving STEM. The hope is that more STEM instructors will move away from the traditional lecture format as the primary mode of teaching undergraduates and that institutional leaders will reward those faculty who use inclusive, student-centered teaching practices effectively.

Also deserving reexamination are the ways in which laboratory instruction is being delivered to college students. As with alternatives to conventional lectures, student-centered teaching strategies can be tailored to undergraduate laboratory courses. For instance, inquiry-based learning experiences, when incorporated into undergraduate instructional laboratories, can help students apply the process of science by posing questions that require students to engage in scientific explorations of their natural world and that challenge their conceptions of scientific phenomena. This approach also better prepares students to tackle interdisciplinary problems that mirror those they will encounter outside universities and colleges.

One particular approach to inquiry—an authentic research experience—plays a critical role in capturing the imagination of undergraduate students. By sustaining their interest in science, students are more likely to complete degrees in their intended STEM majors. The positive outcomes associated with research engagement are prompting others to explore ways by which to scale this inquiry-based learning strategy to entire undergraduate classes. These course-based undergraduate research experiences, or CUREs, can be devised to support the participation of diverse groups of students, including directly admitted and transfer students as well as students with limited time for activities due to off-campus employment or housing that necessitates commuting long distances. Altogether, CUREs embody an inclusive teaching approach that helps to keep students on track for completing bachelor degrees in STEM majors.

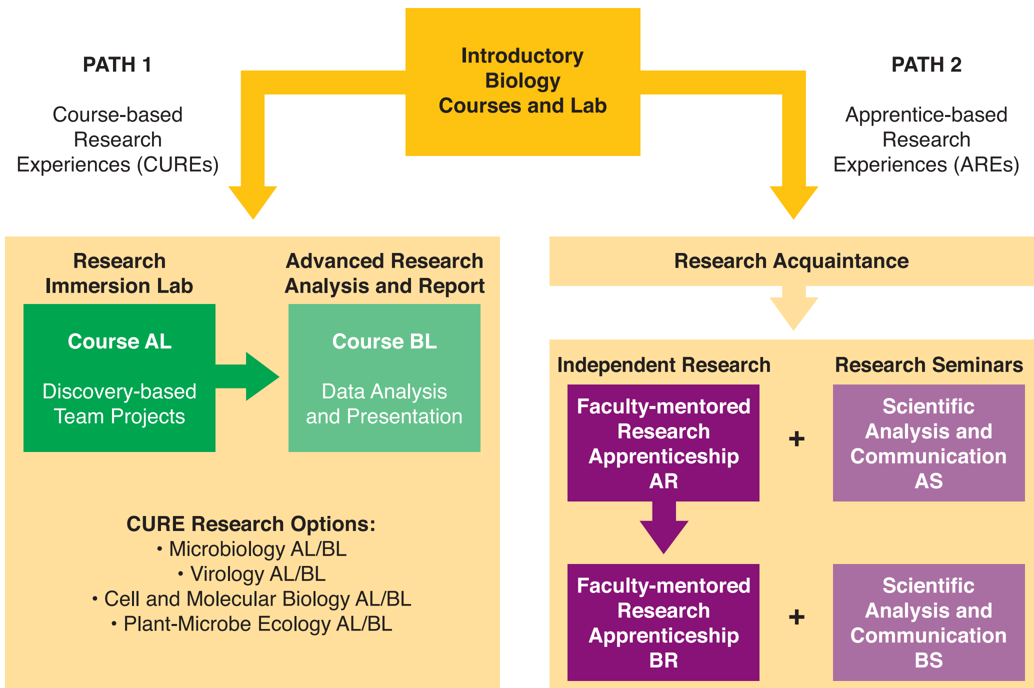
## Creating a Framework for Undergraduate Research Participation

In 2010, the University of California, Los Angeles (UCLA) implemented the competency-based research laboratory curriculum (CRLC), a framework that enables large numbers of upper-division undergraduate students pursuing a life sciences major to experience authentic research. After com-

**SUMMARY**

- **Course-based undergraduate research experiences (CUREs) and apprentice-based research experiences (AREs) represent inclusive, student-centered instructional strategies that can improve student learning and help to keep them on a scientific career pathway.**
- **Using backwards course design ensures that educators and faculty align research activities with the learning outcomes and that selected assessments provide adequate evidence of student achievements, visualized via curriculum mapping.**
- **Rubrics are suitable assessment tools for measuring how students perform in these research-based laboratory courses.**
- **Faculty benefit from teaching CUREs and mentoring students in AREs in ways that enhance both their teaching portfolios and research productivity.**

FIGURE 1




**Competency-based research laboratory curriculum (CRLC) for Life Sciences majors. Course requirements for each path are enclosed in separate gray boxes stemming from arrows labeled Path 1 and Path 2, in reference to the course-based undergraduate research experiences (CUREs) and apprentice-based research experiences (AREs), respectively, described in the text. Figure reproduced, with permission, from C. Shapiro et al., J. Microbiol. Biol. Educ. 16:186–197, 2015.**

pleting requisite lower-division core courses, students fulfill departmental major laboratory requirements by following one of two paths. Path 1 engages students in CUREs as a laboratory option, while path 2 embraces apprentice-based research experiences, or AREs (Fig. 1).

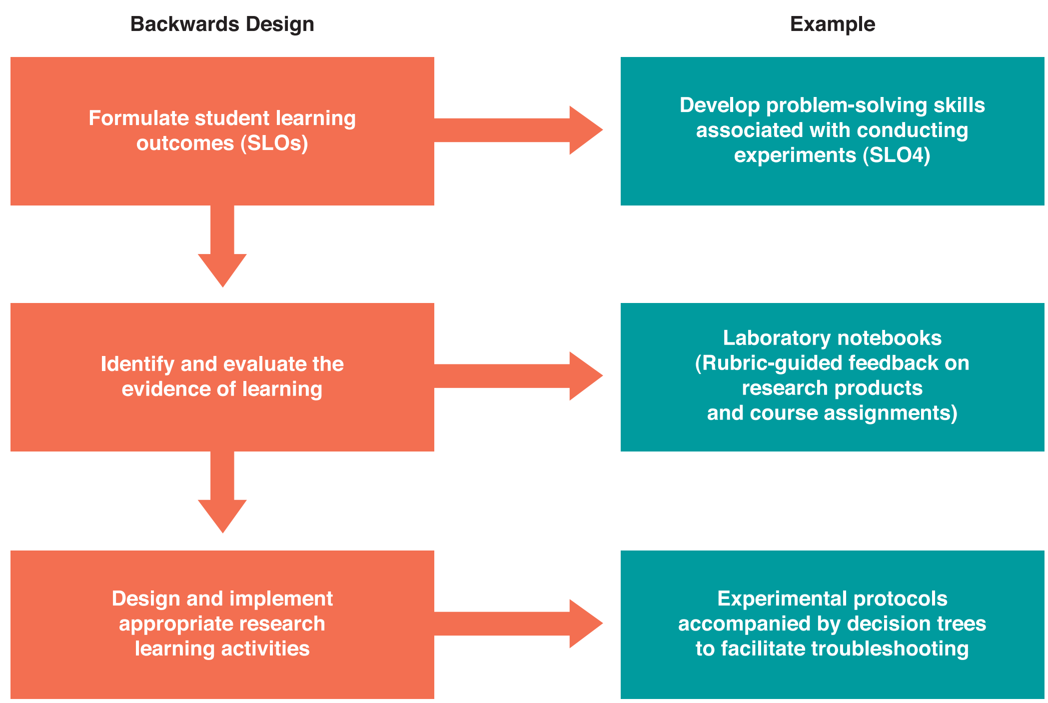
These two laboratory options offer third- and fourth-year life sciences students comparable research experiences that account for varied levels of academic preparedness, confidence and proficiency in laboratory skills, and commitment to or interest in research. Both paths support student learning as well as the development of skills and abilities that align with desired learning outcomes. Development of this program relied on a strategy called backwards design.

## Overview of the Competency-Based Research Laboratory Curriculum

When entering the CRLC at UCLA, path 1 students enroll in one of four 10-week laboratory courses, termed Research Immersion Labs (Path 1, Course AL), followed by a second 10-week course called Advanced Research Analysis & Report (Path 1, Course BL). Throughout both terms, students work together in teams to collect data, analyze preliminary results, read and evaluate items in the scientific literature, give oral presentations, and document their research discoveries and accomplishments. Each pair of path 1 AL and BL courses make up a CURE.

Among four options, each CURE focuses on a different research project (Fig.1). Briefly, in the microbiology CURE, students explore microbial diversity in plant rhizospheres; in the plant-microbe ecology CURE, they examine the effects of inoculating plants with bacteria from the rhizosphere; in the virology CURE, they isolate bacteriophage, and characterize their genome compositions and structures; and in the cell and molecular biology CURE, they investigate the expression patterns and evolutionary history of genes in the sea urchin genome.

FIGURE 2




**Backwards course design applied to the CRLC. Example starts with 1 of the 10 SLOs articulated for the CRLC during its development. Laboratory notebooks were identified as one source of evidence subject to assessment via rubrics. Decision trees were incorporated into experimental protocols as a project activity to facilitate student achievement of the specified learning outcome. (Adapted from Wood, W., Annu. Rev. Cell Dev. Biol. 25:93–112, 2009.)**

Path 2 of the CRLC engages students in two consecutive 10-week terms of independent research, courses AR and BR. This path requires their concurrent participation in sequential research seminars, courses AS and BS, where students read and discuss relevant scientific literature, as well as give presentations about their individual research projects. Despite involving more than 80 different path 2 faculty mentors since its implementation in 2010, the CRLC achieves consistency across AREs by having the AS and BS seminars taught as a series with the same instructors both terms.

## Curriculum Design as an Intentional Practice

Backwards design involves three key stages: (1) identify the desired results by formulating student learning outcomes, (2) determine acceptable evidence of learning to be collected and evaluated during the course, and (3) plan the learning experiences to ensure students achieve the desired results (Fig. 2). We employed this design strategy in the development of the CRLC.

Common to the two paths in the laboratory curriculum are 10 student learning outcomes (SLOs). For instance, students completing the CRLC are expected to develop problem-solving skills associated with conducting experiments (SLO 4 in Fig. 2). Research products and embedded course assignments were identified for each SLO and evaluated to determine the extent to which students achieved the desired learning outcomes. For SLO 4, laboratory notebooks were collected and subjected to assessment for evidence of learning.

CRLC faculty subsequently designed research and learning activities to support students in their development of the knowledge, skills, and abilities reflected in the SLOs. In the case of SLO 4, faculty asked students to use decision trees to rationalize unexpected experimental results and to troubleshoot and repeat failed experiments. These activities were logged and explained in their laboratory notebooks. Alignment of learning outcomes, assessments, and CRLC project activities was all part of this backwards design process.

### Making Performance Standards Explicit Using Rubrics

The CRLC learning outcomes require students to exercise lower- and higher-order cognitive skills (LOCS or HOCS, respectively), as defined by Bloom's Taxonomy. This hierarchy comprises six levels, with each level connected to action verbs that are appropriate for learning at that level. More importantly, the verbs describe a type of competency or conceptual understanding that can be directly measured by evaluating embedded course assignments and research products.

Research-based laboratory investigations enlist benchmarks of student progress not readily captured by, say, multiple-choice exams. Thus, CRLC student performance standards are formulated using rubrics— evaluation tools that scale levels of ability and conceptual proficiency. One set of such rubrics was generated by using action verbs to describe what CRLC students are expected to do on an assignment shared by CURE and ARE students. These rubrics were then used to evaluate and compare student learning in each path.

The analysis suggests that course-based research experiences gradually reduce the achievement gap between high-performing ARE students and their peers in CUREs. We might not have recognized this result had we relied entirely on self-reported data generated through surveys. Furthermore, we could not readily compare CUREs to AREs without having shared student learning outcomes (SLOs) for all our student participants.

Our rubric creation process involve categorizing items as LOCS or HOCS, and, when finer distinctions are preferred, at one of the six levels of Bloom's Taxonomy. Rubric items, in turn, can be translated into a list of learning objectives, which serve as explicit statements about the performance expectations of a "successful student" who engages in a particular research or learning activity. Learning objectives represent measurable instructional goals that are not as broad as student learning outcomes (SLOs). A list of learning objectives can be given to students to guide them in building skillsets while making explicit the performance criteria, which they are expected to meet on a given assignment or research product.

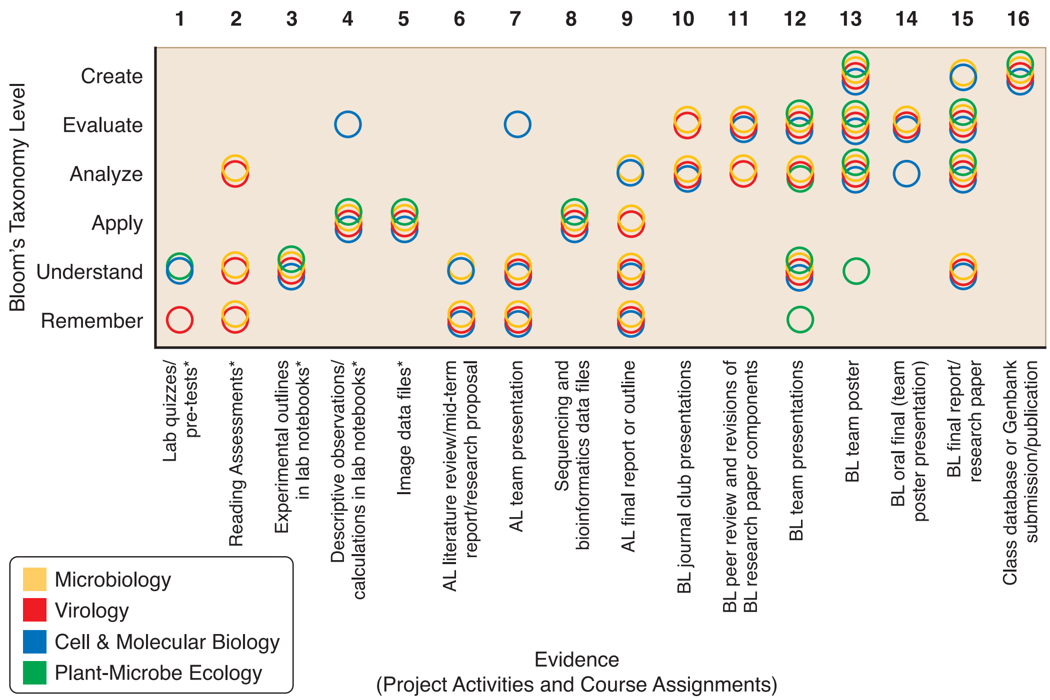
Plotting the learning objectives for various project activities and course assignments over time produces a visual representation of a CURE learning experience (Fig. 3). This visualization, referred to as a curriculum map, shows that successful execution of the research projects by students in all four CUREs of the CRLC requires cognitive skills spanning the six levels of Bloom's Taxonomy. Curriculum maps are excellent tools for promoting discussions among faculty about how to align learning outcomes in ways that meet program, departmental, and college accreditation goals.

### Research-Based Laboratory Courses Engage Research Faculty

By integrating research into the undergraduate curriculum, the CRLC benefits a broad range of students. Moreover, this approach benefits faculty members, providing them with teaching and mentoring opportunities that make them better teachers and also can help with their own research programs. For instance, several students who studied under Ann Hirsch, a CRLC instructor, later joined her laboratory research group and contributed to several peer-reviewed publications. "Becoming involved in a research-based course helped me transform my teaching in ways that clearly benefited students, was much more fun for me to teach, and even enhanced my research portfolio," she says.

Since UCLA implemented the CRLC in 2010, many participating faculty mentors report increases in productivity in their own research programs. Collectively, across more than 80 research laboratories, faculty have published at least 65 peer-reviewed research articles with ARE students as contributing authors. During this period, hundreds of CURE students were coauthors of Genbank submissions based on their analyses of 16S rRNA gene sequences and bacteriophage genomes as part of this program. Additionally, a cohort of CURE students was acknowledged as coauthors on a 2013 ASM *Genome Announcements* report by Graham Hatfull of the University

FIGURE 3




**Applying Bloom's Taxonomy to map evidence of student learning and research accomplishments across the curriculum. Data points represent a subset of the learning objectives associated with various project activities and course assignments (Evidence) in each of the four CUREs (see color detail in the key). Learning objectives were classified according to the six levels of Bloom's Taxonomy based on the intellectual operations students were asked to perform. The first three levels (Remember, Understand, Apply) are considered lower-order cognitive skills (LOCS) and the top three levels (Analyze, Evaluate, Create) higher-order cognitive skills (HOCS). For illustrative purposes, the numerical score assigned to each Bloom's level (1- Remember through 6- Create) was adjusted by ±0.1 or 0.2 to permit visualization of the overlapping data points.**

of Pittsburgh and his collaborators, and another 46 CURE students were cited as collaborators in other reports, one in 2014 in the *Journal of Virology* and another in 2015 in *eLife*.

Participating in the CRLC also led instructors to develop and publish innovative instructional materials and make other scholarly contributions to STEM education research. They include five video protocols describing laboratory techniques common to several of our CUREs (four published in the *Journal of Visualized Experiments* and one recently submitted to MicrobeLibrary), an opinion piece in *Frontiers in Plant Science* describing the merits of CUREs that engage civic-mindedness among STEM undergraduates, a research article in *Biochemistry and Molecular Biology Education* describing a peer-assisted learning strategy used in one of the CUREs, and a research article in the *Journal of Microbiology and Biology Education* comparing the impact of CUREs and AREs within the context of the CRLC.

## Conclusion

More than 1,000 UCLA students participated in the CRLC since 2010. Each year, this research-based curriculum trains hundreds of diverse, talented, and ambitious undergraduates, many of them headed for careers in science. Not only do students gain from this program, but also the faculty teaching and mentoring CRLC students benefit from this approach by leveraging the opportunity to balance, intertwine, and enhance teaching effectiveness with increased research productivity. Moreover, this framework for integrating research into the life sciences curriculum is scalable, providing large public research universities a means for engaging undergraduates in authentic scientific inquiry, thus increasing the likelihood of those students persisting in STEM majors, and, in turn, STEM careers.

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## Suggested Reading

**Allen, D., and K. Tanner.** 2006. Rubrics: tools for making learning goals and evaluation criteria explicit for both teachers and learners. CBE-Life Sci. Educ. **5:**197–203.

**Anderson, L. W., D. R. Krathwohl, P. W. Airasian, K. A. Cruikshank, R. E. Mayer, P. R. Pintrich, J. Raths, and M. C. Wittrock.** 2001. A taxonomy for learning, teaching, and assessing — a revision of Bloom's taxonomy of educational objectives (abridged ed.). Addison Wesley Longman, Inc., New York.

**Corwin Auchincloss, L. C., S. L. Laursen, J. L. Branchaw, K. Eagan, M. Graham, D. Hanauer, G. Lawrie, C. M. McLinn, N. Pelaez, S. Rowland, M. Towns, N. M. Trautmann, P. Varma-Nelson, T. J. Weston, and E. L. Dolan.** 2014. Assessment of course-based undergraduate research experiences: a meeting report. CBE-Life Sci. Educ. **13:**29–40.

**Crowe, A., C. Dirks, and M. P. Wenderoth.** 2008. Biology in Bloom: implementing Bloom's Taxonomy to enhance student learning in biology. CBE-Life Sci. Educ. **7:**368–381.

**Russell, S. H., M. P. Hancock, and J. McCullough.** 2007. Benefits of undergraduate research experiences. Science **316:**548–549.

**Sanders, E. R., and J. H. Miller.** 2010. I, microbiologist: a discovery-based course in microbial ecology and molecular evolution. ASM Press, Washington, D.C.

**Shapiro, C., J. Moberg-Parker, S. Toma, C. Ayon, H. Zimmerman, E. A. Roth-Johnson, S. P. Hancock, M. Levis-Fitzgerald, and E. R. Sanders.** 2015. Comparing the impact of course-based and apprentice-based research experiences in a life science laboratory curriculum. J. Microbiol. Biol. Educ. 16: 186–197.

**Shortlidge, E. E., G. Bangera, and S. E. Brownell.** 2015. Faculty perspectives on developing and teaching course-based undergraduate research experiences. BioScience. Advance Access published December 9, 2015, doi:10.1093/biosci/biv167.

**Uchiyama, K. P., and J. L. Radin.** 2009. Curriculum mapping in higher education: a vehicle for collaboration. Innov. Higher Educ. **33:**271–280.

**Waldrop, M. M.** 2015. The science of teaching science. Nature **523:**272–274.

**Weaver, G. C., C. B. Russell, and D. J. Wink.** 2008. Inquiry-based and research-based laboratory pedagogies in undergraduate science. Nature Chem. Biol. **4:**577–580.

**Wiggins, G., and J. McTighe.** 2005. Understanding by design, 2nd ed. Association for Supervision and Curriculum Development, Alexandria, Va.