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A low-resource intro-level biology lab CURE for equity, inclusion, and authentic research skill-building

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Recent calls for increased inclusion in & access to authentic course-based research have been building on the momentum of support for Course-Based Undergraduate Research Experiences (CUREs). However, these courses can be very challenging to implement at scale or with low resources. To equitably provide these critical science process skills to the largest possible cohort of students, we have developed a new student research project within our first-year biology lab. Our student team research project is integrated throughout the semester, building authentic science process skills from start to finish. Students start from a research idea, develop a multi-site experimental design, do hands-on data collection at home, analyze quantitative data, and present their findings in a conference-style format. We have also embedded structured time for building collaborative skills. This novel change to our lab curriculum runs online, hybrid or face-to-face; it has no lab budget costs; and it has been well-received in multiple offerings of our course of ~200-600 students. It also has allowed us to improve our assessments: we evaluate writing (graphical abstracts) and/or oral presentation skills. Further, our lab exam can now be more cognitively challenging because our new curriculum better prepares students to analyze, evaluate, and synthesize. This article demonstrates that we can reduce barriers to doing authentic research, at scale in introductory courses; and we include here all materials needed to adapt this project to your own context.

Keywords: CUREs, inquiry-based learning, introductory, team collaboration skills, equity & inclusion

Link to Supplemental Materials: https://doi.org/10.37590/able.v43.sup19

Introduction

Many introductory lab courses are constrained by resources and scale, and thus are often cookbook-style, or based on sample identification & basic equipment skills. In contrast, recent calls to action recommend transforming our curricula to foster authentic scientific process skills and stronger biological literacy in our students (Brewer and Smith 2011; Clemmons et al 2014). These “process of science” core competencies can be well-supported in labs based on principles of inquiry and authentic research experiences, such as CUREs (Course-based Undergraduate Research Experiences; Brownell et al 2012; Dolan 2016). The ABLE community is working hard to bring these curricular changes to our institutions; indeed, almost half of the major workshops at the 2022 conference were devoted to CUREs and inquiry labs (ABLE 2022). However, implementing CUREs can be challenging, as they often require a high amount of resources (time, people, and cost) and thus are often not included in a program until the junior or senior year.

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The value and impact of CUREs has been further emphasized amidst calls for equity and inclusion in undergraduate education. By including authentic research experiences in our required courses, we can overcome structural bias and barriers to doing research, at scale. This can level the playing field, providing a more inclusive entry point for historically excluded communities (Bangera and Brownell 2014; Eagan et al 2013).

Given the value of CUREs, particularly for equity reasons within a required lower-division course, we developed a low-resource CURE for our high-enrollment introductory biology lab. This course on cells, molecules, and animal/plant physiology includes approximately 1000 students per year (majors and nonmajors) with structured weekly 2-hour experimental labs (48-72 students at a time, in teams of 4).

In this article, we describe how we have integrated a take-home “multi-site” project throughout the course by flipping some of the lab exercises while supporting students taking their original team project from start to finish. We include the project activities, as well as thoughts on mentoring experimental design, effective team collaboration, troubleshooting, and dissemination. We also discuss supporting teaching assistants’ professional development, and other considerations to adapt to your own context.

Student Outline

Objectives

Design a controlled experiment to isolate and test an independent variable, including the use of appropriate controls.

Plan the practical steps of an experiment and creatively solve the practical problems that arise along the way.

Communicate effectively in written and/or oral formats, employing a scientific vocabulary

Demonstrate professional, collaborative laboratory conduct:

- *Elicit, listen to, and incorporate ideas from teammates with different/diverse perspectives and backgrounds.*
- *Work effectively with teammates to complete experiments.*
- *Critique others' work and ideas constructively and respectfully.*
- *Proactively manage your team, including ongoing constructive communication about group expectations, processes, and problem-solving.*

Introduction to Team Projects

This semester, **your team will undertake a shared, hands-on research project, from start to finish**. This week in lab, you'll be deciding on your team's project, and setting your research plan. The project will require you to articulate your research question, define your variables, design your controlled experiment, plan, and communicate with your team, collect & interpret real data, & share findings (written and in a presentation). Every team member is involved throughout, including everyone collecting data at home and being part of the dissemination (sharing of findings).

Timeline

You have three major checkpoints during upcoming weekly labs.

<u>Lab 3:</u> A team check-in; during lab, define your shared project, build your shared project timeline and data collection plan.

- o *Between weeks 3 & 6, at your own pace: get supplies, & collect data. Each student does the experiment at their own home, so that as a team you have a larger data set.*

<u>Lab 6:</u> Finish data collection before your lab; in lab make analysis plan

- o *Between weeks 6 & 9, at your own pace: analyze data and prepare your presentation.*

<u>Lab 9:</u> It all comes together!

- o *This week's lab prep is done with your team, as a group assignment.*
- o *In-lab with your team, present to your lab section <u>or</u> submit a written graphical abstract*
- o *You will also evaluate the contributions of your team members and yourself to your shared project.*

Week 3 In-lab activities: Experimental Design

During today's lab, you and your team will work together to design your first original scientific experiment! This will be done in 3 parts: First, you will examine the available research projects and choose one theme as a team. Second, you'll work together to design an experiment for that theme. Third, you'll work out the practical details for how you'll each collect your share of the experimental data in the coming weeks because your journey as a scientist starts today!

Part A: Project Theme Choices

1. Seed germination and plant growth

In this experiment, you will investigate the impact of environmental variables on seed germination and/or seedling growth – whether in soil, or in a Ziploc bag. While growing these seeds, you will investigate rates of germination and/or growth in your treatment conditions. These conditions could be intended to support seed germination (sun, temperature, etc.) or deter it (irradiation of the seed, heating, treatment with chemicals such as peroxide). What affects the direction/speed of growth?

You might instead be interested in the further growth of already-sprouted plants, and how they can be affected by hormones. For example, mint plants are fast-growing, and can be treated with plant hormone. Could you design an experiment to make them branch out rather than grow taller?

2. Fruit enzymes and jello jigglers

Gelatin, an animal protein, is the component of jello that gives it firmness/structure. Some fruits, such as pineapple, have enzymes that may break down the gelatin and prevent it from “setting.” This project theme encourages you to characterize something about either the enzyme, or the gelatin itself. For example, what can you learn about the enzyme? Is it heat-sensitive? Is it pH-sensitive? Does the amount of enzyme make a difference? Is it found in the fruit juice, or only in intact fruit? Does the enzyme also work on gelatin substitutes such as fruit pectin?

3. Sourdough starter

Microbes live all around us and can be harnessed to help make our food. In this project, you will grow your own sourdough starter from scratch just by mixing flour and water. For ~2 weeks, you will measure some characteristics of your starter culture to track the growth of your “microbial zoo” over time. You’ll also choose independent variables to see what might impact the growth. Following the project, you may be able to use your starter to make your own bread!

4. Preventing microbial growth

In contrast, maybe you’re interested in preventing microbial growth. Microbes grow on our food (for example, growing on berries) or can be cultivated (on home-made agar plates). In this theme, you’ll design an experiment to test the impact of environmental conditions or applied treatments on the growth of microbes. For example, some websites say that aloe vera will prevent mold growing on blueberries. Does it make a difference if the berries are in the fridge? Or maybe you’re interested in testing out the effect of cleaning supplies or kitchen materials on the growth of bacteria in a dish?

5. Osmosis/diffusion in plant (potato tubers) or animal (eggs) models:

In this experiment, you will use root vegetables (e.g., potatoes) to investigate osmosis. The cell membranes of these sticks are selectively permeable, allowing water but not all other molecules to cross. Your team will design an experiment using common kitchen reagents (root vegetables, sugar, salt) to investigate rates of osmosis, and membrane permeability, in these root vegetables. Alternatively, you could use eggs to investigate osmosis and diffusion. You can remove the shell through ‘decalcification’ and then soak the eggs in varying solutes (such as table sugar) to understand egg physiology. Or you can use food coloring to and other conditions to measure the rate of diffusion through the egg.

6. Capillary action in plant stems

In flowers, liquids move from the base of plants up to the flowers through the plant’s vasculature system. Using white flowers such as carnations or vegetables like celery together with food coloring, you can test hypotheses about what factors affect the rate of fluid movement. Does the size of stem matter? What about temperature, tonicity, size of the food coloring molecule, other chemical characteristics? Does the liquid always move the same direction, or can it go in either direction?

7. Another project idea that you have!

You’ll need to think this through, and it must meet the overall project constraints/goals.

Part B: Designing an Experiment

After choosing one of the topics above, work through the following questions: you may need to jump back and forth as your experiment evolves based on what you consider and choose to do. Remember to keep in mind the overall constraints and goals for this project – listed at the end of today's lab materials.

Question 1: What is your Research Question?

Question 2: What is your Hypothesis?

Question 3: What is your Independent Variable?

Question 4: What is your Dependent Variable(s)? (at least one of these needs to be quantitative/numerical - i.e., you can measure it as a number.)

Question 5: How will you measure your Dependent Variable(s)? (Be as specific as you can here!)

Question 6: What materials and space will you need?

Question 7: What are some potential confounding variables? (You may want to collect data on these, as you perform your experiment, as a backup)

Question 8: What control groups might be important to include? What are these controls being used to check/show/test?

Question 9: What standardized variables will you keep the same, between all groups?

Question 10: How many replicates will you have for each treatment/control group? (Note that each team member will be collecting data at their home, but you can decide how to split replicates up amongst the group. Will you each perform each condition? Or will one person perform all replicates for a given condition?)

Question 11: What are the safety risks of your experiment (including pandemic guidelines)? How will you manage/minimize these?

Question 12: Roughly sketch a flow chart to illustrate the steps of your experimental setup / procedure, in chronological order.

At this point, you should have your TA or instructor look at your flow chart to assess the overall viability of your experimental design. You can work on the rest of the questions in this section while you're waiting. Your TA will give you detailed feedback on your project plan next week - this is a quick check for overall feasibility.

A last few quick checks on your project idea, based on the overall guidelines - talk about these, and just make sure you can answer "yes" to all of these questions. If not, please adjust your experiment to address these before you start.

Question 13: Is it achievable and reasonable? (Can you collect all the data, without getting overwhelmed? Is it overly easy, and too trivial? Is the data reasonable to analyze?)

Question 14: Will all your teammates be able to get the materials, space, and time to do the project? Timing and space constraints: All your data needs to be collected by your lab in week 6. Will all teammates have enough time and undisturbed space to complete their part of the project, between now and week 6? Will you be able to get materials (and, possibly, buy & share them in a safe socially distant manner)?

Question 15: Is it inexpensive (less than ~$10/person)?

Question 16: Are there any ethical issues with your experiment?

Question 17: Is it connected to our course material?

Question 18: And finally: why are you excited about doing this project?

Part C. Teamwork

Modern science is done in teams, who work collaboratively on projects. This is a team project, which involves building team skills as a core part of being a scientist. Team skills are not always easy, but they are super important: when we surveyed recent SFU science graduates, the number one skill that they wished they'd had more of in their degree was collaborative work skills. So, we're going to continue working on it here. Note that this group project requires reasonably equal contribution from every team member, as you are all getting graded together and will have a chance to evaluate each other at the end of the project. So, leaving your team to work individually on your own project is not meeting the learning goals of the course. As a group, you have the responsibility for managing your project, your team relationships, and team contributions. If you're feeling frustrated, you need to try and resolve your group problems early on, not just at the end. If, during the project, after having tried several ways to address any issues, please check in with your instructor for ideas.

Overall constraints & goals to keep in mind: Your project design needs to be…

Achievable:

- *Can you collect all data between your lab days in weeks 3 and 7 (from start to finish, including acquiring materials).*

Shared

- *Every team member will collect data at their own location*

An experiment

- *Needs to have a research question, an independent variable (that you manipulate), and a dependent variable (that you measure). There are lots of neat biological studies that are *not* experiments (e.g., observation of natural phenomena), but this is your chance to design an *experiment* where you test out an idea and see what happens.*

Reasonable

- *Have your priorities straight: a **tight experiment** (well-designed, small experiment that clearly tests for one independent variable, including good controls) **is better than a broad experiment** (that tries to test for too many things at once, and gives data that is messy or uninterpretable… or has too many ways to fail).*
- *We want this to be a reasonable workload, not overwhelming (and not boringly small).*
- *But, don't be afraid to try something that is a little ambitious and interesting!*

Inexpensive

- *No more than approximately $10 per person.*
- *Why? We want this to be inclusive, and equitable across teams – and we want to see good scientific thinking, not expensive tools/kits that do the work for you.*
- *If money becomes an issue for you personally, please privately let your lab instructor know. We have lots of good ideas about how to do science on a $0 budget; we will not judge you and will protect your confidentiality if you don't want your team to know your situation.*

Ethically straightforward

- *Collects data on cells/biomolecules/plants/microbes, rather than humans (to avoid issues of ethical testing on humans & protecting individual privacy)*
- *Can't believe we have to say this, but: it can't involve questionable/illegal behaviors*

Connected to our course material!

- *When you interpret your findings, you'll be putting them in the context of what is known about biology/biochemistry/physiology. There are lots of neat experiments out there that focus on *other sciences* but this is your chance to do a *life sciences* experiment.*

Assessed for reasonable safety

- *You are responsible for knowing the safety of your reagents/experiment/setup. We can help with this if you reach out. Because you are doing diverse projects of your own choosing at your own homes, it is infeasible* *for us to fully assess the overall safety and risk of each project. So, you'll need to assess risk, minimize it, & be comfortable with it.*

- *We have compiled project themes that are low-risk, but: you need to know that there is no such thing as zero-risk. For example, many food and cleaning supplies in regular kitchens/homes are hazardous; and, "natural" is not the same as "safe."*
- *You'll talk with your group about this, but here are some general safety considerations:*
    - *Reagents (alone or in combination) – can be hazardous to touch/breathe/splash/ingest. You need to know the hazards of your own reagents, and the necessary precautions to work with them. This includes preparing any materials – e.g., cutting, heating, wearing appropriate eye/clothing/hand protection, getting materials outside in nature, etc.*
    - *COVID – you need to follow all current pandemic guidelines, particularly if/when you go and get materials, and if you divide your materials among teammates.*
    - *Individual allergies/sensitivities/constraints of team members & their housemates.*
    - *Your own mental health & stress are important. Set a reasonable non-overwhelming amount of time you can all work on this and stick to it! Build in wiggle room to work around midterms, schedule changes, setbacks.*

And, critically important: **Interesting to you**

- *Don't pick a project that you don't care about!*

Week 4: Project Peer Consultation (20 minutes)

Today you'll be checking in on your project, in whatever stage it is at. (Some teams may have started getting materials together, or collecting data, or running pilot experiments; others may be in the planning phases or have come across issues that they need to troubleshoot. All of these are fine. You'll be meeting with another team to briefly explain your project, get advice, and hear their questions/ideas.

Quick Team check-in (~5-10 minutes)

Check-in and talk things over: where is your team at, with your project? Have you learned anything new since last week's lab? What are your next steps? Do you need to revise your plan at all? Write down a few useful notes.

What is something you're unsure about, or something you could you use advice on, for your project so far?

Get ready to briefly summarize your experiment, to informally share with another team (~2-3 minutes to summarize, ~5 minutes for questions and discussion). Be ready to be brief, and to focus on your overall plan, your specific variables, where you'd like some advice/ideas.

Consult with another team (10 minutes per team).

You will take turns with another team to informally present your experimental overview. Each team should assign a note taker. The listening team's goal is to be constructive and help the presenting team work through their experimental plan. Ask questions for understanding/clarity (not for criticizing). Don't be afraid to ask questions that are specific and questions that are big-picture. Focus your ideas on the places where they are asking for advice, or where things aren't clear.

Check back in with your team (5-10 minutes)

The notetaker should report to your team a summary of the notes you wrote & ideas you heard. Based on the consultation, decide on your next steps. Are there any changes you need to make to your experimental plan, or how you define your variables? Is there any outside research you need, to help improve your project?

Week 5: Team Check in

First, a quick project check in:

Talk together: Look at your team project timeline. How are you doing towards your goals? Have you been able to get your materials/reagents? Have you had any setbacks? Any successes? Do you need to adjust your plan? (you can go adjust your plan/calendar in the timeline you wrote in this notebook.)

Roughly speaking, how equal are everyone's contributions so far? *This is your chance to be honest about your team progress and contributions, so please take this opportunity.*

Week 6: Data Analysis

During today's lab, you and your team will start organizing and presenting your Research Project methods and findings. You will pool your raw data and observations, and work together to graph and interpret this final data.

Graphing and Interpreting your Data

Question 1: For your quantitative data, what type(s) of graph(s) is/are most suitable for **presenting** this data? For each, why is this graph type appropriate? Work with your team to make at least one preliminary graph that clearly presents your most interesting finding(s).
Here are some suggested steps for how to proceed:

1. For each experimental group, calculate means and standard deviations for each of your dependent variables.
2. Compare these statistics between experimental groups and make a list of the most interesting comparisons. For example:
    - Do you see the differences between experimental groups that you predicted, based on your hypotheses?
    - Did you see any unexpected differences?
    - Do you see a lack of difference, even though you expected to see a difference?

    Note: All the above situations are interesting and useful results, so don't feel like you "messed up" just because you didn't see the results you originally predicted. We can learn as much, if not more, when unexpected things happen, than when things happen as planned).
3. Interpret the graph(s) as a team and decide which one(s) are most interesting.

Question 2: Insert your graph(s), and one-sentence interpretation(s) below.
Question 3: Look over any qualitative data you collected. Talk these over with your team and summarize your findings from this data here (in words). What conclusions can you draw from these data? How will you tell the "story" of these data? How can you use them to further describe your quantitative data? Can you transform any of them into quantitative data, by counting or otherwise?
Question 4: Look at your "other" observations, including any parts of the experiment that you had to discontinue. Talk them over with your team. Do they provide any suggestions for improving the method the next time, or ideas for future experiments?
Question 5: Looking at your data, are there any surprises? If so, what biology might you need to research, to understand the context or reason why these results occurred?

Week 9: Assessment

Teams hand in their deliverable

Week 10: Evaluation of individual and team contributions to the project

This is assigned as a quiz in our LMS.

Materials

Students gather their own necessary materials based on their own experimental design, with a cap of $10 per student for equipment or reagent purchases. This has an added element of understanding supply chain and ordering dynamics in real research situations. We explicitly state that if this cost is prohibitive for any student, we will discreetly cover the cost ourselves.

Notes for the Instructor

This activity was designed to provide first year students in a large introductory cell biology and physiology course with an authentic research experience. The laboratory is "flipped" in that students perform their experimental work at home and spend lab time working on experimental design and data analysis, allowing the teaching team to provide real-time feedback and guidance on these intellectually challenging processes.

Week*	Project Component	Modality
3	Experimental Design	In Lab
4	(Time permitting) Inter-team research meeting	In Lab
Interim	Data Collection Ongoing team check-ins	At Home In Lab
6	Data Analysis	In Lab
Interim	Report Preparation Ongoing team check-ins	At Home In Lab
9 (optional)	Team Deliverable (Abstract submission or oral presentation)	In lab

**This timeline is based on a 12-week semester. In other weeks, students complete regular structured laboratory activities.*

The assessment choice (oral/written) varies by semester, depending on grading resources and available lab time. Full grading and assessment guidelines we provide are included in Appendix A. We strongly recommend encouraging students to reflect on their group dynamics during the course, to support fruitful collaboration while minimizing instructor micromanagement. For this, prompts are provided to students during regular (non-project) labs throughout the semester (included in Appendix B) and again at the end of the project (Appendix C).

Overall Design

Working in teams of 4, students first design an experiment based on a list of course-related topics. In-class support is focused on guiding students through the challenges of experimental design while preserving their ownership of the project. Common points of discussion include how to narrow down a research question, how to choose appropriate dependent and independent variables, how to quantitatively measure a dependent variable, and how to identify relevant controls and confounding variables. Detailed feedback on the project plan is provided to students before the next lab section. A peer-evaluation component can be implemented, where teams share their project plans with each other for feedback. Students then spend 2-3 weeks collecting materials and executing their project plan at their own homes.

Another class timeslot is devoted to data analysis. Students arrive having compiled their team results, and class time is spent deciding how to analyze, interpret, and graph this data to best convey the conclusions of their research. In-class support is focused on relating the collected data to the original research question. Common points of discussion include appropriate grouping and averaging of data points, reframing the data to make quantitative comparisons, and addressing experiments that "didn't work" either due to unexpected results, confounding variables, or lack of useable, quantitative data. We focus on interpretation and scientific reasoning in our discussions with students and contextualize student experiences to authentic research practices as much as possible.

Fostering Student Collaborative Skills and TA support

This project relies heavily on teamwork, intentionally: modern scientific research is done in teams, at multiple sites. If we want students to work effectively in groups, then we need to teach them to work in groups. Thus, we explicitly weave collaborative skill development regularly throughout the semester. Broadly speaking, we act as mentors/advisors to their projects and teams, rather than managers. Students are coached on best practices throughout the project using lab manual prompts, and discussions with teaching assistants.

Consistent team check-ins are built into the project to encourage frequent reflection and discussion of team dynamics - both formative and summative. In the interests of brevity, we have included these largely as appendices; however, we do not want to minimize their value. If we want students to work effectively in teams, we need to explicitly support them building skills to do so. An example of one team check in used while data collection is in progress is provided in the Student Outline.

In a similar vein, we rely heavily on the support of our teaching assistants to advise and mentor student groups. Tailored mentoring of teaching assistants throughout the project enables these trainees to facilitate group discussions around experimental design, data analysis and team dynamics while maintaining student ownership of the experimental process. This is often a novel role for the TAs who are more comfortable with helping students with equipment or working through practice problems to get the “right” answer. To support our TAs in these critical facilitation skills, we dedicate time at our regular teaching team prep meetings (prompts in Appendix D). We also aim to explicitly re-frame student project concerns as valid research challenges, with appropriate research vocabulary, to normalize student identity as researchers and give a language for discourse (Brown 2006). Further, we have an extensive TA guide related to troubleshooting of specific projects, as well as common data analysis/interpretation hurdles (Appendix E).

Evidence of Effectiveness

As instructors and TAs, we have been impressed by the student work in this project. It frequently appears positively in our end-of-semester student evaluations (fig. 1), and, anecdotally, the TAs speak very positively of it. Further, as a result of this lab transformation, we have improved the quality of our lab exams to include cognitively challenging questions on these critical skills of experimental design and data analysis. In terms of inclusion, we feel strongly that this course project has equitably removed some barriers to research that may have been present and is including students who may have found a new connection to the research world.

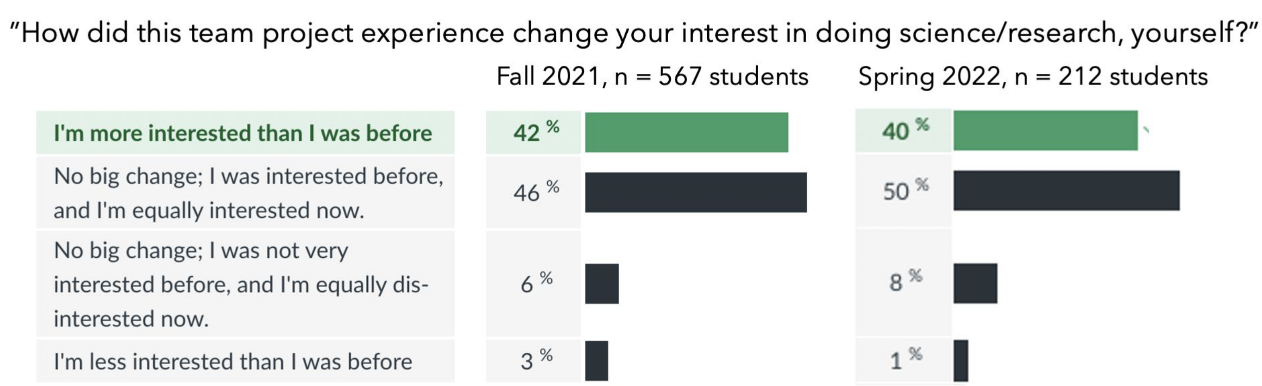

Figure 1. Student response to a survey question about their interest in doing science after completing the CURE.

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