

Designing Course-based Undergraduate Research Experience (CURE) Labs with Citizen Science and Service-learning

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Education research finds support for the value of authentic research experiences to students' educational gains in biology laboratory courses. Here we outline a methodology to incorporate authentic course-based undergraduate research experiences (CUREs) into the lab using the community approaches of citizen science and service-learning. We provide a concrete example of a sophomore-level genetics service-learning lab course that uses biological samples provided by citizen scientists. We then frame steps to assist instructors to develop their own citizen science or service-learning lab curriculum. Depending upon the resources available at different institutions, these steps may vary but we hope they, in addition to examples from the detailed case study, provide a solid foundation for a potential community driven course-based undergraduate research experience.

Keywords: service-learning, citizen science, course-based undergraduate research experience (CURE), project-based laboratory learning, community partner

Introduction

Science is a process best learned by doing, meaning students should carry out the process of science in their lab courses. While inquiry labs have been shown effective in allowing students the opportunity to take part in the scientific process, greater student learning gains can be observed when students are involved in authentic or “real” research projects (Corwin et al. 2015). Two vehicles to engage students in the process of science in course-based undergraduate research experiences are service-learning and using citizen science projects and datasets.

Research Projects Foster Student Engagement in Undergraduate Lab Courses

Evidence tells us that students engage better in scientific thinking if they practice science (Chang and Mao 1999, Luckie et al. 2004, Weaver et al. 2008), and they will buy-in more thoroughly if that practice has an authentic or real-world application (Furco and Root 2010). Current practices in undergraduate research courses include inquiry-based labs, taught on the continuum of guided-inquiry to open-inquiry, and course-based undergraduate research experiences (CUREs; Auchincloss et al. 2014, Shortlidge et al. 2017) that scaffold students into research in other settings such as faculty labs (Weaver et al. 2008) and support development of strong scientific process and

data interpretation skills (Brownell et al. 2015). We address two community-driven approaches to embed authentic research projects into undergraduate laboratory courses: service-learning and citizen science.

Service-learning

Students who participate in service-learning actively work or engage in their communities with a goal to provide something to those communities while attaining, applying, and integrating discipline-specific content knowledge (Fiske 2002, McDonald and Dominguez 2015). Many campuses and university systems have implemented service-learning programs and initiatives ([US News and World Report](#)) with specific implementation in courses (e.g., Bernot et al. 2017). In laboratory science, the learning component should align with course learning objectives, preferably surrounding the steps of the scientific method: ask a question, pose a hypothesis, design an experiment, conduct the experiment, analyze the data, and report the results.

Citizen Science

In citizen science projects, students conduct research by collecting and analyzing data in collaboration with the general public and other scientists (Fiske 2002). Similar to service-learning in the local community, students can contribute their research effort to a community

by opting in to an established citizen science project (e.g., Caruso et al. 2016). Alternatively, faculty can design a citizen science project that will impact their area and allow for integration of efforts by students, citizens, and scientists to address a community question or concern. One enormous benefit for data analysis and statistical training is the ability to acquire a larger data set for analysis, even with small class sizes.

Why Community Outreach

In addition to helping students to become engaged as scientists with a research question, community-based projects have the added benefit of helping students grow as citizens and members of their community (Fiske 2002). Students engaged in community projects gain a greater understanding of their roles as ambassadors for science and how the institution of higher learning can impact the surrounding community (Vanasupa et al. 2006, Tucker et al. 2013). Students who have community-based experiences are more prepared for problems outside of the classroom and have enhanced employment opportunities (Bennett et al. 2016, Wurdinger and Allison 2017).

Genetics Case Study

Below we provide a course-based case study from one of our courses, a sophomore-level genetics course with a required lab component. Students who opt into this

course are primarily first- and second-year Biology majors interested in undergraduate research and are often on the pre-medical track. If first-year students earned prior credit for the standard introductory biology first semester course using Advanced Placement Biology credit, then they are allowed to enroll in the sophomore-level lab course in their first semester on campus. Lab sections are capped at 20 students with two TAs and an instructor. The low student to instructor ratio allows for instructional practices that require feedback. The Genetics lab course approach contains elements of both service-learning and citizen science.

Primer to Design Project-based Labs

After the case study, we provide a primer of detailed steps that we have developed over 16 semesters and eight laboratory courses to culminate in the development of citizen science and service-learning course-based undergraduate research experiences. Our intent is to provide examples and procedures to help instructors further develop CUREs with the additional authentic elements of citizen science and/or service-learning. These steps, while comprehensive, are intended as a guide for project success. Depending on institutional specifics, we acknowledge that certain steps should be omitted or modified to meet the pedagogical needs of the instructor, students, or institution.

Student Outline

Genetics Case Study: Service-learning with Citizen Science in a Genetics Lab Course

Objectives

By the end of this course, you will be able to:

- 1) Generate genetics hypotheses, supported by the primary literature, using the European Honey Bee *Apis mellifera*.
- 2) Design experiments and interpret results using basic statistical analyses.
- 3) Create and troubleshoot genetics lab protocols.
- 4) Write effective and accurate notebook entries and lab reports in the style accepted by genetics scientific journals.
- 5) Work with community partners to communicate scientific ideas to them in terms they can understand, while including appropriate scientific uncertainty.
- 6) Use appropriate lab safety standards and precautions.

Introduction

This genetics laboratory course is designed for exceptional students interested in learning important concepts and practical techniques in the field of genetics. The course is project-based, where students will design and conduct a novel laboratory experiment aimed at exploring aspects of transmission genetics, population genetics, and molecular genetics in collaboration with beekeepers from the Metro Atlanta Beekeepers Association and the Georgia Tech Urban Honey Bee Project. Our beekeeper collaborators throughout the metro-area will provide worker bee samples that can be assessed for the presence of RNA viruses using published techniques. As with all research, we will begin with a question and then follow the scientific method to generate a hypothesis, design and conduct an experiment, and analyze the data to draw a conclusion. Because we'll be exploring new questions to us and to the metro-area urban and rural honey bee populations, we'll probably also bump into the primary frustrations of scientific research – assays that require troubleshooting, delays when protocols don't work perfectly at first pass, and results that don't match our thinking about the system. We'll do this because asking real questions in a relevant study system is what scientists do, and learning how to navigate the process and solve the ensuing problems is the best training you can have for your senior research experience and to pursue careers in scientific research, medicine & human health, or other fields that require problem solving and logic.

Experimental Overview and Lab Work

On the course website, we will collaborate to develop the weekly plan to complete a genetics experiment on urban honey bees with beekeeper community partners. The opening weeks will introduce students to bees as a study organism, primary literature on bee genetics in urban and rural environments, and practice with the fundamental lab assays of polymerase chain reaction and gel electrophoresis. Effective reading of the relevant primary literature will be taught and is a necessary skill to conduct research and contribute results to an active research field. While we learn these basics, we'll explore hypotheses, predictions, experimental designs, and protocols to support the answer to the research question of how urbanization affects viral composition in urban bee colonies.

Once we finalize an experimental design as a group, each student pair will analyze a subset of samples to contribute to a complete data set with sufficient replication for technical and statistical rigor. The process will likely involve repeated use of protocols from the first few weeks; consistent lab practices generate the repeatable results necessary for scientific inquiry and to provide accurate and reliable results for our community collaborators. Once we have results, we'll analyze them statistically to test each hypothesis. Statistical analyses will be taught using the programming language R (www.r-project.org), which is a flexible coding language used in many data science applications; a basic knowledge of R is a highly transferrable skill in current research and the workforce.

Lab safety is spelled out in the course syllabus and in lab each day, and students sign a lab safety contract in the first week we meet in the wet lab. The course schedule on the website will specify if lab work will be “wet lab” research or “dry lab” work. “Wet lab” weeks require proper safety attire: wear lab coat, long pants, close-toed shoes, and long hair pulled back. Safety glasses are provided in lab.

Writing Training and Assessments

In any given week, we may have “Journal Club” in lab during the down time between assays or to prepare the next idea for our experimental design. Prepare for Journal Club by completing the reading in advance, analyzing the paper with

the “dissecting a scientific paper” approach we’ll introduce in the first week, and finding your voice during the discussion. We learn best the processes of science by asking questions, talking through ideas, and putting our opinions out for critique. During Journal Club, discussion of any relevant idea is fair game, and every idea should be greeted with respect for discussion. Likewise, no critique is personal but rather addresses the idea itself. Students who read thoroughly and bring in ideas for lecture and other areas of science to support their discussion points usually feel more confident to put forward ideas. At each instance of journal club, we expect every student to contribute aloud to the journal club conversation, either in small group or in full class discussion.

After lab each week, students will complete a lab notebook entry in their own words. Students should set up their notebooks at bio2355.biosci.gatech.edu/notebook, following the instructions on the site. Taking time in the notebook to write up ideas and results in your own words will serve as practice for your end-of-semester journal article and save time when writing your journal article, as anything you include in your lab notebook may be included verbatim in your journal article. Lab TAs will comment on your lab notebook weekly to help you clarify your ideas and how you write about those ideas. Most weeks, we’ll assign short writing piece as a building block for your journal article. Short writing assignments will be peer reviewed and revised before submission for grading, and these building block submissions contribute to the grade for the final journal article. Because this course revolves around original research that students conduct, the output has the possibility for publication in a scientific journal, where each student is a contributing author.

A secondary but no less important writing assignment centers around communicating relevant results to each beekeeper that provided samples. Most beekeepers are not trained scientists and will need translations and context to understand the technical results about their colonies and about the outcome of the statistical analysis for our research question. The beekeepers interests are two-fold: they support student scientific exploration to study urbanization and viral composition while they also seek specific information about the viral health of their own colonies. This second writing assignment asks students to communicate scientific findings to non-scientists, another fundamental communication skill.

Discussion

Service-learning science includes all aspects of the scientific method from research question generation through communication of results both to other scientists and also back to the community partner. We have prepared ahead of the semester by establishing a general sampling protocol and calling for beekeeper citizen science collaborators throughout the metro-area to provide worker bee samples than can be assessed for the presence of RNA viruses. We know therefore that the general question you each address will center around how urbanization correlates with RNA viruses present in metro-area bee colonies. The science that unfolds over the course of this semester-long project will focus on your interpretation of the urban/rural definition and the cleanness of the group dataset that we generate using genetics techniques in lab. In terms of errors introduced into the class data set at the bench, we will distribute measurement errors across the dataset in an experimental design that spreads the samples across different teams of students. Our design will have technical replication (within colony) and experimental (biologically relevant) replication across colonies. We will work as a class to generate a large enough dataset to allow for effective statistical analysis, but you will have scope as an individual scientist to establish your own operational definition to situate each colony along an urbanization scale (e.g., Youngsteadt et al. 2015). At the end of this work you’ll create a journal article to document your work and a ‘beekeepers’ document that presents the results to a more general audience that will include our beekeeper collaborators and campus constituents. As we work, if you have alternate ideas for how best to present our results to our community partners and collaborators, those ideas can be worked into the course.

Cited References

Youngsteadt E, Appler R, López-Urbe M, Tarpy D, Frank S. 2015. Urbanization increases pathogen pressure on feral and managed honey bees. *PLoS One*. <https://doi.org/10.1371/journal.pone.0142031>.

Materials

Materials for CURE learning depend upon the project itself, giving instructors enormous flexibility to generate projects within their budget and aligned with equipment availability, needs of community partners, instructor expertise, and student learning goals. We discuss materials and preparation more thoroughly below.

Notes for the Instructor

Below we provide an outline to create a citizen science or service-learning course-based project. These ideas are grouped into three time periods: pre-project preparation, project design and pilots, and project implementation. In our own courses, we use this model to develop semester-long projects. The format can be readily modified for short- or long-term projects.

Pre-project Preparation

Project Ideas

When selecting a project idea, we use four guiding principles: 1) the course format and student demographic, 2) the course and programmatic learning goals, 3) the needs of the community partner, and 4) the available resources. Resources we consider include the instructor's own area of research expertise and available support for equipment use, supplies costs, and prep lab expertise and time.

We first assess the target course for student demographics and for scale: the mix of majors versus non-majors, whether the level is for first-year versus upper-division students, and the number of lab sections and students in the course. This sets clearly defined starting parameters to structure the project and determine how students will interface with community partners.

For instance, in the Genetics Case Study students were early-career biology majors who mostly resided on campus. The course met for 2 hours and 50 minutes weekly on campus, and the protocols to address the research question and meet the course content learning objectives were extensive. Coordination with 20-30 beekeepers from the greater metro area would take several weeks, yet the samples were needed by the third week of the semester. The quick-turnaround meant that students only met in person with one of the beekeepers who donated samples. In spite of the limited face-to-face interaction, students in their discussions and assessments frequently referenced the reasons the beekeepers contributed samples to the project and the value of the research results to the individual beekeepers. Service to the broader community motivated students because the project became an authentic learning experience with tangible outcomes.

Second, we establish learning goals for the laboratory course using the Vision and Change Core Competencies (Brewer and Smith 2011). Vision and Change includes two learning goals tightly in agreement with the principles of service-learning and citizen science: a) appreciation of the relationship between science and society and b) communication and collaboration with other disciplines. A proposed project or CURE that incorporates service-learning or citizen science should also retain a primary focus for students related to the remaining Vision and Change Core Competencies: to c) apply the process of science, d) use quantitative reasoning, e) use modeling/simulation, and f) be interdisciplinary. Course-specific learning goals help narrow the project focus to generate CUREs that include the core competencies and disciplinary practice from Vision and Change (2011) or other relevant competencies.

Third, the community partner's needs, interests, and contributions come into consideration. The intended collaboration guides and defines the student project in scope and detail. The needs of the collaborator range from broad to specific. For our majors introductory courses, the partner is willing to sacrifice research on specific questions of interest to allow the students complete autonomy to produce their own research questions. While these are rarely complete or publishable, they meet our course-learning goal to engage students' interest in science as a process. With iteration over several semesters, the research focus can be improved to further meet the community partners' needs. For the Genetics Case Study, the community partners were also the citizens who contributed samples. They were willing to support university-level training in genetics research while also gaining potential insights about virus presence or absence in their own bee colonies. In some cases, the community partner provides resources, equipment, or access to materials or study sites required for the project.

Fourth, the most tractable projects occur when the instructor's own area of research expertise serves as a foundation to train themselves, other faculty, or teaching assistants to support the student learning, keeping in mind the course level and prerequisite knowledge of the students. As with any research question, exploration and review of the relevant literature ensures that project ideas are well-aligned to learning goals and feasible to implement in the course given instructor expertise, availability of equipment, supplies, and prep lab expertise and time.

As in scientific research, projects can develop over several semesters from proposal to pilot to experiment. For the lab course associated with the Genetics Case Study, the current service-learning project is the fifth iteration of a CURE, and the second round of service-

learning in the course. As a result, many of the materials, TA training elements, and prep lab pieces pre-existed the current service-learning project. Three years earlier students piloted a short bee genetics project during the last two weeks of a summer lab course. The following semester, students conducted a larger scale project on bee genetics and generated one page “future directions” grant proposals on bee research. We brought the nascent research idea, which married our interests in the ecological impacts of urbanization with honey bee Colony Collapse Disorder, to a small group of faculty with expertise in CUREs, evolutionary genetics, urban honey bees, social insects, and reverse-transcriptase PCR assays. This group met once to brainstorm and advise on how to implement a similar protocol to Youngsteadt et al. (2015), which led to the service-learning project in the following semester.

Finding Protocols and Piloting

By leveraging the resources available or attainable and the instructor’s own research experience, the instructor can identify protocols that meet the learning goals for the lab. Literature searches reveal recent articles that provide necessary elements for the success of the project, be they primers for PCR, an experimental design easy to replicate at scale, or an effective positive control to determine if the project protocol can work.

For some projects, such as the Genetics Case Study described, pilot work before the semester is essential to test reagents and primers, establish protocols that meet safety conditions in an undergraduate research lab, and provide timing assurance that the project can be apportioned into weekly 2.5 hour sessions without compromising sample quality. As an example of lab safety, we made the decision that the students in the Genetics lab course would handle only dead worker bees to reduce the risk of exposure to bee stings. We also accounted for university regulations on lab safety and animal care and handling: While insects are not subject to IACUC regulation, vertebrate animals systems are more tightly controlled, adding permissions steps that require further advanced-planning if the proposed research involves vertebrates. Each institute has its own safety protocols with respect to use of organisms and reagents in student labs, so please consult with campus guidelines and regulations.

While the Genetics Case Study presents an example of a research project conceived of by the instructor, other projects are more open ended or student defined, where the students themselves propose their equipment and supplies lists for review and approval during the course of the semester. With student-proposed research, the instructor serves to help students to find generalized protocols, probe the student protocols for

experimental feasibility, and help students understand the steps, reasoning, and reagent function.

Create Collaborations

The task of identifying community partners can happen first, which effectively primes the project idea from the potential collaborative result. Alternatively, specific partnerships can be probed after establishment of a general research area or direction. In the Genetics Case Study above, we wanted to develop a more regional project around urbanization based on a standing collaboration with the Georgia Tech Urban Honey Bee Project, so the project director connected us with an area beekeeping association. We presented them with the project proposal in a quick PowerPoint pitch before their next members’ meeting, and individual beekeepers opted in to provide samples for the student research in exchange for results related to their own colonies.

In our introductory courses, we line up collaborators for upcoming student-proposed research projects and the collaboration agreement is finalized before the research question. The partner outlines tentative research areas that the students can further develop as their research questions solidify, which may require additional back and forth with the community partner to align with the needs of the students.

Forging connections with campus and community organizations, both not-for-profit and otherwise, can help to implement the instructor’s (or student’s) project ideas or, alternately, generate strong research ideas that are grounded in community needs and plans for improvement. Citizen science organizations may be local or more widely based, and probably have pre-defined projects and protocols at least partially established. Instructors can also champion new citizen science initiatives. In either case, if students will work directly with non-university affiliated collaborators or visit off-campus sites, student release forms in accordance with university legal policy are recommended.

Prepare Readings and Syllabus Materials

As with many lab science courses, our labs have a learning goal related to reading and comprehending primary literature. When the project is already defined, as in the Genetics Case Study, our approach is to prepare a set of readings for the students from primary resources. To scaffold effective reading in the primary literature, we include instruction on how to approach the field-specific writing style found in primary articles. In the Genetics lab course, we use a guide to dissecting a scientific paper modified from

(<http://evolution.berkeley.edu/evolibrary/teach/journal/dissectingpaper.php>). For a more general course, such as

non-majors introductory biology, an alternative to primary research papers is an instructor-written overview for students in the form of handouts, a lab manual, or a syllabus description of the project and its foundation in either citizen science or service-learning. These written documents, especially the course syllabus, serve to direct and steer the project as it unfolds, allowing for flexibility but keeping the project on track to meet the learning objectives and course timeline. In the Genetics Case Study, the timeline and overview were provided in an editable webpage format (<http://bio2355.biosci.gatech.edu/archival-projects/bee-project-fl6-schedule/>) that the instructor updated weekly after class to keep pace with the project. We provided quick TA feedback for weekly lab notebook entries, peer-review of each writing assignment (Introductions, Methods, *etc.*) to contribute to the final journal article assessment, and TA written feedback on a graded revision of each element. Each of these served to scaffold students to produce a final journal article-style submission at the end of the semester.

TA Training

Training teaching assistants to mentor CUREs takes a broader approach than a focus on content knowledge of the planned experiment, experimental outcomes, equipment training, and specific lab safety relevant to the upcoming lab session. While those elements remain necessary to some degree, the successful TA for a CURE needs training to mentor student work on teams, assist students to design experiments, and critique student writing. Courses that incorporate service-learning or citizen science can also involve the TA as a field site mentor, a contact with the community partner, or a guide for students struggling to find appropriate language or actions to work with and understand the needs of a community partner.

Therefore, in addition to weekly lab prep sessions for each course, we implemented a TA training curriculum (syllabus available upon request) to provide teaching training for interactive learning, teamwork, mentorship, learning to assess writing and provide feedback, and how to deal with student resistance. These approaches better prepare TAs to successfully mentor student projects and research progress. In our majors introductory labs, TAs take students to field sites administered by the community partner and help the students interact on site with the community and the biology to consider research questions that impact the partner.

TA expertise can develop the course in directions orthogonal to the instructor or community partner's own expertise. In the Genetics Case Study, a TA with coding skills in R led an in-class overview of R for the students. The TA took ownership to lead both lab sections for the

statistical analysis week, providing basic code and teaching students how to modify and implement it. Taking the lead to develop a lab lesson developed the TA's teaching skills to translate advanced coding practices to the novice level. Inspired by the TA-led session, the instructor built basic R code and installation instructions, which have been modified as the project has shifted direction. Students now download and install R before class, then work together in class to use provided code to analyze three model data sets before formatting their own data, selecting the appropriate analysis, and modifying the code to fit any special features of their data. As a first pass at programming and statistical analysis for many students, this approach in our course anecdotally empowers students rather than setting up resistance to coding.

Project Design and Pilots

Students Craft Research Questions

For students, one of the most difficult aspects of a semester-long project is creating an appropriate research question. Often this is the first time that students have had to think about science as an interactive process. Student-designed research questions can be approached along the spectrum of guided-inquiry versus open-inquiry projects (Abraham 2004, Chatterjee et al. 2009).

On the guided-inquiry end of the spectrum, the instructor has a little more control over the process, from background through experimental design, and the experimental setup can be similar for all students. With guided-inquiry, students have a more solid foundation and move at a similar pace to each other throughout the semester. However, students may not have as much freedom to practice crafting research questions and working through the frustrations that are native to the process. In addition, students may feel less ownership over their project. In guided-inquiry projects, the instructors guide students toward known research questions, giving them less scope for scientific creativity. The Genetics Case Study is an example of this type of project, where only the definition of the independent variable (degree of urbanization) was left open to student design creativity. Our observation is that student control over this one aspect of the project provided sufficient creative scope to motivate the students while keeping the project aligned with course and programmatic learning goals surrounding specific genetics skills and instructor genetics expertise.

On the other end are more open-inquiry projects. Students have more freedom to ask original questions and practice crafting research questions. Students may feel more ownership of the process but have much more frustration with the open-ended nature. Student teams tend to move at different speeds, so adjustments for pace need to be built into the syllabus. Assessments like the

Hypothesis Scorecard (Luckie et al. 2013) help evaluate student progress and monitor the variable pace of different students and teams.

Placement of the course along the guided-open spectrum depends on instructor comfort level and the learning goals of the course. Compared to students in introductory courses, upper-division students should be more comfortable with the process of science, allowing for student-driven research questions. However, the amount of guidance provided should be dependent on the learning goals of the course and the instructor's own familiarity with the research topic; students at all levels can benefit from both approaches. As instructors grow more familiar and comfortable with student lab projects, a key move is to shift from the guided-inquiry end of the spectrum towards more open-ended projects.

Students Select, Modify, or Create Protocols

With research questions resolved, students next need to grapple with how to address these questions with specific lab or field protocols. Again, how guided or open the project is will affect how students go about finding or using protocols. Guided-inquiry projects can have protocols provided by the instructor, which serves to standardize the experimental design. In the Genetics Case Study, protocols are provided, but only after students attempt to write their own from the methods sections of the relevant research papers.

Open-ended projects allow students the responsibility to seek out relevant protocols with varying levels of assistance. In these cases, protocols require instructor approval before implementation. In the second semester of our majors introductory biology course, students work with common model organisms and are tasked to locate protocols to address their research question. This often involves pilots and a series of trials to identify conditions and protocols that work best for their experimental design.

Students Craft Experimental Design

After establishing an experimental protocol, students define an experimental design with appropriate controls and replication that avoids the statistical phenomenon of pseudoreplication. In parallel with their experimental design, we require students to sketch a diagram of their anticipated results, should their hypothesis be supported. The diagram includes details about sample size and indicates the probable statistics the experiment requires. Novice experimenters often fail to realize the importance of a detailed and sound experimental design to interpret their data at the end of an experiment and need to be challenged to generate a mock graphical representation to develop their thinking around appropriate experimental

design and to build their visualization and abstraction skills surrounding presentation of scientific thinking (Angra and Gardner 2017, Schleinschok et al. 2017). Once the design is approved, students next map out the quantities of equipment, supplies, and reagents they need, which allows them to recognize the scale of their proposed research and to scale up or down as necessary to make the experiment tractable for the timeline they are working under, while maintaining a statistically robust design.

Students Pilot the Protocol

As a final step in the design phase, instructors provide students the opportunity to practice the techniques and troubleshoot the particular difficulties of their protocol. Technical challenges can derail even the most promising of projects. Address these early on in the process to allow the rest of the semester go smoothly. It is important to encourage students throughout these steps as frustration with technical challenges can dampen students' enthusiasm for the project.

Project Implementation

Students Expand to Full Experimental Design

Once the project has been designed and set up, it is time for students to conduct the full experiment. The time allotted to experimentation in the course should have sufficient buffering to allow for the realities of science: repeating assays, iterating a protocol over several weeks, and redesigning the experiment mid-project. Students need time to make mistakes and fix them if necessary. We have had good luck with iteration, where students repeat the same protocol several weeks in a row until they've processed all their samples. Building time for replication or iteration into the course can help account for any complications that arise with the experiment (Corwin et. al. 2015).

To plan our lab courses, we usually block off 3-6 weeks mid-semester for data collection to allow for experimental troubleshooting, iterative data collection, and the possibility to reassess the experimental design if a design isn't working for a group. For a large group project, this translates into building the weekly schedule in real time; each week after lab we assess what needs to happen next and plan the following week's lab time. Building the schedule in real time allows for flexibility to adjust the schedule to the realities of a research project.

Students Pool Data

Pooling the student data after the experiment can be an effective way to maximize the impact of students' projects. Pooled data provides a working dataset for individuals or groups that struggled with a particular

experimental method. In addition, pooled data can help to increase the statistical power for the experimental design, which can not only help the students to understand the importance of replication in science but also provides a more robust result for the community partner.

Students Learn Statistical Analysis

Experimental science contains a data analysis component that serves as a springboard to teach scientific uncertainty (Brewer and Smith 2011). The course goals likely include specific quantitative benchmarks or practice of specific statistical tests. Data analysis with statistics is a complex field. In practice, students will develop statistical skills slowly over time. Each exposure increases their quantitative literacy. Projects constrained to specific questions are easier to mentor for appropriate statistical analysis, but put the burden of explanation on the instructor. Open-ended experimental designs often lead to complex analyses outside the scope of lower-division lab courses. With these cautions in mind, plan explicitly how students will analyze quantitative data for the planned project. Consider the instructor's own applied statistical knowledge and whether the course has scope to address parametric versus non-parametric approaches, as well as student access to statistical packages.

In the Genetics Case Study, students were typically in their first or second year and had not yet been formally exposed to a course in biostatistical methodology. We chose to constrain the research questions to three relatively simple parametric approaches dependent upon how each student defined the independent variable (urbanization). The choice of R was logical for this course. R is freeware with a quick learning curve and a very approachable coding language and user interface. Furthermore, coding is a skill current students will find useful in any career track.

Students Participate in Writing Workshops and Peer-review

The practice of writing about and explaining their own data provides students an opportunity to grasp the biological findings of their research. In the peer-review practice, students read each other's writing with the guidance of questions or a rubric. Not only does review of other students' work help fellow lab mates, it also highlights areas in which the reviewer should improve in their understanding or presentation of their own data, supporting the development of better science communication skills (Reynolds and Thompson 2011). Peer review additionally prepares students better to communicate their data to a wider audience.

Assess Student Learning Via Final Presentations, Laboratory Reports, and Other Projects

The ability of students to effectively communicate their findings to other scientists and to the community partner provides an assessment capstone for a student-driven research project. The course learning objectives and the level of the students help to determine the best assessment approach. The assessment itself provides a vehicle to communicate the student findings to the community partner.

Final presentations can be a good way to develop "soft skills" for both majors and non-majors and help them practice their oral communication skills. Lab reports in the style of a scientific paper develop field-specific writing skills. Grant proposals focus on higher-level writing and argumentation skills. Instructors can also allow students more scope for creativity, such as developing an app or creating a public service announcement about their project to communicate their findings to the community.

Report Results to Community Partners

While student reporting and meeting with the community partners can be important for student growth as well as strengthening connections between the partner and the students, it may take a little further work on the instructor's part to make sure that the community partner is gaining a benefit from the collaboration. Meeting post-course with the community partner to synthesize the experimental results can assist the community partner in making changes based on the students' findings. Additionally, an instructor meeting with the partner can help to strengthen the bond with the partner and allows time to brainstorm the next step in the relationship to extend the partnership into the future.

At this wrap-up meeting, depending on the expertise of the community partner, the instructor may want to highlight curated, scientifically important information that the students have discovered. Curation allows the scientist to frame scientific uncertainty in language more familiar to the average citizen. Additional points of discussion also include how the information benefits the community partner. If you hope to continue the collaboration, take time to strategize how to continue and expand the project in future iterations and consider what further benefits may be gained by the students, the community partner, and the community as a whole.

Course Assessment

While assessment is not a focus of this article, any classroom approach should be evaluated to ensure student learning, course outcomes, and student perceptions match student, instructor, and programmatic expectations.

External surveys such as the Colorado Learning Attitudes about Science Survey (<https://www.colorado.edu/sei/class/CLASS-Bio.html>) or the Student Assessment of their Learning Gains survey (<https://salgsite.net/>) provide students an opportunity to formally provide their evaluation of the course, their learning, and their experience in the course.

Conclusion

Authentic, engaged learning in science laboratory courses has transformed in recent years. With change comes the potential for resistance from students, from colleagues, and from administrators. As scientists, we turn first to evidence to persuade others to support a change in pedagogy against resistance. For service-learning and citizen science, evidence abounds on the benefits to student learning (Tawfik 2014, Ellerton et al. 2016) and student engagement (Moely et al. 2002, Pelco et al. 2014, Webb 2016), with some evidence for retention in STEM (Axsom and Piland 1999). Our approach is to establish, in stages, a community centered project to the end of engaging students in doing science, to collect data on the learning gains and student perceptions along the way, and slowly create momentum and evidence from within our own program that lab sciences with community engagement is in the best interests of students. We also think it's loads of fun for the faculty as well!

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