Hands-On, Hands-Off: The Community College Genomics (ComGen) Course-Based Undergraduate Research Experience

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Abstract

Science is a process of discovery where failure is inherent and iteration is necessary, yet instructors often teach the scientific process as if it is a controlled, highly supervised, confirmatory practice of following directions to get a known answer. We believe this mismatch occurs because instructors often struggle to feel comfortable in facilitating open-ended inquiry and giving students the trust and autonomy to experience an authentic scientific process. In this quarter-long lab curriculum, we bring the scientific process into the classroom in the form of an authentic course-based undergraduate research experience (CURE). We present a pedagogy, which is hands-on for students and hands-off for instructors, that incorporates and celebrates the learning that occurs from failing safely and often. The research project presented in this article is a genomics-based CURE where students sequence and analyze DNA genome segments. Throughout the lesson, we present core instructional structures and techniques that are transferable to any project and help scaffold and support the learning impact of the CURE. In the following curriculum, we outline this pedagogy, applied to a model CURE focused on sequencing a bacterium, and suggest ways that both the pedagogy and the core components of our CURE (i.e., journal club, posters, lab notebook, and self-assessments) transfer to other courses, and other research projects.

Learning Goals

Students will:

◊ gain meaningful experience, confidence and independence in a laboratory environment and research context using common molecular biology techniques.
◊ demonstrate critical thinking and creative problem-solving skills.
◊ understand how science is done in a research setting and develop a deeper understanding of the scientific process.
◊ make decisions with incomplete information and learn from failure.
◊ work in a self-directed manner.

◊ Science Process Skills:
  » Analyzing data
  » Gaining comfort with making decisions with incomplete information
  » Reading research papers
  » Displaying/modeling results/data
  » Communicating results
  » Gathering data/making observations
  » Interpreting results/data
  » Predicting outcomes
  » Reviewing prior research

Learning Objectives

Students will be able to:

◊ describe current methods used to analyze and manipulate DNA, and use current biology laboratory equipment, tools and techniques to sequence and analyze parts of a bacterial genome, including maintaining a professional style laboratory notebook.
◊ interpret and summarize scientific literature.
◊ learn the educational value of iteration and failure in scientific inquiry.
◊ make scientific observations.
◊ analyze and interpret data.
◊ communicate results visually and orally.
◊ self-assess and reflect on their progress.
◊ independently research and apply lab protocols.
◊ gain experience in using common molecular biology techniques.
INTRODUCTION

Undergraduate research is a high-impact practice that significantly increases student learning, success, and retention (1). Course-Based Undergraduate Research Experiences (CUREs) make the benefits of undergraduate research accessible to large numbers of students by incorporating research into existing pathways and courses, especially in a student’s first or second year of college (2). Undergraduates who participate in research were markedly more likely than their peers to feel that they were engaged and thriving in the workplace after graduation; the problem-solving, communication, and information literacy skills that students acquire are highly valued by employers, even in careers that are not related to research (3). Furthermore, CUREs have powerful equity benefits. Undergraduate research is one of the most important factors to reduce equity gaps by increasing student engagement and success, especially for students historically or currently marginalized in STEM (4, 5).

Several CUREs have been developed recently to broaden participation and improve student learning and educational outcomes (see CUREnet; 6); however, the majority were not designed to replace an entire section of a course, although there are some notable exceptions referenced here (7-9). Furthermore, most were not developed and refined at community colleges, which serve a more diverse, primarily first and second year student population, and are often more resource constrained. There are also several genomics education consortiums that have developed inquiry-based curriculum to engage undergraduate researchers in biology (see Genomic Consortium for Active Teaching [10], UCLA’s Undergraduate Genomics Research Initiative [11], Science Education Alliance Phage Hunters Advancing Genomics and Evolutionary Science [6] and the Genomics Education Partnership). However, these are all primarily four-year college and university consortiums and focus more than our consortium on crowd sourcing genomics data analysis through undergraduates. Our CURE is born from ingenuity to overcome resource and time constraints and was designed to allow students to learn how to generate genomics data rather than just analyze existing data. Our CURE curricula is highly transferable, has low barriers to implementation, is affordable and can easily be implemented. Furthermore, our CURE addresses an often-overlooked aspect of doing and designing CURES, which is an explicit emphasis on the pedagogy of how you authentically facilitate inquiry and what instructional strategies support the inquiry process throughout the research project.

In this article we present a quarter long authentic course-based undergraduate research experience (CURE) that is integrated into a 10 to 11-week lab curriculum for a second-year biology major’s course - Cell Biology. By providing opportunities for research in introductory classes in students’ first two years in community colleges across Washington State, this project, called the Community College Genomics (ComGen) project, reached an extraordinarily diverse cross section of college students early in their academic careers. The lab curriculum presented in this article is a product of a 12-year process of developing, piloting, revising, and disseminating this curriculum and pedagogy across 21 community colleges, where we have seen the power of this pedagogy transform the learning environment and outcomes for students. For this reason, here, we hope to emphasize the pedagogy over the project topic or specific techniques. The structure of this curriculum, the pedagogy, and the way it exemplifies how to transform your laboratory into an authentic research experience are transferable to any research project or topic. The topic of the project we present is focused on sequencing the genome of a bacterium. However, after training faculty in our pedagogy and project, we have seen them use the pedagogy and transform their lab classrooms into authentic research courses, but focus the inquiry on a research topic they are more passionate about using biology techniques with which they feel more comfortable. We invite our readers to do the same. We will present the ComGen project as an example to highlight our pedagogy and provide an illustration of how to make a lab section a course-based undergraduate research experience.

The ComGen Project CURE presented here is focused on sequencing the genome of a strain of Pseudomonas fluorescens that protects wheat roots from a devastating fungal disease called Take-all. P. fluorescens strains vary in their ability to protect the wheat, but the strain whose genome we are sequencing is one of the most effective ones. Our collaborators in the USDA research lab provided a small fragment genomic library, and our students work in pairs to sequence a single clone from the library. Students then analyze the sequence they generated and compare it to the known sequences of other strains that are less efficient at protecting the wheat from disease.

Our Pedagogy

Hands-on/Hands-off

The foundation of our pedagogical approach is hands-on for the student and hands-off for the instructor. This means that the instructor intentionally takes a supporting role in facilitating the student experience of open-ended inquiry and all that entails—ambiguity, failure, iteration, and discovery. The instructor provides opportunities for students to take ownership of their learning, be autonomous, take safe risks, and monitor themselves and their progress. Hands-on for the student means that every student gets direct experience, is trusted and held to high expectations by being given opportunities for meaningful decision making and having opportunities to make mistakes and learn from them. Safety, in this sense, means the student can take cognitive risks by asking questions, or revealing what they do not know. There is no penalty in their grades or final product for experimentation, and there is not a lot of known information given to them initially that they are trying to confirm and get validated by the instructor. For example, students do pre-lab work and come into the lab with ideas of protocols. These are checked by the faculty member for any obvious safety concerns and safe materials are provided, but otherwise, students are accountable for their work and reference themselves and their peers to refine the protocol. For the student to take ownership of their learning, and to feel safe enough to experiment, follow their self-researched protocol, and make mistakes or ‘fail’, the teacher must refrain from constant intervention and pre-emptive problem-solving and from providing all the answers or information all the time. This requires the instructor to relinquish some control and reconfigure the power dynamic in the classroom with an expanded vulnerability that is more equitably shared by
instructor and student (i.e., hands-off for the instructor). This shift in power and hierarchy in the classroom is a very important equity-creating practice and can be thought of as a high rigor/high support environment that is most supportive of all learners (13). This allows legitimate, meaningful participation of the student in their own learning. This reflects the “cognitive apprenticeship” model, where the student learns through shoulder-to-shoulder experience with the faculty member while immersed in an authentic setting (14). The difference in this approach to teaching is the difference between a helicopter parent that is constantly monitoring and preemptive and a parent that is securely present, but providing a safe foundation for exploration, in which the child feels secure enough to experiment. Both scenarios provide an equally “safe” environment and do not put their children at risk however, the secure parent allows the child to develop a stronger sense of ownership, self-trust, and self-discovery.

Fail often and safely

The concept of failure as a critical catalyst for student learning is the other foundational part of our approach. We define “failure” as encountering challenges in getting the “expected” results from an experiment. Failure transforms into a mechanism for learning when it becomes productive struggle (15), iteration is expected, and a growth mindset is modeled (16). This curriculum was explicitly designed to create opportunities for mistake-making, iterating after failure, and decision-making without complete information. Failure creates some of the most valuable learning opportunities in this curriculum. When students confront disconfirmation, the experience of not getting the result they expected, they must examine their thinking and assumptions. If this reflection is supported by the instructor through self-assessment prompts and retracing their steps in your lab notebook, this can help students build metacognitive skills. They also experience an increase in self-motivation to problem-solve, because mistakes are not punished or preemptively planned out by the teacher. Instead, they are rewarded as an opportunity to learn and failure is experienced as inherent to discovery and inquiry and framed as valuable. The instructor needs to reframe failure for the students, celebrate it, and make it safe by making it common and rewarding, since it leads to better, more informed outcomes and is not reflected negatively in grades.

The hands-on/hands-off approach and emphasis on failure as learning are highly transferable to any classroom and fundamental to reconfiguring a standard lab course into an authentic research setting. This lesson also applies the critical components of CUREs: collaboration, discovery, broad relevance, iteration and use of scientific practices. These critical components are helpful guideposts for restructuring content and highlighting what is pedagogically important in course-based research experiences regardless of the research topic of the course.

Broader Relevance and Importance

The broader relevance and importance of the CURE makes the curriculum authentic and serves to build a larger sense of community. Students in this course sequence a genome to help identify new genes that play a role in ongoing genomics research. Each clone is unique, and therefore the results are unique, which allows each student pair to truly own their novel results. At the beginning of the term, students were introduced to the most up-to-date research on this project. We used videos (S10. ComGen - Lab 3c-ComGen Videos) with real scientists to introduce the ongoing research and make this project relevant to the students. This degree of immediate relevance and importance, with a clear path for students to make a unique contribution, is incredibly meaningful for the student experience in this CURE.

Use of Multiple Scientific Practices

The intent of CUREs is to allow students to learn by doing and to anchor the student experience in the real practice and process of scientific inquiry. In our CURE, students use the tools of a scientist through engagement in genomics techniques in each lab. Students are given broad guidelines on how to complete each of the procedures and a general timeframe. They must manage their time, do pre-lab research on protocols (included in each lab), on their own and share best practices with their peers in order to complete this project. Students maintain professional lab notebooks and self-assess their notebooks against a standard rubric throughout the quarter. Students also participate in journal club, where they read selected primary literature on topics relevant to genomics and discuss them in a group. This exercise is used to expose students to the evolving nature of science, as well as demonstrate the current scholarship, terms, and scientific writing form and style. This activity further allows students to engage in critique about the quality, methods and results of research articles (17). Poster presentations allow students to practice synthesizing and communicating scientific results as well as engage in a scientific community. This bundle of scientific skills, that are technical, collaborative, self-regulating, and cognitive, are the foundational learning outcomes of this CURE and provide students with a well-rounded arsenal of “scientific practices.”

Collaboration

Collaboration is a fundamental component of building a social learning environment and a community of practice that replicates the larger scientific community. Throughout this course students engage in collaboration in various ways. In the learner-centered environment, where the teacher is more “hands-off,” the teacher and student enter a more collaborative, as opposed to transactional, relationship. The entire course is structured like a community of practice, in which membership is centered around a common interest—research—and students can have legitimate participation as they are inducted into the practice, process and culture of authentic scientific inquiry (18, 14). Students participate in a collaborative, loosely structured lab environment where they build relationships with each other and feel mutually supported in their learning process. At the end of the CURE, students present posters and articulate their research to their peers, college administrators, and scientists. Here, they often recognize they are contributing to, and have become part of, something larger—a scientific community.

Iteration

Iteration is approached as a pedagogical strategy, but is also facilitated by the course schedule and structure. Allowing for and celebrating the learning opportunities that failure
presents in a research environment is a critical component of the hands-off approach and part of the training faculty received in this project. Having the students do pre-lab work, where they independently find a protocol and bring it into lab to try, creates an opportunity for ownership. Inevitably, their protocols are incomplete and often lead to errors so iteration is necessary to confer with peers or the instructor, and continuously improve their protocol in real time in lab. Communicating expectations clearly and giving constructive feedback frequently are productive to creating an authentic research environment. However, providing detailed protocols, constant validation, or anticipating and intervening before the students make mistakes undermine the students’ abilities to develop trust in themselves, achieve technical thoroughness, and learn from their mistakes (19). Self-assessment is used to review lab notebooks and progress and provides opportunities for students to learn and strengthen metacognitive skills, reflect on their process, and gain independence and confidence (20). Self-assessment allows students to iterate, re-examine, modify and reflect on their work without penalty. It shifts the focus of assessment from external disapproval or validation provided by the teacher to internal reflection, self-correction and motivation originating from the student (20). The lab schedule is iterative, allowing students to repeat making a gel, for example, multiple times after bringing in their own protocol, conferring with their peers and learning from their mistakes. Mistakes, along with room/time to correct them, create some of the most authentic opportunities for problem-solving, metacognitive evaluation and regulation, and ownership of the learning process.

**Intended Audience**

This course is taught in the major’s biology sequence at Washington Community Colleges and serves as the entire laboratory curriculum for a quarter long course. The course is comprised of mostly first- and second-year students pursuing a degree in science, but also some pre-allied health students or non-majors. This course was taught at 18 different community colleges and at two universities. It was primarily taught in the following course: BIO 211/BIO 222, Biology Majors (Cell and Molecular Biology). This is the first in a three-course sequence for science majors and pre-health students. Topics include cell structure, metabolism and energetics, genetic control of life, biotechnology, and an introduction to evolution.

**Required Learning Time**

This lesson is a series of eight labs that are used as the entire ten-week long lab curriculum for a cell biology course. Each lab is three hours, for a total of 24 hours. The time of each lab and journal club activity can vary according to the skill level and experience level of the students.

**Prerequisite Student Knowledge**

Students are required to have a C or better in the first course in the major’s biology or chemistry sequence (Biology 160 or Chemistry 161).

**Prerequisite Teacher Knowledge**

Faculty should primarily emphasize gaining comfort and knowledge in teaching inquiry through the hands-on/hands-off pedagogy and facilitating learning from failure, and should also read literature on the core aspects of CUREs: collaboration, discovery, broad relevance, iteration and use of scientific practices. Depending on the project the faculty member chooses, they should also be familiar with the specific techniques. In the case of this curriculum, faculty need to know basic molecular biology techniques needed for plasmid isolation, gel electrophoresis, and performing sequencing reactions and basic sequence analysis.

Faculty in our community of practice have certainly employed our pedagogy starting with little to no experience with the techniques being used. They learned new techniques and piloted new projects in real-time with students in their classrooms. Students like to be involved and give honest feedback in the process. In fact, it can be quite helpful for the teacher to get a more authentic experience of being hands-off as they are legitimately learning along with the student and iterating the project in real-time. We therefore encourage you to try it, pilot a new research project, learn these techniques or other new techniques, and prepare yourself primarily in the teaching pedagogy and approach of hands-on/hands-off.

**SCIENTIFIC TEACHING THEMES**

**Active Learning**

As a model CURE, students are, by definition, in an active experiential learning environment. They are hands-on. They collaborate, build on each other’s work, help each other, and give and receive feedback. Students are given time and opportunity to learn from mistakes and failures and to repeat experimental steps and analysis, exactly as would be done in a research environment. They are immersed in a laboratory learning environment where they engage in multiple scientific practices that are driven by the instructor or students, with an unknown outcome and novel findings. Students participate in the following major activities: independent pre-lab protocol research and class discussion, lab work, iteration and reflection, documenting results and reflections in lab notebooks, reading scientific literature and presenting articles in journal club, and presenting posters.

**Assessment**

Students are assessed through several embedded, formative assessments, as well as some summative assessments.

**Self-Assessment**

Self-Assessment is a major component of learning how to effectively keep a lab notebook and participate in laboratory work. There are specific self-assessment assignments (Supporting Files S37-S39) that are sequenced throughout these labs to assess student learning at different stages and allow for reflection and self-correction. These are handed in at week 3 and week 7 to provide instructor feedback and make sure that students are not putting off this important exercise.

**Lab Notebook**

Students are required to record exactly what they did, their materials and methods, their thinking and logic, questions and observations. This serves as a document of their research process, as well as their thinking and learning process, which can be used for retrospective reflection and self-correction. This aspect of the lab notebook works in tandem with the self-assessment course component. This model turns evaluation over to the students by having them complete the self-assessments. If the instructor does the evaluation, they
undercut and devalue the student’s work and autonomy and miss this opportunity for supporting students in building self-regulation and metacognitive skills. An additional way to help students self-assess the lab notebook quality is to allow them to use their lab notebook as they complete the Lab Final. The grade on the Lab Final then also functions as a grade on the quality of the lab notebook.

**Poster**

Each lab pair is graded on the preparation and presentation of one poster. It is also important to give the students a chance to present the poster publicly, as it adds a level of authenticity and gives them that experience of presenting at a simulated professional poster session. The more exposure the students get to the larger campus audience during this presentation the better. Students who have their posters displayed in the science building report feelings of pride.

**Lab Final**

The lab final was developed as an objective direct assessment of skill and knowledge acquisition resulting from their research project. It tests students on both laboratory procedures and molecular techniques and research topic knowledge. For the lab final and instructor key email the primary author, Gita Bangera.

**Survey**

We used a retrospective survey, modeled on the CURE survey (21), to assess self-reported student learning outcomes. The survey is administered online at the end of the course, consists of 18 questions and takes approximately 20 minutes to complete. This survey asks students to reflect on: (1) their highest degree intentions and intended major prior to and after this course, (2) on their level of experience in targeted skill areas prior to taking this course and after taking this course, (3) the perceived benefits of this course in multiple technical, affective and cognitive domains and (4) their qualitative reflections regarding specific course components: lab work, lab notebooks, self-assessment and journal club. In these open-ended prompts, students were also asked the following:

1. Please describe how useful these specific components [journal club, lab work, self-assessment] were for you as a learning activity. How did it help you learn?
2. To what extent, did each of the following course components [journal club, lab work, self-assessment] contribute to you identifying yourself as a scientist?

(See S40. ComGen - Student Learning Outcomes Survey for the full survey.) For this paper, we will present a subsample of our data (from 2016-2017) that is representative of the student learning outcomes resulting from this CURE over the entire life of this project.

**Inclusive Teaching**

This series of laboratory lessons is a model course-based undergraduate research experience that is designed to maximize educational equity. Studies demonstrate marginalized students, such as students of color, low-income students, first-generation students, student veterans, and students with disabilities, benefit the most from undergraduate research experiences and experience compensatory gains in academic success when compared to their White peers (1, 22, 4). Furthermore, there is research to suggest that the completion of a research experience early in their academic career is the single most impactful method for increasing the retention and academic success of historically marginalized students in STEM (5, 23).

This project maximizes the participation of historically marginalized student populations in research because it was developed and taught at community colleges, which serve the majority of these student populations, and brings in these equitable teaching techniques into the first and second year courses. Our approach of doing research in existing courses democratizes research and increases access. This series of lessons are designed to replace the required laboratory section of a major’s biology course; it is integrated into the student pathway and accesses far more students than a special topics course or independent study model. CUREs work for diversifying science and research because they are built into the core student experience and don’t require students to do anything “extra,” and therefore minimize barriers for historically marginalized populations (2). Furthermore, our pedagogy of fostering high expectations, forming a community of practice, and de-risking failure supports an inclusive learning environment.

**LESSON PLAN**

This lesson is a series of eight labs that are used as the entire lab curriculum for a quarter-long cell biology course. The course meets twice weekly for lecture and a 4-hour lab period. A full lab section would have 24 students. Students work in pairs and each pair is given their own genetic sample to sequence and analyze. All lab materials in the supporting materials are organized by week and lab number. The Journal Club (Supporting Files S25-S34) and Self-Assessments (Supporting Files S36-S39) are grouped together in the supporting materials but how they are sequenced throughout the labs is articulated in the Lab Schedule below.

**Lab Overview**

Students work in pairs to sequence a single clone from the genetic library of *Pseudomonas fluorescens* strain L5. 1-96. Students then analyze the sequence they generated and compare it to the known sequences of other strains that are less efficient at protecting wheat from the disease, Take-All.

Students with little or no molecular biology experience start with learning lab safety, use of micro pipettors, and maintaining a lab notebook. They then research methods to pour agarose gels and prepare gels with their own individual protocols without much scaffolding from the instructor. Students learn the variability of protocols and troubleshoot why their gels did or did not work and formulate a standard protocol for gel preparation. Students then isolate plasmid DNA using standard lab kits, digest DNA with restriction enzymes, and analyze the DNA by gel electrophoresis. Students sequence the DNA either by preparing the sequencing reactions themselves or by sending the plasmid DNA to a sequencing facility. Students analyze the DNA sequence using BLAST and other sequence analysis tools, both identifying the gene(s) encoded in their DNA fragment and comparing it to the known sequences of the other (less effective) strains. It is expected that most of the sequences will be similar, and it is a rare sequence that
is likely to be missing from all previously sequenced genes compared in the BLAST analysis. This step requires students to think about the different implications of getting a sequence that perfectly matches a known strain versus getting sequence identity to species other than P. fluorescens.

To help students gain the experience of reading and analyzing research literature, the lab experience also includes Journal Club. The instructor conducts one session showing scholarly reading strategies and tools and then each student group is expected to do one in depth presentation of an article in a series of eight Journal Club presentations. This happens every week. In addition to the selected team’s presentation on an article, all students are asked to read a related popular science article or the selected scientific article and answer reading comprehension questions.

Finally, students put together their analysis and inferences in a poster and present it in a department-wide or college-wide event.

Lab Format

The student pre-labs follow a common format: (1) the learning objectives, (2) before lab (preparatory work done by the student independently), (3) in lab (the hands-on exploration activity conducted in the lab) and then (4) questions and prompts for the student’s lab notebook that guide their inquiry and identify what to document under the sections of background, materials and methods, results, and discussion. If additional lab prep is needed, there is an accompanying lab staff prep instructions document. In fact, since students do their own prep (e.g., making their own gels) and work, other than buying a few reagents, there is very little lab tech work for these labs. Some resource sheets or product information are shared with the student when it is appropriate. Some of these lessons also include instructor documents, which have pertinent background information for instructors or provide proactive troubleshooting advice for common hang-ups.

Journal Club

Journal Club, a time to digest and interrogate primary literature, is included in almost every lab and often done first thing in lab or as it is convenient during a procedure with wait time. The essential structure is that all students read either a review of a pertinent lab topic or a primary article directly. Then, a selected group of three to four students present a primary article cited in that review or the primary article they read and go more in depth into methods and discussion. Through this practice, the students gain scientific literacy skills. They see examples of and practice scientific communication, build topical content- and protocol-understanding, and get to see firsthand how science is a living, evolving process that they can contribute to. Ideally, the articles instructors choose show protocols and techniques that their students are learning, as well as demonstrate how the concepts they are researching are connected to other real-world applications and an evolving field of science. Faculty that explicitly teach their students strategies and skills for building scientific literacy (e.g., breaking down jargon, mapping the anatomy of an article, etc.) and allow for repeated practice tend to be the most successful at supporting students in building these skills. Through journal clubs, instructors also bring students into the larger community of practice of biology. The journal club taps directly into the current practices of science and brings that evolving knowledge to the student. Since the journal article is a mechanism for scientists to communicate with one another, the student becomes a proxy scientist by engaging with the article. It is as if the student can eavesdrop on a “conversation” between the experts in the field. This helps the student to identify themselves as a scientist within a larger community of practice, both in their own classroom and the larger related scientific field. Typically, eight papers are done in a quarter with the instructor demonstrating the first journal club and teams of 3 students doing the other seven presentations. This works in a 24-student class or lab section. Although groups of 3 are ideal, as that size allows for each student to contribute substantially and have time to present, this can be adjusted for classes of other sizes. A list of journal articles, a journal club rubric, and associated journal club assignments are in Supporting Files S25-S34.

Lab Notebook

The lab notebook (Supporting Files S35 and S36) is the primary record of the research process and is an organizational tool that serves as an archive of process and protocol. Keeping a lab notebook is a standard requirement in professional research and one that has many learning benefits for students. The lab notebook teaches project management skills, such as attention to detail and organization, as well as critical thinking and problem-solving skills. Additionally, through reflection and retracing of steps, the lab notebook can illuminate errors. These can then be altered and improved upon, which supports the students’ metacognitive development. On the most practical level, the lab notebook is maintained with the idea that either the student (later in time) or someone else must be able to read and understand what has been done. The more readable and complete the notebook is, the more useful it is.

Poster

The poster and final presentation (S24, ComGen - Poster and Presentation Rubric) is an essential tool to help students pull together and understand the research project that they have worked on over the quarter. It is important that the poster be prepared over the duration of the course and not just pulled together at the very end. The first step in preparing the poster is the Self-Assessment Assignment 2 (S38, ComGen - Lab Notebook Self-Assessment 2), which results in the draft for the introduction portion of their poster. The pre-labs for all the labs include lab notebook prompts, which curate methods, diagrams, and results/summary analyses that can be put directly into the poster. The results and discussion sections are further refined during Lab 8: Bioinformatics.

Lab 1: Introduction to ComGen Project and Lab Techniques

Lab Activity

The learning objectives of this lab are to implement use of standard molecular biology lab equipment, to understand safety measures in a molecular biology laboratory, begin the laboratory notebook, describe the significance of the bacteria and provide background on the ComGen project. Students should have read the document (S35, ComGen - How to Set Up Your Lab Notebook) prior to lab and they should have completed the (S1, ComGen - Lab 1a Intro to ComGen and Lab Techniques Pre-lab STUDENT) work prior to lab. As students enter the lab, the instructor checks their
pre-lab work in their notebook, provides feedback and then signs the document. Instructor makes it clear that this will be the practice at the beginning of every lab and a pre-lab signature is required to get points for the lab. This practice encourages students to come prepared for lab. There are no reagents required for these labs other than colored water for students to practice pipetting.

Journal Club

In this lab, the instructor introduces journal club format (described above in Journal Club section), shares the Journal Club Rubric for presentations, and assigns students the Journal Club Assignment 1 to be completed in lab (Supporting Files S25, S26, and S34). Then, the instructor demonstrates how to read and think through an excerpt of a scientific article, introducing the main structure, and tips such as writing in the margin and circling vocabulary words. The instructor then forms presentation groups based on the student preferences identified from Journal Club Assignment 1 and lets each group know which week they are presenting and which article they will be presenting.

Introduction to the research project

The instructor provides links to the videos outlining the research project (S10. ComGen - Lab 3c-ComGen Videos) and students are expected to watch the videos to start writing the introduction section of their poster (the self-assessment for this happens as part of Self-Assessment 2 [see Lab 3]). While the videos provided in this publication are about the bacterium and its relevance to the ecosystem, the key factors to emphasize are the nature of science, building on previous work, and the social aspects of being a scientist. The instructor can customize the videos for their own research project and incorporate these key messages.

Lab 2: Making and Running Gels

The learning objectives of this lab are to demonstrate the ability to make and run electrophoresis gels and to gain an understanding of electrophoresis and running different percentage gels. Students should complete the (S4. ComGen - Lab 2a-Making and Running Gels Pre-lab STUDENT) before the lab starts. As before, the instructor checks their work and looks for improvements over what they did for the first week. Introduce this lab by telling students that this is a time for experimentation. The instructor should encourage experimentation by indicating there is no wrong way to do this lab and reminding students they are looking at variations that will work. The instructor should have different buffers available for students to try. (e.g., TAE and TBE). The instructor leads a short discussion at the beginning of class in which they talk about visualization of DNA and the difference between loading dyes and discuss the dyes used to visualize DNA. Then, students compare various ways to visualize DNA. The instructor should tell students what DNA visualization dye (Gel Green) they will be using and to pay attention to the dilution factor. They use DNA that was made in a previous quarter to load on the gels. The instructor demonstrates the loading of the ladder as it is a little more expensive. The instructor should discuss the importance of the DNA ladder as both a positive control for a functional gel and the norming tool to identify the size of the isolated plasmid.

This is the stage for the instructor to execute the “hands off” approach by answering student questions with questions rather than answers. For example, the instructor might ask/say “Well, what do you think the options might be?” or “What did your pre-lab research tell you about that?” or “Maybe you need to google that and see what others do.” This is also the opportunity to help students get comfortable with the repeated failure of lab experiments by highlighting the learning that can come from such failures. The instructor should make a big point of celebrating any challenges that come up and to be honest and vulnerable about the failures they have experienced. For example, “You poured the agar too hot and it poured all over the table? Awesome! I couldn’t tell you the number of times I have done that” or “You let it cool too much so it partially gelled before you poured it and your DNA ran weird? That happens all the time.” It is important to model failure as learning and de-risk it for students. This is research; it is important to emphasize figuring out what went wrong and finding ways to fix it.

Journal Club

All students will have completed Journal Club Assignment 2 (S27. ComGen - Journal Club Assignment 2). The student group assigned for this week’s presentation will present their article and take questions.

Lab 3: Bacterial Culture for Plasmid Amplification

The actual activity time for this lab is very short and the rest of the lab time should be used to check student Self-Assessment 1, assign Self-Assessment 2 and allow time for reflection.

Self-Assessment 1

In this lab, the first thing the instructor does is check the student’s Self-Assessment 1 (S37. ComGen - Lab Notebook Self-Assessment 1), which is an evaluation of Lab 2. It should be completed prior to this lab and is designed to check the quality of their lab notebooks. Before checking the completion of their Culturing Bacteria Pre-lab (S8. ComGen - Lab 3a-Culturing Bacteria Pre-lab STUDENT), the instructor is looking for them to have learned significantly from doing the self-assessment. It is helpful to discuss the process of self-assessment and what they learned while checking their lab notebook.

Lab activity and reflection on pre-lab research

The learning objective of this lab is to learn how to inoculate bacterial cultures using aseptic technique. The individual bacterial clone that each pair of students will be analyzing is inoculated into liquid medium from a prepared agar plate. The instructor should demonstrate how to aseptically transfer 3-5ml of antibiotic-containing broth to the tubes and inoculate the bacteria from the plate. After the instructor has verified that students have done their pre-lab research, there is a discussion about generating a genomic library, restriction enzymes, plasmids, transformation, and growth media. The students start two cultures, both of which they will pellet in the next lab with one for initial DNA prep and one for a second DNA prep. This is a good place to ask students to reflect on if their before lab research was detailed enough to come up with a good procedure and ask them to identify what information would have been helpful.
Self-Assessment 2
The instructor assigns Self-Assessment 2 (S38. ComGen - Lab Notebook Self-Assessment 2), which includes watching the research background videos, if the students haven’t already done so (see Lab 1; S10. ComGen - Lab 3c-ComGen Videos), and writing their self-assessment which becomes their introduction for their final poster. The instructor shares with the students that Self-Assessment 2 gives them the tools to start their poster early and to get feedback on their introduction section.

Journal Club
All students will have completed Journal Club Assignment 3 (S28. ComGen - Journal Club Assignment 3). The student group assigned for this week’s presentation will present their article and take questions.

Lab 4: DNA Isolation
The learning objectives of this lab are to isolate plasmid DNA from a pellet and to analyze DNA quantity and quality for sequencing. Students should have completed Pre-lab DNA Isolation (S11. ComGen - Lab 4a-DNA Isolation Pre-lab STUDENT) before lab. Ideally, the instructor should do very little introduction to this lab, as it takes many students the full lab time to complete all tasks. The instructor explains to students how to harvest the cells from each of their inoculation tubes into a microfuge tube, so that at the end each student pair has two cell pellets.

One of the cell pellets is used immediately for DNA isolation and the second tube is frozen for their second lab attempt. The instructor also reminds students that they shouldn’t be using the special spin column tubes until later in the procedure and reiterates the safety concerns with disposal of anything that has touched live cells. This is the first really challenging lab that the students encounter with multiple steps and high potential for mistakes. How the instructor handles errors made in this lab is critical! When errors occur in this lab (and they will), the instructor should do very little introduction to this lab, as it takes many students the full lab time to complete all tasks. The instructor explains to students how to harvest the cells from each of their inoculation tubes into a microfuge tube, so that at the end each student pair has two cell pellets.

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The instructor reminds students that they will need to have clear, and preferably typed, procedures for both the making and running gels part from Lab 2 and the DNA isolation part from Lab 4 in their notebooks ready to follow for Lab 5. The instructor also reminds students that part of their pre-lab assignment is checking with other lab groups to make sure that they have the most optimal procedure to run for the next lab session.

Journal Club
All students will have completed Journal Club Assignment 4 (S29. ComGen - Journal Club Assignment 4). The student group assigned for this week’s presentation will present their article and take questions.

Lab 5: Repeat DNA isolation and Visualization
This lab’s learning objective is for students to iterate and refine their procedure for isolating DNA. Students should have completed the Repeat Isolation and Quantification Pre-lab (S13. ComGen - Lab 5a-Repeat Isolation and Quantification Pre-lab STUDENT) before the lab, and they should have complete procedures in their notebooks for both procedures. The instructor checks and signs notebooks as usual, often letting students get started on the lab while they continue to do this at the beginning of lab. Students have already done this once, so there is no pre-lab discussion during this lab. Students have not visualized the first DNA sample yet, so they don’t know whether they successfully isolated DNA, and if so, how much. If the instructor has access to a nanodrop to get DNA concentration and A260/A280 purity, it is great to use that tool. If not, DNA visualization using agarose gel is perfectly acceptable.

Journal Club
All students will have completed Journal Club Assignment 5 (S30. ComGen - Journal Club Assignment 5). The student group assigned for this week’s presentation will present their article and take questions.

Poster preparation
Instructor should remind students to put together the remainder of the poster so that they can add their results and discussion section once they have their DNA sequence analyzed.

Lab 6: Restriction Enzyme, PCR, and Sequence Analysis of Plasmid DNA
The learning objectives of this lab are to set up sequencing reactions, set up restriction digest and set up a polymerase chain reaction (PCR). Students should have completed the Restriction Enzyme Analysis of Plasmid Pre-lab (S15. ComGen - Lab 6a-Restriction Enzyme Analysis of Plasmid Pre-lab STUDENT) before this lab. Instructor discusses the purpose of each procedure, the steps to the procedure and asks students to list the reagents that go into each reaction.

Most sequencing reactions have most of the reagents already in them and the students mostly add their plasmid DNA (and in some cases primers). Therefore, it is important to have the students discuss and write on the board what is already in the sequencing mixture and why each is necessary. Note that if the students are simply sending their DNA sample to a sequencing facility, this discussion becomes even more critical.

Students store the completed restriction digest DNA in the freezer and the instructor will usually have to take the sequencing reactions out from the thermocycler after completion and send the material to the sequencing facility.

Self-Assessment 3
At this point in the sequence of labs, students are well into their lab notebooks and it is a good time to have them self-assess their quality. For homework, students are asked to complete Self-Assessment 3 (S39. ComGen - Lab Notebook Self-Assessment 3).
Journal Club
All students will have completed Journal Club Assignment 6 (S31. ComGen - Journal Club Assignment 6). The student group assigned for this week's presentation will present their article and take questions.

Poster preparation
Instructor should remind students to put together the remainder of the poster so that they can add their results and discussion section once they have their DNA sequence analyzed.

Lab 7: Run Gel to Analyze Samples
The learning objectives of this lab are to run the gel to analyze samples, to analyze insert size using restriction enzymes and to analyze insert size using PCR. There is no pre-lab, as this is an iteration on making and running gels. Students must come to lab with a refined procedure for making and running a gel. Since this is the third gel that the students have run, they should be much more confident with this procedure by now. Their data result/summary and analysis section of their lab notebook is critical for this lab. They need to determine the size of the plasmid insert from a combination of the PCR and restriction digest data. This step is challenging for students both conceptually and practically, and it is important to support students in their “productive struggle” both in the lab and during office hours. The “hands-off” part of the philosophy is critical here – instructors should support and facilitate the student’s efforts without jumping to provide too much help. Students should put together a diagram and calculations on their poster showing insert size and summarizing the sequencing results on the diagram in terms of how much sequence they obtained at each end of the insert. For students whose gels show no DNA, the instructor can allow them to use another student pairs’ materials or sequence or provide one or more optional open lab periods (if that is feasible) to allow students to repeat the full set of experiments. Having done all the procedures at least once, students are usually able to complete the most important steps quickly.

Journal Club
All students will have completed Journal Club Assignment 7 (S32. ComGen - Journal Club Assignment 7). The student group assigned for this week’s presentation will present their article and take questions.

Poster preparation
Instructor should remind students to put together the remainder of the poster so that they can add their results and discussion section once they have their DNA sequence analyzed.

Lab 8: Bioinformatics Lab (& Poster Review)
The learning objectives of this lab are to analyze the DNA sequences and to begin work on posters. The instructor encourages students to attempt to do as much of the bioinformatics as they can before lab, following the instructions on the Bioinformatics Pre-lab (S23. ComGen - Lab 8-Bioinformatics Pre-lab STUDENT). For this lab, it is helpful to get a room that has computers. This lab is run as a help session for the bioinformatic analysis and for review and editing the poster. Again, this step is challenging for students both conceptually and practically, and it is important to support students in their “productive struggle” both in the lab and during office hours. The “hands-off” part of the philosophy is critical here – instructors should support and facilitate the students’ efforts without jumping to provide too much help. The instructor should share the poster rubric in this lab so students understand how they will be graded. The student’s lab notebook is the main source of information for pulling content for the poster, and every part of the poster besides the discussion have been curated up to this point. The poster preparation and presentations are the most powerful parts of the student experience and provide the rare opportunity for exercising both critical thinking and synthesizing skills. Students have shared that it is at this stage that they experience a significant shift in their thinking and learning.

Journal Club
All students will have completed Journal Club Assignment 8 (S33. ComGen - Journal Club Assignment 8). The student group assigned for this week’s presentation will present their article and take questions.

Lab 9: Poster Presentation
The poster presentation is most effective as a formal, campus- or departmental-wide event with attendance from people outside the class, so that students have a chance to talk to outsiders about their work and be recognized in the larger campus community. The more authentic it is in mirroring a real scientific conference, the more students step up to the challenge and present quality, well-articulated work. In our survey of student learning outcomes, the poster presentations are repeatedly mentioned as a time where students really feel confident, part of the scientific community, and proud of their work and what they learned over the process of this course. It is a powerful culminating experience that solidifies in the student's mind all the learning that has occurred and how much they have gained from the experience.

Lab 10: Lab Final
The final lab exam is given in the final lab period. The instructor allows students to use their lab notebooks on the final lab exam and this is shared at the beginning of the quarter to encourage good quality lab notebooks. Students are also asked to complete the survey (S40. ComGen - Student Learning Outcomes Survey) for extra credit.

TEACHING DISCUSSION

Faculty Guidelines and Barriers
In our experience of working with 50 different faculty members, we have found that faculty teach authentic CUREs because they enjoy how independent, self-motivated, inquisitive and engaged their students become when they do meaningful research. The classroom of a CURE is a distinct learning environment and will not be immediately recognizable, especially to younger students in their first or second year. The level of self-direction, autonomy and reframes on evaluation and failure are unique and need to be explicitly introduced as different expectations for this modified classroom. Some students will resist this level of autonomy and high expectations. To be transparent and protect yourself from negative evaluations, you need to emphasize the importance of learning this way and manage expectations. Be proactive about encountering tensions, and highlight the benefits of
learning through discovery, both when things are positive and negative. For example, self-assessments are often places where students appreciate autonomy to correct errors without punitive measures or consequences to their grades. Highlight their autonomy in these times to show how useful it is for their learning and how you trust them to fix their own errors.

Many faculty worry that CUREs are more work. We have found that the increase in student engagement, higher expectations for students, and shift to self and peer assessment, build self-regulating behaviors and increase student motivation - lessening faculty work over time.

Doing research is often intimidating to faculty, especially faculty at community colleges without external ongoing research labs and activities. When research is done for student learning everything shifts. In fact, it is important that instructors are not research experts, because they can empathize and co-learn along with the students. The data quality and product of the research is not really the point—student learning is. Success should be evaluated based on the student learning outcomes instead.

Managing Student Expectations

Students will exhibit a range of comfort with the level of autonomy and self-direction required for this CURE. Some students will really enjoy managing their own project, be ready to research their own protocols, and see the value in failure without getting frustrated; other students will not. Continuously articulating the value of learning this way, being consistent about celebrating failure and rewarding vulnerability and experimentation, and reminding students of the high expectations helps immensely. Knowing that students come in with different levels of experience and comfort learning this way and being clear about how learning “how to learn” this way is one of the key outcomes of this course can help manage student expectations and the instructors’ own expectations.

Overcoming Institutional Barriers

When transforming a course, especially a standard major’s course, it is common to experience pushback from other faculty, deans or lab techs. Articulating the value of CUREs to these colleagues and demonstrating effectiveness through all the national level literature on the positive impacts on student learning through undergraduate research experiences is worthwhile. Most instructors do not have to have data for their class or their campus to demonstrate this is an effective way to teach. Lean on the national data and studies from other colleges. Be cost conscious and collaborate on the lab prep design and decision-making with your lab techs so they feel they have input and are valued in the decision-making, knowing it might add workload or cost for them. Where possible, bring the lab techs into the conversation while designing the labs.

Effectiveness of Lesson

Student Learning Outcomes of this Course-Based Research Experience

The student learning outcomes of this CURE have been continuously assessed for 12 years (human subjects protocol BC-IRB-26). Here we present our most recent data from 2016-2017 from a sample size of 241 students who took the major’s biology course. These data are from the survey on student learning referenced in the assessment section of this article. Students reported statistically significant gains in their experience level in the following areas targeted by our model:

1. In working on a lab or project where no one knows the outcome
2. In reading primary scientific literature
3. In analyzing data
4. In presenting posters
5. In maintaining a lab notebook.

Through analysis of the qualitative data, we found that in 67% of the responses, students demonstrate insights on the practice and process of scientific inquiry. Our data indicate that a dominant student learning outcome of this CURE is a better understanding of the nature of scientific inquiry and failure. For example, a representative quote of this type of learning is this student’s reflection on lab work. “Lab work in this class helped me increase my tolerance for possible errors in lab and how to remedy them and the steps to take after. Prior labs in other classes were very straightforward and dictated, but the labs for this class taught me that not all real lab work is error free as in the typical classroom.” Furthermore, students feel this CURE taught them transferable skills and gave them valuable experience for their life after college. In 48% of student responses, we saw students articulate the value of this CURE in developing career related skills as this student quote demonstrates, “I see myself as much more professional and employable. I now know how to search for my own protocols, make and run gels, do PCR, and Sanger Sequencing. I feel that I have real world skills that I could use in my educational career and in my job.” The student learning from this CURE is undeniably positive and heightened by the authenticity, sense of ownership, hands-on learning and autonomy of the students’ experience.

Modifications and Adaptations

Developing Your Own CURE Based on This Model

This curriculum is intended to provide a template for faculty to use to develop their own CURE. This curriculum was disseminated through a faculty professional development program and through that experience, we witnessed how our model is transferable and can be used with different research topics. To develop your own CURE based on this model, we suggest you do the following:

- Be selfish. Choose a research topic that interests you, that makes you excited and motivates you to learn. Your excitement translates to your students and the initial work of getting a project set up requires enthusiasm and self-motivation. If the project doesn’t excite you, it will seem like too much work and will be hard to motivate students. In addition, this model mirrors the authentic experience in a research lab, where a new student rarely has the opportunity to strike out into a new research project and usually builds on the work that is ongoing in the lab.
- Choose a research project that is connected to ongoing research, is a community science project with crowd-sourced data collection, has existing data collection protocols, an existing database, and/or a meaningful output for data. This lowers the barrier for entry, you
don't have to develop everything, but it also gives broader relevance to the project. Students get to see real scientists doing the same work and the story of the research is more meaningful if the data goes somewhere, if the research is connected to a current problem, part of ongoing current research, or answers a pressing question.

- Be realistic about how much data students can actually collect in a quarter timeframe. It is actually very little. The data demands of the project need to be low to emphasize learning, experimentation, and time for iteration and failure. The focus here is to use research as pedagogy not to use students as “additional hands.”
- Be gentle with yourself and your students as you pilot the project for the first time. Your ability to be vulnerable will translate to the students and encourage them to be more vulnerable in their own learning.
- Get early support from your Dean, administration, and lab techs. The sooner they feel involved and part of the pilot, the better they can support you. They are integral to your success, so making it a shared experiment and getting their early buy-in shares some of the risk.
- As you plan the content and structure of the labs, consider when you can get more hands-off and students can get more hands-on. Let the students do as much of the work as possible. Ask yourself where you can create opportunities for them to bring in content or research protocols? Where can they make safe mistakes, and how they can be validated and collaborate with their peers to find the answer rather than be evaluated or validated by you?
- As you plan the sequence of the labs, think about ways to front load content to allow for iteration and failure. Consider where you can loosen up the structure so that they have to manage their time and practice self-direction and project management skills.
- Consider how you might find an authentic audience beyond the classroom for their poster presentations and elevate that aspect of the course, so that it feels professional and important.
- Consider what “cookbook” labs could be eliminated to make room for this, more authentic process.

Example projects

Our community of practice used the Hands-on/Hands-off pedagogy and core components of our CURE (i.e., journal club, lab notebooks, self-assessments, posters) with many different research projects. Some examples that did not use the wheat genomics project include:

1. A Tacoma Community College faculty member transformed the lab for a standard 200-level microbiology pre-allied health course into a CURE based on barcoding a microbial “class pet,” isolated from Kombucha, and incorporating all the standard microbial techniques into investigation of that research sample.

2. A faculty member at Bellevue College co-taught a course called Biology and Race, cross-listed as an ethnic studies and introductory biology course, looking at the biological and cultural understandings of race and racial identity. They used an abbreviated version of this ComGen CURE genomics sequencing curriculum to provide hands-on experience with DNA sequencing. This was paired with parallel research on the student's own genetic heritage and ancestry results.

3. A faculty member at Clark College developed a multi-quarter research project for 100- and 200-level students that replaces their lab section to study an endemic species of gastropods and successfully transferring the pedagogy (i.e., specifically student researched methodology, lab/field notebooks, self-assessments, hands-on/hands-off etc.) of this CURE to ecological field research.

4. A faculty member at Spokane Community College developed a climate research project based on documenting changes to sword fern populations. Students collect field data and monitor fern plots on campus during the school year and report data to the Fern Watch: Save the Redwoods, a national database and community science project that is monitoring the effects of climate change on sword ferns. She used the hands-on/hands-off, pre-lab work, self-assessment, celebrating failure, and field notebooks aspects of this project.

5. A faculty member at UW Bothell, took these same lab protocols, but used a different genetic library of corn genomes exposed to drought and controlled conditions. The framing for the project is different, related to epigenetics and how environmental conditions affect levels of methylation of the DNA, but all the protocols and pedagogy are the same.

SUPPORTING MATERIALS

- S1. ComGen - Lab 1a-Intro to ComGen and Lab Techniques Pre-lab STUDENT
- S2. ComGen - Lab 1b-Solutions and Pipetting Worksheet STUDENT
- S3. ComGen - Lab 1c-Pipetting Prep LAB STAFF
- S4. ComGen - Lab 2a-Making and Running Gels Pre-lab STUDENT
- S5. ComGen - Lab 2b-Electrophoresis Prep LAB STAFF
- S6. ComGen - Lab 2c-GelGreen Product Sheet STUDENT
- S7. ComGen - Lab 2d-Biotium 1kb Ladder Information STUDENT
- S8. ComGen - Lab 3a-Culturing Bacteria Pre-lab STUDENT
- S9. ComGen - Lab 3b-Starting a Culture Prep LAB STAFF
- S10. ComGen - Lab 3c-ComGen Videos
- S11. ComGen - Lab 4a-DNA Isolation Pre-lab STUDENT
- S12. ComGen - Lab 4b-Isolating Plasmid DNA Prep LAB STAFF
- S13. ComGen - Lab 5a-Repeat Isolation and Quantification Pre-lab STUDENT
- S14. ComGen - Lab 5b-Electrophoresis Prep LAB STAFF (same as S5)
- S15. ComGen - Lab 6a-Restricion Enzyme Analysis of Plasmid Prep-lab STUDENT
- S16. ComGen - Lab 6b-Restriction Enzyme Digest Prep LAB STAFF
- S17. ComGen - Lab 6c-Eurofins Sequencing Guidelines INSTRUCTOR
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Table 1. Assessments.

| Activity                      | Assessment                                                                 | Notes                                                                                                                                 |
|-------------------------------|-----------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------|
| Self-Assessment               | Rubric and reflection (Supporting Files S37-S39)                           | This is an evaluation done by the student, peers, and the instructor at different points throughout the course to allow for correction and reiteration. |
| Lab Notebook                  | Rubric (S36. ComGen - Lab Notebook Evaluation Rubric)                      | Students are exposed to this rubric at the beginning and the guidelines for documenting lab work. They use self-assessments or peer assessments throughout the course to continuously improve their notebook. |
| Journal Club                  | Rubric (S34. ComGen - Journal Club Rubric)                                 | Journal club is done every lab day, facilitated by a different student group.                                                           |
| Poster                        | Rubric (S24. ComGen - Poster and Presentation Rubric)                      | This is done at the end of the course prior to the final research poster presentation. Students also get an authentic assessment at the actual poster presentation as they present to an audience beyond their classroom. |
| Final Exam                    | Multiple Choice Test                                                       | This is an exam to test research project and laboratory knowledge. (Not included in supporting materials, please email us if you want a copy.) |
| Reflection on Student Learning Outcomes | Post-Course Retrospective Survey (S40. ComGen - Student Learning Outcomes Survey) | This is modeled off of the Lopatto 2008 CURE survey and captures self-reported student perspectives on their learning outcomes. |
Table 2. Lab Schedule.

| Lab | Description | Estimated Time | Journal Club & Articles | Self-Assessment of Lab Notebook | Associated Supporting Materials |
|-----|-------------|----------------|-------------------------|---------------------------------|---------------------------------|
| Lab 1: Introduction to ComGen Project and Lab Techniques | Implement use of standard molecular biology lab equipment (pipettors). Understand safety measures in a molecular biology laboratory. Begin laboratory notebook Describe the significance of *Pseudomonas fluorescens*. Describe the ComGen project. | 3 hours | S26. ComGen - Journal Club Assignment 1 S34. ComGen - Journal Club Rubric S25. ComGen - Journal Club Articles | S35. ComGen - How to Set Up Your Lab Notebook | S1. ComGen - Lab 1a-Intro to ComGen and Lab Techniques Pre-lab STUDENT S2. ComGen - Lab 1b-Solutions and Pipetting Worksheet STUDENT S3. ComGen - Lab 1c-Pipetting Prep LAB STAFF Homework: S10. ComGen - Lab 3c-ComGen Videos (Due Lab 4) |
| Lab 2: Making and Running Gels | Demonstrate the ability to make and run electrophoresis gels. Demonstrate an understanding of electrophoresis and running different percentage gels. | 3 hours | S27. ComGen - Journal Club Assignment 2 | Homework: S37. ComGen - Lab Notebook Self-Assessment 1 (checked in Lab 3) | S4. ComGen - Lab 2a-Making and Running Gels Pre-lab STUDENT S5. ComGen - Lab 2b-Electrophoresis Prep LAB STAFF S6. ComGen - Lab 2c-GelGreen Product Sheet STUDENT S7. ComGen - Lab 2d-Biotium 1kb Ladder Information STUDENT |
| Lab 3: Bacterial Culture for Plasmid Amplification | To grow the bacterial clone for plasmid isolation | 3 hours | S28. ComGen - Journal Club Assignment 3 | Homework: S38. ComGen - Lab Notebook Self-Assessment 2 | S8. ComGen - Lab 3a-Culturing Bacteria Pre-lab STUDENT S9. ComGen - Lab 3b-Starting a Culture Prep LAB STAFF Homework: S10. ComGen - Lab 3c-ComGen Videos |
| Lab 4: DNA Isolation | To isolate plasmid DNA from a pellet. Analyze DNA quantity and quality for sequencing. | 3 hours | S29. ComGen - Journal Club Assignment 4 | | S11. ComGen - Lab 4a-DNA Isolation Pre-lab STUDENT S12. ComGen - Lab 4b-Isolating Plasmid DNA Prep LAB STAFF |
| Lab 5: Repeat DNA isolation and Quantification | To isolate plasmid DNA from second pellet. Analyze DNA quantity and quality for sequencing. | 3 hours | S30. ComGen - Journal Club Assignment 5 | | S13. ComGen - Lab 5a-Repeat Isolation and Quantification Pre-lab STUDENT S14. ComGen - Lab 5b-Electrophoresis Prep LAB STAFF |
| Lab | Description | Estimated Time | Journal Club & Articles | Self-Assessment of Lab Notebook | Associated Supporting Materials |
|-----|-------------|----------------|-------------------------|-------------------------------|-------------------------------|
| Lab 6: Restriction Enzyme, PCR, and Sequence Analysis of Plasmid DNA | Set up your sequencing reactions  
Set up restriction digest  
Set up PCR | 3 hours | S31. ComGen - Journal Club Assignment 6 | Homework:  
S39. ComGen - Lab Notebook Self-Assessment 3 | S13. ComGen - Lab 6a-Restriction Enzyme Analysis of Plasmid Pre-lab STUDENT  
S16. ComGen - Lab 6b-Restriction Enzyme Digest Prep LAB STAFF  
S17. ComGen - Lab 6c-Eurofins Sequencing Guidelines INSTRUCTOR  
S18. ComGen - Lab 6d-Invitrogen PCR SuperMix INSTRUCTOR  
S19. ComGen - Lab 6e-Xbal Restriction Enzyme Info STUDENT  
S20. ComGen - Lab 6f-EcoRI Restriction Enzyme Info STUDENT  
S21. ComGen - Lab 6g-Sequencing/PCR Primer Ordering INSTRUCTOR |
| Lab 7: Run Gel to Analyze Samples | Run gel to analyze samples  
Analyze insert size using restriction enzymes  
Analyze insert size using PCR | 3 hours | S32. ComGen - Journal Club Assignment 7 | | S5. ComGen - Lab 2b-Electrophoresis Prep LAB STAFF  
S22. ComGen - Lab 7-Run Gel to Analyze Samples INSTRUCTOR |
| Lab 8: Bioinformatics Lab | To analyze the DNA sequences that you receive  
To begin to work on your poster | 3 hours | S33. ComGen - Journal Club Assignment 8 | | S23. ComGen - Lab 8-Bioinformatics Pre-lab STUDENT  
S24. ComGen - Poster and Presentation Rubric |