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RESEARCH ARTICLE:

Redesigning Undergraduate Laboratories: From Recipes to Research

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Abstract

In an effort to introduce discovery-based learning in our undergraduate laboratory curriculum, we joined two collaborative, crowd-sourcing efforts to engage early career undergraduates in searching for novel antibiotics or bacteriophages as antimicrobial therapies. This was the first step in transforming the curriculum into one focused on providing research experiences to all our undergraduates. Our goal was to engage students in open-ended research projects that foster a sense of ownership, advance knowledge, and introduce relevant skills. We also developed courses built on faculty research programs and biotechnology industry practices. In one, students design cell culture models of tissue regeneration. Another connects to faculty research investigating stress responses in a model of mycobacterial tuberculosis. In an immunotherapies course, students design cell culture and protein purification strategies to maximize generation of a monoclonal antibody. In our newest course, students examine number and diversity of soil nematodes in urban locations. This course has evolved to include interdisciplinary research into the environmental history of the sites. Assessments demonstrated gains in concrete skills and related concepts, and in aspects such self-efficacy. All are measures shown to increase retention and student future success.

Keywords: *course-based undergraduate research; authentic research; discovery-based learning; undergraduate laboratory teaching*

Introduction

The call to improve undergraduate STEM (science, technology, engineering, math) education in the United States was initiated over a decade and a half ago. Among the many reports and proposals was a strong and consistent recommendation to reimagine the undergraduate laboratory curriculum by replacing traditional lab courses with authentic research-based courses (NRC, 2003; President's Council, 2012; Brewer and Smith, 2011). In the ensuing years, several studies have validated the personal and professional benefits of research experiences for undergraduate students, including gains in areas such as disciplinary skills, information literacy, and professional ethics. Less tangible gains include growth in self-efficacy, understanding the research process, and clarification of career paths. All these measures have also been shown to have positive impacts on retention and future success of students in STEM disciplines (Lopatto, 2007; Hunter *et al*., 2010; Jones *et al.*, 2010; Finley and McNair, 2013).

The traditional model of providing undergraduate research experience is to have students work in faculty research laboratories, but even at large research universities this model is not scalable to the extent necessary to include large numbers of students. The CURE (course-based undergraduate research experience) is a model wherein groups of students address research questions in a course-

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based laboratory setting. These courses provide students with access to a research experience beginning early in their undergraduate careers, and are more easily scalable, as they do not rely on access to individual faculty research laboratories. Fortunately, a number of studies have shown that many of the same benefits accrue to students who take these courses, including increased knowledge, research skills, and self-efficacy (Wei and Woodin, 2011; Auchincloss *et al*., 2017; Corwin *et al.,* 2015; Linn *et al*., 2015; Mader *et al*., 2017).

Our laboratory curriculum has evolved in four identifiable stages: I. the introduction of a crowd-sourcing model of discovery; II. the design and delivery of two courses tied to funded research programs of department faculty members: III. a discovery lab based on current biotechnology industry practice; and IV. an interdisciplinary effort with a faculty member from another department and discipline. In 2014 we made the decision to transition our previously very traditional laboratory curriculum to one founded in open ended, discovery-based design. We started this initiative by joining what is now an international consortium of institutions participating in a crowd sourced model of students engaged in antibiotic discovery, then termed the Small World Initiative (now the Tiny Earth Initiative). We subsequently joined the Howard Hughes Medical Institute SEA-PHAGES (The Science Education Alliance-Phage Hunters Advancing Genomics and Evolutionary Science) initiative, another international, crowd sourcing model with students isolating and characterizing potentially novel bacteriophage. These two models continue to be part of the core of laboratory experiences for our first- and second-year students.

Initial assessment of student responses to these two authentic research opportunities led to us to develop additional research experiences based on our own faculty research translated to a course-based model. We currently have two such courses, tied directly to ongoing work in faculty research laboratories, where students have an opportunity to make a real contribution to the research effort. Since about 50% of our undergraduates go on to work in the biotechnology industry, we recently developed a laboratory course where students are given an open-ended opportunity to optimize the production and purification of a monoclonal antibody of the sort currently termed a “biologic”.

The final novel and very recent innovation to our laboratory curriculum tied a first- and second-year lab in ecology with a history of urban ecology course taught in our Humanities and Arts Department. Students in the lab isolated and characterized nematodes, regarded as environmental sentinels, from soil samples gathered from local industrial sites. Students researched the history of these sites dating back to the early 19th century, and the two research cohorts investigating each site shared their findings, both scientific and historical, with one another. The two disciplines were integrated as an investigation of environmental justice as it relates to the current use of the sites which have undergone decades of what Frickel and Elliot (2018) term “industrial and residential churning”. All laboratory design followed the principles of backward course design (Wiggins and McTighe, 2005; Davidovitch, 2013), guided by learning outcomes for our department which directly map to the laboratory curriculum. Those published guidelines state that graduates of the undergraduate Biology & Biotechnology program are able to:

- Demonstrate mastery of a range of quantitative and procedural skills applicable to research and practice in the discipline
- Generate hypotheses, design approaches to test them, and interpret data to reach valid conclusions.
- Demonstrate oral and written communication skills relevant to the discipline.
- Describe the broader scientific or societal context of their work.
- Understand and adhere to accepted standards of intellectual honesty in formulating, conducting, and presenting their work.

In addition to assessing progress specific to the stated learning outcomes, we also used more qualitative measures of learner-centred personal and professional growth associated with this approach. In what follows, results from selected outcomes measures for each of the courses described are presented.

Methodology

Calls for laboratory reform and the personal and professional benefits ascribed to undergraduate research experiences strengthened our burgeoning resolve to adjust our laboratory curriculum to reflect a more authentic experience. In 2014, we decided that the transformation would begin with our lower-division laboratory curriculum and was initiated by our acceptance into the first cohort of the Small World Initiative (SWI) now called Tiny Earth Initiative (TEI) (Tiny Earth, 2022). Our initial success with this program led to our subsequent decision to join the SEA-PHAGES programme (SEA-PHAGES, 2022) run by HHMI. Both initiatives are based on a crowd sourcing model where students design experiments, collect data, and contribute to a national database. These collective data are of interest to both the educational and scientific research communities.

The learning outcomes for both initiatives correlate well with our departmental outcomes, including hypothesis generation, experimental design, and data analysis. Both focus on skills generally associated with early-career laboratory experience, including aseptic technique, serial dilution, microbial culture, and basic biochemical identification, selection, and purification strategies. To address the outcomes related to communication, students in both courses learn the use of record keeping using electronic laboratory notebooks. Additionally, specific sessions on information literacy (e.g. library research) and poster design and presentation were integrated into the course. The course culminated with a public poster session including an informal reception so that the faculty within and beyond our department could learn about the course and interact with the student presenters, emulating sessions at professional meetings. Since the research foci of both courses can be related to the current antibiotic resistance public health crisis, students readily put their work into broader scientific and societal contexts.

Consortium members have ready access to protocols, practices, and support from the consortium staff and share experiences, recommendations, and suggestions with other members. Thus, course design involved selection and modification based on institutional resources rather than requiring *de novo* design. That being the case, we chose to focus this section on assessments. While a number of published studies have reported data regarding benefits of these specific experiences for undergraduates gathered using validated instruments such as the CURE (Course-based Undergraduate Research Experience) (CURE Survey, 2005) and SURE (Survey of Undergraduate Research Experience) surveys (Sure III, 2005), we also assessed qualitative measures such as interest in pursuing the research beyond the course constraints. Here we report these and other outcomes measures from our experience, including changes in student attitudes, persistence in pursuing research, and perceived gains.

Students enrolled in the TEI based course were predominantly in their first (34%) or second year (55%), some of whom had not taken a college laboratory course before. Nearly all were biology and biotechnology majors (81%) with the rest biochemistry, chemical engineering, bioinformatics, and biomedical engineering majors. Student attitudes, skills, and perceptions were assessed over the first three offerings of the course as described below. During each of two-hour laboratory sessions each week, objectives were discussed, a variety of materials and supplies provided, and protocols made available through the electronic laboratory notebook; however, no specific instructions were given as to how to proceed. At the beginning, midpoint, and end of the course students were surveyed about their reaction to the unstructured nature of the laboratory sessions. The poll was anonymously conducted using student polling software to collect and display the data and so that students could see the attitudes of their classmates. The average results from the first three times the SWI/TEI course run representing a total of 77 students can be seen in Figure 1. Over time, the responses shifted to show an increased level of comfort. Anecdotally, the ability of students to see that there were others in the course who shared their feelings had a reassuring effect, making students more at ease regarding their level of uncertainty about the course.

Results and Discussion

In this section, we present the findings from our survey as we discuss them in line with the objectives of this paper. First, the students responded to a query about their experiments. Student responses to the query "*Making up my experiments makes me feel …*"

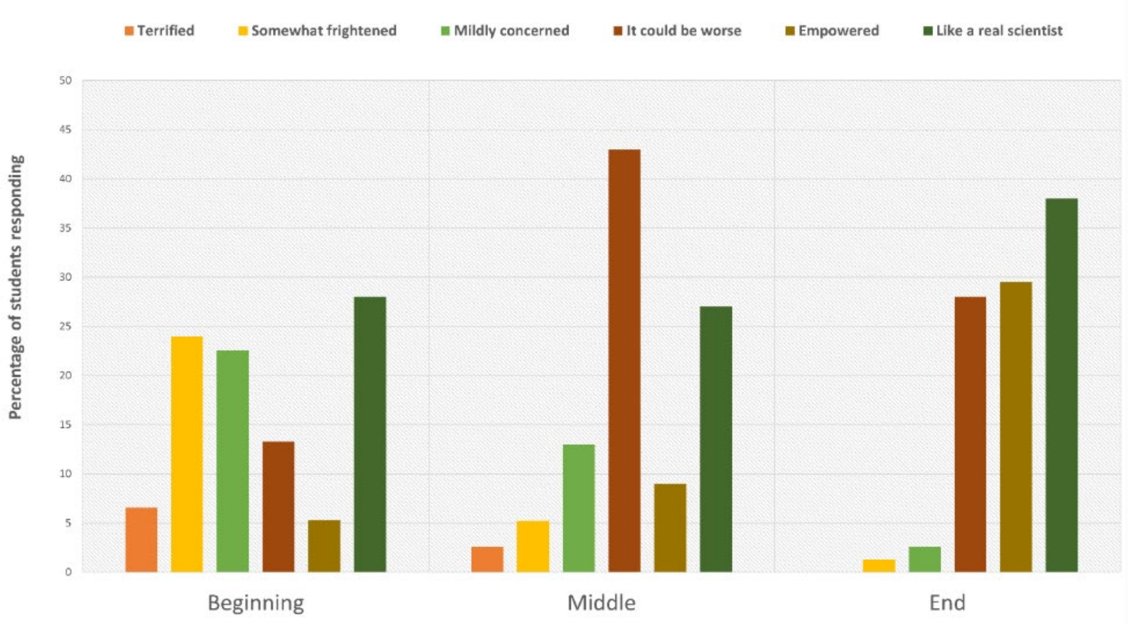

Figure 1: Student attitudes on discovery-based experiments.

Since one of the goals of discovery-based research is to give students a sense of being part of a larger community of scientists and that their research can make a difference, At the conclusion of the course the students were asked two questions to measure their attitudes toward the research they did as part of the class. They were asked if they would consider continuing the research as their senior year research project, a graduation requirement for all students, and whether they believed they had contributed to a larger body of scientific knowledge. The results of this poll are shown in Figure 2.

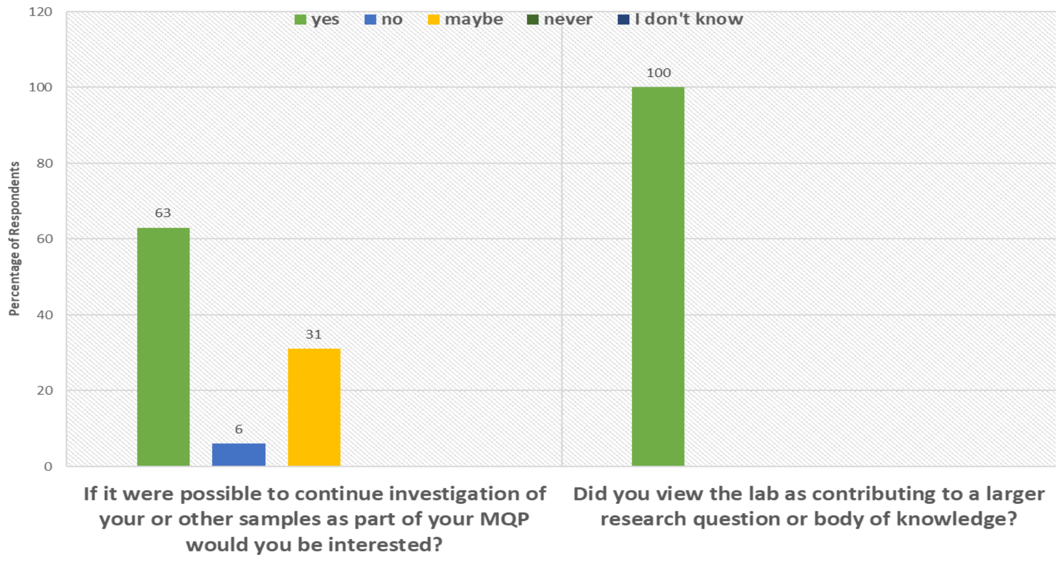

Figure 2: Student attitudes toward their research. Student responses to the prompts provided.

These results show that all the students did perceive that they were contributing to a body of scientific knowledge that was bigger than just their experiments or those of students in the course. The fact that 63% of the students became interested enough in their research during the class that they would continue it as their senior research product reinforces the power of this mode of teaching to engage students in the research process.

Student self-assessment of learning gains (SALG Surveys)

To determine if students believed they had gained in understanding the concepts, learned skills, and changed attitudes during the course - "Student Assessment of their Learning Gains" (SALG) surveys were deployed pre and post course (Seymour *et al*., 2000). The results of these surveys are shown in Table 1 (N=19 pre and 24 post). In the SALG survey, students were asked to rate each question using a Likert scale of *not applicable*, *not at all*, *just a little*, *somewhat*, *a lot*, or *a great deal*. These were given a numerical value 1–5 and the change for each student pre- and post-course were calculated. Positive change indicated movement up the scale and negative numbers down the scale. Note that 31 questions were used in the survey and only the 11 with statistically significant results (Δ post-pre, * p< .05, ** p< .01) are shown in Table 1.

Table 1: Selected survey questions

	Δ (post-pre)
Understanding: Presently, I understand …	
How to operate basic molecular biology equipment such as spectrophotometers, electrophoresis equipment, centrifuges, and microfuges	0.8*
How to perform and analyse polymerase chain reactions under a variety of conditions	1.1**
The analyses of DNA and amino acid sequence data using software and central databases	1.6**
The concept and mechanisms of antibiotic resistance	0.9**
The production and use of secondary metabolites by organisms	1.7**
How ideas we will explore in this class relate to ideas I have encountered in other classes within this subject area	1.2**
Skills: Presently, I can …	
Work safely with microbes and other biologics	1.1**
Use aseptic techniques	1.6**

Attitudes: presently, I...	
Read biology when it is not assigned	0.7*
Am confident that I can work in a biology laboratory	0.7*
Am comfortable working with complex ideas	0.7**

It is evident from Table 1 that the students perceived they gained understanding in areas that are pertinent to a course based on microbiology, molecular biology, and antibiotic discovery. Likewise, they reported gains in laboratory relevant skills. There was also some positive change in attitude about biology more broadly defined. As part of the more directed surveys given during the course students were also asked open response questions about their attitudes post course. Below are two quotes representative of student reflections received.

> *"I really enjoyed working with a lab that allows you to create and perform experiments ... and have discovered that this is the type of research I like."*
>
> *"I enjoyed the fact that it was so discovery oriented and that experiments weren't assigned with strict protocols. I feel it really helped me improve as a student and a scientist."*

As a final summative assessment of student learning gains in the scientific process students were given the following prompt at the end of the course: "Design one new experiment to either: 1) find a new isolate or 2) further characterize your isolate". These responses were then evaluated by a faculty member familiar with the course and subject matter, but not actually involved in the instruction. The responses were examined for the use of the scientific process and the ability to apply it. Of the students responding, 80% suggested different or even novel strategies (soil agar, anaerobic conditions, etc.). The remainder (20%) reiterated what they had done to collect their current isolates. This shows that this course, based on a discovery model, did promote student understanding of the scientific process and supported experimental and creativity.

SEA PHAGES lab course

The goal for students in the SEA PHAGES programme is to isolate novel bacteriophage from soil samples in a discovery-based fashion similar to that used in SWI/TEI. This design complemented what we were already doing. Our students were surveyed pre- and post-course using the Persistence In The Sciences (PITS) survey (Hanauer, Graham and Hatfull, 2016) as part of the programme, the results of which have been published (Hanauer *et al.*, 2017). Although the published data do not show the results for individual consortium institutions, overall, the benefits of the programme were consistent with those we saw in the antibiotic, discovery-based CURE.

Spurred by the successful launching of the crowd-sourcing lab courses at the introductory level, in 2016, our department convened a faculty retreat to explore ways to expand the authentic research paradigm to our upper-level lab curriculum. Since discovery and communication are inherent aspects of research in the sciences, our faculty research programmes seemed ideally suited for framing our next initiative both in tangible and practical ways. Our goal was to maintain the authenticity of the research while making it possible, given the constraints of time and budget, for students to obtain clear results that they could analyse and communicate to a scientific audience. Two faculty research efforts were identified, which had the potential to support student screening of variables directly relevant to the ongoing research. This would ideally provide a framework to develop student scientists who had the skills and the self-efficacy to contribute to discovery, and who could communicate the novelty and impact of their findings.

In academia, written communicating of discovery is done through the primary literature (peer-reviewed journal articles) and by detailed recording of experimental findings and the processes behind them (lab notebooks). Oral communication, another of our learning outcomes, is done through public presentations, often at professional gatherings. Providing opportunities for our students to gain the skills and confidence to necessary to do meaningful research, and to communicate their findings in ways consistent with standards in the discipline are at the heart of our department's stated goal to support life-long learning in the discipline. Below we describe the format and context of two upper-level courses that resulted from this effort. Following the trajectory of course design and implementation, we identify the relevant learning outcomes and the skills and concepts included in each course and present the results of our assessments.

Molecular biology and genetic engineering lab (MBGE)

Given the complexities of modern molecular methods, this course places a focus on precise elements of design and careful manipulation of DNA, RNA, enzymes, and cells. Adherence to the concepts permits the students to build confidence technically at the bench. This in turn yields clear and reliable experimental results, which allow students to develop a sense of identity as scientists making valuable and unique contributions within and beyond the course.

The Molecular Biology and Genetic Engineering course was developed based on the research program of a faculty member in our department. The goal of this research is to discover how gene regulation mediates response to environmental triggers in *Mycobacterium smegmatis*, a soil bacterium that serves as a realistic and safe model for *M. tuberculosis.* In the related course, students worked in pairs using contemporary cloning methods (e.g., Gibson Assembly) to create new strains that could be assessed for changes in gene expression, at both the mRNA and protein levels, as well as for changes in growth. Each pair worked with their own gene/DNA sequence, created unique strains, and designed procedures to grow, treat, and analyse their cultures. This design was intended to allow students to feel a personal investment in what they were creating. Collectively the class explored a range of experimental variables, and each student team placed their original work into the collective context, so that the class operated as a community of scientists through discovery and sharing of knowledge and information. The learning outcomes for this course were:

- demonstration of quantitative and procedural skills related to molecular biology
- ability to design appropriate experiments using contemporary approaches and techniques
- ability to collect, record, and analyse experimental data to assess the validity of a stated hypothesis

Students emerged with the ability to present their original findings clearly in written and verbal formats while adhering to the standards, style, and intellectual honesty expected of life scientists.

The technical laboratory skills students learned included small-volume liquid handling (micro-pipetting); polymerase chain reaction (PCR); nucleic acid isolation, purification, and quantitation; transformation; microbial cell culture; and spectrophotometry. Additional skills included analysis and annotation of DNA sequences, primer and oligonucleotide design, record keeping using a digital laboratory notebook, and presentation of their scientific findings at a poster session. The broad concepts that underpin these skills included the need to include controls, data normalization, and the use of replicates in data analysis. In their experimental design and implementation, students had to consider safety, time, budget, space, and equipment constraints. Concepts more specific to this course included how primers could be designed to modify and amplify DNA sequences for cloning, detection, and quantitative analyses.

Cell culture models lab (CCM)

Encouraged by the assessment data and student feedback from the MBGE course, we developed the second authentic research-based lab, Cell Culture Models of Tissue Regeneration (CCM). This one was based on the research enterprise of a faculty member who investigates tissue regeneration, using an epidermal wound-healing model. This lab allowed students to create their own cell-based models, test and assess their designs, and write up their work using the format of peer-reviewed journal articles. Students were given a choice of several mammalian cell lines, biocompatible materials (some obtained from faculty in biomedical engineering), and culture configurations to construct a three-dimensional (3D) model to mimic a wounding or disease state. Students worked both individually and in groups of 3–4 persons in lab exercises and writing initiatives as described below. The most significant products of this course were the 3D models and the journal articles that describe their designs and validations. In addition to collaborating with research faculty in biology and biomedical engineering on the wet-lab component, we consulted with writing faculty in our Humanities and Arts Department to develop a structured approach to writing. This effort was recognized at the institutional level by a "writing-intensive" designation for this course. We expected that upon conclusion of the course students would be able to:

- demonstrate mastery of the procedural skills required to conduct cell culture-based experiments
- describe the roles of cell and material interactions in cell/tissue survival and functionality
- design appropriate models and experiments using contemporary approaches in cell biology
- present their findings clearly in the format of a peer-reviewed research journal article

This lab also emphasized the collaborative nature of science. Students relied on their group members in both the laboratory and writing initiatives, which had the added benefit of building both trust in others and confidence in oneself as a professional scientist. Fundamental skills in this course were sterile mammalian cell/tissue culture, media preparation, preparation and use of biocompatible hydrogels and scaffolds, microscopy, and maintenance of cells in multiple culture formats. Students also learned how to assess cell proliferation and viability. The course was designed so that every student acquired these technical skills individually early in the term. Writing was taught from the outset via "process pieces", where each student completed several structured writing assignments focused on individual skills such as journal article reading, editing, note-taking, and presenting results using figures and tables.

As the term progressed, the course evolved to assume a team-based approach in both the lab and writing. Student teams performed primary literature searches related to applications of 3D culture systems. Each team wrote a background on the cell lines and materials they intended to use in their model. After choosing their model system, each group created a design plan that included methods to assess the efficacy of their mode. Team members worked collaboratively to start and maintain their cultures for 1–2 weeks, recording the results that were eventually used to determine how well their design served as a model. The process pieces were integrated into their final journal article, which constituted the major writing deliverable. Conceptually, students gained an appreciation of the importance of sterility when building, maintaining, and testing their cell-based systems. The modelling aspect of the course led the students to view cells not only as discrete units, but also as building blocks of tissues and organs. Students explored the concept of biocompatibility – what makes materials biocompatible, how these materials could be used as substrates, and the importance of cell-material interactions in creating a useful model. The key writing concepts taught included how to use the primary literature to identify a gap in current knowledge, how to use existing information to inform experimental design, and how process pieces, refined by iterative feedback and revision cycles, contributed to the final written product.

For the MBGE and CCM laboratories, we used two assessment tools, the CURE post-survey (Lopatto and Tobias, 2010) and a novel skills and concepts inventory (SCI; Roberts and Shell, 2022) we designed to evaluate learning gains. The CURE survey was also used to evaluate the outcomes of a third industry model course (IPL) which is presented in the next section. The results for all three courses are presented in Tables 2–4 below.

CURE survey results

In Tables 2 and 3, percent reporting positive gain is a summation of the percent of students choosing moderate, large, and very large in response to the prompt: *please rate how much benefit you gained in each of the following categories as a result of your work in this class.* Students selected one of the following answers for each category: no or very small gain, small gain, moderate gain, large gain, very large gain, not applicable/prefer not to answer.

Table 2: results related to gains in specific knowledge and skills contained in the learning outcomes

	IPL	**MGBE**	**CCM**
Prompt: Rate how much gain you experienced in …	**% reporting positive gain**		
Learning laboratory techniques	93	92	94
Generating valid hypotheses	93	67	81
Designing valid experiments	93	75	94
Appropriately displaying and analysing data	100	100	81
Interpreting results to reach valid conclusions	100	96	81
Understanding of how scientific knowledge is constructed	86	88	81
Average gain in specific knowledge and skills	**94**	**86**	**85**

Table 3: results for benefit gained in students' ability to place results into a broader scientific context, in their ability to collaborate, and in understanding ethical standards in scientific research.

	IPL	**MGBE**	**CCM**
Prompt: Rate how much benefit you gained in…	**% reporting positive gain**		
Placing results in the appropriate broader scientific or societal context	79	88	88
Collaborating with other researchers (including students and instructors)	93	100	94
Understanding and applying accepted standards of intellectual honesty in research	93	79	88
Average gain in broader skills	**88**	**89**	**90**

Table 4: results for prompts designed to measure self-efficacy and personal achievement

	IPL	**MGBE**	**CCM**
Prompt: Rate your level of agreement with the following statements.	**% responding somewhat agree or strongly agree**		
Completing my research project gave me a sense of personal achievement.	71	92	75
I am confident that I am prepared to handle the challenges involved in scientific research.	79	79	80
I have a clear understanding of how scientists integrate theory and knowledge from previous research in the design of their research projects.	86	92	84
I get personal satisfaction when I solve a scientific problem by figuring it out myself.	86	100	96
Average agreement with statements related to increased self-efficacy and personal achievement	**81**	**91**	**84**

Students were asked to indicate the degree to which they agreed with the following statements about their work in the class, and were asked to choose between strongly agree, somewhat agree, neither agree nor disagree, somewhat disagree, and strongly disagree. Here the percentages of students responding "*agree*" or "*strongly agree*" were combined.

SCI survey results

The SCI instrument assesses learning gains focused on specific skills and concepts and was developed for and deployed in the MBGE and CCM laboratories. For the MBGE course we identified primer design, PCR, DNA sequence annotation, mRNA isolation and quantitation, cDNA synthesis, and qPCR as the key skills/concepts. The survey prompt was: “Please rank your familiarity/comfort/ experience with the following on a 0-4 scale, where:

0 is ‘I am completely unfamiliar/have no experience with this concept/technique’
1 is ‘I have heard of/done this concept/technique once but am not comfortable’
2 is ‘I am somewhat comfortable with this concept/technique’
3 is ‘I am familiar with this concept/technique’
4 is ‘I am an expert with this concept/technique’

Learning gains were calculated as the difference in student reported scores between the first day of the course and the end of the course. Results are shown in Figure 3.

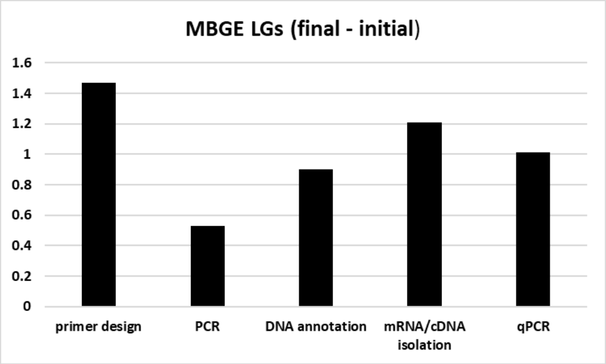

Figure 3: Student learning gains for course-specific skills and concepts for MBGE

The skills/concepts we identified for CCM included tissue culture techniques, presenting findings via scientific technical writing, cell-cell interactions, cell-material interactions, and materials as 3D scaffolds for cells/tissues. The survey prompt and scale were identical to the one above for the MBGE course. Results are shown in Figure 4.

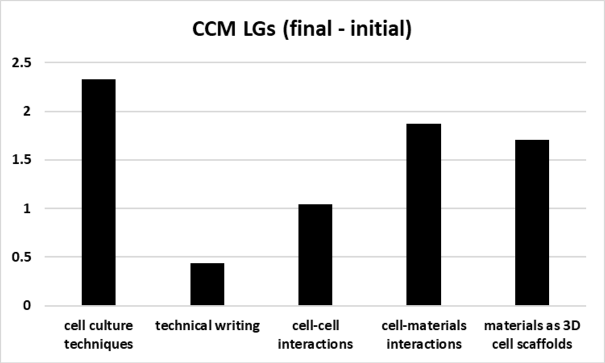

Figure 4: Student learning gains course-specific skills and concepts reported for CCM

These results indicate that students perceived notable learning gains in key skills and concepts in each course. For MBGE, students reported a gain of >1 for mRNA/cDNA isolation and primer design, likely skills to which they had no prior exposure. By contrast, the small gain reported for PCR was likely a reflection of students having been introduced to this technique in our introductory lab courses. Similarly, the students in CCM reported a very high degree of confidence in their technical writing obtained from course and project work across the curriculum. The raw final score for technical writing was 3.7, approaching the upper limit imposed by the 4-point scale. The largest learning gains were for cell culture techniques, and the interactions of cells with themselves and materials both in 2D and 3D configurations, again skills they have not likely encountered in other laboratory courses.

A component of the surveys solicited open-ended comments from the students based on their experience in the course. A comment representative of student reflections received is provided below.

> *I liked that the students were able to come up with their own experiments. We received good feedback and direction on our application designs from the instructors, but ultimately, we were able to control the direction of our project. I also liked that the main point was to come up with and test an application.*

These data and comments indicate that the authentic research-based laboratories do effectively promote the development of key skills and concepts relevant to current research enterprises. Transitioning to authentic research laboratories exposes our students to the processes of science discovery and dissemination, and supports the development of skills required for real world applications. A peer-reviewed publication (Nguyen *et al.,* 2020) with a student alumnus of the MBGE course as a co- first author is a tangible artifact of the authenticity of the research experience offered by this lab.

Industry practices lab (IPL)

This course, unlike the ones based on department faculty research, was designed to model a research and development (R&D) process relevant to the current biotechnology industry. Because of the recent rise in the use of monoclonal antibodies as therapeutics, we chose this as our model system. Rather than provide specific protocols for production and purification, students were given the opportunity to design their own protocols, as well as select media formulations, culture conditions such as plating density and time to harvest, and purification approaches. Backward design of the course was consistent with the departmental learning outcomes related to laboratory instruction. These include:

- Mastery of qualitative and quantitative skills relevant to the industry
- Hypothesis generation and testing, experimental design and data interpretation
- Demonstration of written communication skills/record keeping relevant to the industry
- Ability to function in a team/collaborative environment

This course combined concepts and skills that previously existed as components spread across several short, skill-based laboratory modules. These include the major concept that proteins have physical and chemical properties that can be used to identify and quantify them in a mixture, and that these same properties can be applied to a purification process. We added the concept that culture conditions influence both the production and purification requirements of a monoclonal antibody and the non-intuitive relationship between cell proliferation and specific protein production. The specific procedural skills in this course included basic mammalian cell culture including media preparation, seeding, passaging and maintenance of cultures, as well as automated cell counting. Additional skills related to product purification and analysis included column chromatography, polyacrylamide gel electrophoresis, and enzyme-linked immunoassay (ELISA). Specific quantitative skills involved in the calculation and interpretation of data related to production included assessing quality, yield and purity of the protein product.

Hypothesis generation preceded and informed design decisions and testing protocols. These decisions were underpinned by conceptual understanding of the parameters that impact cell growth and protein production such as oxygenation, pH, temperature, substrate, and nutrient supply. The use of electronic laboratory notebooks was selected as a record-keeping system both relevant to the discipline and common in the industrial context. These concepts and skills were introduced to the students in a class-wide session at the beginning of the course and reinforced along the way as student groups chose their approach to optimize the production and purification of the monoclonal antibody being secreted by our hybridoma cell line. The final goal of the course was for each group to run and evaluate a larger-scale purification based on their trial results.

Throughout the course, students worked in teams and the class as a whole operated in a collaborative manner. The intent was to mimic the role of a Research and Development team tasked with optimizing a standard operating procedure.

A quantitative assessment of these outcomes and the additional benefits of self-efficacy and a sense of personal achievement was done using an anonymous survey instrument distributed to students at the end of the course the first two times the class was offered. This is a junior/senior level lab, and as expected, all students had taken at least one prior biology lab. However, prior experience in a CURE lab ranged from 21% with no prior experience, to 36% having taken 1, to 43% having taken more than one lab. The survey results are shown in Tables 2-4 in the columns labelled IPL (industry practices lab). Averaging the responses related to knowledge and skills, students reported an average 94% gain in specific knowledge and skills associated with this course. An average 88% gain was seen in broader skills related to context, collaboration, and ethics. For statement prompts related to increased self-efficacy and personal achievement, 81% indicated agreement with the four statements.

The following comment was representative of those solicited in the institutional course evaluation.

> *I really liked the opportunity to do 'real research' and that the professor let us test many things. She never steered us in any direction but let us decide, and see if we failed or succeeded. This process of trial and error is what we will face in the real world and I appreciated that.*

This general sentiment was reiterated by multiple students, again reinforcing the benefits of a CURE-style upper-level laboratory course.

Interdisciplinary environmental justice course

In addition to the two crowd-sourcing consortia we joined, we also developed an authentic research-based, course-targeted towards our first- and second-year students and focused on ecological sampling and population analysis. Skills specific to the laboratory included isolating nematodes and soil analysis including soil type, moisture content, nutrient, and specific environmental contaminant levels. Some soil samples were sent to our regional extension service laboratories for chemical analysis. The overarching concept related to this lab is that nematodes are known as indicators of environmental health, and that changes in population diversity can be used to indicate changes in environmental quality (Wilson and Kakouli-Duarte, 2009).

A colleague who is an historian in our Department of Humanities and Arts has taught a course in urban environmental history, and we chose to combine this course with our laboratory offering under the umbrella of environmental and social justice. One group of students was enrolled in the history course, and the other in the biology lab course. The two course cohorts had one session each week in which they shared the results of their research with the students from the other course who were working on the same soil sample collected from four sites around the city. Given the city's industrial heritage, sites were selected by the instructors based on current and former use beginning as early as the 19th century.

Both groups completed shared readings in the text *Sites Unseen* (Frickel and Elliot, 2018), which models the use of archival data and analysis to begin to examine human ecology past and present. Combining reconstruction of the urban industrial history with current soil analysis provided the basis for our investigation of environmental justice, the theme for the integration of the disciplines. Students in the history section worked using fire and insurance maps and other documents to build a history of site use. During in-person site visits, they also recorded observations about current use including areas covered by vegetation, number of trees, residential building types, and access to transportation. Students from the lab cohort for each site were encouraged to join their colleagues on the site visits to get a sense of the current conditions.

Students in the lab isolated the nematodes from the soil and characterized them based on data related to feeding types (e.g., bacterivores, fungivores, plant parasites) and behavioural responses (i.e., approach, avoidance) to known and unknown attractants and repellents. These data were used to generate population diversity indices, as a measure of current environmental quality. Although we have only offered this course one time, results from student surveys suggest that the interdisciplinary nature of the course offerings was an initial attractant to students and that they generally appreciated it. 88% of the students reported that the integration of the disciplines was a factor that attracted them to the course, and 72% found the potential to put their work into a community context compelling. After having taken the course, all the student respondents agreed or strongly agreed that they would like to take more courses where there was an opportunity for interdisciplinary work.

Table 5: students' feedback regarding the courses

	Strongly agree (%)	**Agree (%)**	**Neutral (%)**	**Disagree (%)**	**Strongly disagree (%)**
I would like more courses with an opportunity for interdisciplinary work	61	39	0	0	0
Integration of the soil studies with site history made the work more meaningful	61	39	0	0	0
Working with students in another discipline helped clarify and communicate the purpose, meaning and results of my research	44	44	11	0	0
I could communicate what I did and why it was broadly interesting to someone outside side my discipline	100	0	0	0	0
Overall, the course gave me new insight into the concept of environmental justice	39	56	5	0	0

Students overwhelmingly (94%) reported that the focus on social and environmental justice made taking the course more appealing to them, that the integration of soil studies with the site histories made the work more meaningful, and that they gained new insight into the concept of environmental justice. The integration also had an impact on their professional skills, with 88% reporting that working with students in the other discipline helped them clarify and communicate the purpose, meaning and results of their research, scientific or historical. At the end of the course, all respondents expressed confidence that they could communicate what they had done and why, explaining the relationship between site history and current environmental conditions to others outside of their discipline.

Concluding Remarks

We set out with the goal of transitioning our laboratory curriculum from one based in a traditional "cookbook" format where students follow prescribed protocols to generate an expected set of results, to one based in open-ended and discovery-based authentic research. Our trajectory through this process began with our first- and second-year courses, and has now progressed through the entire undergraduate laboratory curriculum. We began with a crowd-sourcing consortium model by joining existing initiatives, and progressed to designing our own offerings based on our faculty research and upon current industry practices. Most recently, we initiated a specific interdisciplinary course, co-taught with a faculty member in our Department of Humanities and Arts whose scholarly focus is on the discipline of history.

In all cases, our course design methodology was guided by our departmental learning outcomes, which mirror closely those described by Ewell (2001) and embraced by the URSCI philosophy. Our assessments, using both validated and self-designed surveys, have focused on gains in skills and concepts as well as attitudes and measures of personal development. Our results demonstrate student gains in concrete skills and related concepts, as well as in aspects of self-efficacy and confidence as scientists. Success in these areas has been shown to portend student success in the classroom and research, and increase retention in STEM. Although only one of the courses we developed and described here was intentionally designed as interdisciplinary, all have the potential to be reimagined using a similar model. All of the courses share a connection to human health concerns – antibiotic resistance, tissue regeneration, infectious bacterial disease, and cell-associated therapies. As such, following the model we developed for our environmental justice course, each has the potential to be offered with or redesigned to include topics in the humanities and arts or social sciences.

As an example, we can envision a course in the history of tuberculosis combined with the Molecular Biology and Genetic Engineering lab described here, which focuses on modern approaches to attacking this ancient medical scourge (evidenced in Egyptian mummies and characterized in medical texts in the 1800s). One of the Cell Culture Models or Industry Practices lab courses could be paired with an economics course focused on access to medical care and the cost of research and development. Each of these pairings would facilitate investigation and discussion of diversity, equity, and inclusion (DEI) considerations in science, technology, and medicine. We have just begun to develop the model pairing soil ecology with environmental history used to engage students in the concept of social justice. Similar approaches could be used across the laboratory curriculum, spurred by interdisciplinary collaborations.

While specific learning outcomes can and should clearly be developed for individual courses, all assessments of learning can broadly focus on knowledge, skills, abilities, and attitudes. In the sciences, positive achievement in these areas has been associated with high impact practices, of which research experience is one (Lopatto, 2010). Providing this experience through course-based authentic research may be an answer to having a scalable model to provide the opportunity to more students who will constitute the future workforce that will contribute to the global STEM economy.

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