MINI-REVIEW | Institute on Teaching and Learning

Beyond the single course: teaching research throughout the curriculum

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Mazzer PA, Melroe Lehrman B. Beyond the single course: teaching research throughout the curriculum. Adv Physiol Educ 43: 168–171, 2019; doi:10.1152/advan.00215.2018.—Our STEM majors arrive on campus as rule followers—“Tell me what to do, and I’ll do it,” is their refrain. To break this mindset, we redesigned our suite of laboratory courses to scaffold research throughout the program. Every laboratory incorporates both discipline-specific and research-specific skills. Foundational courses introduce research skills, leading to upper level student-driven research. This model should be extensible to any curriculum and makes research an integral part of the undergraduate career.

INTRODUCTION

While individual courses can prepare students for the world of research (2), and research experiences for undergraduates can have a positive impact on students (7), not all programs have the faculty or funds to successfully take these on. It has been stated that integrating research into courses not only will provide the student with authentic research experiences, but also has the ability to reach more than just the handful of students who were lucky enough to land a research position (6). Course-based undergraduate research experiences (CUREs) have proven to be just as effective, if not more so, in teaching students how to think and act like scientists (5). CUREs have also resulted in positive outcomes for faculty members (9). With all of this in mind, it is clearly beneficial to incorporate a CURE into the undergraduate curriculum, but is one enough? Can students learn all the skills necessary to carry out future research endeavors in just a single course?

We chose to attempt a different solution: to give students research experience distributed across the entire curriculum. To create a curriculum that featured research within it, first we needed to determine what skills we expected students to learn in the mentored research experience we were trying to mimic. The list of skills that resulted from our brainstorming are given in Table 1. The next step was to map those skills onto our introductory courses so that they could be mastered alongside the standard laboratory skills generally taught in those courses. The traditional introductory sequence in a biochemistry major includes two semesters of General Chemistry and two of Organic Chemistry. Our students usually take University Chemistry and Organic Chemistry I their freshman year, and Organic Chemistry II

and Analytical Chemistry their sophomore year. An overview of how we chose to distribute research skills into those four courses is shown in Table 2. Our first semester, University Chemistry, is built using argument-driven inquiry (ADI), so it focuses on introducing students to experimental design, arguing from data, and communicating using different professional styles. Organic Chemistry, in the second semester, traditionally introduces good record keeping, along with a large number of new laboratory techniques specific to organic synthesis. During the second semester of Organic Chemistry, the students are segued into using literature as a source of experimental protocols, and they learn basic experimental design by leading them through a scaffolded drug synthesis process. Finally, in the fourth semester, Analytical Chemistry, the students are expected to carry the process from initial question through final report essentially on their own.

Four-Semester Introduction to Research Skills

University Chemistry. ADI as an instructional model is designed to mimic the process of research in a guided manner. This approach not only helps to produce the next generation of scientists, but also provides experiences for future science educators and creates awareness about the process of science for nonmajors (8). Currently, our University Chemistry course is taken by almost one-half of the campus, ranging from science majors to athletic training and nursing majors. The ADI model, which allows for student input based on interest, is an appropriate fit due to the diversity of the students taking this course.

The laboratory follows what we call a “sandwich model,” consisting of a preparatory day, an experimentation day, and a peer-review day. The preparatory day introduces students to a problem and guides them through a method or technique that will help solve the problem. Students practice the method or technique, both physically and conceptually, and plan how they will use it to solve the problem. On experimentation day, students carry out their plans and compare results with the rest of the “research team.” Before leaving the room, students must record data from all of the groups to use in making their argument. As homework, students individually write a report following a rubric. Students participate in a peer review session on the final day before starting the preparatory work for a new problem. Students are then given a few days to make corrections before uploading their final report. Aside from learning foundational techniques and basic components of research, students are challenged in the art of communicating science. The first form of communication is interpersonal, as each
room behaves like a research laboratory. Groups must talk with one another to determine who will be testing what and how they will be doing it. Strong communication before experimentation day tends to result in better experimental plans and more reliable data. This skill is further developed after students have generated data and the research team works to turn data into results. The style of written communication, which comes in the form of a letter, is casual but argumentative. While many students have mastered the fill-in-the-blank style of a laboratory report, they often struggle when trying to explain chemical concepts and experimentation to nonprofessionals. Rubrics include points for grammar and organization, along with the description of the experiment and argument provided. We have anecdotal indication that this strategy is succeeding, as a new faculty member from another university states that our students are better writers than those at his previous institution (T. Lubben, personal communication).

Organic Chemistry I and II. Biochemistry students advance from University Chemistry into the first semester of Organic Chemistry. The first semester is fairly traditional, and is treated much like a preparatory laboratory for the second semester. Students focus on techniques and methods common to organic synthesis, but this time the emphasis is on record keeping. Organic Chemistry, full of colors and smells, makes a great course to develop observation and recording skills. Students are not only required to make observations through the written word, but also asked to describe through sketching. As we advance with our current digital initiative, we see photos and videos in our future.

Students further develop these introductory organic skills in the second semester. We return to the sandwich model and complete three basic synthesis laboratories, while dipping our toes into an independent drug synthesis project (Fig. 1). At the beginning of the semester, students are introduced to the project and given short assignments as a way of scaffolding for the end-of-the-semester project. With a budget of $100 and access to scientific literature, students are asked to 1) identify a pharmaceutical drug to synthesize; 2) map out the entire synthetic scheme, with mechanisms; 3) design or find a procedure to complete the synthesis; and 4) create a shopping list. These four items are pitched to the faculty member for approval. Once approved, students put together a more formal proposal and start the synthesis midsemester. At the completion of the project, students write a formal laboratory report and present the project to the class, complete with a cost analysis to make 500 mg of their drug. This project has been a highlight for many students as it is their first independent laboratory experience. Student teams rally together in hope of actually making their drug of choice and ending the semester on a successful note.

Analytical Chemistry. Introductory Analytical Chemistry courses traditionally introduce students to statistical methods of the research laboratory, as well as a large number of qualitative and quantitative techniques that can be used in chemical analysis. Statistical treatment of data (propagation of error, t-test, F-test, and Grubbs test for outliers) is covered extensively in the lecture portion of the class. This is the first topic covered in the class, as we expect the students to use these statistical approaches for all laboratory investigations during the rest of the semester.

One of the problems with trying to do extensive independent research in an analytical laboratory is that students reach the class with experience only in two major types of instrumenta-

| Table 1. List of basic research skills students are expected to gain from mentored undergraduate research |
|---------------------------------------------------------------|
| Basic Research Skills |
| ● Searching literature |
| ● Using literature as source of protocols |
| ● Creating limited, testable hypotheses |
| ● Designing complete experiments |
| ● Keeping accurate records |
| ● Presenting data appropriately |
| ● Analyzing data |
| ● Drawing conclusions from data |
| ● Communicating research results |

Using literature methods; experimental design; statistical analysis of data; segue to independent projects.

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| Table 2. Mapping of research skills onto the first four introductory courses in our program |
|-----------------------------------------------|
| Class | Skill |
| First semester: University Chemistry | Arguing from data; introduction to experimental design; communication |
| Second semester: Organic Chemistry I | Record keeping; literature searching |
| Third semester: Organic Chemistry II | Using literature methods; experimental design |
| Fourth semester: Analytical Chemistry | Statistical analysis of data; segue to independent projects |
investigate fresh vs. canned tomato products? Organic vs. traditionally farmed fresh tomatoes? Different brands of the same product? Having decided on a hypothesis, they are also responsible for going to the literature and finding a protocol to separate and quantify lycopene using the instrumentation available to them. After completing the experiment, they are expected to write a comprehensive laboratory report on the final project. By this point, usually second semester, sophomore year, students have been brought through the list of skills in Table 1 and are at least minimally competent in carrying out independent research from design to report.

Upper-Level Research-Based Laboratory Courses

After the four-semester introductory sequence, we expect that our majors will be ready to handle independent research projects, either in a traditional mentored experience or in our upper-level courses. In upper-level courses that require specific new techniques, we once again implement “short-form” laboratories. For example, Biochemistry I must teach several biochemical-specific techniques, such as enzyme kinetics and dialysis; these are covered in the first portion of the course with short forms. Following that, students conduct an independent extraction and characterization of an enzyme and write a formal report. Our Genetics course includes a bioinformatic CURE (1). Depending on the professor teaching the course, this project has varied. It has taken the form of a data-mining project on miRNA targets using published genomic data in GenBank in past years. This year, under a new instructor, students extracted environmental DNA from a local reservoir and used next-generation sequencing to survey algae in the lake. Our genetics course CURE has already resulted in our first course-derived, student-driven paper (4).

Biochemistry II is often one of the final science courses our students take; thus we have created a culminating experience for that course. While students are often expected to write summative reports during their high school and undergraduate courses, research proposals are somewhat unusual (3). However, writing an original proposal is often a component of graduate qualifying exams, even though few students have had formal experience with proposal writing. Therefore, we created a research proposal as our final undergraduate course laboratory. Because proposals represent a new writing style, the process is heavily scaffolded, with an interim assignment each week of the semester (see timeline, Fig. 2). By this point in their undergraduate career, students are able to work through the process of developing an original question, researching it in the literature, and creating an experimental design to test a hypothesis.

Conclusions and Looking Forward

Our complete suite of courses as described here has been in place for only 4 yr, so we are yet to develop robust assessment of the curriculum. However, we have learned several things from the experiment so far. First, we have demonstrated to ourselves that it is in fact possible to teach research skills alongside discipline-based skills in our introductory laboratory courses. Initially, we had some concern that the addition of research skills would take time away from the traditional skills taught in a particular course. However, as we restructured the courses, we found it quite doable. Second, where students needed to master several new techniques in a particular laboratory, such as in Analytical Chemistry or Biochemistry I, the short-form approach allowed the teaching of several new skills quickly. Third, we found that this teaching approach actually reduced the out-of-class professor workload. Students turned in fewer full laboratory reports than in a traditional laboratory course, and the ones they did turn in tended to be better written because students had taken greater ownership of the project. Also, if students design their own experiments, they also prepare several of their own chemical solutions, thus reducing laboratory preparation time.

While full assessment of gains of student skills is not yet complete, we do have initial indications that students are better prepared for mentored research projects after completing the first two introductory years. We have just completed the pilot year of a new, university-wide Capstone Experience. In the future, a graduation requirement for all students will be to complete an independent piece of scholarship, which they will present on Capstone Day, a 1-day university symposium for seniors. During our pilot year, while not required to, all of the seniors in our program volunteered to participate. In the post-presentation survey, 100% of our seniors agreed with the statement: “My academic program prepared me well to perform a capstone project.” While this is informal feedback, we believe it is an indication that we have been effective at coaching basic research skills within the curriculum.

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DISCLOSURES

No conflicts of interest, financial or otherwise, are declared by the authors.

AUTHOR CONTRIBUTIONS

P.M. conceived and designed research; P.M. prepared figures; P.M. and B.M.L. drafted manuscript; P.M. edited and revised manuscript; P.M. and B.M.L. approved final version of manuscript; B.M.L. performed experiments.
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