JOURNAL OF CHEMICAL EDUCATION

Article

pubs.acs.org/jchemeduc

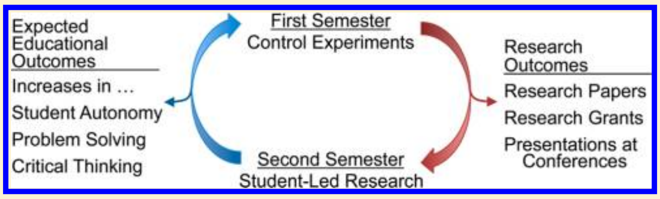
A Hybrid Integrated Laboratory and Inquiry-Based Research Experience: Replacing Traditional Laboratory Instruction with a Sustainable Student-Led Research Project

Matthew R. Hartings,* Douglas M. Fox, Abigail E. Miller, and Kathryn E. Muratore

Department of Chemistry, American University, Washington, D.C. 20016, United States

Supporting Information

ABSTRACT: The Department of Chemistry at American University has replaced its junior- and senior-level laboratory curriculum with two, two-semester long, student-led research projects as part of the department's American Chemical Society-accredited program. In the first semester of each sequence, a faculty instructor leads the students through a set of previously performed experiments and introduces the students to a research project, specific laboratory techniques, and instrumentation. As such, the first (fall) semester takes the form of a control experiment. During the second (spring) semester, students design and carry out experiments of their own choosing that are based on their research interests and that build upon the first semester's work. In the subsequent academic year, the research is continued by a new set of students. The research from the previous academic year's second semester becomes the control experiments of the current academic year's first semester. In this way, the research project continually grows and develops according to student decisions. During these two semesters, students are assessed on their ability to perform experiments, maintain proper record keeping, designing and following safety protocols, proposal writing, and written and oral presentations of their work. This program, which grants ownership, or autonomy, of a research project to our student body, has been well received by the students, helped to meet departmental objectives, and led to a research publication and a funded grant proposal.



KEYWORDS: *Upper-Division Undergraduate, Materials Science, Curriculum, Interdisciplinary/Multidisciplinary, Laboratory Instruction, Inquiry-Based/Discovery Learning, Problem Solving/Decision Making, Nanotechnology*

INTRODUCTION

Upper-level laboratory courses are often the first opportunity within the curriculum of a chemistry department for majors to acquire and develop many of the skills that they will rely upon as professionals. Lab courses have been traditionally taught with a discipline specific approach. A somewhat established change to chemical curricula has been the introduction of integrated laboratories.[1−6] In these laboratories, students experience techniques and protocols from multiple disciplines within the context of studying one particular chemical process. Aside from these courses, other departments offer laboratory credit through an inquiry-based learning process.[7,8] This can involve more formal and faculty-developed laboratory exercises or a less formal independent research experience in a faculty research group.[7,9−11] In the Department of Chemistry at American University, we have instituted a novel laboratory curriculum that combines the integrated laboratory and inquiry-based laboratory approach within the context of a research project. As an added feature of this curriculum, the research decisions that the students make are transferred from one year to the next. The most important role of the faculty is to act as facilitators, enablers, and mentors. In this way, the students are given ownership of the research goals and are responsible for the direction the project goes from year to year. In other words, we have instituted a departmentally funded student research project within the construct of an advanced laboratory curriculum. We feel that this feature, giving the students autonomy, is of key importance to achieving our goals for student education: engagement, self-motivated problem solving, and critical thinking.

We have observed several benefits from this curriculum change (instituted in the 2011/2012 academic year) that should make it attractive to other departments. The students have responded favorably to the change. The students and faculty have produced one published research article[12] from this work and are in the process of submitting a second publication. The faculty are active in submitting research grants based on, and intended to support, the students' work. We have been awarded one grant as part of these efforts. The changes have increased the flexibility in faculty teaching schedules. The new curriculum also has the added benefit of potentially increasing alumni engagement with the department. We feel that this curriculum would be straightforward to implement in departments with a total of 20 or fewer chemistry or biochemistry majors per year. A similar laboratory approach could also be implemented in larger departments with some adjustments.

DOI: 10.1021/ed500793q
J. Chem. Educ. XXXX, XXX, XXX−XXX

Laboratory Instruction

There is a diversity of approaches to upper-level laboratory curricula. Each of these approaches has its strengths and weaknesses in terms of targeted student outcomes. Departments must weigh these along with other educational philosophies (i.e., valuing historically accepted practices or embracing new educational standards) and the logistics for how they can staff and house advanced laboratory courses.

Traditional laboratory instruction consists of well-vetted experiments that are meant to reinforce an important topic from one particular chemical discipline. These laboratory exercises often correspond to the lessons from a lecture class. A faculty member can take comfort in not needing to develop an experiment that will yield a substantive and poignant result. Another benefit of traditional laboratories is that they come with questions and reflections for student assessments as well. Because these experiments have been shown to work, students can display proficiency, or capability, by accurately repeating findings. And, while as instructors we also look for chemical logic and problem solving, these laboratories are primarily meant to hone proficiency in technique and analysis. These laboratories give the students a "safe" environment in which they know that if they do the right things, they will get the right answer.

In the 1970s, unified or integrated laboratories started to appear in upper-level curricula.[1−6] The philosophy behind teaching lab skills in such a manner is that no discipline is isolated from another. To study an enzyme, for instance, one must understand the protein active site (biochemistry), understand the substrate and its conversion (organic chemistry), have an appropriate measurement technique (analytical chemistry), perform a kinetic analysis (physical chemistry), and understand the significance of their results (quantitative analysis). Separating instruction by discipline could potentially undermine the ability of a student to appreciate the way all of these parts need to come together to make a complete study. In comparison to traditional laboratories, where technique is the focus, integrated laboratories tend to originate at the scientific problem or question to be approached. That is, the students are introduced to the problem and subsequently to the techniques and disciplines needed to approach the problem. This holistic approach is a response to calls for more multidisciplinary and transdisciplinary studies and, perhaps, better resembles the type of work students might encounter in a research environment.

Another, more recent, call-to-action for the educational community has been a request for increased inquiry-based instruction.[7,8] This call is best highlighted in the National Science Education Standards.[13] Inquiry-based instruction has been shown to increase student engagement and knowledge retention. In the laboratory setting, this is a natural extension of integrated laboratories.[11] The problem is still central, but students are expected to play a larger role in developing or determining how to approach finding a solution. The types of inquiry-based learning are broadly varied and can run through a spectrum from faculty assisted instructional laboratories to independent research on a faculty research project. The instructional laboratories can include laboratory courses that look to answer specific questions, such as "how does the UV−vis absorbance spectrum of a dye solution change with concentration of the dye?". These laboratories can also include broader research-type questions, such as "what factors affect the kinetics of metal−ligand substitution reactions?". These laboratories are framed by the understanding that scientific research deals with the unknown. In some instances, results from these laboratories are aggregated from one year to the next and are used to expand understanding of different processes.[14] And, while traditional lab instruction carries the assumption that the outcomes are well understood, inquiry-based laboratories often highlight that, by performing experiments, it is the students who must create or build their own knowledge and understanding.

At American University, we have instituted a junior−senior level, student-led, student-driven, faculty-assisted laboratory curriculum that is based within the context of a research project. This new curriculum borrows approaches from the integrated and inquiry-based styles and runs over the course of two semesters. During both semesters, students are critiqued on their research note-taking and their adherence to safe lab practices. In the first semester, the students are introduced to a project along with relevant techniques and analyses that are normally covered in an advanced lab course. This instruction is performed within the framework of a research project that has evolved based on the work of students from previous academic years. As they progress through the initial semester, the students become more familiar with performing literature reviews and learn how to develop safe laboratory procedures through understanding and minimizing risk due to exposure. In the second semester, the students design and implement a set of experiments that are meant to advance the research from the first semester in the direction of their choosing. They write white papers outlining their proposed experiments and set a schedule for the semester. They present their research in both written documents and oral presentations.

While there are other programs that use research as a context for teaching laboratory technique, to our knowledge, this is the first example of a hybrid faculty-guided/free-inquiry approach in which students control research directions on the short-term (semester) and the long-term (multiple years). This pedagogical approach mimics real research: the first semester is a control experiment, and the second semester is dictated by the expertise and interest of the researchers. This style is not just teaching students through research; it is students doing research. And, in a change from other departments that do use research as an educational tool, our students' research gets carried and evolves from year to year. That is, the second semester experiments from one year become the control experiments for the next year. This research project belongs to the students, not the faculty. As such, our students are given real ownership, or autonomy, over both their education and their research.

Ownership in Education

Increasing student ownership, or autonomy, has been promoted in the pedagogical literature as a method for fostering student engagement and enhancing lifelong learning.[9,15−18] Specifically, autonomy places more emphasis on self-regulated learning in which students value the learning process rather than the rewards that come from the education system (i.e., grades). There are several ways that educators support autonomy in the classroom environment: (1) organizational autonomy support: students play a role in how the class is structured (group composition, evaluation, due dates, etc.); (2) procedural autonomy support: students are involved in choosing and obtaining classroom materials and in deciding how competence is evaluated; and (3) cognitive autonomy

DOI: 10.1021/ed500793q
J. Chem. Educ. XXXX, XXX, XXX−XXX

Prior to 2011–2012 AY

Chemistry Majors

Course	Hours in Lab	Credits
Biophysical Chemistry	48	1
Instrumental Analysis	64	2
Biochemistry	48	1
Physical Chemistry	64	2
Inorganic Chemistry	48	1
Quantitative Analysis	64	2
Totals	336	9

Biochemistry Majors

Course	Hours in Lab	Credits
Biophysical Chemistry	48	1
Instrumental Analysis	64	2
Biochemistry	48	1
Cell Biology (Bio Dept.)	48	1
Genetics (Bio Dept.)	64	2
Microbiology (Bio Dept.)	48	1
Totals	320	8

Teaching Responsibility for Chemistry Faculty: 6 classes

2011–2012 AY and Beyond

Chemistry Majors

Course	Hours in Lab	Credits
Experimental Biological Chemistry I	112	3
Experimental Biological Chemistry II	112	3
Experimental Chemistry Laboratory I	112	3
Experimental Chemistry Laboratory II	112	3
Totals	448	12

Biochemistry Majors

Course	Hours in Lab	Credits
Experimental Biological Chemistry I	112	3
Experimental Biological Chemistry II	112	3
Cell Biology (Bio Dept.)	48	1
Genetics (Bio Dept.)	64	2
Totals	336	9

Teaching Responsibility for Chemistry Faculty: 4 classes

Figure 1. Curriculum changes for chemistry and biochemistry majors at American University. An overview of the laboratory credits required before and after the described curriculum changes. For the students, the number of required laboratory credits has increased, while the number of required laboratories has decreased. This leads to a reduced teaching strain on faculty scheduling requirements. The number of laboratory hours has also increased and meets the requirements of the American Chemical Society accreditation program.

support: students are able to imprint upon the class their values and interests (find multiple solutions to a problem, devote time to decision making, find relevant information, re-evaluate errors, receive informational feedback, openly debate ideas).[18] Supporting these different types of student autonomy can lead to multiple outcomes. According to Assor et al., freedom and decision are less important than the ability of students' autonomy to reflect their interests and values.[19]

In this respect, it was important to the faculty at American that students direct not only their own research, but also the research of the students that follow them. And the students who come into the program need to see that the role of the faculty is primarily to guide and enable. In its essence, these efforts attempt to encapsulate a research group within the structure of a laboratory class. In terms of professional training, there may be no better preparation for future scientists than to let them do science in a safe and welcoming environment. To emphasize that the research is both real and student-owned, the department sends students to present their work at conferences, hosts a Web site for the group's work,[20,21] and places a large emphasis on publishing their experimental results.

■ IMPLEMENTATION

Background

Departmental Demographics. The Department of Chemistry at American University currently has six tenure track faculty members. In the 2011/2012 academic year (the year this program was implemented), our majors included eight seniors (five chemistry, three biochemistry), 11 juniors (one chemistry, 10 biochemistry), 18 sophomores (six chemistry, 12 biochemistry), and 22 freshmen (nine chemistry, 13 biochemistry). All of the chemistry majors receive American Chemical Society-accredited degrees, while the biochemistry degree is not accredited. The aggregate number of students in both majors is fairly consistent from one academic year to another. Before the implementation of our new upper-level laboratory curriculum, laboratories were required for our biophysical chemistry (one credit), instrumental analysis (two credits), quantitative analysis (two credits), biochemistry (one credit), physical (two credits), and inorganic chemistry (one credit) laboratories. Chemistry majors were required to take all of these laboratories. Biochemistry majors were required to take the biochemistry, instrumental analysis, and biophysical laboratories in the chemistry department along with cell biology, genetics, and microbiology laboratories in the biology department.

Reasons for Change. At the time of implementation, there were a number of factors that were pushing our department to make changes to our curriculum. We are sharing them here because there may be other departments that are under similar constraints. We had just undergone an American Chemical Society (ACS) review of our ACS-accredited degree program. The panel had two primary recommendations for our department. First, we were not offering our advanced classes often enough. Because of our low number of chemistry majors, we were only able to offer inorganic chemistry, inorganic chemistry lab, physical chemistry, physical chemistry lab, biochemistry lab, quantitative analysis, and quantitative analysis lab once every other year. The ACS Guidelines and Evaluation Procedures for Bachelor's Degree Programs (ACS Guidelines) state that certified majors must have instruction in "the five major areas of chemistry" (analytical, biochemistry, inorganic, organic, and physical).[22] These must be augmented by at least four semester-long or six quarter-long, in-depth courses, which cannot consist of independent research study. These courses could include a second semester addition to a foundational course, or they could include an integration of multiple areas into a single course. Importantly, there must be four "in-depth"

DOI: 10.1021/ed500793q
J. Chem. Educ. XXXX, XXX, XXX−XXX

classes offered each academic year by a certified department. Second, we were cited for requiring too few laboratory hours (ACS Guidelines state 400 h beyond introductory chemistry laboratory) for our majors. Before our curriculum changes, our chemistry and biochemistry majors spent 280 and 336 h in lab, respectively. These issues, in conjunction with departmental scheduling issues, accelerated our plans for revamping our advanced laboratory offerings. Specifically, we had difficulty maintaining scheduling flexibility to cover all of our advanced courses and laboratories given our relatively small numbers of faculty and majors and a requirement from our college's administration that minimum class sizes include six students. Our department had very few options for effectively responding to sabbatical leaves and yearly fluctuations in the number of chemistry majors.

Curriculum Changes

We replaced our six foundational area-focused laboratory classes with four new integrated advanced laboratories (experimental biological chemistry I and II and experimental chemistry laboratory I and II). Figure 1 shows how these changes have affected the requirements for both our chemistry and biochemistry majors. Our chemistry majors are responsible for taking both sets of laboratories, while our biochemistry majors are required to take only one set. The number of hours that each set of majors spend in instructional laboratories has increased along with the total number of credit hours within each major. The number of courses that our faculty must account for has decreased. For purposes of comparison, it is instructive to see that the laboratories for biophysics, biochemistry, and instrumental analysis have formally been replaced with experimental biological chemistry I and II (EBC 1 and 2) and that the laboratories for quantitative analysis, physical chemistry, and inorganic chemistry have been replaced with experimental chemistry laboratory I and II (ECL 1 and 2). In practice, however, we have tried to incorporate as many disciplines as we can into EBC and ECL.

When designing the initial first semester of EBC1 and ECL1, we had to generate general topics that were within the capacity of our students and facilities, that drew from our students' interests, and that would be open to further exploration. For EBC1, we chose to study the protein-templated synthesis of gold nanoparticles (AuNPs).[23−26] During that first semester, faculty designed experiments for the students that included nanoparticle synthesis, determination of protein concentration using the Bradford assay, PCR and vector mutation, gene transformation, protein expression, column chromatography, UV−vis kinetics studies, quantifying molecular fluorescence, and determining conductivity of novel materials. One of the reasons why we chose this project is because it could touch on so many different subdisciplines of chemistry (biochemistry, biophysics, instrumental analysis, quantitative analysis, inorganic chemistry). Another reason why the faculty chose this project is because we saw an opening in the literature to explore bioconjugation of these nanoparticles to other biologically relevant molecules. Finally, this project, at its inception, drew upon the expertise of the individual faculty members overseeing this research. This aspect gives our department flexibility in distributing the faculty teaching load.

For the initial first semester of ECL1, the faculty chose to study how polymer films, containing exfoliated clays, impede analyte diffusion.[27−29] During this semester, the students attempted a number of reactions that were meant to cross-link the clay-containing polymers. Some of the cross-linking agents included glutaraldehyde, tetrakis(4-sulfonatophenyl)-porphine, and several organic acids. The polymer−clay composites, and their ability to absorb analytes and prevent diffusion, were analyzed with powder X-ray diffraction, differential scanning calorimetry, Fourier transform infrared spectroscopy, atomic absorption, UV−vis spectroscopy, fluorescence spectroscopy, and solution conductivity.

During the typical first semester, we also formally introduce our students to scientific literature searches and scientific writing. We hold a training session with our university's resident science librarian on the use of different search platforms (SciFinder, Web of Science, PubMed, etc.), use of reference organization software, and the familiarization with methods for discrimination between search results. Students are individually responsible for completing two writing assignments: an overview of relevant literature done in the style of a research paper introduction and a methods and results report. The faculty will often comment on the introduction with each student over several iterative drafts. (An example of a syllabus and a grading rubric for the first semester is given in the Supporting Information.)

During the second semester, the focus turns toward the interest of the current rotation of students. Working in groups, students are required to formulate a reasonable proposal, set a schedule for their work, and formulate safe and effective protocols for their research. The proposal is written in the form of a three-page white paper. The white paper must include a description of the major research hazards along with the steps that students will take to minimize their risk in lab. During this time, the faculty act as facilitators, overseers, and mentors who help to guide, refine, and reassure the students in their decision-making processes. Each group of students is responsible for a final written report, which mimics a full research paper, and an oral presentation at the end of the semester. (An example of a grading rubric for the second semester is given in the Supporting Information.)

As the class evolves from one academic year to the next, the faculty choose one student project (or a combination of several student projects) as the basis for the research in the first semester. In this way, the students' research is sustained from year to year, and the direction of the research is always set by student interest and initiative. We would like to clarify that while our initial first semester for each laboratory was set up by the faculty, the first semester is normally dictated by experiments and protocols that students have designed to study a very specific process. To facilitate this process, students are required to keep electronic notebooks.[21] These notebooks make it possible for all of our students to have ready access to previous data and protocols. And, in practice, the electronic notebooks make it easy to check on student notekeeping and data analysis.

The only prerequisites we maintain for this course are sophomore-level organic chemistry and lab. During the development, the faculty members discussed multiple options for prerequisites or corequisites. However, we could not find a way to incorporate these while acknowledging the realities of scheduling conflicts and requirements for our students at American. Some other departments who are mimicking our approach may be more successful at mandating requirements. However, we will note that our students have been quick to pick up on new concepts in the laboratory. When the situation demands it, we also spend a brief amount of time at the

DOI: 10.1021/ed500793q
J. Chem. Educ. XXXX, XXX, XXX−XXX

beginning of a laboratory period introducing new techniques or concepts.

RESULTS

There are several different sets of results explored in this manuscript. The first set includes the student response to these courses. The second set includes how the research has evolved from inception. The final set includes a brief description of the actual research results that are outcomes of our laboratory experimentation.

Student Responses

Students' responses to this curriculum change have been overwhelmingly positive. Table 1 shows a comparison of student answers to a questionnaire that they receive, from the university, at the end of each semester. The relevant questions, with answers ranging from one (strongly disagree) to seven (strongly agree), being highlighted here are (A) "I am satisfied with what I learned in this course"; (B) "on a scale of one to seven, overall this course was"; and (C) "I learned a good deal of factual material in this course". The data, shown in Table 1, go back to 2006, which is when these questionnaires were instituted. The time since our curriculum change (academic years 2011−2013) is being compared to the prior years (academic years 2006−2010). Each set of years includes the results of classes taught by multiple faculty members. For the data covering EBC/ECL, the laboratory courses overseen by four separate faculty members are assessed. According to our students survey results, they perceive that they are learning more and are more satisfied with the new laboratory curriculum than were the students in earlier years. These data also suggest that students perceive that they learn more and are more satisfied with the second semester portion of each laboratory. Taken as a whole, the data might be taken to imply that our students both value and feel that they learn more in environments where they have more autonomy. This conclusion assumes that our students have increasing perceptions of autonomy going from 2006 to 2010 to the EBC1/ECL1 semester to the EBC2/ECL2 semester.

Table 1. Students' Perception of Learning in the Years Prior to and after the Curriculum Change[a]

Years	2006−2010	2011−2013	
Average Enrollment	10.7	10.3	
		EBC1/ECL1	EBC2/ECL2
Question A	5.8	6.3	6.6
Question B	5.5	6.3	6.6
Question C	6.0	6.3	6.5

[a]Note: Students were asked the following questions on a survey given at the end of each semester and were told to qualify their answer on a scale from 1−7, with 1 indicating strong disagreement and 7 indicating strong agreement: "(A) I am satisfied with what I learned in this course; (B) on a scale of one to seven, overall this course was _; and (C) I learned a good deal of factual material in this course". These results indicate that the students value our current offerings more than the previous laboratory offerings. The results also indicate that students feel that they learn more in the offerings in which they have the most autonomy.

These data are also corroborated with the narrative statements given by our students at the end of each semester.

Student A: "Thank you for this semester. You taught me a lot in regards to independent working in lab and more; this is the only lab that I feel that I've grown the most in."

Student B: "Coming up with the experiment was unique. It gave motivation for the rest of the semester."

Student C: "Gives students the unique opportunity to really explore a topic and can lead to very exciting results."

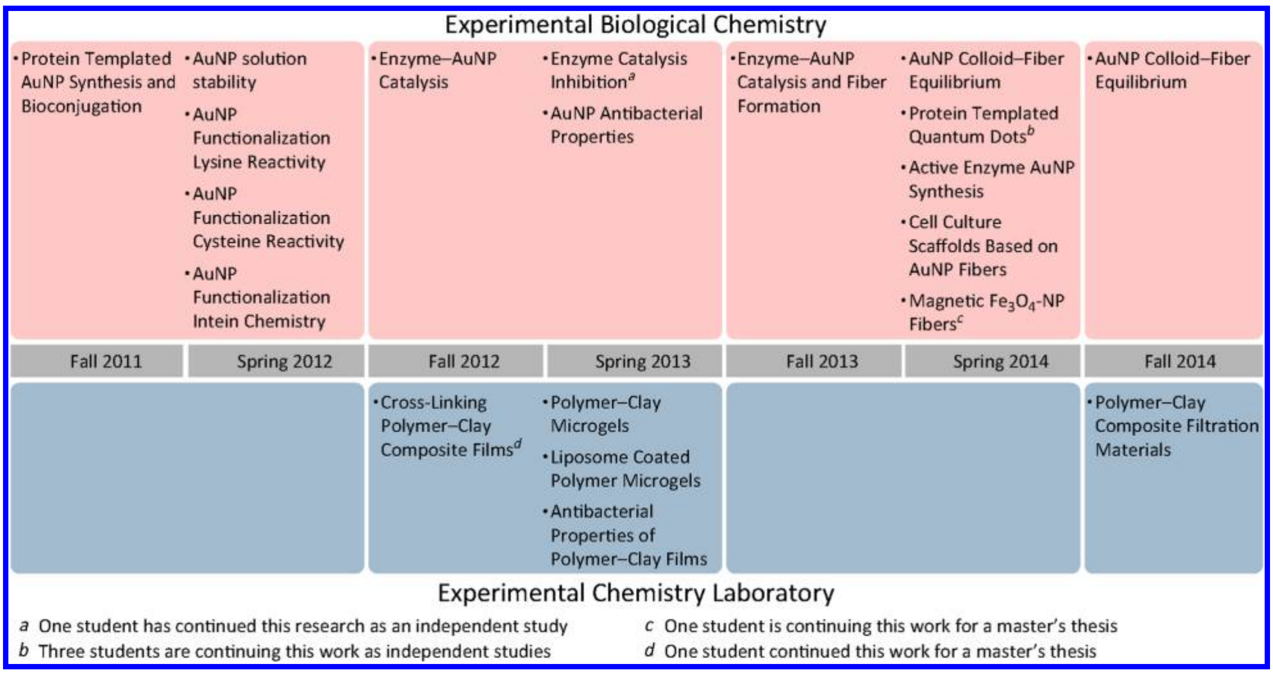


Figure 2. Evolution of student research over several semesters. The research performed has changed based on the research and interests of our students. An aspect that we would like to highlight is that several students have continued their proposed research outside of their enrollment period in the laboratories. We feel that this is a strong indicator of the autonomy that the students experience with their proposed research.

DOI: 10.1021/ed500793q
J. Chem. Educ. XXXX, XXX, XXX−XXX

Student D: “Enables applications [of topics] learned throughout the major.”

Student E: “Helped me feel confident using instruments and more comfortable working in a lab setting.”

Student F: “Engages the students to problem solve what they need to do to learn information about the materials being tested.”

Student G: “Enabled students to think critically.”

Another set of anecdotal data that indicates student satisfaction with our program changes is the number of students who have decided to pursue their research from these laboratories outside of the classroom setting. We have had two students, one from ECB2 and one from ECL2, continue their second-semester projects as the research for their master’s degree theses. Four students have continued their EBC2 projects for independent study credits in the semesters following the end of the laboratory class. (This data is highlighted in Figure 2.)

One aspect of our curriculum changes that we thought might be lacking was in assuring technical proficiency on the laboratory protocols covered in more traditional laboratory courses. While we have not observed that student technical proficiency is an issue, we have put in place two control measures that directly address this concern. First, as part of our assessment rubric for the second semester (included in the Supporting Information), we require that each group of students use a new instrument and perform a new synthesis during the course of their designed research project. In adhering to this guideline, the students show that they are capable of achieving proficiency in laboratory techniques that are new to them. We would argue that, often, showing this capacity is more important than displaying proficiency in a controlled lab procedure. Second, we are instituting a set of laboratory practical exercises that the students must perform individually. While student research is performed in groups, these lab practicals will help to ensure that all of our students are comfortable executing experimental protocols.

We note that the rubrics provided in the Supporting Information contain all of our assessments for a semester. Students are not directly graded on technical proficiency or accuracy of their data or analysis. We do, however, require that our students respond to comments in their online notebooks and update them accordingly. We use comments in the student notebook to ensure that our students are performing their work correctly. Any points taken off for poor procedure or incorrect/incomplete analysis will come out of their notebook grade. While our grading scheme has changed from our approach before the curriculum changes, the average grades our students are getting have not changed.

Research Evolution

Figure 2 shows how the research has evolved from one year to the next. Because we are only on our second iteration of ECL1 and ECL2, the discussion here will be focused on EBC1 and EBC2, which have gone through three full iterations.

As we mentioned earlier, the EBC1/2 sequence was designed to explore and develop protocols and materials associated with a protein-templated synthesis of AuNPs. During the first semester (fall of 2011), our students performed experiments described within the Curriculum Changes section. One important observation that they made is that by changing the ratio of Au^{3+} to protein in their nanoparticle reaction mixture, a novel material could be generated. While the protocol was supposed to generate a homogeneous solution of colloidal AuNPs, the altered reaction conditions resulted in purple fibers in a clear solution. We used this unexpected result as a “teaching moment” that in research, unexpected outcomes often lead to some interesting science. We slightly altered our syllabus for that semester in order to explore this material in more detail. We published our findings in a research paper.[12] And, while there was a slight detour in order to better understand these results, the main drive of the semester was in exploring ways to modify the homogeneous AuNPs through bioconjugation.

During the spring semester of 2012, our students were, for the first time, tasked with producing their own projects. As could be expected, many students wanted to propose very ambitious projects during initial conversations with faculty. In this period of proposal development, which takes two weeks (four class periods), one of the most difficult roles for the faculty advisor is to help the students see a reasonable pathway from where the previous semester ended to the societal or research problem they are interested in addressing. For instance, one group of students very much wanted to use our nanoparticles to make cancer diagnostics and therapeutics. The faculty asked them, “what is the first thing that you would do to make the nanoparticles effective for this?”. Upon reflection, they replied, “we would target the nanoparticles to only interact with one type of cancer cell.” The faculty asked, “how would you do that targeting?” They replied that they would attach antibodies to the nanoparticles. The faculty asked how they would perform the attachment. They replied that they would attach the protein-coated nanoparticles to antibodies using succinimidyl ester bioconjugation to lysine residues on both the protein coating and the antibody. The faculty responded, “antibodies can be expensive, how would you build the protocols for and understand the efficiency of your bioconjugation?”. The students thought on this and decided that they would develop and test their protocols using amine functionalized dye molecules and green fluorescent protein. In having this thoughtful conversation, we came to the framework for what could be accomplished in a semester’s time. Of course, the students also had to determine how they were going to analyze their reaction products and assess the stability of the bioconjugates that they made. They also had to determine how to separate conjugated nanoparticles from unconjugated nanoparticles. We bring this example up to provide guidance for others who wish to implement similar programs.

During the spring of 2012, our four student groups worked on the following projects: nanoparticle solution stability, nanoparticle functionalization through lysine reactivity, nanoparticle functionalization through cysteine reactivity, and nanoparticle functionalization through intein chemistry. The most promising and consistent results from this semester came from the experiments on nanoparticle solution stability. The faculty decided to focus the following semester (fall of 2012) on studying the stability of the nanoparticles in different solution environments in parallel with testing the functionality of the proteins used to make the nanoparticles. For these tests, several readily available enzymes were used to synthesize nanoparticles. The activity of the pure enzymes in solution was tested against the activity of the enzyme−nanoparticle systems. In the spring of 2013, the students decided to study the inhibition of an enzyme and to develop antibacterial materials with the nanoparticles. The students working on enzyme inhibition were introduced to computational methods, which

DOI: 10.1021/ed500793q
J. Chem. Educ. XXXX, XXX, XXX−XXX

helped them to narrow their search for potent inhibitors while illustrating potentially important protein−ligand interactions. In the fall of 2013, we continued to study the catalysis of enzyme−nanoparticle conjugates as well as tried to better understand the energetics of nanoparticle−fiber formation. The five student groups in the spring of 2014 worked on the following projects: studying the equilibrium between homogeneous solutions of colloidal nanoparticles and nanoparticle−fibers, synthesizing protein-templated quantum dots, preparing nanoparticles with higher enzyme activity, preparing cell culturing scaffolds that incorporated the nanoparticle−fibers, and synthesizing fibers of magnetic nanoparticles. In the current semester, fall of 2014, our students are studying the equilibrium between homogeneous colloidal nanoparticles and nanoparticle−fibers and are working to understand the dynamics that control the size and shape of a growing nanoparticle−fiber.

Perspectives from Experience

Our expectations of workflow, pace of research output, and student experience have changed since the inception of this curriculum change. It is interesting to note how the faculty members originally designed the EBC program to study nanoparticle functionalization. Given that our students are currently performing biomineralization experiments, it is easy to see how results and student intuition and interest can drive a project into unexpected places. As faculty members in charge of our own personal research programs, the observation of students making real research decisions and influencing the direction of a project is both fulfilling and enlightening. Having gone through several iterations of EBC1/2, we have derived the following schedule for reasonable data publishing. We have found that the second semester work, at a minimum, provides several proof of concept experiments for whether a proposal is possible or interesting. We have had several cases where second-semester experiments have come close to producing publication-quality (and quantity) results. However, in terms of what we expect, the second semester usually provides some very crude results with hints toward reasonable results. In planning how we approach the fall semester, the students take these crude results and refine them under the direction of the faculty. We expect that this first semester work, building off of the previous second semester's work, will often result in publishable data. Also, because a different faculty member teaches these courses in a rotation each semester, different perspectives can be brought to the project from one semester to another.

Several challenges to teaching these laboratories have been noted. First, the fall semester typically needs to include a few extensions to the main project to provide students with the grounding to propose their own projects during the spring semester. The first semester also must include the use of more instrumentation than a project was initially designed to use. Students sometimes lose sight of the main goal of the project during these extensions. Second, it is important to find ways to ensure technical proficiency on laboratory protocols such as assigning students to write standard operating procedures for the new instrument they use in the second semester or instituting a set of laboratory practical exercises. Finally, as teachers, the faculty can offer too much advice and not ask enough leading questions in the second semester. Maximizing student ownership of their project is paramount to the long-term success of these courses.

While we worked diligently during the development of this program to craft a project to which all of the faculty could comfortably contribute, we have followed the research (and our students) as the years have passed. Another approach to teaching this type of course could involve skewing the research toward the expertise of the particular faculty member that is teaching during a particular semester. We have been cognizant in our attempts to not do this. In our opinion, it is unavoidable for faculty to inject their own curiosity into a project, but we do try to be faithful to where the students and the research are leading. In doing this, our department is trying to maximize student autonomy over the course. We feel that other approaches, which might include skewing the project toward the interests of the faculty teaching during the semester, can be as successful as our approach has been. However, in doing this, we feel that care must be taken to continue to build off of the class's previous research accomplishments in crafting a semester's work.

Outside of the faculty who developed this program, one other faculty member has taught one of these laboratories. In the future, we expect this curriculum to be a great benefit to young faculty members who join our department. In fact, the laboratory will provide an established research program in which new junior faculty will play an active role during a time when they are trying to get their own laboratory started.

One final observation is that our students do take ownership and responsibility for their research and education in this setting. They are disappointed when an experiment does not work out as planned. They are thrilled when they get a good result. Also, they really push themselves to hone their craft. They think critically, solve creatively, and conduct themselves as emerging scholars.

■ CONCLUSION

The curriculum changes to the upper-level laboratories instituted in the Department of Chemistry at American University have led to measurable, beneficial effects in student engagement, professional accreditation, faculty teaching schedule flexibility, and research output. We feel that these changes would be attractive to other departments that are looking to change their upper-level laboratory offerings. One of the primary reasons for the success that we have seen is the manner in which student autonomy informs and impels the research that is performed from one year to the next. In the future, we hope to be able to work with educational researchers to study student perceptions of autonomy and the effect of autonomy on problem solving and critical thinking skills.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

Grading rubrics and sample schedules. This material is available via the Internet at http://pubs.acs.org.

■ AUTHOR INFORMATION

Corresponding Author

*E-mail: hartings@american.edu.

Notes

The authors declare no competing financial interest.

DOI: 10.1021/ed500793q
J. Chem. Educ. XXXX, XXX, XXX−XXX

■ ACKNOWLEDGMENTS

The authors would like to thank Prof. Stefano Costanzi for the help in implementing these courses and for review of this manuscript.

■ REFERENCES

(1) Dillner, D. K.; Ferrante, R. F.; Fitzgerald, J. P.; Heuer, W. B.; Schroeder, M. J. Integrated Laboratories: Crossing Traditional Boundaries. *J. Chem. Educ.* **2007**, *84*, 1706.

(2) Dillner, D. K.; Ferrante, R. F.; Fitzgerald, J. P.; Schroeder, M. J. Integrated Laboratories: Laying the Foundation for Undergraduate Research Experiences. *J. Chem. Educ.* **2011**, *88*, 1623.

(3) Gron, L. U.; Hales, D. A.; Teague, M. W. Creating a Research-Rich Chemistry Curriculum with an Integrated, Upper-Level-Undergraduate Laboratory Program. *J. Chem. Educ.* **2007**, *84*, 1343.

(4) Miller, K. M.; Hage, D. S. Survey of Long-Term Integrated Laboratory Use in Undergraduate Chemistry Programs. *J. Chem. Educ.* **1995**, *72*, 248.

(5) Richter-Egger, D. L.; Hagen, J. P.; Laquer, F. C.; Grandgenett, N. F.; Shuster, R. D. Improving Student Attitudes about Science by Integrating Research into the Introductory Chemistry Laboratory: Interdisciplinary Drinking Water Analysis. *J. Chem. Educ.* **2010**, *87*, 862.

(6) Wolfson, A. J.; Hall, M. L.; Branham, T. R. An Integrated Biochemistry Laboratory, Including Molecular Modeling. *J. Chem. Educ.* **1996**, *73*, 1026.

(7) Chase, A.; Pakhira, D.; Stains, M. Implementing Process-Oriented, Guided-Inquiry Learning for the First Time: Adaptations and Short-Term Impacts on Students' Attitude and Performance. *J. Chem. Educ.* **2013**, *90*, 409.

(8) Walker, J. P.; Sampson, V. Argument-Driven Inquiry: Using the Laboratory To Improve Undergraduates' Science Writing Skills through Meaningful Science Writing, Peer-Review, and Revision. *J. Chem. Educ.* **2013**, *90*, 1269.

(9) Black, A. E.; Deci, E. L. The Effects of Instructors' Autonomy Support and Students' Autonomous Motivation on Learning Organic Chemistry: A Self-Determination Theory Perspective. *Sci. Educ.* **2000**, *84*, 740.

(10) Cooper, M. M.; Kerns, T. S. Changing the Laboratory: Effects of a Laboratory Course on Students' Attitudes and Perceptions. *J. Chem. Educ.* **2006**, *83*, 1356.

(11) Hollenbeck, J. J.; Wixson, E. N.; Geske, G. D.; Dodge, M. W.; Tseng, T. A.; Clauss, A. D.; Blackwell, H. E. A New Model for Transitioning Students from the Undergraduate Teaching Laboratory to the Research Laboratory—The Evolution of an Intermediate Organic Synthesis Laboratory Course. *J. Chem. Educ.* **2006**, *83*, 1835.

(12) Hartings, M. R.; Benjamin, N.; Briere, F.; Briscione, M.; Choudary, O.; Fisher, T. L.; Flynn, L.; Ghias, E.; Harper, M.; Khamis, N.; Koenigsknecht, C.; Lazor, K.; Moss, S.; Robbins, E.; Schultz, S.; Yaman, S.; Haverhals, L. M.; Trulove, P. C.; De Long, H. C.; Miller, A. E.; Fox, D. M. Concurrent Zero-Dimensional and One-Dimensional Biomineralization of Gold from a Solution of Au^{3+} and Bovine Serum Albumin. *Sci. Technol. Adv. Mater.* **2013**, *14*, 065004.

(13) *National Science Education Standards*; The National Academies: Washington, DC, 1996.

(14) Alaimo, P. J.; Langenhan, J. M.; Suydam, I. T. Aligning the Undergraduate Organic Laboratory Experience with Professional Work: The Centrality of Reliable and Meaningful Data. *J. Chem. Educ.* **2014**, *91*, 2093.

(15) Deci, E. L.; Vallerand, R. J.; Pelletier, L. G.; Ryan, R. M. Motivation and Education—The Self-Determination Perspective. *Educ. Psychol.* **1991**, *26*, 325.

(16) Dweck, C. S. Motivational Processes Affecting Learning. *Am. Psychol.* **1986**, *41*, 1040.

(17) Hanauer, D. I.; Frederick, J.; Fotinakes, B.; Strobel, S. A. Linguistic Analysis of Project Ownership for Undergraduate Research Experiences. *CBE-Life Sci. Educ.* **2012**, *11*, 378.

(18) Stefanou, C. R.; Perencevich, K. C.; DiCintio, M.; Turner, J. C. Supporting Autonomy in the Classroom: Ways Teachers Encourage Student Decision Making and Ownership. *Educ. Psychol.* **2004**, *39*, 97.

(19) Assor, A.; Kaplan, H.; Roth, G. Choice Is Good, but Relevance Is Excellent: Autonomy-Enhancing and Suppressing Teacher Behaviors Predicting Students' Engagement in Schoolwork. *Br. J. Educ. Psychol.* **2002**, *72*, 18.

(20) *Biomaterial Design Laboratory*; American University Department of Chemistry: Washington, DC, 2015. http://nw08.american.edu/~hartings/BDLabs/ (accessed February 2015).

(21) *AU Biomaterials Design Lab—OpenWetWare*; American University Department of Chemistry: Washington, D.C., 2015. http://openwetware.org/wiki/AU_Biomaterials_Design_Lab (accessed February 2015).

(22) *Undergraduate Professional Education in Chemistry*; American Chemical Society: Washington, DC, 2006.

(23) Bakshi, M. S.; Kaur, H.; Banipal, T. S.; Singh, N.; Kaur, G. Biomineralization of Gold Nanoparticles by Lysozyme and Cytochrome C and Their Applications in Protein Film Formation. *Langmuir* **2010**, *26*, 13535.

(24) Bakshi, M. S.; Kaur, H.; Khullar, P.; Banipal, T. S.; Kaur, G.; Singh, N. Protein Films of Bovine Serum Albumen Conjugated Gold Nanoparticles: A Synthetic Route from Bioconjugated Nanoparticles to Biodegradable Protein Films. *J. Phys. Chem. C* **2011**, *115*, 2982.

(25) Burt, J. L.; Gutierrez-Wing, C.; Miki-Yoshida, M.; Jose-Yacaman, M. Noble-Metal Nanoparticles Directly Conjugated to Globular Proteins. *Langmuir* **2004**, *20*, 11778.

(26) Khullar, P.; Singh, V.; Mahal, A.; Dave, P. N.; Thakur, S.; Kaur, G.; Singh, J.; Kamboj, S. S.; Bakshi, M. S. Bovine Serum Albumin Bioconjugated Gold Nanoparticles: Synthesis, Hemolysis, and Cytotoxicity toward Cancer Cell Lines. *J. Phys. Chem. C* **2012**, *116*, 8834.

(27) Singla, P.; Mehta, R.; Upadhyay, S. N. Clay Modification by the Use of Organic Cations. *Green Sustain. Chem.* **2012**, *2*, 5.

(28) Gohil, J. M.; Bhattacharya, A.; Ray, P. Studies on the Cross-Linking of Poly(Vinyl Alcohol). *J. Polymer Res.* **2006**, *13*, 161.

(29) Yu, Y. H.; Lin, C. Y.; Yeh, J. M.; Lin, W. H. Preparation and Properties of Poly(Vinyl Alcohol)-Clay Nanocomposite Materials. *Polymer* **2003**, *44*, 3553.

DOI: 10.1021/ed500793q
J. Chem. Educ. XXXX, XXX, XXX−XXX