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# Team-Based Learning, Faculty Research, and Grant Writing Bring Significant Learning Experiences to an Undergraduate Biochemistry Laboratory Course

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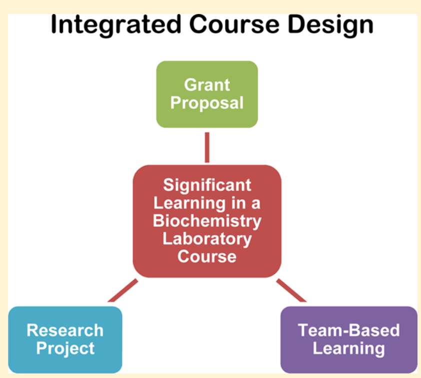
**ABSTRACT:** This biochemistry laboratory course was designed to provide significant learning experiences to expose students to different ways of succeeding as scientists in academia and foster development and improvement of their potential and competency as the next generation of investigators. To meet these goals, the laboratory course employs three different practices that support an 'Integrated Course Design' approach: (1) incorporating basic laboratory techniques with faculty research projects, (2) promoting team-based learning, and (3) developing, de novo, a mini-NIH grant proposal that serves as a capstone project. On course evaluations, students give the biochemistry laboratory course the highest ratings for course and teaching effectiveness, and these ratings are a higher percentage overall compared to similar chemistry laboratory courses offered in the program. Students also state that the practices of the laboratory course went beyond their prior experiences in traditional lab courses. They have reported that they were excited to be involved in current research, were intellectually challenged to think in new ways, were impressed by the work accomplished with their teams, were encouraged by the growth in understanding and ability to formulate new questions, and better realized the impact of chemistry on numerous aspects of human health and everyday life. Thus, the biochemistry laboratory course experience has positively affected student satisfaction in the chemistry program, as well as student self-efficacy.




**KEYWORDS:** *Proteins/Peptides, Upper-Division Undergraduate, Biochemistry, Curriculum, Collaborative/Cooperative Learning, Communication/Writing, Inquiry-Based/Discovery Learning, Problem Solving/Decision Making, Ethics*

## INTRODUCTION

Numerous lines of evidence and formal assessment studies have pointed to the importance of the undergraduate research experience in attracting students to science, increasing their number and retention in the field, and preparing them for a successful career.[1−3] The undergraduate research experience has been shown to be an effective tool for the preparation of students for graduate school, for teaching, and for other avenues of the workforce. As numerous undergraduate students cannot participate in traditional research under the direction of a mentor, the need for developing a research, team-based laboratory course is becoming increasingly realized.[4]

Using an 'Integrated Approach to Designing College Courses',[5,6] a laboratory course has been developed that supports significant learning by engaging students in ongoing faculty research projects, having them develop a mini National Institutes of Health (NIH) grant proposal on a topic unrelated to the research project, and cultivating student collaboration through team-based learning practices. This course design aims to equip students with authentic research experiences, expand students' interest in biochemistry and science in general, emphasize reflection, enhance critical thinking skills, ensure that the students learn the theories behind the biochemical techniques used in the course, nurture and guide students to become independent researchers, and make students aware of the chemistry around them and its application to everyday life. As a result, increased student satisfaction, self-efficacy, and academic success have been reported and observed.

## OVERVIEW OF THE UNDERGRADUATE BIOCHEMISTRY LABORATORY COURSE

### Course Composition and General Description

The biochemistry laboratory course is a one semester, two-credit hour laboratory course that meets 6 h per week and is typically populated with 10−12 fourth-year biochemistry and biology majors as well as some Master's level students in chemistry. It is designated as the required writing intensive course for the biochemistry undergraduate major. The composition of the students in the course is usually about 85% undergraduate and 15% graduate students. One of two upper-division undergraduate lectures is a prerequisite for the course: Biochemistry I, the first semester of a two-semester sequence of biochemistry, or Foundations of Biochemistry, a one semester survey course. These courses cover the basic principles of

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biochemistry techniques and their applications. While no laboratory text is required, detailed biochemical protocols and techniques used in the research projects are provided. Typically, students work in teams of two to four to carry out the diverse activities (Table 1, Box 1) of the laboratory course. Early on, students develop the ability to obtain the needed information largely from the primary literature. Assessment of each student's learning is carried out independently and relative to all students in the class. Each student's final grade is assigned on the basis of cumulative scores of innovative exchanges and active discussions, class participation, lab notebook, topic approval, hypothesis development, specific project aims and experimental design, NIH grant proposal oral presentations, NIH grant proposal written drafts and the final written report, in-depth written and oral peer-review of other class members' NIH reports and research project ideas, teamwork and collaboration, and oral technique presentations. There is flexibility in grading as it is not based on obtaining correct results but rather on specific assignments and critical thinking, which ensures that students are rewarded based on their independent contributions as opposed to that of the entire team. However, teams perform better as a whole than individuals could on their own by the end of the research-based projects, thus raising the quality of the learning experience for each individual.

**Table 1. Example of the Basic Biochemistry Laboratory Course Syllabus Schedule**

| Week | Scheduled Activities |
|---|---|
| 1 | Introduction to laboratory and syllabus explanation |
| 2 | Lecture on the research project and development of the NIH grant proposal; learn to use an appropriate library research database such as PubMed and SciFinder Scholar to search for relevant papers; intro to protein bioinformatics software; selection of grant proposal topic (project must involve at least one protein with a known 3D structure); prepare buffers |
| 3 | Prepare material and carry out research project; discussion of how to be a successful scientist in academia |
| 4−5 | Research projects; NIH hypothesis/specific aims |
| 6−7 | Research projects; background/significance of NIH topic; lab notebook check |
| 8−9 | Research projects; NIH experimental design/methods |
| 10−11 | Research projects; techniques presentations; written NIH grant proposals due for peer review |
| 12 | Research projects; in-depth discussion of written NIH grant proposal critiques; lab notebook check |
| 13−14 | Final grant oral presentations |
| 15 | Final grant proposals due |

**Box 1. Laboratory Course Objectives and Techniques Used**

- Use database search engines to find primary literature
- Use protein bioinformatics tools
- Perform calculations, dilutions and make buffers
- Perform transformation and plasmid DNA isolation
- Restriction endonuclease digestion of plasmid DNA and agarose gel electrophoresis
- Protein expression and purification, centrifugation, and SDS gel electrophoresis
- Perform column chromatography
- Determine protein concentration and use a UV−vis spectrophotometer
- Carry out ELISA-based binding assays and dot blotting
- Perform Western blotting and co-immunoprecipitation
- Solid-phase peptide synthesis and purification by high performance liquid chromatography
- Perform enzyme activity assays and calculations
- Discuss how to be a successful scientist in academia
- Write a formal mini-NIH grant proposal
- Peer-review critiques of NIH grant proposals
- Prepare and deliver numerous oral presentations
- Teach science through presentations to students with little or no science background

### Development of Significant Learning in the Laboratory Course

The desire to provide students with significant learning experiences in biochemistry led to alignment of the course outcomes in the laboratory course with activities and assessments centered on the following three practices: incorporating authentic research, development of a mini grant proposal, and team-based learning (Table 2). These practices integrate the six dimensional framework of significant learning: Learning How To Learn, Caring, Human Dimension, Integration, Application, and Foundational Knowledge.[6]

## THE INTEGRATED COURSE DESIGN HAS THREE COMPONENTS

### The Research Project

**Discussion of How To Succeed in Academia.** Early on in the term (Table 1), students are required to read chosen articles for discussion of academic success.[7−10] Each student is then expected to write a short essay highlighting what he or she found interesting and important, and how and why such findings might apply to his or her experience in this laboratory course and to a future scientific career. Moreover, each student is expected to lead a brief (5−10 min), open and active class discussion of the best research practices to be successful in academia, with class feedback by the students and instructor.

This exercise has proven to be very useful and thought-provoking for students on diverse levels. It has allowed students to question the choice of science as a career, see the commonalities and differences they have with their peers, discover that experiments do not always "work", and learn about ethical issues, such as academic dishonesty, facing science today.

**Use of Faculty Research as a Teaching Tool.** A key feature of the laboratory course is that the students are engaged in conducting research-based experiments on ongoing faculty research projects. For 10 years, a research experience has been integrated into the biochemistry laboratory course as a teaching tool in the hope of pursuing a model and template that more fully integrates practical experiences for students and which can be gradually modified to be student-driven.

While interactions between the instructor and students resemble a typical research experience, this biochemistry laboratory course has some aspects of a traditional teaching laboratory setting. For example, standard experiments are used to acquaint students with some basic calculations and procedures like dilutions, preparation of buffers, and determination of protein concentration. Basic techniques like running gels are also taught. The timeline for the projects is driven to a large extent by the syllabus deadlines (Table 1) and, sometimes, student motivation. Students who do not meet deadlines are penalized by point deductions in the grade, but often, students finish ahead of schedule.

Since 2011, the focus of the collaborative research projects has been to design and use peptides as a tool to investigate


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Table 2. Significant Learning Aligned with Course Outcomes, Assessments and Activities

| Taxonomy of Significant Learning[6] | Student Learning Outcomes | Learning Activities | Assessment of Student Learning: Faculty Determine if Students Can Do the Following: |
|---|---|---|---|
| Foundational Knowledge; Application | Perform and understand why and how fundamental biochemical techniques are used. | Laboratory experiments, keeping accurate laboratory notebooks, oral presentations | Communicate clear explanations of the rationale for using certain techniques and the principles behind them, both orally and in written form. |
| Application; Integration; Human Dimension | Use critical thinking to analyze, interpret, and evaluate the data obtained experimentally and from the literature. | Research project involvement, literature reading, oral presentations, reports | Provide clear and effective communication of data and its meaning in literature as well as that obtained in the laboratory, through presentation orally and in written form, with clear understanding of diagrams, equations, graphs, protein structures and other representations. |
| Integration; Learning How to Learn | Develop a hypothesis-driven NIH grant proposal on a topic of choice and design a coherent set of experiments to test the hypothesis. | Grant proposal | Create an effective design of a coherent and clear set of experiments employing fundamental biochemical techniques to address their grant proposal hypothesis. |
| Foundational Knowledge; Application; Integration | Communicate through in-class discussions and formal oral presentations and through formal written reports. | Written report drafts and final, oral presentations | Explain clearly and effectively the NIH grant proposal to students with limited to no science background. |
| Application; Integration; Human Dimension; Caring | Demonstrate the ability to work in teams and in a self-driven fashion, despite challenges. | Teamwork effectiveness | Draw careful conclusions based on scientific evidence and decide, both independently and as a team, when an experiment should be repeated. |
| Human Dimension; Learning How To Learn | Provide critical feedback on peer-driven ideas/proposals. | Peer-feedback | Provide effective and constructive critique of peers' work with a professional demeanor. |

regions important in protein−protein interactions and to identify the minimum sequence required for binding. This can lead to the development of small novel peptide-based drug molecules with therapeutic potency and promise.

The specific protein pairs used as research projects in the biochemistry laboratory course are the following:

**Aspartate Transcarbamolyase (ATCase)-Dihydroortase (DHOase) Pair:** De novo pyrimidine biosynthesis plays a critical role in numerous cellular activities.[11] In mammalian cells, the flux through the pathway is precisely controlled by the multifunctional protein, CAD (carbamoyl phosphate synthetase/CPSase, aspartate transcarbamoylase/ATCase, and dihydroorotase/DHOase), and its activation is a prerequisite for tumor growth.[12] There are physical and functional interactions between the ATCase and DHOase subunits of the protein and the goal is to disrupt this interaction with small peptides that mimic the binding interface. The biochemistry laboratory course uses recombinant plasmids expressing the enzymes from *Aquifex aeolicus* in *Escherichia coli*. *A. aeolicus* is an extreme hyperthermophile which encodes pyrimidine pathway proteins that are homologous to those found in mesophilic organisms.[13,14] The enzymes from the bacterial strains, *Bacillus anthracis* and *Staphylococcus aureus*, are also used. Peptides comprising the amino acids found at the binding interface are synthesized and tested for their ability to inhibit enzymatic activity.

**Insulin-like Growth Factor Binding Protein-3 (IGFBP3)−Importin*β* Pair:** IGFBP3 has been implicated to play a role in Alzheimer's disease (AD). Humanin (HN) is a peptide that exhibits neuroprotective and cytoprotective effects in AD and protects against neuronal cell death induced by IGFBP3. One hypothesis is that this 24 amino acid peptide inhibits IGFBP3-induced cell death by binding to the C-terminal domain of IGFBP3 containing the nuclear localization sequence required for its nuclear import by importin-$\beta$1.[15] One mechanism by which humanin might exert its function is likely via the inhibition of the nuclear import of IGFBP3 by importin-$\beta$1. For this project, peptides which mimic a segment of humanin are synthesized and tested for their ability to disrupt the binding of importin-$\beta$1 to IGFBP3.

**D1−D2 Dopamine Receptors Pair:** The D1 and D2 dopamine receptors are believed to interact directly to form a D1−D2 complex that plays an important role in depression.[16] Recent studies have shown that interfering with the formation of this complex leads to a reduction in depressive symptoms. The research goal is to modulate the specific D1−D2 interaction by designing small peptides that are intended to weaken or completely abolish the association of these receptors by mimicking the sequence at the interface between the two proteins and competing for the binding surface.

Over the past four to five years, the ATCase-DHOase project has been used in the first half of the course since the structure is known in the Protein Data Bank, lending itself to bioinformatics as part of the learning and visualization process. During the second half of the course, either the IGFBP3−importin*β* or D1−D2 dopamine receptor projects are used.

**Methodology and Techniques Used.** Students are directed early on to use an appropriate library research database such as PubMed and SciFinder Scholar to search the primary literature on the protein pairs, described above, to be used in their research projects. Moreover, they are required to use bioinformatics applications such as DeepView−Swiss-PdbViewer and Chimera to visualize and analyze the molecular structures, where available. They must find the area of the protein where the peptides are proposed to interact so that they can connect structure to binding and activity. Several biochemical techniques are used (Box 1) to probe protein−protein interactions such as immunoprecipitation, enzyme kinetics, SDS−PAGE, Western, and dot blotting. Peptides, specific for the pair used, are synthesized using solid phase techniques and purified by high-performance liquid chromatography, and then added in increasing concentrations to investigate and compare the functional and physical linkages of the two subunits in a single pair.

Emphasis is placed on understanding the basics, concepts, logic, application, and limitations of each technique, with the expectation that students will propose the use of some of the techniques carried out in the research project component of the laboratory course (Box 1) in their NIH grant proposals (described below). To that end, each student is expected to choose a biochemical technique that he or she would like to learn more about in detail (and plan on using in the grant proposal) and explain it to the class in a formal oral presentation. The student is required to research the technique—how it is performed, what the data obtained from such technique can


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reveal, how findings are interpreted, and what instrumentation is needed. Students also need to identify one article from the primary literature where the technique was used and explain the article in a critical manner, with emphasis on how the technique was utilized.

## Team-Based Learning

To prepare students to succeed not only in the classroom but subsequently in the workplace, this laboratory course aims to instill in students the value of team-based learning and team achievement through nurturing a productive learning collaboration between undergraduate- and graduate-students under the supervision of the faculty member.[5,17] The lab encourages team effectiveness skills and teamwork practices such as fostering the ability to develop interpersonal communication, negotiation, and cooperation with others to accomplish common goals in the research project described above. Student teams must make decisions on how to divide the tasks and must work together to integrate their findings into cohesive presentations. This leads to much discussion and sharing as well as criticism of ideas, ultimately resulting in a deeper understanding of the project and its importance in the scientific community. By definition, team-based learning is a transformational process beyond the experience of students working in a small team setting. Team-based learning is an intentional aspect of the course design to provide activities and opportunities for the collective team to perform above and beyond what any individual could accomplish on his or her own.[5]

Graduate (M.S.) students working in the instructors' research teams are encouraged to participate in all aspects of the laboratory course as part of their graduate research development. In the biochemistry laboratory course, graduate students are assigned to undergraduate student teams based on the research project used by that team. For example, a graduate student working on the ATCase−DHOase pair will supervise the undergraduate student team working on that project. Throughout the entire term, the graduate students have to adequately explain the components of the research projects in both formal and informal ways to the entire class. Graduate students take an active role in overseeing undergraduate student teams and are engaged in helping them as they encounter different problems. Therefore, they need to be well-prepared and able to clearly and adequately handle a wide variety of questions.

Graduate students' understanding of their research projects increased substantially with the supervision of the research projects in the course. They have indicated that they understand their own research projects significantly better subsequent to their participation in the laboratory course, largely due to the input, constructive critique, and continued questioning provided by the undergraduate students. Moreover, this opportunity appears to provide the graduate students with important training in teaching approaches and effectiveness, something likely required in their chosen future careers. Some undergraduate students engage in further undergraduate research with the faculty either prior or subsequent to taking the course. As a result, they have the opportunity to work more in depth on the given research project with the graduate students under the mentorship of the faculty.

The apparent advantages to integrating teaching with the faculty research projects and this team-based learning approach have been many, which include guiding students in sharing diverse perspectives to evaluate scientific evidence, pooling their knowledge, relaxing into learning that science is a trial-and-error process, realizing the need to refine and/or reformulate hypotheses, and establishing unique identities within their teams.

Many contributions to open-ended questions and discoveries have resulted from the research-based experiments, and some have resulted in publications (see below).

**Data Dissemination.** This cooperative approach to learning between the undergraduate and graduate students has been mutually beneficial. Since 2011, seven presentations have resulted at the annual Undergraduate Symposium, in addition to seven presentations at the annual Graduate Research Conference and 10 poster presentations at regional and national professional meetings. Moreover, an Honors thesis on the IGFBP3−importin$\beta$ pair and an Honors thesis on the dopamine receptor pair, along with six graduate M.S. theses on the ATCase−DHOase pair and two graduate theses on the IGFBP3−importin$\beta$, were generated. Four journal publications also were significantly strengthened by the laboratory course.[15,18−20]

## Development of a Mini-Grant Proposal as a Capstone Project

Grant proposals have previously been shown to be effective as a capstone experience.[21−23] The capstone experience is being progressively recognized as an essential component of undergraduate programs in the sciences as students are better able to synthesize and integrate knowledge.[24] In this laboratory course, the development of a mini NIH grant proposal has been incorporated as a pedagogical tool. The grant proposal was designed to be intensive, provoking active learning with significant effort needed to complete a final oral and written product.

Students in the laboratory course are typically divided into four teams. Each team is expected to develop a grant proposal requesting a "theoretical" one million dollars in funds to support its research. Guidelines for grant proposal development are provided to the students from the NIH Web site. The students are expected to engage in teamwork and develop the grant proposal with their team. The students start by reading an annotated NIH grant application provided by NIH on their own in order to gain a better understanding of how to better develop a fundable grant proposal. Independent of the instructor, students then identify a topic (Figure 1) that they consider to be important in science today and a gap in knowledge that they would like to address related to their chosen topic. This topic is distinct from those of the research projects described above. They begin a search of the literature to identify a protein, with a known crystal structure, that plays a key role in their topic of interest. Students often choose topics and key proteins based solely on interest and/or are ones implicated in diseases that they struggle with personally. Feedback from the instructor is provided and students continue to gather relevant primary scientific literature on their chosen project, formulate a central hypothesis, and develop specific aims to address it. Students are encouraged to begin to explore their best "model" according to their existing knowledge. In doing so, students have to learn how to develop a new sound hypothesis that is supported by existing scientific data from the literature and must be able to build a strong argument in favor of the hypothesis. Students then begin to develop the experimental design and methods section and come up with a list of


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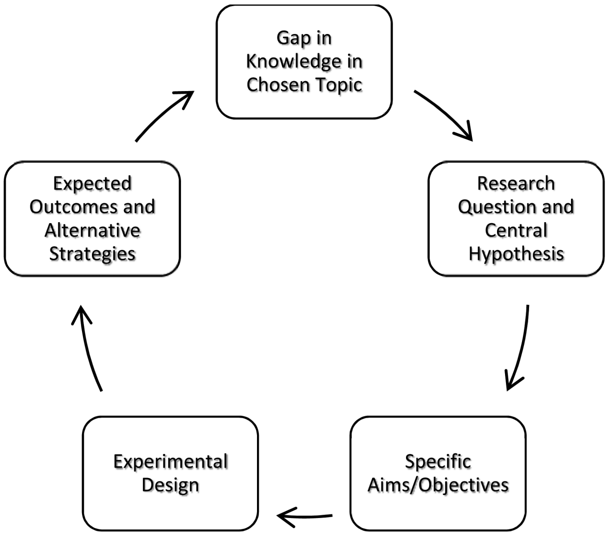


**Figure 1.** Outline of the Grant Process.

supplies to test their hypothesis. Students are required to provide expected and possible unexpected outcomes of their approach and design, anticipate potential pitfalls or problems with their proposed specific aims, provide alternative strategies, and discuss short- and long-term limitations of their experimental research design. Active discussions of all aspects of the grant proposal take place with the class as a whole and ongoing guidance by the instructor outside of laboratory time is typical.

In going through the first draft of the grant proposal process (Figure 1), the majority of students quickly realize that several elements of their proposal are far too general to specifically address their proposed hypothesis. Students realize that their model may not lead them to their desired solution or outcomes. That is the time when they begin to back-track, rethink their ideas, and propose something else. This very process of generating and then refining a model or hypothesis allows students to define the problem and decide how to address it more clearly. In doing so, their thought processes becomes more sophisticated and their understanding deepens, shifting their learning to the higher levels of critical thinking. This type of brainstorming activity allows the students to assess what they already know about a given topic and helps them push this knowledge to a second level of questions that they wish to answer. This also enables the students to consider misconceptions and to begin constructing an alternative explanation that is more consistent with existing scientific evidence. In looking at past semesters, it is interesting that while students performed best on practices that required knowledge or comprehension-level thinking, the most rewarding activities were those that demanded the challenge of synthesizing and creating new ideas or critically evaluating reports and presentations.

Throughout the term, students engage in peer-evaluations and assessment on a regular basis, both orally and in written form. Toward the end of the term, there is a formal "study section or review panel" where each team serves as a panel to evaluate another team's proposal (for example, Team 1 evaluates Team 2; Team 2 evaluates Team 3; Team 3 evaluates Team 4, and Team 4 evaluates Team 1). Students are expected to provide a written critique highlighting strengths and weaknesses of each of the components of the grant proposal (Figure 1). The peer-review process serves to build each student's confidence and maturity in the role of an evaluator, and exposes each student to peer-created models of research proposals. This enables the students to view their work from the perspective of outside colleagues, and guides them to improve development of their own proposals. Faculty assessment of student performance is carried out according to Appendix A and Appendix B, adapted for this course from Oh et al.[21]

**Grant Proposal Oral Component.** Each student is required to communicate the components of the proposal (Hypothesis/Specific Aims, Background/Significance, Experimental Design) in both oral and written form throughout the term. PowerPoint presentations are given by each team on their proposals, and each student in the team is expected to present orally. Oral presentations are carried out in an open, constructive setting so that students are challenged and become less intimidated. During the oral presentations, students are expected not only to explain their research grant proposals but to receive and address all criticisms in a professional manner. All Chemistry faculty from the different subdisciplines are invited, and typically the chair and representatives of most of the subdisciplines attend and provide useful insight and suggestions to the students during the oral presentations. In addition, a class of first year chemistry students is invited to the presentation.

Since one effective way to learn is to teach material to someone else, the students are required to present their final grant oral proposals to an audience with a diverse science background that ranges from very weak to strong. Thus, students need to learn to present their work in both a broad and a more scientifically focused context. In learning how to effectively communicate the grant proposal ideas clearly and concisely to both a scientist and a layman, students benefit in many ways that include

- being able to identify deficiencies in their knowledge of the particular scientific area
- recognizing strengths and weaknesses in their scientific communication in layman's terms
- effectively refining the specific aims of their proposal to better address the scientific question posed
- sharing their biochemical knowledge while attempting to stimulate enthusiasm and interest in biochemistry and science as a whole to their audience

**Grant Proposal Written Component.** Development of the NIH style research proposal is a major writing assignment in the course, worth ~1/3 of the total grade. This exercise represents a challenge as, typically, most students have no prior research experience and none have engaged in developing research proposals prior to taking the course. Each student team has to submit written drafts of each component of the proposal (Hypothesis/Specific Aims, Background/Significance, Experimental Design) three times throughout the term to be critiqued by student peers and the instructor prior to handing in the final revised full proposal (3–5 pages in total), including all the components, at the end of the term. The peer-editing process has proven to be very enlightening to students, as peers question statements and stimulate deeper thought, driving the development of clearer and stronger proposals.

Challenging students to express their ideas in writing is a powerful way to get them to reflect on their own understanding of the material. It helps students consolidate what they are


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learning and shape it into a meaningful picture that accurately reflects their intention.

**Advantages of the Grant Proposal Component.** Unlike the research project described above, where the projects and their implementation have already been in place, here students have to choose and develop, de novo, a proposal unrelated to the research projects. The de novo development of the NIH grant shifts student learning into one that is self-directed. The grant proposal exercise forces students to take more ownership of their work and promotes guided inquiry and critical thinking. With increased ownership of their proposals comes increased student participation and overall excitement. Students communicated their satisfaction in the end-of-course evaluations.

Student evaluations were analyzed over a nine year period (Table 3) including 52 student comments that could be categorized into the following four themes.

**Table 3. Summary of Student Evaluations from 2006 to 2015[a]**

| Comparable Chemistry Laboratory Courses | Ave. No. of Students per Section | No. of Sections Taught from 2006 to 2015 | Student Evaluations: Grade A or B for Instructor Effectiveness | Student Ratings of Grade A or B for Course Effectiveness |
|---|---|---|---|---|
| Biochemistry | 9 | 17 | 98% | 91% |
| Organic | 13 | 56 | 88% | 80% |
| Analytical | 11 | 30 | 85% | 74% |

[a]Three courses of comparable size, expectations for content, skill, and communication ability were compared: the biochemistry laboratory course (this paper), an organic laboratory course, and an advanced analytical laboratory course.

- Theme 1, **Positive Environment**: "fun", "stress-free"
- Theme 2, **Usefulness**: "challenging", "I learned a lot", "my skills improved"
- Theme 3, **Practicality**: "real world", "true research", "not cook-book"
- Theme 4, **Overall Satisfaction**: "Best lab I ever took in college"

More than the other practices in the laboratory course, this activity appears to result in increased intellectual and personal growth. Throughout the course, students are treated as scientists where they gain a glimpse into how to do science, from forming a draft hypothesis based on a critical reading of the literature, formulating specific questions and designing specific experiments, to testing their hypothesis, along with continual review and revision throughout the term. As reviewers of the work of their peers, they engage in critical analysis that leads to revisions of their own proposals. Students have consistently demonstrated increased "ownership" and a distinct sense of accomplishment from their proposals in a self-driven fashion without much prompting by the instructor. Improvement in student overall competence, as evidenced by the progressive increase in quality of the proposals, due to this time-intensive assignment has been noteworthy and deserving of the additional work and effort required of both students and faculty.

Student self-efficacy is captured in comments shared through e-mail such as the following (used with permission):

*I really like the grant proposal project. Having presentations every week helped keep us accountable while also getting us used to defending our ideas/thinking out loud.*

*I think a lot of times in structured labs you have a reproducible experiment with expected results and it limits critical reasoning in a way. The process was useful because it mimicked the challenges you face when working on a research team or in a research lab.*

*As a student the whole process really opened up my individual capability to apply biochemical theory to a more hands on approach. And since this was so hands-on and in depth, it really helped me retain a lot of really cool information.*

According to previous students who have attended graduate school, this assignment was rated as one of the most useful ones in the course, as they felt more prepared compared to their peers. As many of the benefits of authentic research can be realized through developing grant proposals without actually performing any experiments, they felt more at ease when they had to pass qualifying examinations. In addition, many were often asked to write grant proposals early on in the graduate programs on their research project. Many students also reported that the grant proposal exercise served them well as scientists and interestingly, also in other aspects of their personal lives, which they attributed to their improved utility of analytic thinking and persuasive writing.

## Challenges and Considerations

Participation in all aspects of the course is critical. Instructors have to ensure that each student in the team is participating and has performed all of the expected components of the laboratory. This is especially important for students who have not previously worked in a research laboratory and who have only been exposed to more typical laboratory settings where the experiments always "work". To ensure their participation, regular conversations, clear communication, and constant encouragement are necessary throughout the semester. These students are programmed earlier in their education to think that failure is always negative, and they struggle to accept that significant learning can often be realized very effectively from failure. Keeping these students motivated can at times prove challenging. For example, students design peptides with the idea of disrupting the protein−protein interaction interface. When the designed peptides either activate or have little effect, students become discouraged as the data did not support their proposed hypothesis.

At times, students have expressed discomfort both in the design of the experiment and in interpreting ambiguous data. In an effort to address these issues, students are reminded a number of times during the semester that feeling discomfort is expected as they are engaged in inquiry exercises where the results are not known, even to the instructors. It has been reported previously that students often report discomfort the more responsible they become for their own learning.[4] The instructors are always challenged to strike the right balance between instructional support and independent student learning, ensuring that students not be overwhelmed. It is interesting to note that the students' most significant learning seemed to occur when the technique did not work as expected and/or the data did not support the proposed hypothesis. The unexpected results seemed to inspire the most thought about subsequent steps to address the hypothesis.

Students have seemed relatively at ease in providing a review on a topic or in explaining biochemical techniques. Over the years, however, students have initially struggled with developing a well-designed natural flow of questions focused on testing a central hypothesis. They are challenged when tasked to devise



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specific questions and link them to a set of experiments designed in a clear and logical manner. Throughout the course, however, most students become progressively aware of gaps in their own oral and written presentations and in that of their colleagues, generating a more focused proposal which typically showed good improvement at the end of the term.

## SUMMARY

Using an Integrated Course Design approach that incorporates team-based learning, faculty research, and a mini-grant proposal to support significant learning in this laboratory course has helped the biochemistry faculty to continuously modify their teaching activities to be better aligned with assessment of student learning and enhance the metacognitive skills of both faculty and students. Practices include discussions of academic success, critical thinking and creative problem-solving, development of sound hypotheses, learning standard biochemical techniques and their application, facilitating active student communication and participation in data analysis, learning the value of team work, formal presentations and written reports, peer-critique, presenting results to a scientific and nonscientific audience, and dissemination of the work through presentations and publications. With this integrated course design, a significant learning template has been initiated for the course that can be updated with time to better serve, guide, and prepare students to become the competent scientific leaders of tomorrow.

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### Notes

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