Board 99: Learning through Discovery: Empowering Lower Division Undergraduates to Engage in Cross-Disciplinary Research

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Introduction

Active participation in undergraduate research has been shown to play a valuable role in enhancing the educational experience of undergraduate science and engineering majors. In addition to providing training in laboratory techniques, undergraduate research can facilitate development of higher thinking skills, expose students to the excitement of scientific discovery, immerse undergraduates in the culture of laboratory research, and contribute to preparing individuals for careers in the professional workforce [1], [2]. The American Society for Biochemistry and Molecular Biology (ASBMB) recognizes research as an essential curricular feature of recognized undergraduate biochemistry programs [3]. Furthermore, a survey of undergraduate research programs at historically black colleges has reported that underrepresented students in structured research programs report improved persistence in biomedical and behavioral sciences and an increased sense of independence, self-efficacy (students’ belief in their capacity to perform science), and scientific identity [4].

In addition to endorsing learner-centered approaches and participation in discovery-driven research [5], [6], the National Research Council (NRC) promotes the development of genuinely interdisciplinary courses and curricula, leading to scientists and engineers capable of combining specialized disciplinary knowledge with fluency in complementary disciplines [7]. This vision is consistent with a recent report of the California Life Sciences Institute that workforce-ready biotechnology candidates tend to be equipped with soft skills (communication, leadership, ability to work in multidisciplinary teams) as well as experience in (or an aptitude for) using modern data-driven approaches in science, such as robotics, informatics, bioengineering, and computational modeling [8]. The American Association for Advancement of Science (AAAS) has also published a vision statement for transforming undergraduate biology education [9], and among the recommendations are (i) introducing the scientific process to students early, (ii) creating active-learning environments starting in lower division classes, and (iii) integrating research into curricula.

The authors have combined the AAAS strategies with the NRC/California Life Sciences Institute calls for authentic cross-disciplinary experiences by integrating research-based high-impact practices into new and existing freshmen and sophomore courses involving teams of Chemistry/Biochemistry and Mechanical Engineering majors. Previous progress of the faculty at the upper division level has been demonstrated by publications resulting from their National Science Foundation (NSF) CAREER awards [10]-[15]. Furthermore, the authors and their students presented a California State University Program for Education and Research in
Biotechnology (CSUPERB) poster on the team’s preliminary efforts of incorporating bio-related integrated research into an upper division “Kinematics of Mechanisms” (EGME 335) course [16], [17].

Our preliminary direct pre- and post-course self-reported assessment survey results from nine student volunteers involved in the program show that for the limited time of one spring semester and four weeks of summer internship, the program enhanced the students’ (i) readiness for cross-disciplinary research by 32%, (ii) preparation for upper division research by 25%, (iii) acquisition of laboratory problem solving by 28%, scientific communication skills by 28%, and (iv) scientific research literacy by 26%. The survey also reveals that neither the engineering, nor the biological concepts were easy or very difficult for the students spanning both colleges, which means that the course activities and projects were well balanced. On average, the students shared that the biological concepts were a bit more difficult than the mechanical engineering concepts (65% v/s 62.5%). Standardized pre-/post-summer experience surveys were also used to assess the impact of the course modifications on the participants’ scientific self-efficacy and impression of research (Survey of Undergraduate Research Experiences, SURE) [18]. The results from the SURE survey at the end of the Summer 2018 show that out of the 21 comparative learning gains, the EGGN 122 freshmen and sophomore were higher than the national average in 11 and lower than the average in 5 gains. In response to the survey results, the last semester of the program involved improving the students’ preparation for upper division research and scientific communication skills, through a pilot Directed Studies section offered in Fall 2018. The results revealed that the additional sophomore-level pilot section, further enhanced the students’ preparation for cross-disciplinary research, preparation for upper division research, scientific research literacy, acquisition of laboratory problem solving and substantially improved the students’ scientific communication skills by additional 25%. The feedback will be used to improve course for second course offerings in Spring 2019.

The curriculum activities proposed below are considered high impact practices and are designed to strengthen the lower division foundation for authentic cross-disciplinary undergraduate research productivity and preparation for jobs in the biotechnology workforce.

Keywords: kinematics of mechanisms, protein kinematics, biomechanics, biochemistry, DNA nano-mechanisms

Overview and Desired Student Outcomes

The goal of this curriculum development research at California State University, Fullerton (SCUF) was to explore mechanisms to introduce the cross-disciplinary fields of Bioengineering and Biomedical Engineering to Chemistry/Biochemistry majors and Mechanical Engineering majors through the development of a new pilot course and revisions to existing lower division courses. The proposed modifications focused on fostering interactions among early college natural science and mechanical engineering majors by
(i) providing novice level cross-disciplinary research experiences to **first-year undergraduate students**, from the College of Natural Science and Mathematics (NSM) and the College of Engineering and Computer Science (ECS), in a newly developed pilot EGGN 122 “Early Research Experiences in Biomedical and Bioengineering”;

(ii) inviting the prospective students from the pilot EGGN 122 to conduct research during a **four-week summer internship** as part of a cross-disciplinary team. The goal was to complete a promising research project started in the first-year courses;

(iii) combining sections of the current sophomore-level Biochemistry Directed Studies course with Mechanical Engineering Independent Study course to **empower cross-disciplinary sophomore research teams to execute one-semester projects** on Modeling Protein Dynamic Motion and/or Design of DNA Nano-structures using engineering principles.

These aims fit into the long-term commitment of the faculty to integrate research and education into traditional courses, capstone courses, and summer experiences. The research activities also complement the goals of the CSUF Chemistry and Biochemistry Department and Mechanical Engineering Department to increase student persistence and strengthen the lower division research foundation for capstone research experiences. The course modifications were expected to support the four student outcomes (i) enhanced preparation for upper division research, (ii) readiness for cross-disciplinary research, (iii) enhanced scientific research literacy and communication skills, and (iv) increased acquisition of lab problem solving.

Course lectures and discussions were mapped to the desired project activities and the four desired student outcomes. Specifically, the development process contained the following phases:

- Determine faculty goals and objectives; analysis of potential students (students, who take the course are freshmen and do not have prior knowledge in the field of mechanism kinematics, design and its applications);
- Determine faculty role in the learning process and develop an instructional plan;
- Identify other faculty interested in collaborative research and education activities across disciplines;
- Design cross-disciplinary research project activities, assignments, and assessments that are congruent with the four major desired student outcomes.

Curriculum Plan and Methods

(i) **First-year cross-disciplinary experiences**: To stimulate awareness of research opportunities in Bioengineering cross-disciplinary active learning projects and novice level research experiences were introduced into a new pilot course **EGGN 122 “Early Research Experiences in Biomedical and Bioengineering”**.
During Fall 2018, the mechanical engineering and biochemistry faculty volunteered to teach the pilot EGGN 122 consisting of five science and four engineering student volunteers at CSUF. The pilot EGGN 122 “Early Research Experiences in Biomedical and Bioengineering” is a cross-disciplinary freshmen course, which introduces students from both NSM and ECS colleges at CSUF to kinematics of motion, mechanism analysis and synthesis concepts and their applications in mechanical, biomedical and bioengineering. The course material is broken into two main parts. The first 8 weeks of the semester are focused mostly on mechanism, DNA, protein and human kinematics, while the second 8 weeks are related to lectures and activities on DNA structure fundamentals and the design of DNA nano-mechanisms/structures. Each of the two main parts of the course ends with a team cross-disciplinary project challenge related to the Development of Assistive Devices and DNA nano-structures, respectively. The outline of the class is listed below.

**Part I. Mechanism, Protein and Human Kinematics**

1. Introduction to Biomedical and Bioengineering. Human Kinematics and Biomechanics.
2. Introduction to Proteins. Protein Kinematics.
3. Links and Joints in Kinematics and Mechanical Design.
4. Serial Type Mechanical Linkages and their applications in Biomedical Engineering and Bioengineering (Project 1, Activity 1 presentations).
5. Parallel Type Mechanical Linkages and their applications in Biomedical Engineering and Bioengineering (Project 1, Activity 2 presentations).
6. Team Challenge 1: Development of Assistive Technologies (Project Challenge 1 presentations).

**Part II. DNA Nano-Structures/Mechanisms**

7. Introduction to DNA.
8. Biochemical and Physical Characteristics of Molecules (Project 2 presentations).
9. Computational Protein Modeling.
10. Team Challenge 2: Molecular Docking (Project Challenge 2 presentations).

The general scope of each project is outlined below.

**Project 1: Mechanism Kinematics in Understanding Protein Motion**

The goal of this project was for the students to learn how to model simple protein chains and predict their motion, using the previously gained knowledge from mechanism kinematics, robotics and biomechanics.

*Activity 1: Protein conformation in drug design using inverse kinematics:* Students were introduced to proteins and ways of modeling them as mechanical chains, using mechanism kinematics knowledge. Also introduced were methods for drug/ligand design, by changing the conformation of a protein segment from unfolded to native state, provided through
crystallography imaging (see Figure 1). The students were asked to design a drug (ligand) to change the conformation of a protein segment from its unfolded to native conformation, provided through crystallography imaging.

![Figure 1.](image1.png)

**Activity 2: Modeling of protein motion:** The duality between simulating the gait-like motion of kinesin protein moving along a microtubule [19] and human walking was presented to students. The addition of ATP and release of ADP cause the system to change configuration and move to create the walking like movement (see Figure 2). The students were asked to simplify the kinesin motion, model it as a rigid planar mechanisms and compute the joint parameters, based on the two given kinesin motor heads motion trajectories.

![Figure 2.](image2.png)

**Project Challenge 1: Prosthetic Knee Design and Analysis**

For this project the students were briefly introduced to experimental work with Motion Capture (MoCap) Systems and techniques for obtaining lower extremity human biomechanics data (see Figure 3).

![Figure 3.](image3.png)
As a next step, the students were asked to design a self-locking four-bar linkage knee, shown in Figure 4 on the left, based on motion capture data (Figure 4 middle) to be used in a lower extremity wearable passive crutch substitute (Figure 4 right).

Figure 4. Left: Different inversions of the four-bar linkage. Middle: Human foot “teardrop” walking trajectory obtained from Motion Capture System (MoCap). Right: Example of a prosthetic knee design.

The students were asked to use materials of their choice to construct the planar model of the prosthetic knee with the attached leg and foot. Then, analyze how well the designed prosthetic device is able to follow the natural “tear-drop” walking trajectory, as well as present and comment on its performance in five different configurations.

The project activities related to Biochemistry concepts are presented below.

**Project 2: Biochemical and Physical Characteristics of Macromolecules**

To introduce the cross-disciplinary team to PCR and laboratory manipulations of DNA, students used the “Crime Scene Investigator PCR Basics™ Kit” from Bio-Rad (Hercules, CA) to learn a basic technique in DNA fingerprinting and forensic analysis. Students were provided with a tube of “crime scene DNA” and DNA representing four suspects. They learned aseptic technique, prepared PCR reactions for each DNA sample, programmed the thermocycler, ran agarose gel electrophoresis, and identified the DNA fingerprint that most closely matched the crime scene DNA (see Figure 5). These techniques directly prepared them for the DNA Origami reactions undertaken during the summer internship.

Figure 5: Crime scene DNA compared to various suspects through polymerase chain reaction (PCR) and electrophoresis.
Project Challenge 2: Molecular docking on 3D model of dihydromethanopterin reductase B with MolSoft (San Diego, CA)

The goal of this challenge was to give students experience with computational protein modeling using the complimentary online program ICM-Browser (Molsoft, San Diego, CA). Students learn to upload 3-D protein structure files from the Protein Data Bank (pdb files), rotate and view the molecules in different atom display modes (wire, ball-and-stick, space-filling), and measure distances between atoms and constituents within the protein structure, such as the flavin mononucleotide (FMN) coenzymes within the dihydromethanopterin reductase B (pdb 3WIS) protein structure [20] (Figure 6). This exercise provided the basis for the professional level program ICM-Pro (Molsoft) that allows computational predictions of chemical inhibitors that bind to the protein active site and may serve as potential candidates for pharmaceutical drug discovery.

Figure 6: MolSoft Program modeling of pdb 3WIS, a redox enzyme used in bacterial metabolism, bonded to FMN. Left: two FMN binding sites. Right: 3WIS complex.

(ii) Post-first year four-week summer internship: In response to survey results and as an exploratory trial for future collaborative research, during Summer 2018, the faculty volunteered to offer a four-week summer internship for seven prospective students from the pilot EGGN 122 course. The Biochemistry and Mechanical Engineering students teamed up and were introduced to computational and experimental techniques, such as working with CADnano software on DNA origami computational design to form a “Circle F” and a “Smiley Face” structure (see examples in Figure 7).

Figure 7: Left: DNA Origami computational design using CADnano software to form a “Circle F” structure. Middle: Electrophoresis gel comparing DNA Origami structures of a previously demonstrated Smiley Face to the student’s Circle F summer design. Right: Transmission Electron Microscopy (TEM) images of failed Smiley Face formation attempts (around 150 nm in diameter).
Assessment

Anonymous self-reported surveys, related to the four major desired student outcomes were performed at the beginning of the pilot EGGN 122 course (Spring 2018) and at the end of the four-week summer session (Summer 2018). The questions were related to the effectiveness of the major activities, based on students’ perspective (see sample summary of survey questions in Table 1).

Table 1. Survey Questions

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<thead>
<tr>
<th>EGGN 122 Survey</th>
<th>Direct Assessment Spring 2018 (Entry)</th>
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<tr>
<td></td>
<td>On a scale from 1-5, what do you feel is your</td>
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<tr>
<td>1. preparation for cross-disciplinary research</td>
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<tr>
<td>2. preparation for upper division research</td>
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<tr>
<td>3. scientific research literacy</td>
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<tr>
<td>4. acquisition of laboratory problem solving</td>
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<td>5. scientific communication skills</td>
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<tr>
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<th>Direct Assessment Fall 2018</th>
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<tr>
<td></td>
<td>So far, on a scale from 1-5 how much do you feel the course</td>
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<td>6. enhanced your preparation for cross-disciplinary research</td>
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<td>7. enhanced your preparation for upper division research</td>
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<tr>
<td>8. fostered scientific research literacy</td>
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<td>9. facilitated acquisition of laboratory problem solving</td>
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<tr>
<td>10. facilitated your scientific communication skills</td>
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The preliminary direct pre- and post-course self-assessment survey results (at the end of the summer internship) showed that the students improved their:

(i) readiness for cross-disciplinary research by 32%,
(ii) preparation for upper division research by 25%,
(iii) scientific research literacy by 26%
(iv) acquisition of laboratory problem solving by 28%
(v) scientific communication skills by 28%.

In addition, standardized pre- and post-experience surveys were used to assess the impact of the program modifications on the participants’ scientific self-efficacy, and impression of research (Course-based Undergraduate Research Experience, SURE) [18](see Figure 8). In Figure 8, the comparison data from “All Students” are based on all respondents to the survey between June 2012 and April 2018. The comparison data from “Masters” are based on institutions classified as masters institutions by the Carnegie classification system. Out of the total 21 comparative learning gains in the SURE survey, the EGGN 122 students’ learning gains were higher than the average student population for the following 10 areas: tolerance for obstacles, understand knowledge construct, assertions require evidence, understand science, learn ethical conduct,
learn lab techniques, understand primary literature, understand how scientists think, learn to work independently, and potential for science teaching.

Figure 8. Comparative means on the 21 learning gain items. The mean learning gains from "Your Students" data are depicted as green triangles. For comparison, the "All Students" means (blue diamonds) represent the n≤3281 responses from the SURE III from June 1, 2012 through April 23, 2018 and the means from all student data from "Masters" are depicted as red squares. The vertical lines in the "All Students" means depict plus or minus two standard errors.

The highest learning gains were in understanding science, learning ethical conduct and understanding how scientists think. The SURE survey also showed some areas for improvement: understand real problems, ability to analyze data, skill in oral presentation and skill in science writing.

(iii) **Second-year cross-disciplinary course:** To reinforce the bioengineering foundation and deepen early research experiences, a sophomore-level pilot Directed Studies section was
introduced in Fall 2018 to further empower the students with communication (oral presentation and writing) skills and research literacy. The course structure followed the model of a well-developed research-based course with active learning and reading/discussion scientific publications activities. The last 8 weeks of the course were reserved for cross-disciplinary teams to design simple but defined research projects focusing on DNA origami. The execution of the project was given as an option for interested students to pursue in the following semester through existing courses.

Self-reported assessment survey results during Fall 2018 showed that for the short time of one additional semester, the students were able to improve:

(i) readiness for cross-disciplinary research by 4%,
(ii) preparation for upper division research by 2%,
(iii) scientific research literacy by 6%
(iv) acquisition of laboratory problem solving by 7.6%
(v) scientific communication skills by 25%.

Impact

The authors have combined the NRC strategies with the California Life Sciences Institute calls for authentic cross-disciplinary experiences by integrating research-based high-impact practices into a lower division undergraduate course on Early Research Experiences in Biomedical and Bioengineering, involving students from the College of Natural Science and the College of Engineering and Computer Science at CSUF. The pilot program includes the Spring semester during freshmen year, a summer internship, and the Fall semester during sophomore year. The curriculum activities are designed to strengthen the lower division foundation for authentic cross-disciplinary undergraduate research productivity and preparation for jobs in the biotechnology workforce.

It is important to note that the integrated cross-disciplinary based alternative to undergraduate research engagement is a novel technique that provides interesting and unique experiences for the students. Our preliminary direct pre- and post-course self-assessment survey results show that for the short time of one semester and four weeks of a summer internship, the program enhanced the students’ (i) readiness for cross-disciplinary research by 32%, (ii) preparation for upper division research by 25%, (iii) acquisition of laboratory problem solving by 28%, scientific communication skills by 28%, and (iv) scientific research literacy by 26%. The survey also revealed that neither the engineering, nor the biological concepts were easy or very difficult for the students spanning both colleges, which means that the course activities and projects were well balanced. On average, the students shared that the biological concepts were a bit more challenging than the mechanical engineering concepts (65% v/s 62.5%). The results from the SURE survey at the end of Summer 2018 showed that out of the 21 comparative learning gains, the EGGN 122 freshmen and sophomore were higher in 10 and lower than the average in 5
gains. The results also revealed that the additional sophomore-level pilot Directed Studies section, offered in Fall 2018, further enhanced the students’ preparation for cross-disciplinary upper division research, scientific research literacy, acquisition of laboratory problem solving and substantially improved their scientific communication skills by additional 25%. The self-reported assessment, as well as the SURE survey results will be used to improve the course for second offerings in 2019.

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