Sophomore Design Course on Virtual Prototyping

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Dr. Caplan's research focuses on molecular cooperativity in drug targeting, bio-sensing, and cell signaling. Current projects align along three main themes: local drug delivery, endothelial dysfunction in diabetes, and cooperative DNA diagnostics. Recent awards include the Jeanette Wilkins Award for the best basic science paper at the Musculoskeletal Infection Society.

Dr. Caplan teaches several classes including Biotransport Phenomena, Biomedical Product Design and Development II (alpha prototyping of a blood glucose meter), and co-teaches Biomedical Capstone Design. Dr. Caplan also conducts educational research to assess the effectiveness of interactive learning strategies in large classes (~150 students).

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At ASU Dr. Coursen has taught a variety of undergraduate and graduate biological, medical, and business, and engineering courses. He currently teaches several classes including Biomedical Product Design and Development II (alpha prototyping of a blood glucose meter), Biomedical Product Design and Development III (alpha, beta, and gamma prototyping of student designed projects), a course in biomedical ethics, and oversees an off-site undergraduate clinical experience.

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1. Introduction

A sophomore-level design course (BME282) teaches students how to apply the design process to a biomedical product. Course objectives are for students to be able to: (1) apply principles from courses they have completed and from courses that they will take in their BME curriculum to biomedical product design and development to determine quantitative design constraints critical to biomedical device design and (2) integrate these principles and resultant design constraints to perform virtual verification of alpha (virtual, i.e. pencil and paper or computer-aided design) prototypes.

The course asks the students to design a blood glucose measurement device in the hope that students will be able to demonstrate understanding of how this alpha prototyping fits into the biomedical design process. A blood glucose measurement device was chosen because it is ubiquitously recognized as a biomedical device and because design of a blood glucose measurement device requires application of at least one critical component of almost every required class in the BME curriculum.

The course is a 1-credit lab format (2.83 hours, once per week). The instructors begin with a mini-lecture (~15-20 minutes) to establish the goals for that class session. This is followed by approximately 1 hour of students working interactively in teams to accomplish the technical goals for that class period, and then the students complete a brief report on their activities in the final hour of the session. Some lab activities take two weeks to complete so, for those activities, the first week is typically a mini-lecture followed by approximately 2 hours of students working interactively in teams to accomplish the technical goals, and then the following week the students continue working for the first part of the lab session and then spend the final hour of that lab session completing the brief report on their activities. Lab activities are designed such that the short mini-lectures are sufficient to provide adequate instruction for students who have only a high school background and a basic understanding of the design process. Some students struggle with completely unfamiliar topics or techniques, but undergraduate teaching assistants and/or classmates are typically able to help those students complete the lab exercises successfully within the lab period.

- Session 1 covers course goals, and then the students perform a documentation exercise based on writing instructions for folding an origami structure. Students are given instruction in how to write a detailed protocol by reading and analyzing the instructor's description of how to bake chocolate chip cookies, then the students attempt to write a detailed protocol for how to make an origami structure, and finally the students hand their notebook to a classmate who tries to reproduce the origami structure purely from the instructions in the notebook.
- In sessions 2 and 3, students develop a simple ordinary differential equation based model of glucose homeostasis in a non-diabetic and a diabetic individual to understand the mechanisms of glucose regulation, dysregulation, and treatment options for diabetics. Students are provided with a Matlab template including everything needed except a few critical pieces of the equations and a few critical parameters. During the lab sessions, students fill in the equations

and parameters until achieving a reasonable time response of glucose after eating a meal. Then students vary two parameters that simulate Type I and Type II diabetes respectively.

- In session 4, students develop a cartoon depiction of the components of an amperometric blood glucose measurement device and how they fit together into a system that will successfully measure blood glucose concentration.
- Sessions 5 and 6 ask the students to develop a protocol for immobilizing glucose oxidase enzymes on an electrode. Students are given an article for creating a Nafion coating which has a short methods section describing the process. Students must convert that methods text into detailed instructions for completing the chemistry – which in turn leads them to one of the paper’s citations for which students need to navigate the university’s library website. Students also use the Michaelis-Menten equation to calculate the amount of enzyme needed to achieve a $0.1\mu\text{A}$ current and determine which enzyme they would purchase from Sigma. Students are directed to the Sigma-Aldrich website to find a suitable glucose oxidase enzyme and then directed to the definition of a “unit” of enzyme and the specifications sheet to find the enzymes K_m value. Students then calculate the reaction rate at a normal, high, and low value of glucose, multiply by 2 (number of electrons created per glucose consumed), and convert that to a current.
- In sessions 7 and 8, students design a simple current-to-voltage circuit, and they choose an OpAmp and Resistor to purchase from an online supplier. The students are reminded of the relationship $V=IR$ and expected to calculate the resistor needed to achieve voltage readouts in the range that can be detected by an Arduino. A current-to-voltage circuit is described to the students, and instruction is provided about how to choose an appropriate OpAmp. Students are directed to a few suppliers of electronic components and told to choose an appropriate resistor and OpAmp for their device.
- In sessions 9 and 10, students design a calibration test, use least-squares fitting to analyze instructor-provided data from a hypothetical calibration test, and write a simple Arduino code to use the results to convert a voltage reading to a mg/dL value on a liquid crystal display. Students are reminded of how to use dilutions to achieve several concentrations of glucose from a concentrated stock solution and how to make a concentrated glucose solution of known concentration. Students then calculate the necessary amounts and describe that in detail in their notebooks. Students are given hypothetical data which shows linear response at lower glucose concentrations but a plateau at high glucose concentration (so a simple “insert trendline” with Excel will provide an erroneous result); and then, after receiving instructions for how to calculate the sum of the square of the error and how to use the Excel plug-in Solver to minimize that sum, the students best-fit a slope and intercept to the linear portion of the data. That slope and intercept are used to modify Arduino code found in online user forums for how to display a voltage on an LCD screen.
- In sessions 11 and 12, students revisit their original calculation of the amount of enzyme to use to determine if mass transport limitations will cause too much change in their reading with time. Students are given a Matlab template for the PDEPE function and shown the equations that describe glucose diffusing towards the electrode where it is reacted with the enzyme. Students are helped to modify the PDEPE template to describe those equations, and then the students run a simulation using their enzyme concentration. Students analyze what happens if they use a much greater amount of enzyme and much less enzyme. Finally students are asked to determine the amount of enzyme that optimizes between signal-to-noise (more enzyme is better) and the percent change in glucose concentration in 60 seconds (less enzyme is better).

- In sessions 13 and 14, students use SolidWorks to design and spec a case for their alpha prototype, and they develop a simple business plan analysis and perform a simple statistical analysis to determine how often (based on their sales estimates) that their test strips will yield a catastrophic error.
- In the final session (15), students go back through all of the previous assignments to modify their design so that it is consistent throughout. For example, if they changed the amount of enzyme used when completing the mass transport analysis, they should change that amount in their previous assignments. If that causes a need for a new resistor or OpAmp, they should choose a new resistor or OpAmp.

In this study we seek to determine whether students are able to see the connection of courses in the BME curriculum to the design process and their utility in the design process. Hypothesis 1: Students who have taken BME282 are more likely to see the relevance of, be motivated to learn, and/or perceive usefulness of other courses in the BME curriculum. Related to this is Hypothesis 2: Students who have taken BME282 are better able to apply the principles of the design process in a biomedical context.

2. Methods

Students enrolled in BME282 (130 students in the semester studied) were asked to take a survey at the beginning of the semester asking them to rate (on a 5-point Likert scale) their interest in, motivation for, and relevance of several other courses in the BME curriculum. These other courses included BME200 (conservation of mass, energy, and momentum), BME235 (physiology), EEE202 (circuit design), and CHM231 (organic chemistry). These students were given an identical survey at the end of the semester in which they took BME282. We removed data from students who had taken the course about which we were asking questions. Also, only students who took both the pre- and post- surveys were included in the analysis. This left 23 students in our analysis pool.

Table 1. Course descriptions supplied to students when taking the surveys.

BME 200	Conservation Principles in Biomedical Engineering – Applies bioengineering analysis and problem solving of mass, energy, and charge balances to medical and biological systems.
BME 235	Physiology for Engineers – Physiology of the nervous, muscular, cardiovascular, endocrine, renal, and respiratory systems. Emphasizes use of quantitative methods in understanding physiological systems.
EEE 202	Circuits I – Principles for analyzing linear and nonlinear circuits. Uses SPICE and MATLAB. Design and measurement of linear analog electrical systems
CHM 231	Elementary Organic Chemistry – Surveys organic chemistry, with emphasis on the reactivity of basic functional groups. Organic chemistry experiments in synthesis, purification, analysis, and identification.

The question on relevance asked: “Please rate how relevant you think the knowledge you will gain in the following classes would be to a typical career in biomedical engineering.” The Likert scale included the headings: “No relevance”, “Low relevance”, “Moderate relevance”, “High relevance”, and “Essential relevance”. Students were supplied with catalog descriptions of the

courses because most students had not yet taken these courses and might not know what these courses were. These descriptions are shown in Table 1.

The question on motivation asked: “Please rate how motivated you are to learn the material that will be taught in the following courses.” The Likert scale included the headings: “Not at all motivated”, “Slightly motivated”, “Somewhat motivated”, “Moderately motivated”, and “Extremely motivated”.

The question on utility asked: “Please rate how useful you think the knowledge you learn in the following classes will be to your career after graduation from college.” The Likert scale included the headings: “Not useful”, “Slightly useful”, “Moderately useful”, “Very useful”, and “Essential”.

Survey results were analyzed by creating histograms of student responses pre- and post- for each course included in the survey as shown below in Figures 1, 2, and 3 for relevance, motivation, and utility respectively.

Faculty assessment of students’ ability to use engineering design to make a new virtual prototype was assessed upon entry in the subsequent required course in the BME “design spine, BME382, another course that teaches elements of the biomedical engineering design and development process. At the beginning of that junior level course, students were asked to make a virtual prototype of a method of detecting or otherwise characterizing MRSA (*Methicillin-resistant Staphylococcus aureus*) that could be performed rapidly and at the bedside. In 2014 (before students had taken BME282, 91 students were assessed), and in Fall 2015 (when students in BME382 had all taken BME282 prior to entering the course) 82 students were assessed. A single instructor taught these BME382 courses and did the assessment for these students.

Students were assessed for prototyping strategies on a 5-point scale by assessing each student’s work product for the inclusion of diagrams, flow chart, brainstorming process, and explanation of how the prototype would be constructed. The assessment awarded points as follows: (1 point) No diagram or chart, and inadequate description of prototype construction, (2 points) some kind of diagram or chart, but these and the description of prototype construction is not sufficiently detailed, (3 points) some kind of diagram or chart, and these plus the description describes the prototype construction in vague terms, (4 points) diagram and chart are present, but these and the description leave out important details for how to construct the prototype, (5 points) diagram, chart, and description are present and sufficiently detailed to adequately describe how the prototype will be constructed.

Students were also assessed for their application of the design process on a 5-point scale. Faculty assessors looked for effective development of (a) specifications, (b) explanation about the manufacturing process, (c) testing methods, (d) needs, (e) comparison to state-of-the-art, and (f) how the prototype would be validated or verified. The assessment awarded points as follows: (1 point) Less than 2 of the above components are present in a meaningful way, (2 points) 2-4 of the above components are present in a meaningful way, (3 points) 2-4 of the above components are present in a meaningful way and 2 are explained in adequate detail, (4 points) 3-4 of the above components are present in a meaningful way and 3 are explained in adequate detail, (5

points) at least 4 of the above components are present in a meaningful way and at least 4 are explained in adequate detail.

This assessment was initially performed for one set of students who had not taken BME282. The following year, a different cohort of students, ones who had taken BME282, were assessed in the same manner. Scores for each group were averaged and are shown in Figure 4. Statistical significance was determined by comparing the students who had not taken BME282 to the students who had taken BME282 for prototyping and design with a Mann-Whitney U-test, $p < 0.05$.

3. Results

Survey results asking students about their perception of the relevance of several courses to biomedical engineering, the student's motivation to learn the content from those courses, and how useful that course content would be to their careers are shown in Figures 1, 2, and 3 respectively. These show histograms of students' responses on the Likert scales (left to right, 1 to 5) from students who had not taken BME282 (white, outlined) and from students who had completed BME282 (black, filled).

Figure 1. Two cohorts of students were surveyed: ones who had not taken BME282 (white) and others who had completed BME282 (black). Cohorts were asked how relevant they thought 4 classes in the BME curriculum were to biomedical engineering. Plots show a histogram of Likert Scale responses (1-5, left to right): No relevance, low relevance, moderate relevance, high

relevance, essential relevance. These results are not statistically significant by Mann-Whitney U-test ($p>0.05$).

Students' responses regarding how relevant they believed courses in the BME curriculum to be to a biomedical engineering career (shown in Figure 1) shows little difference for BME200 (conservation principles) and CHM231 (organic chemistry), but possible increases in perceived relevance for BME235 (physiology) and EEE202 (circuit design). The difference for BME235 (physiology) is not statistically significant by Mann-Whitney U-test; however, the change in number of students answering "no relevance" or "low relevance" pre- vs. post- may be a real difference. Several students indicated that BME235 and EEE202 had "no relevance", "low relevance", or "moderate relevance" prior to taking BME282. After BME282, students perceiving BME235 to have low or moderate relevance had increased their perception to high relevance. Likewise, after taking BME282, all students perceived EEE202 to have at least some relevance, with the largest gains being in those perceiving EEE202 to have moderate relevance.

Figure 2. Students were surveyed who had not taken BME282 (white) and students who had completed BME282 (black) regarding their motivation to learn material from 4 classes in the BME curriculum. Plots show a histogram of Likert Scale responses (1-5, left to right): Not at all motivated, slightly motivated, somewhat motivated, moderately motivated, extremely motivated. These results are not statistically significant by Mann-Whitney U-test ($p>0.05$).

Student motivation to learn the material covered in these classes is shown in Figure 2. Although these differences are not statistically significant, trends in the data pre- vs. post- for BME200 and BME235 suggest that there may be increased motivation for those two courses. The largest

overall shift is for BME235 (physiology) again showing that students indicating that they were “not at all motivated” or “slightly motivated” prior to this sophomore design experience, mostly increased their motivation for BME235 to at least “somewhat motivated”. For BME200 (conservation principles) there was a marked shift from students expressing some motivation to moderate motivation to learn conservation principles. Several students shifted from no motivation or slight motivation to learn physiology, circuits, and organic chemistry to greater motivation for these courses. In particular for organic chemistry, there were no students expressing no motivation for CHM231 after taking BME282.

Student perception of the usefulness of all four of these courses (shown in Figure 3) increased to some extent. BME200 (conservation principles) was the course for which the greatest increase was observed – from many students perceiving only slight usefulness or moderate usefulness to almost all students perceiving that BME200 is very useful or even essential. The result for BME200, achieved a p -value of approximately 0.15 which is nearly significant. The number of students perceiving physiology (BME235) to be very useful increased. And it appears that most of the students who entered BME282 perceiving organic chemistry (CHM231) to be only slightly useful changed their perception to moderately useful by the end of BME282. Only subtle increases in the perceived usefulness of EEE202 were observed.

Figure 3. Students were surveyed who had not taken BME282 (white) and students who had completed BME282 (black) regarding the usefulness of 4 classes in the BME curriculum to the students’ careers. Plots show a histogram of Likert Scale responses (1-5, left to right): Not useful, slightly useful, moderately useful, very useful, essential. * $p \sim 0.15$ by Mann-Whitney U-test (not significant by $p < 0.05$ criterion).

Finally, we assessed the students' ability to design a virtual prototype to a new problem upon entry into the junior-level class that follows BME282. As described above in *Methods*, students were given a challenge to make a virtual prototype of a method of detecting or otherwise characterizing MRSA (Methicillin-resistant *Staphylococcus aureus*) that could be performed rapidly and at the bedside. The faculty instructor for that course assessed each student's virtual prototype for elements of application of the design process and the level of detail in which the virtual prototype was described. Results are shown in Figure 4.

Figure 4. Ability of students to think of innovative concepts, design solutions to engineering problems and make prototypes based on those designs of students who had not taken BME282 (white) and students who had taken BME282 (black). Design improves from 1.86 to 2.33 (out of 5), which is statistically significant by a Mann-Whitney U-test with $p < 0.05$.

Students who had taken BME282 (red) were, on average, 0.47 points higher on the rubric for application of elements of the design process. In terms of the design rubric, this indicates that the median student who had not taken BME282 describes 2-4 of the elements of the design process (specifications, manufacturing process, testing methods, customer needs, comparison to state-of-the-art, and method for verification/validation) in a meaningful way. Whereas, the median student who had taken BME282 not only described 2-4 of the elements of the design process in a meaningful way but explained 2 of those elements in sufficient detail. Obviously we would hope that a sophomore-level course on design would result in better ability to design. And this result confirms that BME282 does substantially increase students' attainment of ability to apply elements of the design process to their designs in a biomedical context.

4. Discussion

The sophomore-level design experience offered in BME282 is intended to accomplish two objectives. First, we aim to help students understand why they will be taking the technical classes required in the BME curriculum. In doing that, we hope to increase their motivation for mastering the content in those courses and to increase the students' attention while in those courses to how that material might apply to biomedical design. To determine whether we had achieved that objective, we sought to test *Hypothesis 1: Students who have taken BME282 are*

more likely to see the relevance of, be motivated to learn, and/or perceive usefulness of other courses in the BME curriculum.

As can be seen in Figures 1, 2, and 3 above, there were generally gains in all three categories of perceived relevance, motivation, and usefulness. There were possible gains in the students' motivation to learn and perceived usefulness of BME200 (conservation principles), BME235 (physiology), and CHM231 (organic chemistry). In particular, the increase in perceived usefulness of BME200 was nearly statistically significant, indicating a strong likelihood that BME282 achieved this much effect. Although students did not say that they were substantially more motivated to learn or perceive the usefulness of EEE202 (circuit design), they did substantially increase in their perception of the relevance of EEE202 to a biomedical engineering career. After taking BME282, there were no students who said that they were not at all motivated to learn BME200 or CHM231, but there were still a few students who said that they were not at all motivated to learn BME235 (physiology) and EEE202 (circuit design). Based on further anecdotal evidence, we believe that this indicates that, when students buy into the design experience, they do increase in these metrics; however, some students do not buy in and do as little work as they can to achieve a reasonable grade in the course. Future work aims to understand how to best motivate the latter students to participate meaningfully in this design experience so that they achieve this objective of the course.

Although students in BME282 have not yet taken these courses and have only a brief description in the course catalog, one of the aims of this sophomore-level course is to increase students' appreciation of why these courses are part of a BME curriculum. Figures 1, 2, and 3 indicate that BME282 may have achieved this goal (the results were not statistically significant, but in several cases the number of students rating 1s and 2s were lower after completing BME282).

The second objective that this sophomore-level design experience is intended to accomplish is to teach students how to apply the technical skills and knowledge gained in other classes to the biomedical design process to create an alpha prototype that is sufficiently detailed to allow someone to actually build a physical prototype. This is tested in *Hypothesis 2: Students who have taken BME282 are better able to apply the principles of the design process in a biomedical context.*

These data indicate that students who had taken BME282 were more capable of applying the steps of the design process to creation of a virtual prototype that could perform a rapid, bedside detection of MRSA. Likewise, students who had taken BME282 created virtual prototypes with more detail to allow progress to a physical prototype. However, the difference in these metrics indicates that students without BME282 were mostly poor in these metrics; whereas, students who had taken BME282, while better were still at best fair at applying steps of the design process and detailing their virtual prototypes. Anecdotal evidence suggests that the problem is in the lack of detail with which students describe their design process and their virtual prototype. This may result from students not being aware that their descriptions are not detailed, which seems to come as a surprise to students. Instructors and TAs, when asked about this issue, often say that they believe the root cause is students having little to no exposure to actually performing the physical tasks that they are trying to describe. For example, when describing how the enzyme will be chemically conjugated to the electrode, students' descriptions are usually very vague, and

this seems to stem from students having very little practical chemistry lab experience prior to the sophomore year of college. Similar issues were seen in asking students to pick real components (resistor, OpAmp) for their circuit in making the current-to-voltage circuit. Most students had never made a real circuit before, even though almost all students had taken physics lab classes in high school and/or college prior to taking BME282. This is leading our program to reevaluate what hands-on skills and techniques our students are exposed to in their freshman science labs or high school science classes prior to entering BME282 where we see these issues. Our hypothesis is that many of these experiences have been cut due to budget cuts to high schools or limited resources at the college level.

5. Conclusions

This sophomore-level design experience in the BME curriculum may increase student perception of the relevance of and usefulness of other classes in the BME curriculum to biomedical design. It also may increase the students' motivation to learn the material taught in those classes. Students who complete this sophomore-level design experience were better able to apply the steps of the design process to a biomedical design, and their virtual prototypes were more complete and described in greater depth than students who had not completed this sophomore-level design experience. Future work aims to understand why some students are unenthusiastic about participating in these design experiences, in fact, some actively seek to avoid participating at all; and then we aim to use that understanding to address underlying student concerns and to increase the level of participation of those students. We also hope to address issues related to the students' limited exposure to physical manipulation of chemistry, circuits, etc, which may underlie their inability to recognize the insufficient detail that they put into their virtual prototypes.

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