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Work in Progress: Implementing Elements of Engineering Design into Calculus

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California State University System Chancellor's Office Center for Closing the Opportunity Gap Webinar series: Preservice Teacher Candidate Epistemic Agency: Acquiring the Professional Skills of Becoming a Science Teacher" on March 3, 2021. The webinar discussed the interconnected learning experiences that occur in three courses in a credential program. Within these courses are learning experiences grounded in a particular theory of learning teaching and epistemic agency for candidates. We offer a sincere thank you to our presenter: Dr. Antoinette Linton (CSU Fullerton)

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Abstract

To contextualize calculus, first-year engineering students take on a semester-long design project that grounds engineering design as an epistemic practice. The project is designed to motivate students to creatively and collaboratively apply mathematical modeling to design roller coasters. Students are asked to engage as engineers and respond to a hypothetical theme park that has solicited design proposals for a new roller coaster. Students are required to use various mathematical functions such as polynomials and exponentials to create a piecewise function that models the roller coaster track geometry. The entire project is composed of five modules, each lasting three weeks. Each module is associated with a specific calculus topic and is integrated into the design process in the form of a design constraint or performance metric. The five module topics include continuity, smoothness, local maxima and minima, inflection points, and area under the curve. Students are expected to refine their models in each module, resulting in the previous design's iteration to satisfy a new set of requirements. This paper presents the project organization, assessment methods, and student feedback. This work is part of a multiple-year course intervention and professional development NSF project to increase the success of underrepresented and women students in engineering.

Introduction

The attrition rates among STEM (Science, Technology, Engineering, and Mathematics) disciplines are among the highest of any academic discipline [1, 2]. An analysis of lower-division and upper-division courses taken by Engineering and Computer Science (ECS) students at California State University, Fullerton (CSUF) demonstrates an achievement gap between students. The achievement gap begins in the lower-division math and physics courses, which are prerequisites for engineering courses. Figure 1 below presents a box and whiskers plot of the repetition rate between Fall-2014 to Fall-2016 for six lower-division courses. An "×" indicates the three-year average. Calculus I and Calculus II yielded the highest values with average repetition rates of 36% and 45%, respectively. Repetition of these courses will delay students' graduation and potentially discourage first-year students from pursuing STEM careers.

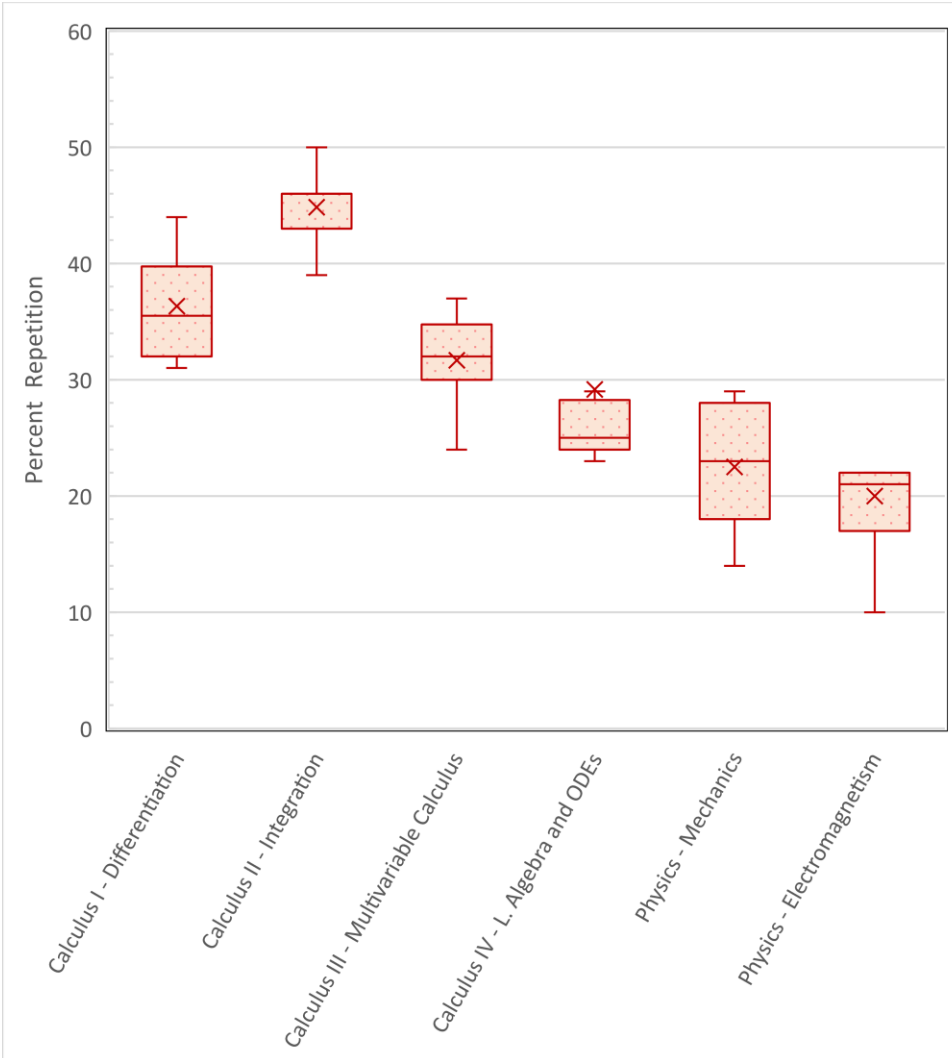

Figure 1 Percentage of students repeating lower-division Math and Physics Courses

For students who pass their lower-division courses and continue pursuing a STEM field, this does not often translate into success in math-intensive engineering courses. Figure 2 shows the percent repetition rate for various lower and upper-division ECS courses. Many courses across ECS consist of repetition rates above 20%. This alludes to students not retaining the material learned in their previous pre-requisite courses, and consequently, students continue to repeat courses and extend their graduation date as reflected in the graduation trends in 4, 5, 6-year graduation rates, shown in Figure 3. Although the 4-year graduation rate has consistently stayed at 5% since 2009, both the 5-year and 6-year graduation rates have steadily increased.

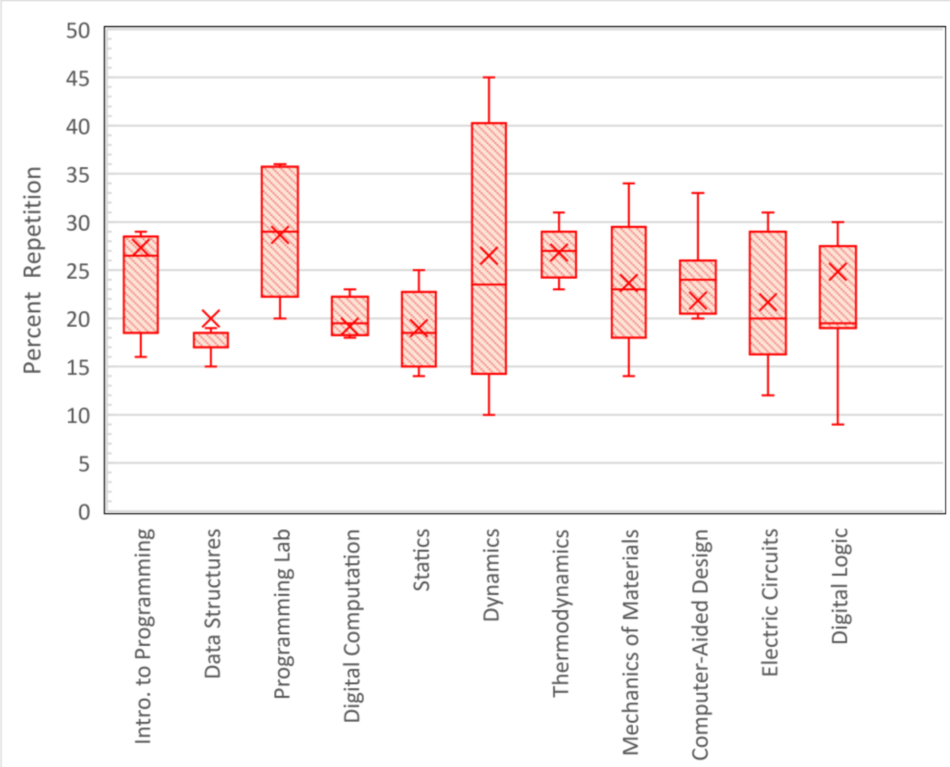

Figure 2 Percent repetition rate for division lower and upper division ECS courses

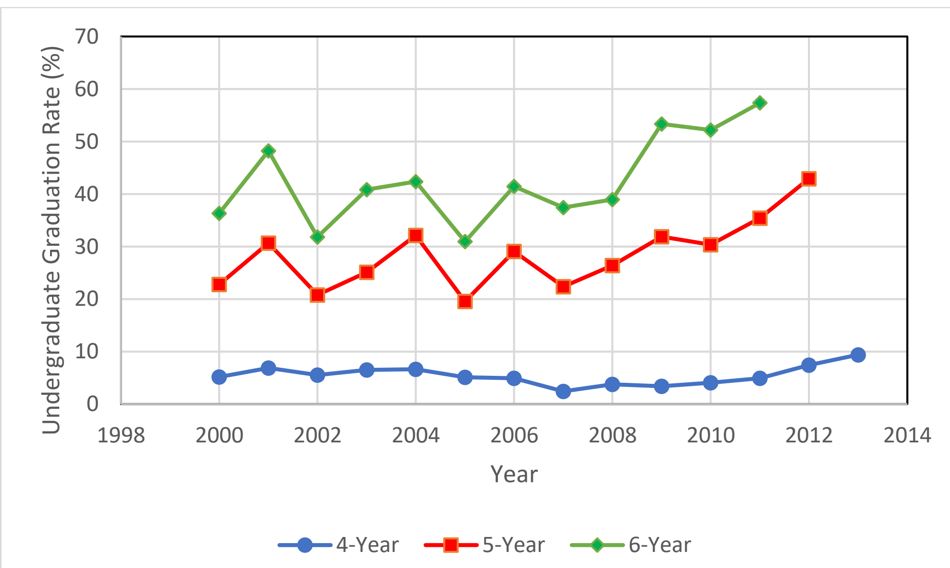

Figure 3 ECS 4-, 5-, and 6-year undergraduate graduation rates

In response, the ECS faculty at CSUF has implemented academic course intervention strategies for first- and second-year ECS students. This paper presents an academic intervention that incorporates project-based learning and engineering design in a first-year calculus course, Calculus I - Differentiation.

Course Background

Calculus I - Differentiation is the first calculus course that ECS students take. The course covers the topics of limits, derivatives, applications and introduces definite integrals. As previously shown in Figure 1, the three-year average repetition rate for this course is 36%. In response to this repetition rate, engineering design as an epistemic practice was introduced. Epistemic practices are vital to student success when learning discipline-specific skills and knowledge [3-5]. Epistemic practices are systems of processes for generating and evaluating knowledge used to develop epistemological understandings. In this case, an engineering design framework serves as an epistemic practice to better understand calculus concepts [4]. The ability to generate, evaluate calculus knowledge and then plan an approach to use engineering to solve calculus problems are two major categories of developing epistemic understanding.

To engage students in engineering design as they learned calculus, calculus students participate in a semester-long engineering project. The project consists of five three-week modules. Students were encouraged to use calculus in their design solutions and refine their initial models as they learn the topics in the course, culminating in a final design and engineering notebook. As an epistemic practice, engineering design was front-loaded early within the course and then used throughout the semester. By using the practice repeatedly, students begin to develop the epistemic elements of engineers- design skills, problem formulation, knowledge, and epistemology.

Problems Solving and Epistemic Practices

The authors argue that problem-solving works most effectively in tandem with a coherent epistemic practice approach such as Model-Based Science Teaching (MBST). In MBST, if the learner has not been taught a process for identifying a problem and constructing a model-based solution for the problem, the ability to strategize approaches to problem-solving and predict outcomes will be underdeveloped, as they will lack particular habits of mind of noticing patterns or a set of relationships between problems and their solutions. Linton provides a concise overview of the epistemic approach based on focused inquiry, directed observation, and guided practice for science learning [6].

Focused inquiry is an investigation into a set of skills or processes needed to engage in science and engineering. The purpose of focused inquiry is to generate student questions about the components of the processes, what types of problems are solved using the processes, the context for which the processes are enacted, and how to know when to start and end the processes. Linton explained, "during focused inquiry students are encouraged to use their background knowledge and experiences with science in everyday situations to make sense of the processes" [6]. Once students are familiar with the science and engineering processes and tools they move on to direct observation. Here, students are given the opportunity to observe a more experienced other use the tools in a particular context while explicitly drawing attention to the steps of the process. Directed observation is important because it links processes to problem solving. Students are allowed to use, critique and suggest different ways to engage in the processes as problems change without having to negotiate learning to do the processes at the same time.

Lastly, students are given the opportunity to practice the skill while solving simplistic problems first during guided practice. Guided practice is a more involved enactment of a skill under the close supervision of an experienced teacher [3].

The development of the ability to generate, test, build and evaluate knowledge, that is, an epistemic-based approach, is an essential and aligned process of habit of mind development. In Costa and Kallick framework [7], specifically, to promote strategic reasoning students need the skills of questioning and problem posing, the ability to apply past knowledge to new situations, and thinking interdependently. Individuals who have developed a habit of mind for a particular disciplinary area are able to notice patterns, are sensitive to contextual cues in a situation and can make choices on how to use information in creative and innovative ways.

Scholars have argued that problem generating and solving are core skills for developing the habits of mind of scientists and engineers [8-10]. More specifically, Jonasen, et. al., argues that introducing students to authentic work-like problems better prepares them for the type of thinking and innovation needed for future technological and societal changes [8]. It enables the habits of mind to develop in conjunction with purposeful skill development through the use of epistemic practices, a condition that is made explicit in this project. Linking problem solving to epistemic practices is necessary for habits of mind to develop in the context of engineering [11]. Thus, we share the view that in order to facilitate the development of future engineers, problem solving and epistemic practices need to be linked together in order to develop creative and innovative habits of mind to compete technologically and socially on a global scale.

Design Project Formulation

To incorporate engineering design elements into Calculus I, a semester-long design project was incorporated into the course. The project centers around the design of a rollercoaster. This project facilitates the design by engaging in a type of structured dialogue-integrating pedagogical and sociocultural aspects of learning with the mathematical/engineering aspects of the course. It requires teams of students (up to three) to apply calculus and engineering design of a roller coaster. Each team must completely define the path (track) of the roller coaster using a set of piecewise functions that are differentiable at all points. Each team is required to document the design process, calculations, and figures in a Design Notebook.

The project is divided into five modules. Each module supplements the topics that are being taught and lasts three weeks. A consistent outcome of each module is a design of a roller coaster track. However, the set of requirements that the design must satisfy increases to reflect the calculus topics that are currently being taught. The list below describes the focus of each module:

1. *Piecewise functions and continuity* – Students must design a continuous rollercoaster track using a set of five piecewise functions.
2. *Derivatives and smoothness* – Students must design a continuous rollercoaster track using a set of five piecewise functions and ensure that the track is smooth at all points.
3. *Continuity and smoothness revisited* – Students revisit the first two modules but instead focus on formulating an engineering approach to obtain a rollercoaster design. Students

are shown how to set up the continuity and smoothness requirements as equations with a set of unknown coefficients such as

$$f_1(x_1) = f_2(x_1) \;\rightarrow\; a_0 + a_1 x_1 + a_2 x_1^2 = b_0 + b_1 x_1 \qquad (1)$$

where a_0, a_1, a_2, b_0, and b_1 are the unknown coefficients. In this fashion, students do not use a guess and check approach.

4. *Evaluating the thrill of a drop* – Students revisit their design and make modifications to maximize the *Total Thrill Score* and verify that their design meets safety requirements (based on the peak slope).
5. *Total cost of the rollercoaster* – Students use the concept of area under the curve to estimate the cost of manufacturing the rollercoaster. It is assumed that the area is directly proportional to the cost of the roller coaster.

Through this format, students will naturally follow a basic engineering design approach by defining their problem, formulating a solution, verifying their solution, and iterating as needed. The flowchart below in Figure 4 illustrates the project timeline:

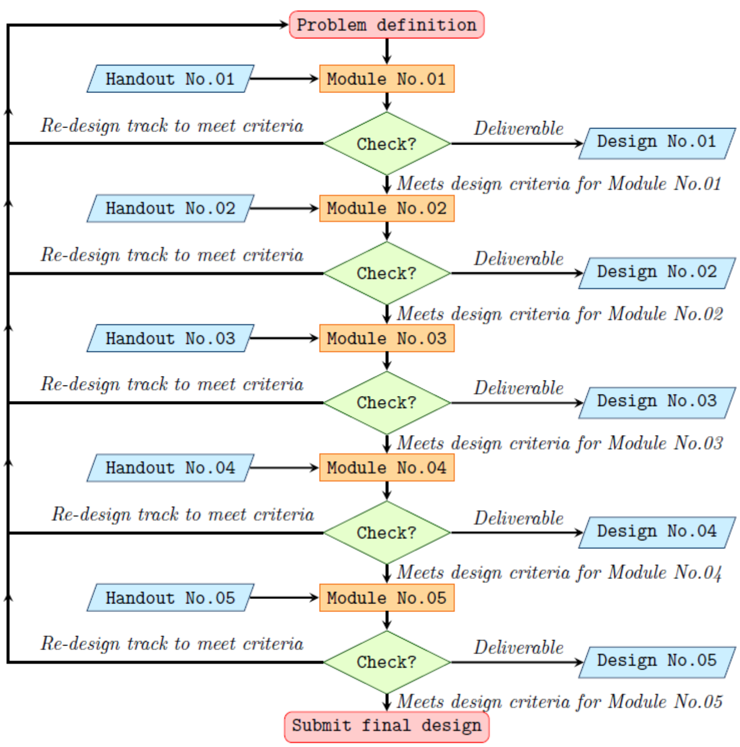

Figure 4 Flow chart of project timeline

Research question

Through this effort, the academic intervention strategy aims to improve the student's success rate in lower-division courses for ECS students. This work focuses on answering the central research question: *Does integrating contextual-based learning targeted explicitly towards bottleneck Math courses improve success for ECS students?*

Project Description

Below is the project description that the students are prompted with:

A local Southern California theme park has recently released a solicitation for the design of a new rollercoaster. In their solicitation, the theme park has requested that all rollercoaster designs meet the following criteria:

- The rollercoaster must contain at least five drops.
- The rollercoaster track cannot exceed a height of 250 feet above the ground or go below the ground.
- The total horizontal length of the rollercoaster must be less than 1,000 feet.
- The rollercoaster must start and end with a zero-degree incline (*horizontal*).
- No ascent or descent can be steeper than 80 degrees with the horizontal (*safety purposes*).
- The cart velocity is zero at the highest point.
- The cost of the roller coaster must be less than $1,000,000.

The performance of each design is evaluated by summing up the *Thrill Score* of each drop [12]. The Thrill Score is evaluated as the product between the steepest angle of descent $\theta_{\max}$ (in radians) and the vertical distance of the drop Δy.

$$Thrill\ Score = \theta_{\max} \times \Delta y \tag{2}$$

Therefore, the *Total Thrill Score* of the roller coaster is given by summing up all of the *Thrill Scores*.

$$Total\ Thrill\ Score = \sum_{n=1}^{N} (Thrill\ Score)_n \tag{3}$$

where N is the total number of drops.

Methodology

To evaluate the effectiveness of the intervention for facilitating mathematics course performance, comparisons were made between the final grades of the intervention course versus non-participants. Analysis focuses on the fall semester participants, as there was not a Calculus I course offered in the spring. Students in the intervention course were assigned the roller coaster project for their learning of calculus. On the other hand, students in the control group experienced the conventional instructional strategy.

This study used three phases for both groups (Intervention and Control), namely: 1) Course opener; 2) Learning Session; and 3) Assessment using a set of Calculus Test problems as post-test. At the phase one the intervention group were given an introductory module that provided a description of the project and how to maintain their engineering notebooks. The control group, on the other hand, underwent normal class proceedings. During the learning process, phase 2, the intervention group was presented with a midterm survey to measure student perspective in identifying the possible impact on learning. During the time when the intervention group underwent the post-test (at Phase 3), the control group was administered the same test. The data will be analyzed using independent t-tests.

Current Status and Preliminary Results

During the 2019-2020 academic year, the course intervention modules underwent a trial run. The trail run intended to develop of the logistics and content associated with implementing the modules on a course website that utilizes the Canvas platform. The course intervention modules are currently implemented in a section of Calculus I. Based on the mid-term process, more than half of the students (56%) felt they were properly prepared for the course and (20%) felt that they could earn an A or B. More students also felt confident that they could conduct an engineering design project (36%). Many of the students (68%) indicated they liked traditional assignments like lectures, quizzes, and homework embedded in the course. Only a small number of students (8%) indicated the intervention was helpful towards learning calculus. This indicates that many students prefer the traditional way of learning calculus and feel confident that they are prepared to engage in these activities.

Benefits of this approach perceived by the students included observing the professor work out examples that they could follow, practicing solving calculus problems for homework, and working together in small groups to complete tasks. Students also indicated that the pace of the course (professor lecture, note-taking, and time given to study) was too fast. Almost half the students (48%) stated that they needed the instructor to slow down and provide more time between introducing the topic and being assessed.

Conclusion

This work presents the initial stages of a course intervention strategy that integrates a semester-long design into Calculus I. The project centers around the design of a roller coaster and its relevance to calculus. The project is divided into five modules designed to supplement the lecture topics: continuity, derivatives, smoothness, etc. Students are expected to iterate with every module on designing a roller coaster track by formulating solutions that satisfy an increasing list of design requirements. In this fashion, students can practice the engineering design process. Preliminary results from the initial set of midterm surveys, most students preferred the traditional forms of learning and assessment. As a result, the method of implementation of the course intervention modules is currently being re-evaluated.

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