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Work in Progress: Engineering Analysis Laboratory Courses Complement First-Year Physics and Calculus

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Abstract

In this Work in Progress paper, we describe two, two-credit engineering courses taken by all first-year engineering majors at our university. First-year engineering students in most universities and colleges take several courses in physics and calculus offered by physics and mathematics departments. These courses typically serve a wide range of majors and hence there is limited opportunity to draw connections between the material to engineering applications. This limited connection is one of the factors attributable to students feeling a disconnect between the foundational physics and mathematics courses they take and the engineering topics that drew them to the major in the first place. This disconnect has been identified as a contributing factor to the relatively large attrition of students out of engineering majors and disproportionately impacts students from minoritized groups. The courses described in this paper are explicitly designed to help students connect the physics and calculus courses they take in the first year to engineering applications, in addition to reinforcing physics and calculus concepts. These courses are taken in consecutive semesters in the students' first-year, the first of which substitutes for the companion laboratory course to the Physics I course offered by the physics department. These courses take a design-and-build approach (as opposed to an experiment-and-measure approach) to topics such as kinematics and applications of integration such as in solving problems like in finding the center of mass of objects. Students gave very high ratings to the course overall in student evaluations, and cite the connections between mathematics and physics with engineering applications as one of the course's strengths. Further, we believe that these courses are factors, among others, that contribute to the low attrition rate from our engineering program.

Introduction

Most engineering programs in North America require students to take calculus and physics courses, offered by mathematics and physics departments, early in their programs. The physics courses usually have laboratory components that are either structured as separate, complementary courses or are directly integrated into the physics courses. While the mathematics and science courses can provide a foundation for students' engineering courses and practice in later semesters and years, it has been observed that it is challenging for students to connect the material learnt in mathematics and science courses with engineering courses and practice in works such as Froyd and Ohland (2005) and Pomalaza-Ráez and Groff (2003). Froyd and Ohland (2005) describe student comments about the abstract nature of the mathematics they learn and the challenges they have with connecting it to physically relevant situations. They further describe comments from faculty members which support the need for drawing connections between the mathematics and physics content to engineering courses and state that "... students need to make better connections among and within mathematics, science, and engineering to perceive mutual relevance and apply concepts and ideas from one subject area to tasks in another" Froyd and Ohland (2005). A more recent study by Hatfield et al. (2022) also shows how these introductory Science Technology, Engineering and Mathematics (STEM) courses are disproportionately a reason for minoritized students to leave STEM altogether. To address the need to better integrate mathematics and science courses with engineering applications, a number of institutions have introduced integrated engineering curricula such as the programs described in Froyd and Ohland (2005), Govindasamy et al. (2018) and others.

In this paper, we describe two, two-credit courses that engineering students at Boston College are required to take in each semester of their first year. These courses are intended to complement physics and calculus courses offered by the physics and mathematics departments at our university to help students connect their learning in these courses to engineering applications, to help develop students' modeling and analysis skills, as well as to help reinforce student learning of topics from Physics I, Calculus I and Calculus II. For background, Boston College is a medium-sized private, Jesuit, liberal arts university with a new general engineering program that has been offered since Fall 2021. The program is housed in a department of engineering which is situated in the college of arts and sciences at the university. Unlike most other majors at the university, students interested in engineering apply for the engineering program specifically.

Course descriptions

Physical Modeling and Analysis Laboratory (Semester 1)

In their first semester, engineering students are required to take a two-credit Physical Modeling and Analysis Laboratory (PMAL) course in addition to Physics I, Calculus I and other core requirements. The students in this course do not enroll in the one-credit laboratory course associated with Physics I that most other students in Physics I at our university take. In part, this course is intended to replace the associated laboratory course taken in Physics I.

In this course, students learn how to model, analyze, implement and experiment on physical systems. Students completing this course are expected to be able to: 1) Model, predict and measure the behavior of physical systems with linear and rotational motion, 2) Use first-order differential equations to model and experimentally validate thermal conduction in one dimension, 3) Analyze and measure the response of resistor-capacitor (RC) circuits, 4) Apply basic physical properties such as conservation in different physical systems, 5) Quantify the effects of measurement errors and noise in simple physical systems, and 6) Communicate their experimental findings effectively.

Emphasis is placed on modeling and analysis in this course, through physical examples that students work through theoretically and a significant experimental/applied component. In addition to modeling and analysis, students in this class reinforce concepts from linear and rotational dynamics, thermal conduction, and differential calculus learned in Physics I and Calculus I. Additionally, students learn about resistor-capacitor circuits, and solving first-order differential equations. The latter is learned in the context of thermal conduction as well as RC circuits, building off material learned in Calculus I.

Course Structure and Description

Students meet twice a week, for a one-hour session early in the week, and a two-hour session midweek. Students complete three homework assignments and four laboratory assignments in this class. Class time is spent primarily working on the laboratory assignments, with a small number of lecture sessions throughout the semester where new concepts are introduced, or concepts from physics and calculus are reinforced. Laboratory assignments were done in pairs, with pairs assigned randomly but with no pairs repeated from previous exercises.

Modeling and Analysis

Early in the course, the students conduct several modeling exercises, starting with thought experiments which are then increased in complexity to apply to real-world systems. For instance, students conduct an exercise called “The Lost Ant” on how an ant can locate itself on a 2-dimensional surface if it knows its distances from three anchor points. Students are then tasked with connecting the exercise with a real-world system that many of them have used, namely the Global Positioning System (GPS). This exercise also helps reinforce the idea of modeling errors (e.g. whether relativistic effects should be considered in GPS systems), which were introduced in earlier exercises in the course. Further, by completing these exercises, students get practice in using intuition gained from lower-dimensional modeling to higher dimension systems. The modeling process we used is illustrated in **Figure 1**, adapted from Downey (2017).

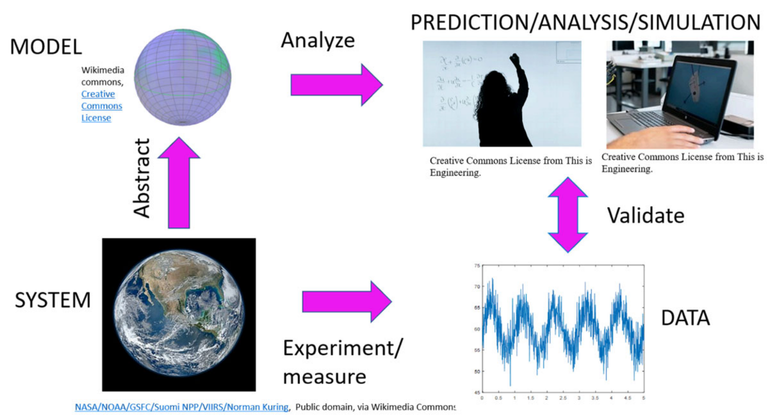

Figure 1: Modeling Physical Systems

Linear Motion Laboratory

The first laboratory assignment in the class is on linear motion. The first part of the assignment is individual, with the second, longer part done in pairs. Students also complete two problem sets which reinforce kinematics concepts from Physics I prior to starting this assignment. This laboratory exercise is motivated by creating a step counter, which many students have experience with. Students are also exposed to sensor measurements and noise in this exercise. This assignment was inspired in part by an early assignment described in Govindasamy et al. (2018). We utilize the MATLAB Mobile application to stream accelerometer data from students’ smartphones to the MATLAB software on their computers for processing. The instructors provided sample data for students unable or unwilling to conduct the experiments. Note that the students were first introduced at a high-level to the accelerometers on their devices and conducted simple experiments to get themselves acquainted with the sensors and interface with MATLAB. Students then conduct simple modeling and analysis exercises using accelerometer data collected from a free-falling smartphone and a smartphone held to the chest of a student making a standing jump (inspired in part by Linthorne (2001)). At this point, students have learned about objects in free fall in Physics. These experiments are helpful in reinforcing this concept. E. g. students are tasked to explain different portions of the graphs of the acceleration for both the phone drop and standing jump experiments. As an example, **Figure 2** shows the one accelerometer reading from the standing jump experiment from an instructor. Students were asked to explain each portion of the graph (e.g. which portions of the graph were when the subject's feet were off the ground), and to estimate how high the jump was by analyzing the data.

This exercise continues with students combining concepts they learned in physics (kinematic equations), and calculus, utilizing concepts such as Riemann sums which can be used to convert accelerometer measurements to estimated velocity and local maxima/minima which can be used to count steps from the accelerometer data. Students are then tasked with modeling what happens when someone holding a phone walks, and the expected graphs of the acceleration as measured on different axes. Working with their laboratory partner, students then developed MATLAB code to count the number of steps taken based on accelerometer data (e.g. see **Figure 2**) that they measured or was provided by the instructor. Note that several student groups decided to extend their work to make their systems robust, and measure other parameters such as distance traveled.

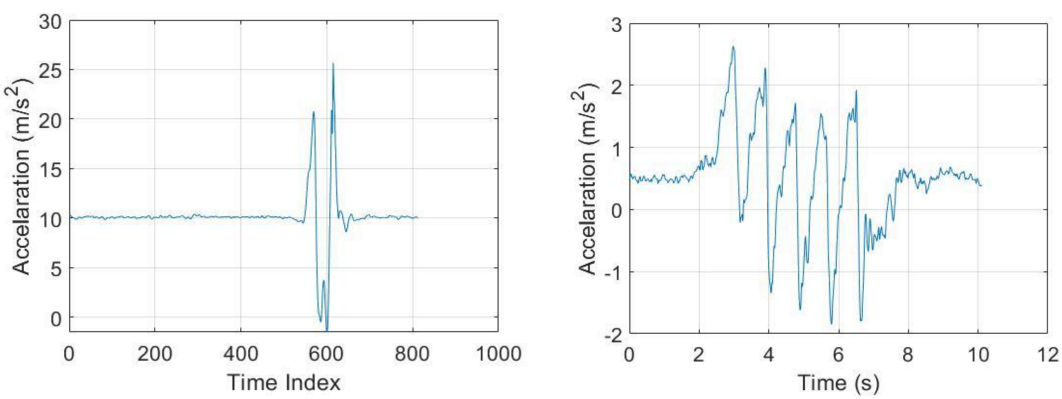

Figure 2: (Left) Acceleration for standing jump. (Right) Acceleration for step count

Thermal Conduction Laboratory

The second laboratory exercise in this class is based on one dimensional thermal conduction, inspired by a module described in Govindasamy et al. (2018). This assignment is intended to reinforce students' understanding and application of concepts in calculus such as manipulating functions, and derivatives. Students are also introduced to solving first order, linear constant coefficient differential equations (LCCDE) through lectures, in class problems and a problem set. While differential equations are typically not introduced to engineering students in the first year, the extent to which they are useful in engineering and how effective they are at reinforcing concepts from calculus were reasons that this topic was here. Additional topics useful in engineering applications such as step functions, time-constants, initial conditions and steady-state values are also reinforced in this assignment.

In this exercise, students electrically heat a sheet of polycarbonate and measure the temperature on either side of the sheet. This exercise is motivated by a low-cost, polycarbonate heated bassinet (Goodier (2018)). Students use the Analog Discovery 2 module to record the signal from an analog temperature sensor. Students conducted a theoretical analysis to predict the form of the equation for the temperature on either side of the polycarbonate as a function of time when a voltage is applied to the heating element. They then used a curve-fitting tool in MATLAB to fit their data to the equation from their theoretical analysis. The students then find that their first order model, while accurate in predicting the behavior of their system over longer time scales, was less accurate soon after the power was turned on. Through a set of guided exercises, students developed a more accurate second order model as a cascade of two first order models.

Rotational Motion Laboratory

The third laboratory exercise in the class involves rotational motion. Students perform a set of experiments to determine the trajectory of objects such as spheres, and hollow and filled cylinders rolling down ramps. The measured trajectories are then compared to predictions from theoretical analysis utilizing Newton's laws, free body diagrams and rotational inertia which are introduced in the Physics I course that the students take concurrently. These exercises are quite commonly included as part of Physics I courses, and to a large extent our assignment is similar to the exercises described in works such as Bankhead (2013). One difference is that we utilize low-cost ultrasonic range finders to measure the motion of the objects and use MATLAB to fit the data to their theoretical predictions. Students collect the ultrasonic range finder data using the Analog Discovery 2 module and process it in MATLAB. Students are tasked to quantify the error between their theoretical predictions and experiments and explain any discrepancies that arise.

Circuits Laboratory

In the final laboratory assignment, students reinforce their understanding of calculus and first-order LCCDEs by designing and implementing an RC filter. Through a set of mini-lectures, students learn about voltage, current, resistance and capacitance and how to analyze simple RC circuits using first-order differential equations. Concepts such as step functions, time constants and steady state values are also reinforced in this assignment. Students then conduct experiments measuring the step and frequency responses of their RC filters. Students are encouraged to discuss how the response of the electrical circuit to a step input is similar to the temperature of a heating element in response to a step input of voltage, but on vastly different timescales.

Engineering Analysis Laboratory (Semester 2)

In their second semester, engineering students are required to take a two-credit Engineering Analysis Laboratory course. This course is taken after completion of PMAL, Calculus I, and Physics I. The course content is meant to reinforce concepts from those three courses, and complement topics (e.g., integration) that students are learning in Calculus II, which is a co-requisite. In this course, students apply integral calculus and scientific principles to develop analytical solutions to engineering problems. They learn how to devise experiments, collect and analyze data, and conduct basic error analysis. The course comprises experimental modules to get hands-on experience with instruments such as power supplies, sensors, electromechanical components, and data acquisition systems. Following this course, students are equipped to apply quantitative analytical techniques to a variety of practical engineering problems. After successful completion of this course, we expect students will be able to 1) Construct basic RC circuits with amplifiers, 2) Apply simple filters to process signals, 3) Use fundamental engineering instruments including computer-based data acquisition (DAQ) systems, 4) Analyze data and conduct basic error analysis, 5) Use integral calculus to develop analytical solutions for engineering design, 6) Apply physical concepts (forces, torques, moments) to engineering design, and 7) Communicate experimental findings effectively through technical lab reports

This is a two-credit course, with one credit covering engineering topics (introductory RC circuits, op-amps, signal processing and filtering, and computer aided design), and 1 credit covering math/science topics (forces, torques, moments, center of mass and buoyancy, and single and multivariable calculus for area and volume calculations).

Course Structure and Description

Students meet twice a week, for a one-hour session, and a two-hour session. Students complete six homework assignments and four laboratory assignments in this class. The one-hour session is a combination of lecture or laboratory assignments where concepts or lab techniques are introduced to the students. The two-hour sessions are primarily utilized for laboratory assignments. Laboratory assignments are completed in teams of two or three depending on the lab module, with teams allotted randomly such that no repeat groups were assigned.

The course is structured as two modules. Each module is designed such that we start with a real-world product - for Module 1 the product is wearable devices/sensors and for Module 2 the product is a boat. From there, we break these products into some of their key engineering components, and assign laboratory exercises to introduce and reinforce these topics. For Module 1, this includes electrical engineering concepts such as RC circuits, operational amplifiers, signal processing and filtering, and experimental data analysis. For Module 2, this consists of forces, torques, moments, center of mass and center of buoyancy calculations, and single/multivariable calculus. From there, the students then build a functioning prototype for each module: an electrocardiogram (ECG) circuit for Module 1 and a boat hull for Module 2.

Module 1: ECG System

The first half of this module is three weeks, and consists of breaking down wearable sensor systems into their key engineering components. During the 1-hour sessions, we conduct interactive lectures to introduce key concepts of (1) RC circuits, (2) operational amplifiers for signal amplification, and (3) signal processing and filtering, including low-, high-, and band-pass filtering. The 2-hour sessions include laboratory exercises where students build circuits using the aforementioned components, and characterize their behavior with inputs from a signal generator (Analog Discovery 2 with Waveforms Software). Upon completion of these exercises, students compose a laboratory report that includes their calculations, results, and key observations.

The second half of this module is also three weeks, and consists of taking the concepts learned above and applying them to the design and construction of their own ECG circuit. Building the circuit requires the students to choose resistors and capacitors to meet specific requirements for signal amplification and filtering. Once the circuit is built, students attach electrodes to themselves to collect ECG signals. The students then perform a variety of tasks (e.g. collect data at rest, after walking, after moving up and down the stairs) so as to collect data under different physiological conditions. The final aspect of this exercise is to utilize Matlab to develop code that will calculate heart rate from the signal data. Students compose a second laboratory report for this aspect of the module to assess their understanding of the concepts.

Module 2: Designing the Hull of a Boat

This project was inspired by a course module described in Dusek et al. 2018. The first half of this module is four weeks, and consists of breaking down boat design into some key physical and mathematical concepts. During the 1-hour sessions, we conduct interactive lectures to introduce key concepts of (1) vectors, torque, and center of mass, (2) multiple integrals, (3) center of buoyancy and force, and (4) stability and righting moments. During the 2-hour sessions, these concepts are reinforced with targeted laboratory exercises. These exercises include finding the center of mass of objects, and performing integration for center of mass and buoyancy of different shaped containers. Upon completion of these exercises, students compose a report that includes their calculations, results, and key observations.

The second half of this module is also four weeks, and includes the design of the hull of a boat using multivariable calculus, torques, moments, center of mass, center of buoyancy to meet specifications. The design specifications that we provide include: size constraints, an ability to carry a payload, and that the boat must right itself when tipped. Students therefore need to conduct calculations for center of mass and buoyancy to determine where to place the payload, and torque calculations to determine boat stability and righting moment. To complete these tasks, students use Mathematica for hand analysis, symbolic math, to perform calculations, and to design the shape of the boat hull using mathematical curves. They utilize Mathematica to create a Computer-Aided Design (CAD) file of their design, and the instructional staff then use a Computer Numerical Control (CNC) router to fabricate the final prototypes out of foam (with a defined density). On a final "demo day", we set up a large water tank at the front of the classroom, so that students may test their boat designs compared to the set performance requirements. Students are not allowed to test their prototypes until the final demonstration. To conclude this module, students compose a fourth and final laboratory report for this aspect of the module to present their calculations, design, and assess their understanding of the concepts. **Figure 3** shows an example of calculations and a photo of prototype testing.

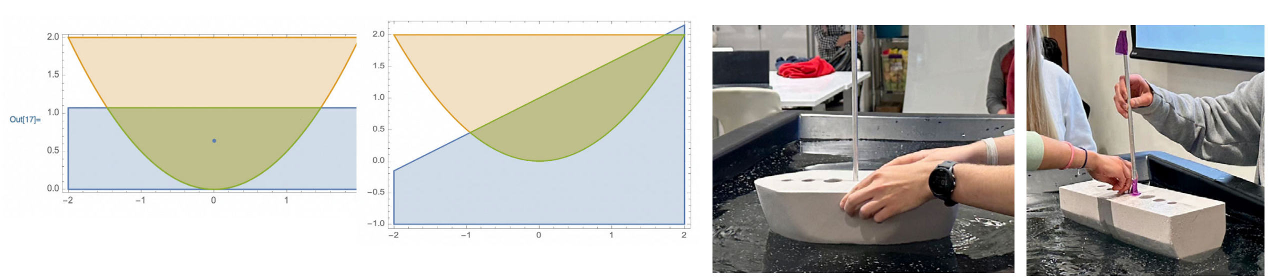

Figure 3: (Left two) example 2D calculations using Mathematica, showing center of buoyancy calculations. (Right two) Photo of final boat prototype and testing.

Discussion and Conclusion

We observed a high degree of student engagement in all iterations of the courses offered so far. We found students to be generally very enthusiastic in carrying out the experiments, and expressed appreciation for being able to apply concepts they learned in physics and calculus to analyze and design real-world systems such as a step counter. In course evaluations, students reported finding the course helpful in highlighting the relevance of the physics and mathematics content they learned in other classes to real-world applications, and that the course helps them reinforce content learned in their physics and calculus courses. Students also cited the interactive and collaborative nature of the class as one of its strengths. Since these are first-year courses, students were able to get to know others in their cohort better by working together on their laboratory assignments, in particular since the laboratory partners were changed for each assignment. Further, much of the laboratory work took place during class periods which contributed to improved interactions between students in different lab groups. Interactions between different lab groups were enhanced by the white-board surface tables in the classroom which were used by students to share ideas with multiple teams. Further, the vast majority of class sessions were run in a studio style, with the instructor walking around the room helping students contributing to the interactive atmosphere of the classroom. Students further cited the practice they got writing lab reports as an additional strength of the course. For the first three assignments, the instructors provided outlines (with diminishing levels of detail) in order to guide students on how to best present their ideas and findings. No outline was provided for the final laboratory assignment. We believe that this gradual decrease in scaffolding for the reports together with detailed instructions helped contribute to the students' perception of the practice they got writing reports as one of the strengths of the course.

In our view, the two courses Physical Modeling and Analysis Laboratory and Engineering Analysis Laboratory have been generally successful in helping students connect material they learned in physics and calculus courses to engineering applications. While a number of factors undoubtedly contribute to the low attrition rate (< 6%) of students from our program, we believe that the connections students make between foundational mathematics and physics to relevant engineering applications is a significant factor contributing to this low attrition rate. Students reinforced their understanding of the material in the physics and calculus courses through additional practice in these courses. Further, additional skills were developed in these courses that were useful in later courses in the engineering curriculum such as students familiarity with MATLAB, building circuits and data acquisition. Overall, we believe that this model of creating small-footprint courses that aim to explicitly connect mathematics and physics students learn from courses taught in other departments to engineering applications is promising as it can help achieve many of the goals of fully integrated courses in math/science and engineering whilst not requiring a full scale integration of the early stage curriculum for engineering majors. Moving forward, we intend to collect and analyze data on concepts from Physics I and Calculus I & II that students felt were reinforced in this course, and the extent to which they felt these courses prepared them to utilize the mathematics and physics concepts learned in their first year courses in later courses in their program.

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