Work in Progress: An "Engineering for Everyone" Class that Incorporates Modeling, Simulation, and Biomimicry into the Engineering Design Process

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Abstract

This is a Work in Progress paper that describes our development of a first-year engineering class at University of North Carolina at Chapel Hill. We are a comprehensive university with an engineering department. While we require our engineering students to take our introductory engineering classes, we also want to attract students from across campus to these courses, creating a culture of “engineering for everyone”. This has several advantages, as it provides students in different majors with some exposure to engineering, and the academic diversity in the classroom enhances our activities and discussions.

This paper focuses on one of our introductory engineering courses, APPL 101 Exploring Engineering, which exposes students to several aspects of the design process that are often overlooked in first year design experiences. With a series of mini-design activities, students develop mathematical models and simulations, and use their predictions to inform their system design. Then, they use biomimicry to brainstorm design ideas and a sustainability analysis to study the impact of their design on the sustainability issues. Through these activities, students learn programming skills in MATLAB, interpret the results of those simulations, and make connections with other fields, such as environmental sciences and biology. These activities appeal to students in many different majors.

This class has been taught for four years although the first two years were impacted by COVID. As a result, this class is just starting to reach steady-state in terms of its content. Future assessment will consider the achievement of our student learning outcomes. In addition, for students who plan on an engineering major or minor, we will look at the impact of this class on retention in the program. For students who are outside of the engineering program, we will explore how this class has affected their acquisition of engineering skills and an appreciation for the importance of engineering.

Introduction

University of North Carolina at Chapel Hill is comprehensive university that does not have a school of engineering, but our Department of Applied Physical Sciences has an engineering focus. We have developed a new degree in Applied Sciences which is a general engineering program that connects engineering to the liberal arts and prepares our students to tackle the complex, interdisciplinary challenges in our society. This builds on our existing minor in Applied Sciences and Engineering, which started in fall 2020.

As we designed our first-year engineering courses, we considered the typical goals of first-year engineering classes at other institutions:

- Expose students to a real-world engineering experience through examples or design projects [1,2].
- Develop a variety of engineering skills that will be useful later in the curriculum [2].
- Develop the students’ engineering identity [3].
- Increase retention, especially for students who are under-represented in engineering [4].

We share these goals for our first-year classes, while adding a goal of "engineering for everyone" because our program is part of the College of Arts and Sciences, and we aim to connect engineering to the liberal arts. While we require our engineering students to take these first-year classes, we also want to attract students from across campus. Often, students in non-engineering majors will shy away from taking engineering courses because of logistical enrollment issues and pre-requisites, or they fear that these classes will be intimidating. This separation between engineering and other majors can leave students inadequately prepared for their careers, when they will be working with others from a variety of backgrounds.

A culture of "engineering for everyone" can help bridge that gap. This idea has been implemented in various forms at other universities. The University of Dayton developed an engineering course, "Technology and the Engineering Method for Non-Engineering Students", that introduced non-engineering students to engineering tools and methods [5]. It fulfilled a general engineering requirement but only for non-engineering students. Miami University took this concept one step further by implementing a series of general education courses that attracted both engineering and non-engineering students [6]. These included a foundational course with no pre-requisites, a three-course sequence of classic engineering courses that had some STEM pre-requisites, and a capstone design class that was open to seniors in all majors. While these classes fulfilled general education requirements, they were not specifically required for all engineering students, as they had alternative options.

We built on this history by creating two first-year engineering courses that were required for all engineering students, but also fulfilled general education requirements for all students at our institution. With a mix of students in the course, the engineering students will learn to work together with liberal arts students on engineering projects, while the liberal arts students will become familiar with the language, tools, and mindset of engineers, which could be important in their careers as well as for personal growth in a 21st century society. In addition, the academic and demographic diversity in the classroom enhances our activities and discussions.

With all of these goals in mind, we developed two first-year engineering courses. One class, APPL 110 Design and Making for Engineers, focuses on design and fabrication through a series of design projects using the campus makerspace. The second class, APPL 101 Exploring Engineering, provides an overview of engineering, while focusing on other aspects of the design process, such as biomimicry to brainstorm design ideas, modeling and simulation to address design questions, and sustainability analysis to study the impact of designs. These classes are complementary and can be taken in any order. While they are required for all engineering students, other students can choose one, both, or neither of them.

While our department designed these classes to fulfill our goals as described above, we also designed them to meet the requirements for general education courses at our university. In addition, we consulted with other departments on the content of these courses, and several of them chose to add these courses to the list of electives for their majors.

This paper focuses on the development of one of these courses, Exploring Engineering, and presents some of our initial findings and assessment plans.

Methods: Class structure and activities

We carefully considered many aspects of the class so that it would attract and retain both engineering and non-engineering students, while still fulfilling all of our goals. The class has no pre- or co-requisites, which eliminates obstacles for non-engineering students to take the course. It is a relatively large class with up to 72 students, but it is taught in an active learning classroom where students sit in groups of eight around tables to facilitate discussions and group work. There are two teaching assistants for each section, who are either graduate students or undergraduates who have previously taken the class.

The class is designed for first year students, but it enrolls students from all class years. Since our major is just beginning and our minor is relatively small, most of the students in these classes are not studying engineering and are not first year students. For example, in Fall 2023, we taught two sections with a total of 139 students. Only 21 of them were engineering students. The other most popular majors with more than 10 students enrolled were STEM majors: Neuroscience, Computer Science, Psychology, and Biology. We also had students who majored in non-STEM subjects, including Business, Studio Art, Political Science, and Economics. Most of the non-engineering students were juniors and seniors, while most of the engineering students were first years or sophomores. All of these demographics will change as our new engineering major grows and becomes a larger percentage of the class.

We have several activities that help students to develop their engineering identity and expose them to real world examples of engineering in our lives. Students write a “microstory” to introduce themselves by describing an event or experience with engineering that led them to take this class. Student also conduct an interview with a non-engineer to discuss the impact of engineering on their work.

For another activity, students give a short presentation on an “innovation in engineering”. The goal is for students to explore the engineering considerations behind recent innovative products. These are fun and interesting two-minute presentations in which a student describes a recent engineering innovation. They explain the need, user considerations, scientific challenges, and product implementation. This information is summarized on a single slide that they present to the class, divided into four quadrants with one for each section mentioned above. Each student does this assignment individually. With about 70 students, we have about 3 presentations per class over 24 of the class periods during the semester, typically at the start of class. Including time for questions, this takes up less than 8 minutes of the 75-minute class period and provides an interesting “warm up” to start the class.

For the core topics throughout the semester, our starting point is the Stanford Design Thinking Bootleg [7], which is a widely used roadmap to guide users through the design thinking process. This consists of 5 modes, as shown in color in figure 1. Over the course of the semester, we add three additional modes to this roadmap, shown in grey: (1) *simulation* to test and enhance ideas; (2) *biomimicry ideation* to provide a source of new design ideas, and (3) *sustainability analysis* to measure the impact of designs using sustainability metrics.

We chose these additional modes in part because they are an important part of the design process that are missing from the Bootleg. In addition, we decided on these topics because they appeal to both engineering and non-engineering students as useful career skills. The biomimicry and sustainability topics are also of personal interest to many students across different majors at our University.

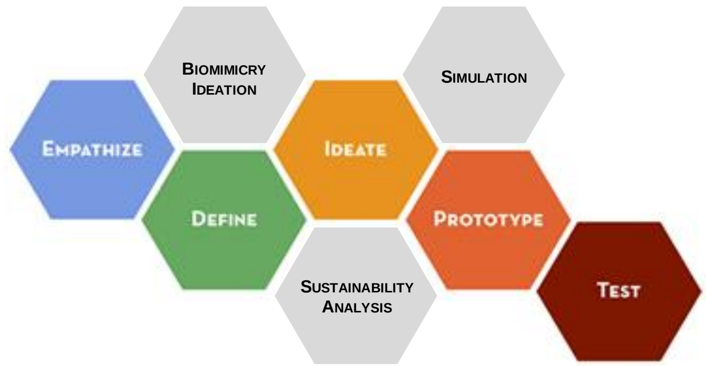

Figure 1: The five "modes" of the Stanford Design Bootleg [7] (shown in color), plus the three additional engineering tools that we address in our class (shown in grey)

Module 1: Simulation

The goal for this module is for students to develop simulations and use the results to optimize an engineering design. This provides students with an engineering context for simulation and programming activities, which has been done at other institutions [8,9]. Because these tasks can initially be intimidating, we first introduce simulation through several "explorable explanation" activities that promote learning through playing. These online simulations are interactive and visual-based:

> Forest fire simulation [10]: This is a simple simulation of how forest fires spread. Students can adjust parameters that determine the likelihood of tree growth, forest fire spread, etc. They can also apply "fire breaks" and other mechanisms to mitigate the spread of forest fire. As they explore the simulations on this site, students work in small groups and answer discussion questions about the simulation results.
>
> Parable of the Polygons [11]: This simulation describes how people tend to congregate with others who share similar qualities. Again, students can adjust parameters and see the impact on the results.

While engineers tend to think of simulations as being useful for modeling complex technology, these examples demonstrate that simulations have a variety of applications in society. For each of these simulations, students complete a worksheet, which prompts them to adjust the input parameters of these models to and discuss the impact on the results. While the worksheet is completed individually, the classroom is lively with group discussions.

Once the students have been introduced to modeling and simulation through online activities, they are ready to start programming their own simulations. The challenge is that due to the nature of our class with no pre-requisites, the students' prior programming experience varies widely between zero and extensive experience. We use several activities and techniques to help level the playing field. Through online tutorials such as Matlab Onramp [12] and online textbooks [13], students become familiar with basic programming syntax and the Matlab interface. We design the simulation assignments using Matlab live scripts, which consist of a mixture of instructional text and the basic structure needed for their simulation code. This makes the assignments less intimidating for those without prior experience. Our goal for these activities is focused on the use and interpretation of the models, not for students to become expert programmers. For our engineering students, they will have many more opportunities to boost their programming skills throughout the curriculum.

Each simulation assignment is presented as a design problem. Students develop a simulation and verify the simulation results against real data. Then they try different input parameters to optimize the design. They submit their findings in a two-page report, plus their Matlab code. While these are individual assignments, we encourage students to work together, and we provide time during class for them to work and get feedback from their peers, teaching assistants, and faculty.

Table 1 has more information about three of these assignments. They start with relatively simple tasks and increase in complexity. Without going into extensive detail, we provide students with a review of the underlying physics, which most students have previously seen in college and/or high school classes. We also provide students with the equations needed for these simulations, and part of their task is to convert these equations to programming syntax.

Table 1: Summary of three of the simulation assignments

Design question	Simulation	Model verification and measurements
	Bike Share System with only two locations [14] 	
Determine how often the bikes need to be reset to their original locations in order to maintain a roughly equal distribution of bikes between the locations.	Model a simple bike share system with only two locations. There is an X% chance that users will return the bike to the same location and a 1-X% chance that it goes to the other location.	No verification. For measurements, try different values for X% and look at the impact on bike movement. When do bikes need to be reset to their original locations?
	Basketball shooting machine (Original image is from ref [15]) 	
Determine the velocity and angle needed for the machine to pass a ball from the baseline to a user standing 4.57m away at the free throw line (ideal trajectory shown in red above).	Model projectile motion (x and y position and velocity vs time) for an object. Because the basketball is moving at a relatively low velocity, drag can be ignored.	Verify the model by comparing the simulated velocity and position to the experimental data that was captured from videos using Tracker software [16]. Then, try different values for the initial basketball velocity (x,y) to obtain a trajectory that appropriately passes the ball to the shooter.

Design question	Simulation	Model verification and measurements
	Skydiver 	
Determine the parachute size needed to reduce velocity so that the diver has a "safe" landing. It's up to the student to do research and determine what would be "safe".	Model projectile motion (x,y position and velocity vs time) for an object, including the effects of drag.	Verify the model by comparing it to real data obtained by making a "grocery bag" parachute prototype, dropping it from a height, capturing the trajectory on video, and using Tracker software [16]. Then test the model with different values for the diameter of a skydiver's parachute to investigate the impact on terminal velocity.

Module 2: Biomimicry Ideation

For our biomimicry module, the goal is for students to conduct research on natural solutions that address real word problems. We introduce students to the field of biomimicry through a nature walk activity at our on-campus arboretum. Using the signage in the arboretum, students can identify the flora, and guided by worksheet prompts, students think about opportunities for biomimicry innovations in this local environment.

For the remainder of this module, we guide students through a research project based on the Biomimicry Toolbox framework [17]. We provide them with a list of example topic areas for their project and they conduct initial research using the Ask Nature field guide [18]. Over a several week period, students choose a design topic based on some prompts that we provide, and they proceed through the steps of the biomimicry design process as outlined in the Toolbox (see figure 2). With this toolbox, students learn how to define a problem, reduce it to the essential functions, reframe them in biological terms, look for models in the natural world, and apply those biological models to address the original problem. Each step is first presented in class, and students complete a series of worksheets (some example worksheets are located at reference [17]) that guides them through the process.

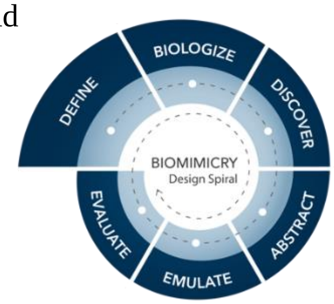

Figure 2: Biomimicry Toolbox Framework [17]

By the end of this module, students submit all of their worksheets and an individual 10-page report that encompasses all of their work on this project.

Module 3: Sustainability analysis

The goal of this module is for students to understand the considerations around sustainability, and to implement a sustainability analysis on an engineering design. Students are now combined into small groups and each group chooses a project that they will develop for this module. This may be based on one of the student's biomimicry topics.

We use the VentureWell Tools for Design and Sustainability as our guide [19]. For each step, we present an overview and provide students with worksheets or other activities to implement these components of the framework.

- **Whole Systems Mapping:** Students sketch a pictoral map of the entire system, incorporating all elements of their product, its life cycle, and any other products that might impact its performance. For example, when developing a clothes dryer, you must also consider the performance of the washing machine.
- **Life Cycle Analysis:** For their product, students develop a list of materials, manufacturing processes, and disposal processes. They determine the sustainability impact using established databases, such as ReCiPe [19]. From the results, students quantitatively assess the sustainability of their product.
- **Greener Materials and Lightweighting:** Students investigate the impact on sustainability and performance by using greener materials and by minimizing the quantity of materials used.

Students also develop a low fidelity prototype of their design, take measurements to assess its performance, and analyze the results. Students submit their results from these sustainability tools, their performance data, plus a final report and final presentation.

Discussion

We have offered this class for four years. Currently, we offer two sections in the fall and one in the spring. Each section has about 70 students and two teaching assistants who attend class to help with student questions during project work time, and they support the grading of assignments.

For the first two years (2020 and 2021) that we offered the class, the semester was significantly impacted by COVID and it was taught as a hybrid class. As a result, the class has changed significantly each semester as it shifted from hybrid to in-person and we continued to add and modify the class activities.

This year, we made adjustments to address the availability of artificial intelligence (AI) chatbots, such as ChatGPT [20] and Matlab AI Chat Playground [21]. The biggest impact is on the simulation module because students can easily generate their code with these AI chatbots. As a result, we have put less emphasis on programming for these assignments, as described previously. Instead, our emphasis is on using the simulation, interpreting the results, and communicating the conclusions. This is likely to be more appealing to students in non-engineering majors, so this also supports the “engineering for everyone” goal of the class.

We have not yet undertaken a formal assessment of how the class is achieving its objectives. However, we have some indirect measures that demonstrate that the class is appealing to both engineering and non-engineering students. For example, interest in the class is high and there is a wait list to get into the class each semester. We initially offered only 1 section per year of the class and we have increased that to three sections, which continue to be full. We also have former students who are interested being teaching assistants, and they are a mixture of engineering and non-engineering students.

From student comments on our course evaluations, we have anecdotal evidence that we are achieving our goals for both engineering and non-engineering students:

- "Not everyone comes into the course with a grasp of engineering. But, once you leave, you have a good feel for engineering."
- "The assignments were interesting and engaging. The class focused less on memorization and more on actually learning the involved skills."
- The course "strongly encouraged developing practical skills (writing, working in teams, communication) that are transferable in any industry."

Informally, we also see from the quality of our students' work that most students are achieving the goals of each of the three modules.

In the future, we plan to conduct formal assessments to evaluate our success in achieving the goals of this class. This will be accomplished through student surveys administered at the start of the semester, end of the semester, and 1-2 years after taking the class. For the non-engineering students, we will ask about:

- their understanding of the field of engineering
- their confidence in working with engineering tools
- their confidence in working with engineers to address interdisciplinary challenges
- whether this course impacted their career trajectory

For the engineering students, we will ask similar questions, plus additional questions about their identity and mindset as engineers.

We will also collect data to monitor our success in student retention in engineering, although we will not have a control case for comparison because this class has been taught since before the implementation of our engineering major. We anticipate that the class may also help in retaining a diverse group of students in the major and we will collect data to investigate this hypothesis, but again we will not have a control case for comparison.

As we continue to collect data from the class and from surveys, we will make adjustments to the class so that it can serve as a model to prepare students for interdisciplinary collaboration between engineers and other professionals.

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