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WIP: Development of a Chemical Engineering Activity for First-Year Engineering Students

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Introduction

This Work in Progress Paper outlines the development and initial implementation of a Chemical Engineering activity embedded in a first-year engineering design (FYED) course at Rutgers University. The goal of this activity was two-fold: to reinforce foundational concepts learned in the engineering design course while simultaneously introducing students to important concepts relevant to real-world chemical engineering applications. The activity was developed by the Chemical and Biochemical Engineering (CBE) department with the FYED course faculty to meet the needs of various stakeholders: the students, who need activities to support academic motivation, skill development, and exposure to major options; the FYED course faculty and staff, who must meet curricular goals with the resources available to teach approximately 1000 students; and the CBE department, which aims to introduce foundational chemical engineering concepts, foster engineering problem solving, clarify the nature and scope of the field, and create effective pathways for student outreach and recruitment.

One goal of the FYED course sequence is to increase the engagement of first-year students with the different engineering departments at Rutgers. Departments and the FYED team communicated to determine concepts in the FYED curriculum that could best align with appropriate real-world examples from the majors offered by all disciplines in the School of Engineering. The CBE department and the FYED team identified that examples from CBE might best tie into portions of the course related to data collection, visualization, and the use of data in the problem-solving process.

We developed an activity based on Boyle's Law that uses pressure and its effects on materials as a framework for practicing these skills. This activity connects an engineering challenge in food and beverage manufacturing - the development of alternative marshmallow formulations that replicate the texture and structure of traditional gelatin-based products. Food and beverage manufacturing is the second largest employment sector for chemical engineering graduates from our university, making this example a relevant real-world CBE application.

In this paper, we present the design of this activity, as well as example results from student data collection. We will discuss some of the benefits and challenges to developing an activity with multiple stakeholders with intersecting goals. Finally, we will discuss the next steps in our research on the efficacy of this activity, and how it fits into the goals of both the CBE department and the FYED team.

Background

In this section we will describe the 3 stakeholders in the design of the activity described in his paper. Additionally, we will discuss the importance of the underlying material in data literacy and problem solving that this activity reinforces.

First-Year Engineering Students

The first year of study is a critical time for engineering students. Rutgers services over 1000 first year engineering students, who all must take the FYED sequence. At Rutgers, students come in without a major declaration and have the first year to consider the engineering major that is the best fit for them. Additionally, students must acclimate to the expectations of the engineering curriculum. Students must be supported in their preparation for future engineering coursework with skills and foundational concepts (such as CAD, computer programming and data literacy) that will carry over to those classes. Finally, student motivation must be fostered in order support student success and retention [1] [2]. Research shows that the first and second years are the most likely times for students to drop out of engineering programs, so the support of student needs in the first year is essential for courses like the FYED sequence [3][4].

First-Year Engineering Design

This two-course sequence focuses on incorporating aspects of data literacy and analysis into the engineering design process [5]. FYED also provides engineering departments at Rutgers opportunities to reach students through co-developed course materials that reinforce practical applications of taught engineering concepts while allowing departments to engage students who are still making choices about majors.

One challenge with the FYED course sequence is that there are a large number of desired outcomes and learning objectives, with a relatively low number of course hours. As such, we try to choose activities and modules that can fulfill multiple outcomes at once. The major learning outcomes from FYED that this activity contributes to are:

1. Engineering career preparation, accomplished through introducing the different departments at Rutgers.
2. The engineering design process and problem solving, accomplished through assigning a large design project in both semesters of the sequence.
3. Data literacy, accomplished through discussion of the role of data in engineering design and applications, and through practicing basic data analysis.

Chemical and Biochemical Engineering

Chemical and biochemical engineering encompasses a broad range of applications, from pharmaceutical manufacturing to biotechnology and energy systems, advanced materials, and food production. The scope of the field can make it challenging for first-year students to develop a clear understanding of the discipline. Because chemical and biochemical engineering operates at the intersection of molecular-scale phenomena and industrial-scale processes, it requires students to grasp abstractions that may not be apparent from the discipline’s name alone. This breadth, while representing one of the field’s strengths for career flexibility, presents a communication challenge when introducing the discipline to students who are actively choosing engineering majors. This challenge is particularly relevant at Rutgers, where the CBE department is situated within the nation’s pharmaceutical manufacturing corridor and feeds graduates primarily into pharmaceutical and food and beverage industries, two sectors with strong regional workforce demands that students may not initially associate with chemical and biochemical engineering.

Data Literacy and Problem Solving

Data literacy [6] [7] and problem solving [8] are both crucial, interrelated skills for engineers, They are part of the FYED curriculum because of their prevalence throughout different engineering disciplines, and the lack of preparation of many incoming engineering students. Data literacy is a precursor to more advanced (and equally prevalent) areas such as applied statistics and data science and focuses on ensuring students understand the fundamentals about how data is collected, how to document data collection, and how to begin to make sense of said data. Literature on teaching data literacy suggests the use of real-world applications, and emphasizing the practical nature of understanding data, including understanding experiencing mistakes, challenges, and “messy” data [9] [10].

Similarly, a structured method for approaching problem solving is integral to all engineering disciplines and relates closely to engineering design. We teach students a problem-solving method that aligns with research-informed processes [11] [8]. We believe it is crucial to tie data into the problem-solving and engineering design processes, as data is always crucial to informing and testing the success of solutions and designs.

It is from this topical starting point that the CBE and FYED teams began to collaborate on possible activity ideas, with the CBE department eventually suggesting and developing the activity described in the next section.

Activity Design and Implementation

The activity was designed around a central driving question: what makes a marshmallow light and fluffy? This question frames the investigation in terms of a relevant product development challenge while directing students toward fundamental concepts of pressure, volume, and material structure. Such a question is important in food chemistry, where understanding the texture of gelatin-based marshmallows is important when engineering marshmallows using alternative ingredients. For example, vegan marshmallows must reproduce the characteristic texture while incorporating protein or carbohydrate matrices with densities that differ from traditional gelatin.

Initial Activity: Marshmallow Experiment

Students were given an experimental setup consisting of marshmallows, a hand pump vacuum chamber with a vacuum-sealed lid, digital calipers, and an electronic scale (Figure 1). We introduced students to how chemical engineers study the structure of materials, including food products, and asked them to investigate the “fluffiness” of marshmallows using pressure concepts.

The experimental procedure followed a well-structured engineering problem-solving method adapted from established frameworks in engineering education [8]. We used a seven-step method includes 1) recognize and understand the problem; 2) gather data and verify its accuracy; 3) identify relevant theories or principles; 4) state assumptions; 5) solve; 6) verify and check; and 7) document so that others trust your solution, can replicate it, and can use it to solve other problems [Rowan]. By explicitly introducing this framework, the activity teaches disciplinary thinking alongside technical content, helping students develop systematic approaches to unfamiliar problems. Table I provides the seven-step method and questions and sample solutions that could be applied at each step.

Figure 1. Experimental setup for students consists of marshmallow, handpump vacuum chamber with vacuum sealed lid, calipers, and electronic scale.

Students began by measuring marshmallow dimensions (height and diameter) using calipers, assuming a cylindrical geometry for volume calculations. They also recorded mass using an electronic scale. The marshmallow was then placed inside the vacuum chamber, and students used the hand pump to evacuate air from the jar. As the pressure in the chamber decreased, students observed the marshmallow expand dramatically as the trapped air bubbles within the gelatin matrix increased in volume according to Boyle's Law, which states that pressure and volume are inversely proportional at constant temperature:

$$P_1V_1 = P_2V_2 \tag{1}$$

Students continued pumping until the marshmallow reached its maximum size just before structural failure, at which point they used the calipers to estimate the expanded dimensions through the chamber walls while maintaining the vacuum seal. Continued pumping eventually caused the marshmallow to rupture, releasing the trapped air. When atmospheric pressure was restored by opening the chamber, the marshmallow shriveled to a fraction of its original size. What remained was assumed to be the solid gelatin and dissolved sugars without the air that previously gave the marshmallow its volume. Students measured the final dimensions and mass. Students recorded their measurements in a provided spreadsheet. The spreadsheet calculated volumes and densities of the marshmallow at each stage, as well as an estimate of the pressure achieved in the vacuum chamber and the volume of air that escaped from the marshmallow due to the breakdown of its internal structure, calculated using Eq. 1.

Table I. Problem Solving Step [Rowan]

Problem Solving Step	**Sample Questions/Examples Shared with Students**
Recognize and Understand Problem *"What makes a marshmallow light and fluffy?"*	What will happen to the marshmallow when we lower the pressure? Why? What can we learn from this?
Get Data	Measure the size of your marshmallow before and after vacuum. Where have I experienced pressure before?
Identify Theories	What is pressure? Use Boyle's Law: $P_1V_1 = P_2V_2$ Think about density $\rho = m/V$
State Assumptions	We'll assume the marshmallow acts like a flexible container full of gas. Temperature is constant.
Solve	Calculate change in pressure and density.
Verify	Does our answer make sense? Does everyone's marshmallow behave the same?
Document: Write up your process, so another engineer could repeat your work.	Compare the initial and final densities to quantify the "fluffiness" that gives marshmallows their characteristic texture and provides target specifications

During the experiment, students were asked to consider what their data revealed about the structure of the marshmallows. The difference between initial and final volumes represents the air that was trapped within the marshmallow, allowing students to calculate the volume fraction of air, a key parameter in understanding and replicating marshmallow texture in alternative formulations. Data compiled and cleaned across all sections was then provided to students in a subsequent course session for data visualization and analysis, reinforcing the connection between data collection and interpretation phases of the engineering design process. To clean the data, we removed any incomplete entries. We also removed any measurements that were duplicates or outliers and any values that did not make sense (such as negative quantities).

Follow-up Activity: Data Visualization

In the week following the initial data collection activity, students were asked to return to the data they collected with their classmates to practice making and drawing inferences from data visualizations. Students were introduced to different data visualization methods for understanding the distribution of a single variable (a histogram) and the relationship between two variables (a scatter plot). Students were asked to consider questions related to the original problem formulation, and how to better understand the conditions achieved during the experiment

Q1: Did the pressure achieved in the vacuum chamber affect the measurement of the amount of air in a marshmallow?

Q2: What is the best way to look at variation in how "fluffy" a marshmallow is?

Students were given a cleaned version of the data they collected, with data-calculated values for volume of air in the marshmallow, density of the marshmallow before and after the experiment, and minimum pressure inside of the vacuum chamber. The first prompt was intended to be close-ended to encourage them to look at the potential relationship between two variables, while the second prompt was intended to be more open ended to encourage students to explore different possibilities for how their data might help them answer the question. Students were asked to create plots, share their plots with a partner, and then give feedback to their partner, before finally updating and submitting final plots. The goal of this activity was to give students practice with creating visuals of data while concurrently thinking about the meaning that could be derived from those visuals. This was intended to strengthen the connection between the data they collected and the engineering problem that spawned the experiment in their initial activity. Prior to this activity, students were given a primer on how to create data visuals in Microsoft Excel, and asked to apply the methods they learned during that primer. See Appendix A for example visuals.

Stakeholder Benefits

This activity was designed to benefit multiple stakeholders within the School of Engineering.

For students, the activity connects essential skills to possible engineering careers and provides exposure to a potential major. Students gained hands-on experience with multiple phases of the data collection and analysis process and must consider multiple variables while solving an engineering problem. The vibrant visual of the expanding and collapsing marshmallow creates a memorable experience that reinforces conceptual understanding.

For FYED instructors, this activity constitutes a cost-effective hands-on activity that can be scaled for the large enrollment of the class. The total cost was approximately $15.44 per kit of which is all reuseable and can be used by 3-5 students each session. The recurring costs are only related to buying additional marshmallows which is about $0.14/group of 4 students. Additionally, to simplify the experimental setup a 3D printed part was used which cost ~$0.04 but is reuseable.

This activity also integrated problem solving and data literacy concepts into a sequence of activity, tying together two important and interconnected course outcomes. Although both were basic-level introductions, we believe that integrating them and providing students with a real-world context will provide students with a foundation for future exploration, while giving them a comfort level with messy data and ill-defined problems. As the semester continues, students are tasked with more ill-defined problem spaces, where they will continue to build upon the foundation provided in these activities and apply them to new contexts.

For the Chemical and Biochemical Engineering Department, the activity introduces students to chemical engineering and clarifies its scope beyond common misconceptions. Students are exposed to foundational chemical engineering concepts of pressure, density, and material structure early in their academic journey. The engineering solution method is introduced and applied in a chemical engineering context, demonstrating how chemical engineers approach problems systematically. The activity demonstrates the relevance of chemical engineering principles to everyday materials and phenomena, engaging first-year students through meaningful hands-on outreach and creating effective pathways for student recruitment.

Preliminary Observations and Future Work

In considering the future use, update, and study of this activity and other components of the FYED course at Rutgers, we have identified a number of areas for improvement and consideration for future work.

Future Improvements

The first implementation of this activity resulted in a very messy data set. Out of 387 data submissions, only 150 data points remained after incomplete, anomalous and outlier data was removed. This, in itself, is not an issue. However, the process of observing and cleaning the messy data was hidden from students. Ideally, students would be part of this process, or even have a chance to rectify their own incomplete and anomalous data entries. The prevalence of data entry errors also suggests that students may need more detailed instructions about how to record values during the experiment

We have also identified that the follow-up activity could be strengthened by having more avenues for critical thinking. For example, in our first implementation, the answer to Question 1 was essentially that there was not a relationship between the two variables (See Figure A1 in Appendix A). While this is a valuable thing to observe, identifying two related variables and having students visualize their relationship would be ideal in comparison. Similarly, before creating plots to investigate marshmallow fluffiness, we would have ideally asked students to think about and identify which variables might be the best indication of fluffiness, as the word “fluffy” is inherently ill-defined.

Future Work

Anecdotally, we noticed that students were engaged by the dramatic visual changes during the experiment and the hands-on nature of the experiment. The moment when a marshmallow ruptures under vacuum or shrivels upon pressure restoration elicited surprise and prompts questions about the underlying physics in many students. In the future, we will work to study these subjective reactions more concretely by analyzing student reflections on the experiment. More generally, we will also be researching the academic motivation of students throughout their time in the FYED sequence to investigate whether activities such as the one described in this paper are supporting student motivation.

Similarly, we saw anecdotally that students were grasping the connection of this activity to CBE careers in food product development, deepening their understanding of the diverse work in industry available to chemical engineers beyond traditional perceptions. Notably, sophomore enrollment in the CBE department increased by approximately 65% following the introduction of collaborative activities within the FYED course as part of a broader departmental recruitment effort, exceeding the approximately 20% enrollment growth observed across the School of Engineering during the same period. Preliminary projections suggest continued departmental growth for the class of 2029. While this increase in growth likely reflects multiple contributing factors, future work includes surveying students about their engineering major choice to better understand the role of early exposure activities in shaping their major selection.

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Appendix A – Example Data Visuals

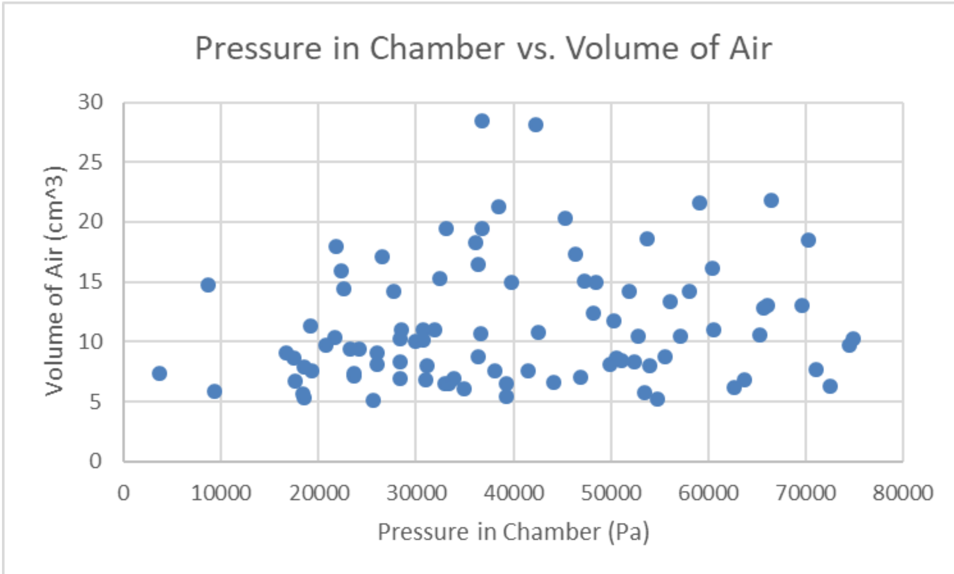

Figure A1. Example figure created during follow-up activity.

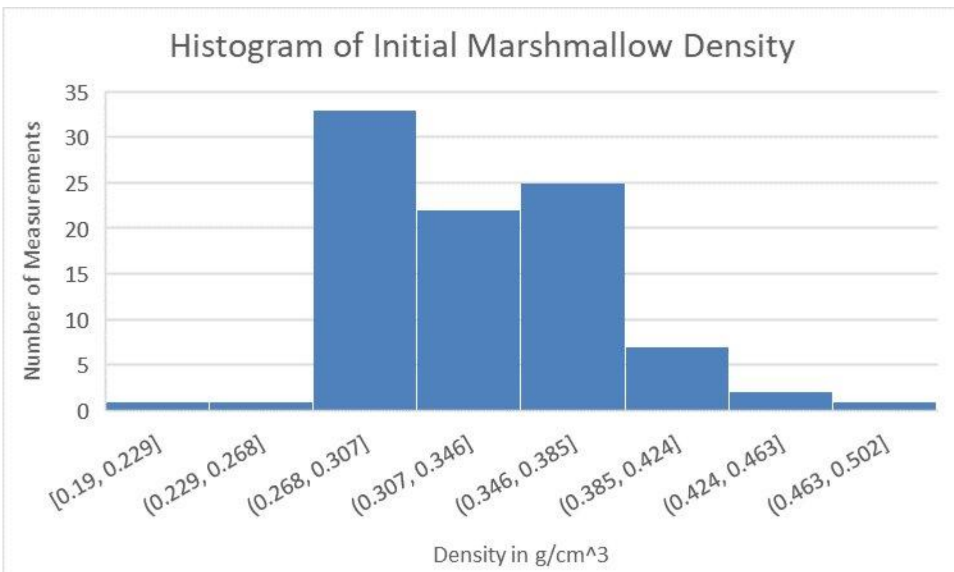

Figure A2. Example figure created during follow-up activity.

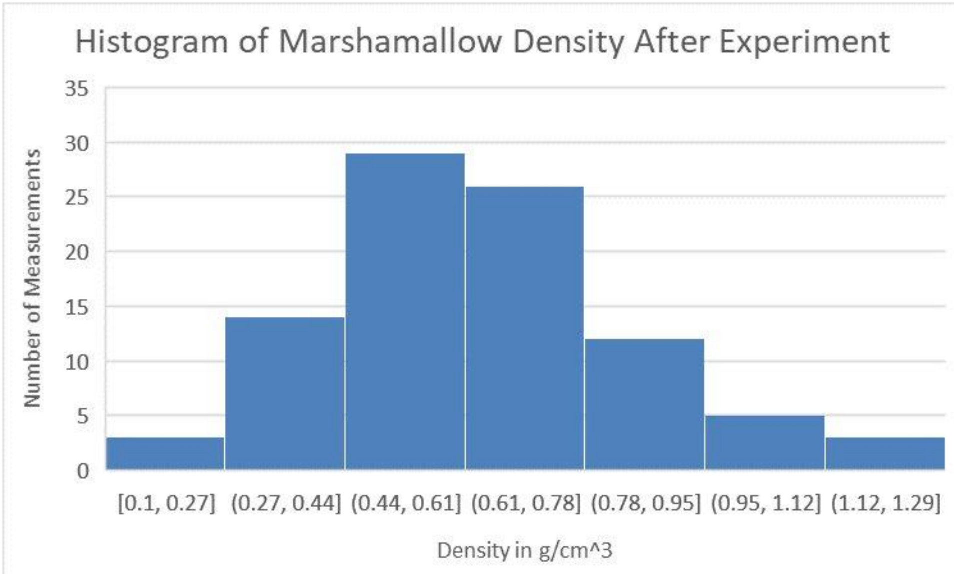

Figure A3. Example figure created during follow-up activity