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Student and Professor Collaboration to Develop a First Year Electrical Engineering Capacitance Laboratory with Common Materials

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Introductory Ideas, Activity Inspiration, Motivation, and Other Works

This paper describes the process of developing a single-class hands-on activity for first-year students in an introductory, first-year electrical engineering course to introduce the idea of capacitance and capacitors. The origination of the activity was in the Fall 2019, but it was trialed more as a prototype activity with significantly less structure. It had been developed as part of an Entrepreneurially Minded (EM) activity, however, this paper is not focused on the EM oriented aspect of the activity [1]. The activity was to be used in Fall 2020, but due to how COVID-19 disrupted the classroom experience, it was not provided to students during Fall 2020. With increasingly familiarity of how to operate a classroom in-person during COVID-19 in a safe manner and following university guidelines, the activity was revived for Spring 2021 but this time with input from a senior undergraduate electrical engineering student to provide improvements in both its presentation, structure, and development. The same student also provided teaching assistance with the activity in Spring 2020 (just prior to COVID-19) but took a more formal role in the development in Spring 2021.

While providing the activity to students in Spring 2020, one of the items that was provided to students for experimentation in making capacitors was Play-Doh. A consistent behavior was noted when students attempted to use Play-Doh as an insulating material in their capacitor designs. When measuring the capacitance of student constructed designs a fluctuating value was observed rather than a constant value. This sparked the idea that there might be some interesting physical behavior in the Play-Doh regarding its electrical properties. It was known that prior to this activity that Play-Dough acted as a conductor with measured conductance properties as provided by Fuse et. al. [2]. The thinking in including it in the activity originally was that the Play-Doh would act as a leaky dielectric, which might provide a good way to introduce the non-ideal properties of capacitors to students. However, the observed behavior was not consistent with a leaky dielectric as the measured capacitance would fluctuate in value (perhaps indicating some kind of charging effect) It was decided to explore this property and attempt to include it into the capacitor activity by allowing students to experiment with different properties of dielectrics. This was thought possible due to the work by Johnson and Thomas and Squishy Circuits [3,4]. Rather than using commercial Play-Doh, students could use conductive dough following the recipes provided by Squishy Circuits [4]. This would provide additional degrees of freedom in term of the properties of the dielectric material of a capacitor. In addition to using the conductive dough, it was thought that a set of characterization experiments should be carried out to provide some standard ideas about how the conductive dough or insulating dough would work as a dielectric. However, when the dough (conductive or insulating) capacitance was characterized the capacitive behavior was deemed to be more complex than expected. The results of the dough characterization are not included here as the focus of this paper is more on how first-year undergraduate electrical engineering students better understood the concept of capacitance after taking part in a hands-on activity.

Something interesting to explore is to examine the existing literature for examples of activities that more broadly educate students on capacitance and capacitors. An earlier example of capacitor laboratory for students in a Physics I course was published by Tullen in 1971 and provided a film (video) unit and associated laboratory to overcome students' difficulty in perceiving text [5]. Another exploration of capacitance utilizes a more precise parallel plate apparatus which the authors use to test the ideal model of a capacitor as derived from Gauss' Law [6]. This study has significantly more experimental precision than the one at hand, but also relies upon more sophisticated equipment and techniques that might be present in a slightly more advanced undergraduate level (second year for instance). Grove et. al. shows that the presence of air gaps in parallel plate capacitor dielectric layers can lead to measurement error, especially when using low-cost multi-meters [7]. This paper also provides a greater level of experimental rigor than the current, however, this again is beyond the level that the current study introduces to students. The current study is meant to be an introductory and simple hands-on activity that is not intimidating. An additional point about studies in existing literature is that they seem targeted more to physics laboratories that seek to require higher levels of mathematical practice.

This paper has two objectives including demonstrating how a simple hands-on activity can lead to increased student understanding, and to request feedback from the broader first-year engineering education research community to further improve the activity for subsequent deployment.

Overview of Course The Activity Was Provided To

The course is a first-year electrical engineering course with the title "Introduction to Electrical Engineering". The pre-requisites for the course are at least a score of 24 on the Math portion of the ACTE or a "C" grade or better in either College Algebra, Pre-Calculus, or Plane Trigonometry. Typically, in Fall semesters, the student enrollment is anywhere from 40-60 students, having 2 sections featuring between 20-30 students each. It is normal for Spring semesters to feature one section that has a much smaller enrollment number, usually between 10-20 students, with closer to 10 students being standard. In the semester that this paper is detailing (Spring 2021), the total enrollment was 11, however only 8 students participated in the capacitor activity. Spring 2021 was also unusual since university guidelines for COVID-19 were in place, which required students and the instructor to wear masks, and maintain 6ft of distance or more as often as possible. This activity was not used during Fall 2021 as less familiarity with the COVID-19 altered classroom was possessed by the instructor. After a full semester of teaching under COVID-19 guidelines, Spring 2021 was more "normal" compared to Fall 2021, thus this activity was returned for use.

Structure of the Parallel Plate Capacitor Activity

The intent of the activity was to create a low cost and easily accessible hands-on activity to help students better understand ideal parallel plate capacitors and to provide them to the context from which they could further explore capacitor technology. A key aspect of the activity was to use materials familiar to students that can come from everyday items that one may find at home. For instance, aluminum foil is a common household kitchen item that can be used as a conductive material for capacitor electrodes. For a list of more materials, along with their potential associated function in a capacitor consult Table 1.

Table 1. Listing of commonly available household materials used to create capacitors in a classroom setting.

Item	**Potential Function**
Wax Paper	Dielectric
Butcher Paper	Dielectric
Aluminum Foil	Conductor/Electrodes
Paper Clips	Conductor/Electrodes
Masking Tape	Dielectric
Plastic Wrap	Dielectric
Conductive Dough	Conductor or Dielectric
Styrofoam (sheets)	Dielectric

Students were introduced to the idea of a parallel plate capacitor by a short lecture on the topic. In this lecture, the definition of a capacitance, capacitors, and basic parallel plate capacitor physics was provided. Most notably, students are provided the equation,

$$C = \frac{\epsilon A}{d} \qquad (1$$

and a discussion is held with the students about how it would be possible to maximize the value of the capacitance, C. It should be note that in equation 1, ϵ is the electrical permittivity, A is the area of the capacitor electrodes, and d is the distance between the electrodes. No distinction is made between $\epsilon, \epsilon_0, or\ \epsilon_r$, as one would commonly do when discussing capacitance. That is something that could be easily altered about the presentation of this activity.

Following the lecture to the students, students are given a time constraint under which they must iterate through as many capacitors designs as possible in a set amount of time. The time provided for this implementation was 30 minutes. Bins are placed in the front of the room containing the supplies provided in Table 1 and students can use whatever ideas they have to prototype capacitors. Testing of capacitors is performed using a standard multimeter with a capacitance check function. Students must bring the capacitor to the instructor of at the front of the room in order to have their capacitor tested. A running total of capacitor measurements is displayed to the entire class by way of a document camera projected to a screen, or by loading a quick spreadsheet showing the information in a projected format. The “winning” strategies seem to be students or student teams that work toward a cylindrical capacitor configuration, though students tend to try out many different configurations. It was not formally recorded how many iterations students worked through, however teams or students obtaining the highest capacitance seem to try at least 3 or more configurations before the time ends.

After the activity ends a debriefing is held with the students where students can discuss what seemed to work well and what did not. Several students typically engage in this conversation and key in on the idea of making the electrode area larger or distance smaller between plates. Fewer students comment on the role of the permittivity in the capacitance formula. Time is spent in discussion with students regarding which of the capacitor building materials might have the highest permittivity based on their experimentation. To further encourage students to explore capacitance and/or capacitors a post activity assignment is given. In this iteration of the activity, a peer-share style presentation was assigned [8]. A peer-share presentation is a short presentation featuring 4-slides that is meant to contain all the information necessary for the audience to understand it without being presented. It is somewhat of a hybrid document presentation format between a slide presentation and a digital book. In this instance of a peer-share assignment, students were required to create a slide that explained basic physics of a capacitor, a slide about the different types of capacitors, and finally a recent news article summarizing some form of capacitor innovation.

Results and Discussion

In order to collect data to use for assessment related purposes, a 6-question survey was provided the students before the start of the activity and immediately after the activity was over. The survey was given online during class time and students accessed the survey through their own devices. The same questions were given to the students in the pre-survey and post-survey and the types of questions and question text is provided in Table 2 below.

Table 2 – The structure of a 6-question survey provided to students before and after the learning activity occurred.

Question Number	Question-Type	Question Text
1	Single-Choice	Which of the following best describes a capacitor?
2	Multiple-Choice	Generally speaking, which of the following factors would need to be increased, to increase capacitance.
3	Single-Choice	Which of the following is the proper units for capacitance?
4	Open Response	Briefly explain how a capacitor works.
5	Open Response	If you were designing a capacitor, how would you make a better capacitor?
6	Open Response	Provide your opinion about the activity. In particular please answer these questions, do you feel it helped you better learn what a capacitor was? Did the activity seem childish? How would you improve this activity?

Figure 1 provides a summary of the data collected from student responses to the survey questions provided in Table 2. Within in each of the 5 plots, 2 bars of data are provided for both pre- and

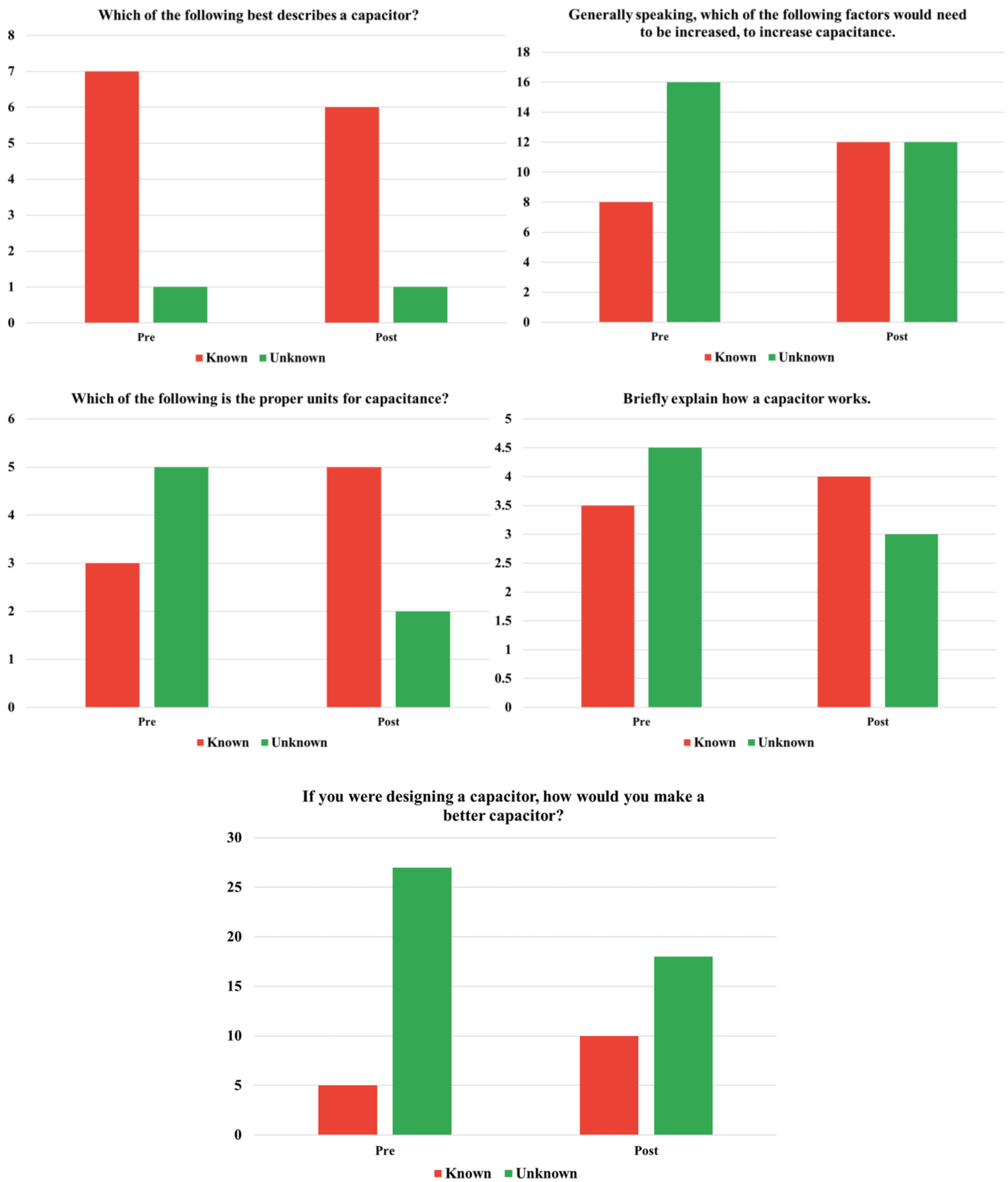

Figure 1. A series of 5 plots that corresponds to students' responses to questions provided in Table 1. The known and unknown categories refer to student knowledge and the pre- and post-data refer to measurement before and after the activity.

post- which correspond to how students answered the survey before and after the activity. The red bars provide information about what students were determined to have knowledge of whereas the green bars are indicative of the information that students did not have knowledge of. Both quantities were plotted and tracked so that one can see the relative gain in understanding before and after the activity. For single-choice types of questions, data compilation was relatively straight forward, as either students chose a correct response or an incorrect response. In these cases, correct corresponds to known information whereas incorrect corresponds to unknown information. For multiple-choice, students could select multiple answers, therefore, the total known score is determined by multiplying the number of students taking the survey by the number of correct answers. The open response questions were graded by coding the written response given by the students. For instance, for question number 4 students were asked "Briefly explain how a capacitor works." A response of "I do not know" would receive a score of 0, whereas a response such as "A capacitor takes electricity and stores the excess electricity that goes through it, up to its farad capacity" would be given a score of 0.5 since the description is somewhat accurate but the student fails to communicate that energy is stored but instead suggests electricity is stored. A score of 1 is given to those responses that are commensurate with a response that someone trained on the topic matter might provide. The highest possible scores for open response were determined by assuming that each student would provide all reasonable answers, where "reasonable" is deemed to be when the student uses terms or descriptions that pertain to the model of the capacitor that was being taught. For this activity, an ideal model of a parallel plate capacitor was used, so referring to non-ideal properties would not necessarily provide additional known points.

One question of interest is whether the students obtained a better understanding of the function of a capacitor which is best observed by examining student responses to question 1 and 4. The results of question 1 show that the level of understanding is roughly the same, or it is possible that students understood a little less. However, when students are given the chance to provide an open response, we can see that the "known" level increases and the "unknown" level decreases, indicative that the activity provided students with an increase of knowledge about the function of capacitor operation. Examining question 3, it is apparent that the students better understood what units correspond to capacitance following participation in the activity.

Questions 2 and 5 both refer to design aspects of the capacitor, wherein students are asked about how to improve a capacitors capacitance or how they might make a better capacitor. Students keyed in on associating capacitance with the capacitor as the quantity they needed to maximize. It is evident from the results that the activity seemed to improve the knowledge students had when it comes to understanding how to improve a capacitor's function.

It seems relatively straight forward that when the known category increases, that the unknown category correspondingly decreases, still yet though, showing both plots provide for how well the student population grasped the overall information space that was presented to them. For instance, examining question 5 in Figure 1 the total point score for the pre- results was 32 and the total point score for the post- score was 28. It was judged that the students could have provided comments that included 4 distinct ways that they could have answered question 5 to demonstrate that they understood how to improve a capacitor. These 4 responses would have been increasing the area of the conducing plates, increasing the permittivity of the dielectric, reducing the distance between plates, and ensuring that the dielectric resistance was very high. In the pre-survey, a total of 8 students responded leading to a total possible of 32 points to be obtained from the class, in the post-survey only 7 students responded, meaning only 28 points were possible to obtain. The increase in the known category went from 5 in the pre-survey to 10 in the post-survey and the unknown category shrank from 27 to 18, in the pre- and post-survey respectively. Because one less student completed the survey after the activity, not all of the points gained in the known category were taken up by a reduction in the unknown category, since not every student had the same consistent gain or decrease in knowledge in the pre- and post- surveys.

It should be noted that the resistance of the dielectric is typically something that is avoided when describing an ideal capacitor model, but a discussion took place during the end of the activity. Some students tried to use a conductive dough as the dielectric between the conducting plates of their capacitors, which caused some interesting behavior (namely fluctuating readings on the multimeter) and led to a faculty led discussion regarding lossy dielectrics in capacitors because of the conductive dough. Thus, students were introduced to some limited knowledge of non-ideal behavior of capacitors.

Conclusions and Future Development

This paper has described an easy-to-implement, inexpensive, and accessible activity that provides a hands-on way to teach the concept of capacitance and capacitors to first-year engineering students. This activity can be easily deployed in one class period, with or without assistance. Based upon a pre- and post- assessment survey, it was shown that students' knowledge increases because of this activity. It is not known whether this activity provides a memorable enough experience that students retain knowledge over a longer period. One way to provide more interesting data on this would be to remeasure student knowledge gain at a later point in time in the course (for instance, the end of semester) to see how well concepts are retained. Also, student learning was not assessed after the peer-share presentation, so delineating the activity knowledge gain from the peer-share assignment might be important. Finally, conductive, and insulating dough could be a great way to add even more dynamicity to the activity. The activity could be restructured so that students could make their own insulating or conductive doughs prior to class time, and then utilize them in their own capacitor designs.

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