E&M Laboratory 1106, Summer 2025

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https://www.physics.smu.edu/tneumann/110X_Summer2025/

Lab 4 — Static Electricity — Parallel plate capacitance Max. points: 48

Learning Objectives

- Understand the principles of parallel plate capacitance and how it is affected by geometry and dielectric materials.
- Experimentally construct and measure the capacitance of parallel-plate capacitors using various dielectrics.
- Determine the dielectric constant of materials through capacitance measurements and uncertainty analysis.
- Apply the concept of parallel-plate capacitance to create and analyze a practical water level sensor.
- Enhance experimental and data analysis skills, including uncertainty analysis and comparison of experimental results with theoretical predictions in electromagnetism.

Your preparation: Work through before coming to the lab

- Review chapter 25 "Capacitance" of Halliday, Resnick, and Walker [1]. [1]. Understand the basic definition of capacitance, the capacitor symbol, and the units of capacitance (Farad). Pay close attention to the calculation of capacitance for parallel-plate capacitors. Make sure you understand how capacitance depends on plate area, separation distance. Carefully study how the introduction of a dielectric material between capacitor plates changes the capacitance. Understand the concept of the dielectric constant and its effect.

- Prepare by reviewing the lab measurement and report section below and the equipment overview and further introductory material on https://www.physics.smu.edu/tneumann/110X_Spring2025/schedule-em/.

Pre-lab: Upload to Canvas before coming to the lab

A reminder: Upload your answers as a text document (exported as PDF) to Canvas before the lab begins (Canvas uploads are no longer possible 30 minutes before the lab starts!).

Pre-lab 1 7 points

- (1 point) How does the capacitance of a parallel-plate capacitor change if the area of the plates is increased?

- (1 point) How does the capacitance change if the distance between the plates of a parallel-plate capacitor is increased?
- (1 point) What is the role of the dielectric material between the capacitor plates?
- (1 point) If two capacitors are connected in parallel, what is the equivalent capacitance?
- (1 point) How does the charge stored on each capacitor in a parallel connection compare to the total charge stored by the combination?
- (1 point) How does the voltage across each capacitor in a parallel connection compare to the voltage across the combination?
- (1 point) Describe a possible way how we can measure the level of a non-conducting liquid in a vessel.

Lab measurements and report: submission by end of class

A reminder: All measurements must be fully documented . The final report must be uploaded to Canvas *by the end of the class* exported as PDF with plots and tables from Excel embedded as images. Canvas will stop accepting uploads 10 minutes after the class ends. If you have not fully completed your report, you must upload the documents as far as you have completed them for grading.

In this lab we study the concept of an electric field. We revisit how it is defined and use the relationship between potential and electric field strength in our measurement.

Measurement 1 *Building your own capacitor* 8 points

Before studying a parallel-plate capacitor in detail, you will work on building your own capacitor.

1. (8 points) Follow the steps to build a simple capacitor with a solid dielectric:
   a) Cut: Cut two equal-sized rectangles of aluminum foil (approximately 10 cm x 10 cm). Estimate and record the uncertainty of the foil's area based on the precision of your ruler measurements of the sides.
   b) Dielectric: Use a sheet of printing paper slightly larger than the foil rectangles as the dielectric.
   c) Assemble: Create a sandwich: one foil sheet, the paper, and the other foil sheet on top. Ensure the foil sheets are well-aligned and have paper dielectric completely between them to avoid shorts.
   d) Connect: Attach wires or leads to each foil sheet, using tape to secure them. Alternatively, consider using alligator clips for an easier connection. Pay attention to potential short circuits if the connections are loose.
   e) Test: This "capacitor" can be connected to a multimeter (set to capacitance mode) to measure its capacitance, which will likely be in the nanofarad range.

f) Photograph: Take a clear photo of your constructed capacitor alongside the multimeter **clearly displaying the measured capacitance value**. This photograph should be included in your lab report as evidence of your build and measurement.

   Points are subtracted if the photo does not clearly show the measured capacitance on the multimeter alongside the capacitor.

Additionally, include the numerical value of the measured capacitance value and its uncertainty with units in your report.

Measurement 2 *Studying the dielectric material of your own capacitor* 10 points

You will now modify your capacitor and study its dependence on distance between plates, dielectric constant and plate area.

1. (2 points) Hypothesize: Before making any changes, formulate a hypothesis about how you can modify the dielectric material of your capacitor to increase its capacitance. Explain your reasoning. Consider factors like the dielectric constant of different materials.
2. (3 points) Studying the dependence on dielectrics: Modify your capacitor to use each of the following dielectrics: printing paper, plastic foil, and cardstock paper. Create a table with columns for material name, capacitance and its uncertainty. Measure the capacitance using each material (you should already have done the measurement with the printing paper in the previous part).
3. (3 points) The capacitance of a parallel-plate capacitor is given by $C = \epsilon A/d$, where A is the area of the plates (aluminium foil), d the thickness of the dielectric and $\epsilon = \epsilon_0 \epsilon_r$, $\epsilon_0 = 8.8 \times 10^{-12}$ F/m. Measure the thickness and its uncertainty of each material using a micrometer and derive the value of ϵ_r for each of your materials. Add this number in an additional column to your table. Include uncertainties in d and A and propagate the uncertainty into ϵ_r.
4. (2 points) The relative dielectric constant ϵ_r of printing paper is between one and four, while for air it is $\epsilon_r \simeq 1$. Does your measured ϵ_r for paper agree with this value within its uncertainties? If not, argue what additional sources of uncertainties might have been neglected, or which uncertainties or effects you might have underestimated.

Measurement 3 *Measuring the water level with a parallel-plate capacitor.* 23 points

In this experiment we measure the water level with a parallel-plate capacitor by exploiting the different dielectric constants of water and air. The setup is a parallel-plate capacitor with metal plates of length and width a and separated by a distance d.

1. (2 points) Measure and record the width and length of the parallel-plate capacitor a including uncertainties. Using a micrometer, measure and record the distance between the parallel plates d including uncertainties. Nominally, the plates should have a length and width of 10 cm and a separation of 1 mm.
2. (1 point) Measure the capacitance C of the capacitor using the multimeter and record its value and uncertainty.

3. (3 points) Predict the capacitance using the formula $C = \epsilon_0 \epsilon_r A/d$ (using $\epsilon_r \approx 1$ for air) and include its uncertainty by propagating the uncertainties in A and d.
4. (2 points) Describe if your prediction and measurement of the capacity agree within uncertainties. If this is not the case, argue why that is the case, for example about neglected uncertainties.
5. (4 points) Fill the capacitor's vessel step by step with water in steps of 2 cm from 2 cm to 10 cm. For each step fill a table with columns for water level h, another column for your estimated uncertainty Δh, a column for the measured capacitance C and a column for the uncertainty ΔC. Also add the $h = 0$ cm value from your first measurement.

   Pay attention to units and units in column names. Half a point is given for each measurement with reasonably estimated uncertainties.
6. (4 points) Determine the dielectric constant of your water by determining $\epsilon_r^{\text{water}}$ from $C = \frac{\epsilon_0}{d} a(a + (\epsilon_r^{\text{water}} - 1)h)$ using a water fill level of $h \simeq 6$ cm, where you have measured a, d and h, and C is your capacitance measurement from above for a water level h.
7. (3 points) Now, using $C = \frac{\epsilon_0}{d} a(a+(\epsilon_r^{\text{water}}-1)h)$, and rearranging for h, $h = (C\frac{d}{\epsilon_0 a}-a)/(\epsilon_r^{\text{water}}-1)$, add another column to your spreadsheet for the predicted value of h in terms of a, d and your measured value of $\epsilon_r^{\text{water}}$.
8. (2 points) Create a plot of water level h vs measured capacitance C for h between 0 cm and 10 cm in steps of 2 cm for both your measured values of C and h and label it with "measured".
9. (2 points) In your plot of $h(C)$ add another curve for your predicted values of h as a function of the measured C. Briefly comment in how far measured and predicted values of h agree.

References

[1] D. Halliday, R. Resnick, and J. Walker. *Fundamentals of Physics*. Fundamentals of Physics. John Wiley & Sons.