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Laboratory Report

Experimental Determination of the Vacuum Permittivity Using a Parallel Plate Capacitor

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ABSTRACT

This experiment aimed to determine the **vacuum permittivity (ε_0)** by measuring the **capacitance** of a **parallel plate capacitor** (Figure 1**)** at varying plate separations. Additionally, a preliminary exercise was conducted to measure and compare the capacitance of **three commercial capacitors** (Figure 2) against their labelled values to familiarize ourselves with the capacitance meter. The experimental value of $\boldsymbol{\varepsilon_0}$ was obtained by **plotting capacitance ($\boldsymbol{C}$) versus the inverse of the plate separation ($\frac{1}{d}$)** and analysing the **slope**. The calculated value was found to be $\mathbf{1.25 \times 10^{-11}}$ **F/m**, yielding a 41% error when compared to the standard value of $\mathbf{8.85 \times 10^{-12}}$ **F/m**. Possible sources of error are discussed.

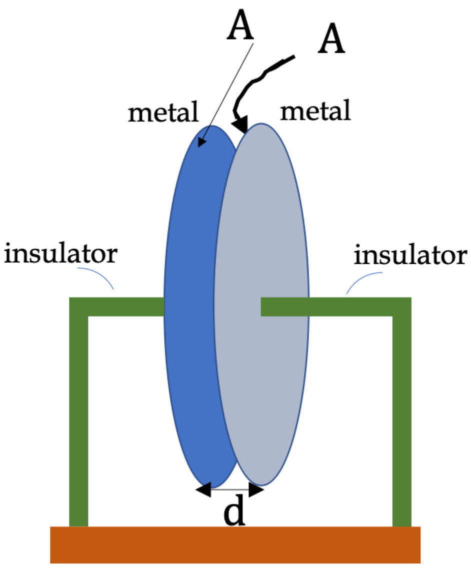


FIGURE 1. *Schematic of a Parallel Plate Capacitor Setup.*

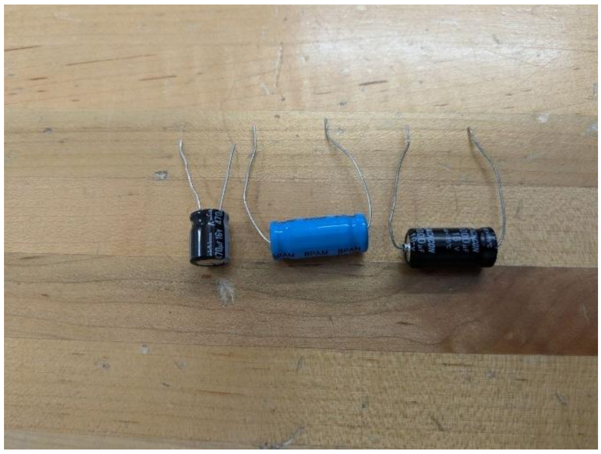


FIGURE 2. *Commercial capacitors used. in this experiment.*

THEORETICAL BACKGROUND

Capacitors are fundamental components in **electrical circuits**, used for ***storing electrical energy***. The capacitance of a parallel plate capacitor is determined by:

$$C = \frac{\varepsilon_0 A}{d}$$

where:

- C is capacitance,
- A is the plate area,
- d is the distance between plates,
- ε_0 is the distance between plates and is the permittivity of free space.

which shows that capacitance is **directly proportional** to **plate area** and **inversely proportion**al to the **separation distance**.

By rearranging the formula:

$$\varepsilon_0 = \frac{C \times d}{A}$$

we can experimentally determine ε_0 by measuring C at different values of d and **plotting C vs. $\frac{1}{d}$**.

The slope of this graph, when divided by A , yields ε_0 :

$$\varepsilon_0 = \frac{slope\ of\ C\ vs.\left(\frac{1}{d}\right)}{A}$$

DERIVATION OF SI UNIT FOR CHARGE (COULOMB):

Charge is defined in terms of **current and time**:

$$Q = I \times t$$

where:

- current I is in amperes (A),
- time t is in seconds (s).

Since $\mathbf{1A} = \frac{\mathbf{1C}}{\mathbf{s}}$, the unit of charge is:

$$1C = 1A \times 1s$$

or equivalently:

$$1C = A \times s$$

DERIVATION OF THE SI UNIT FOR CAPACITANCE (FARAD):

Capacitance is defined as the **charge stored per unit voltage:**

$$C = \frac{Q}{V}$$

Since charge Q is measured in coulombs (C) and voltage V in volts (V), the unit of capacitance is:

$$1F = \frac{1C}{1V}$$

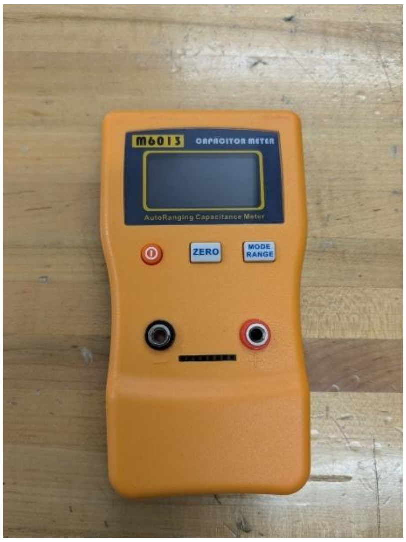
Using the relation $\boldsymbol{V} = \frac{J}{C}$ **(volt = joule per coulomb)**, we get:

$$1F = \frac{1C}{1\frac{J}{C}} = \frac{C^2}{J}$$

Since energy (J) is also $kg \times m^2/s^2$, we derive:

$$1F = \frac{C^2}{kg \times m^2/s^2} = \frac{A^2\, s^2}{m^2\, kg}$$

PRELIMINARY EXERCISE – COMMERCIAL CAPACITOR TESTING:



Before conducting the main experiment, we measured the capacitance of three commercial capacitors (Figure 2) using a capacitance meter (Figure 3) and compared the results with their labelled values.

FIGURE 3. *Capacitor Meter. Ensure the meter is zeroed before use for precise readings.*

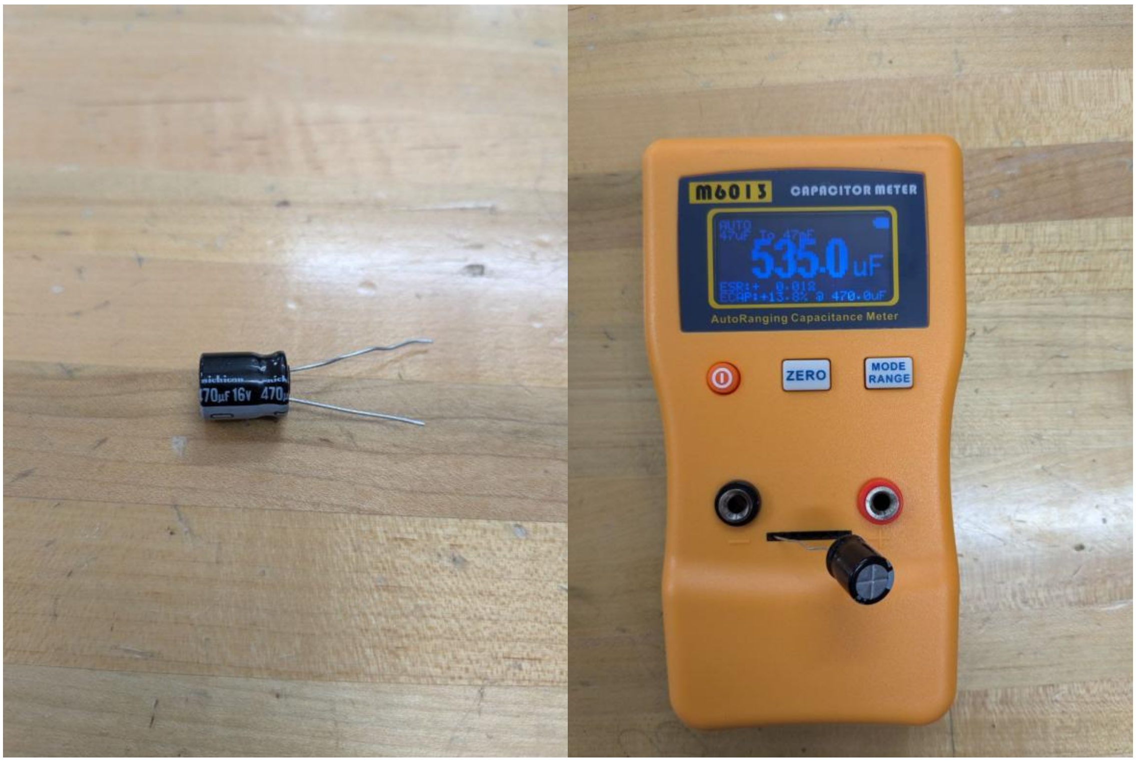


FIGURE 4. *Capacitor 1: 470 μF (labelled) vs. 535 μF (measured)*

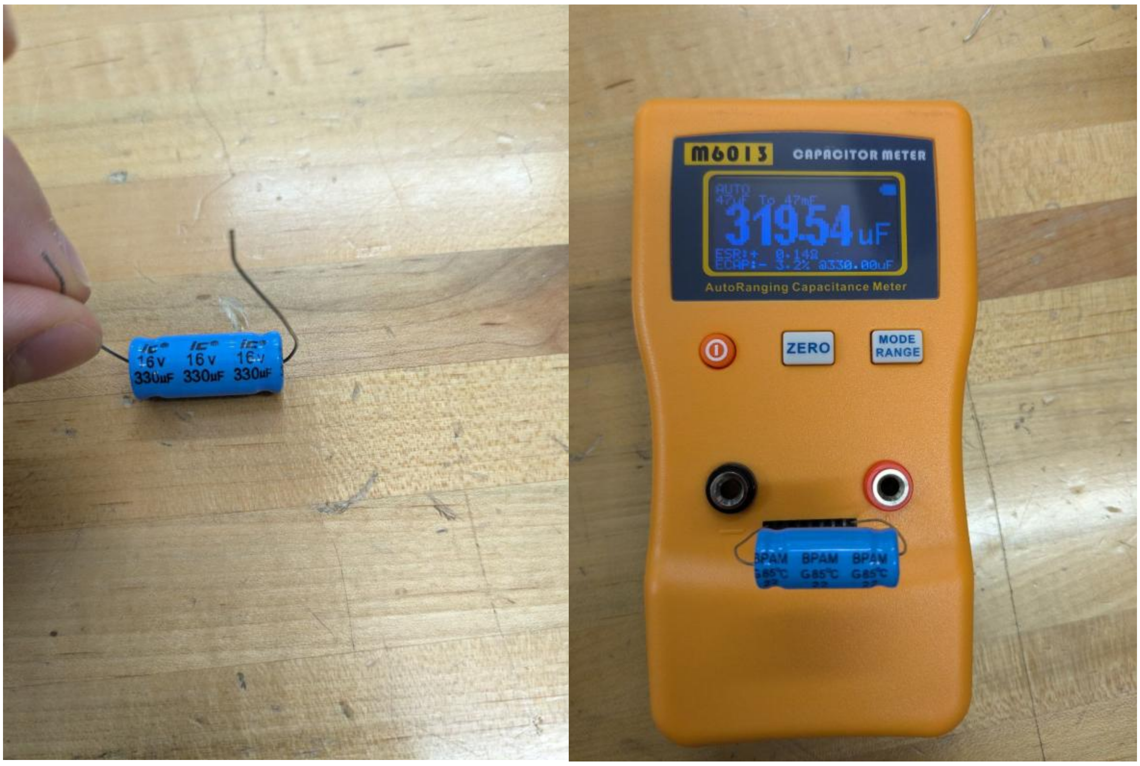


FIGURE 5. *Capacitor 2: 330 μF (labelled) vs. 319.54 μF (measured)*

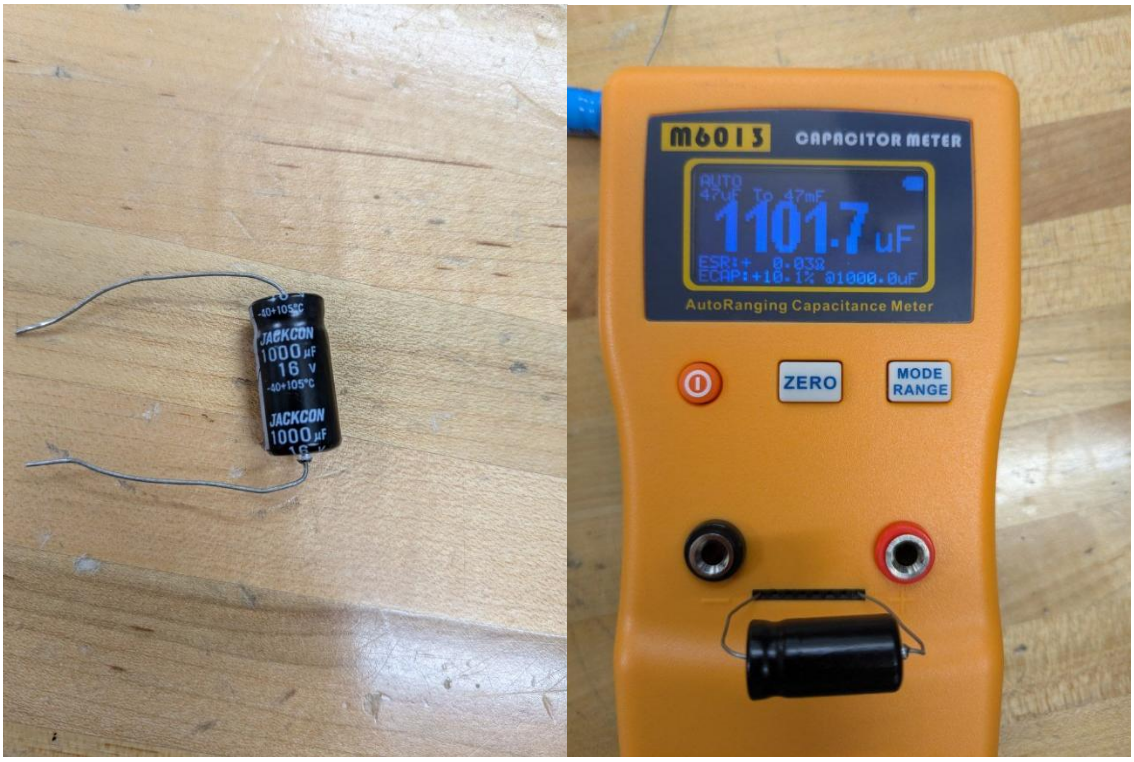


FIGURE 6. *Capacitor 3: 1000 μF (labelled) vs. 1101.7 μF (measured)*

This exercise demonstrated that real-world capacitance values often differ from manufacturer specifications due to tolerance and environmental factors.

PROCEDURE

APPARATUS:

1. Capacitance meter with connector cables (Figure 7)
2. Two circular conductive metal plates (Figure 8)
3. Metered holder for plates
4. Meter stick for plate diameter measurement

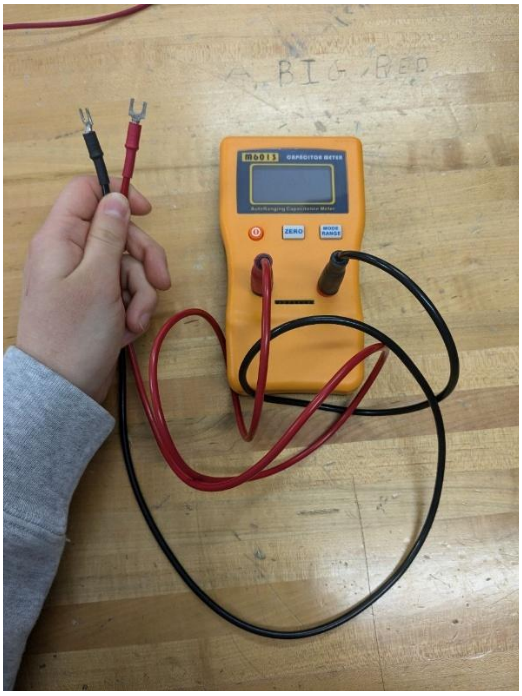
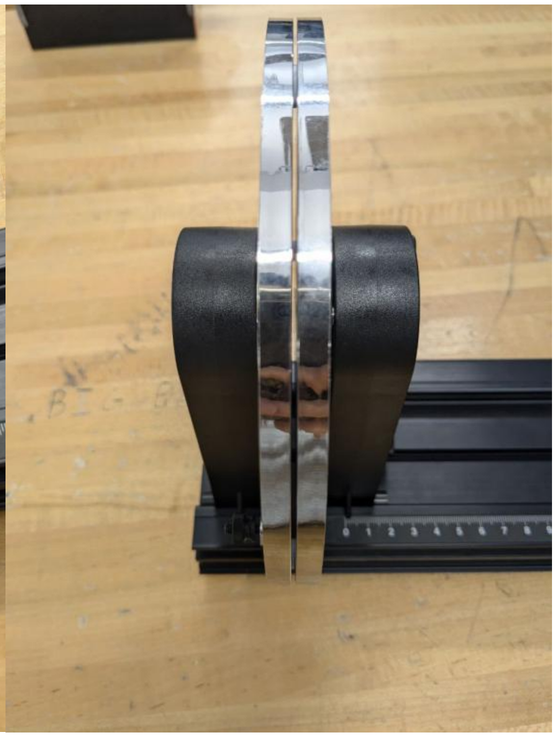


FIGURE 7. *Capacitance meter with connector cables. The meter must be zeroed before use to ensure accurate capacitance measurements.*

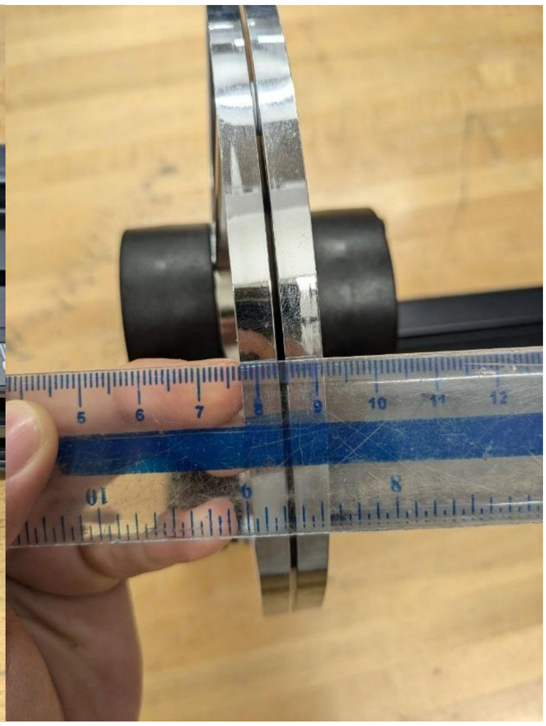
FIGURE 8. *Two circular conductive metal plates used to form a parallel plate capacitor. A small grey rubber spacer on one of the plates ensures that the plates never touch each other, preventing short circuits*

SETUP:

1. Gather all necessary materials.



2. Secure the metal plates onto the metered holder, ensuring they are aligned parallel to each other. The small grey rubber spacer on one plate prevents direct contact between the plates (See pictures above).



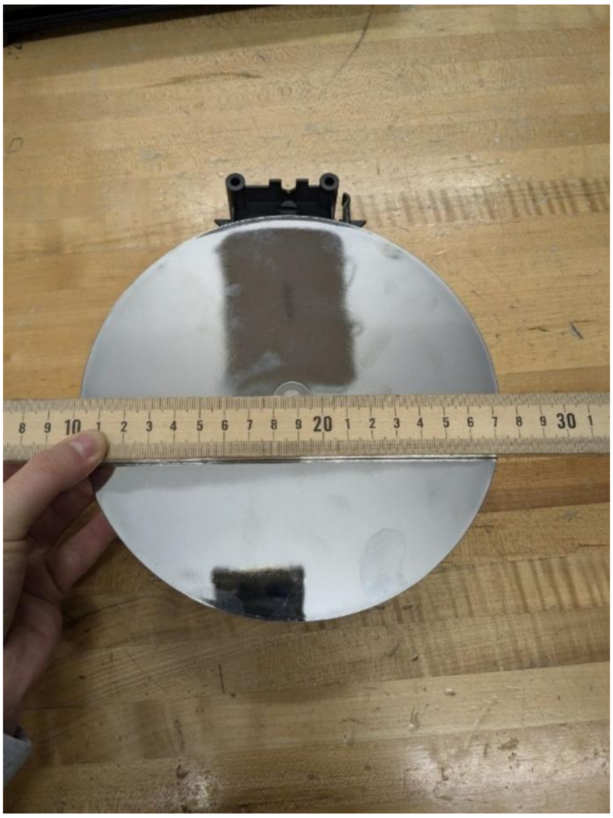
3. Position the plates at an initial separation of 1 mm and verify that the holder's scale reads 0 mm before adjusting the distance further (See pictures above).

4. Connect the capacitance meter to the metal plates using the provided connector cables. The red cable attaches to one plate, while the black cable attaches to the other (See picture above).
5. Turn on the capacitance meter and press the **ZERO** button to calibrate the device before taking measurements. This step is crucial for minimizing errors and obtaining reliable readings.

EXPERIMENT:

6. Set the initial plate separation to 1 mm and record the capacitance value displayed on the meter.

7. Gradually increase the plate separation by 1 mm increments, ensuring the plates remain parallel at each step. Use adjustment screws at the back of the pate for precise alignments (See picture above).
8. After each increment, record the new capacitance reading. Continue this process until reaching a plate separation of 10 mm, collecting at least 10 data points.



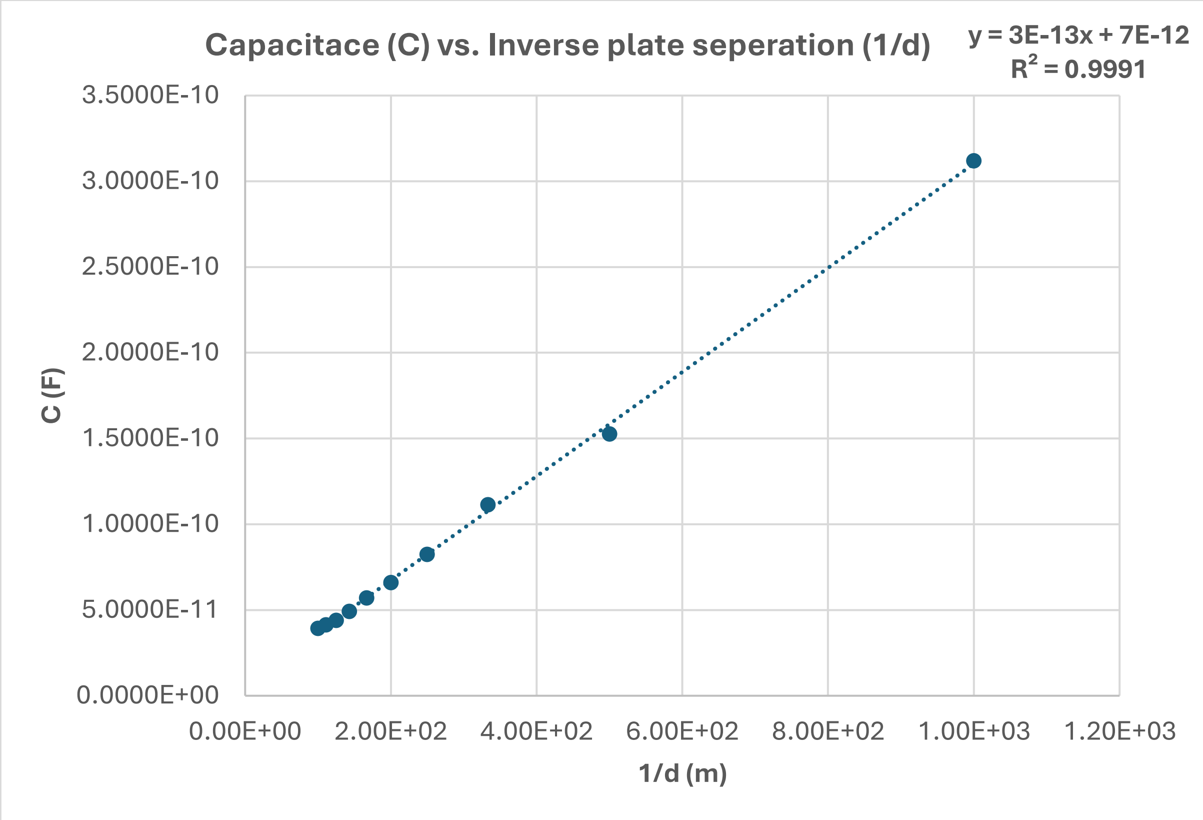
9. Once all measurements are recorded, use a meter stick to measure the diameter of the plates. This measurement is essential for calculating the plate area, which is required to determine the vacuum permittivity (ε_0).

DATA & ANALYSIS

The experimental data collected is summarized in the following tables:

Data Point	d $/mm$	C $/pF$	$\frac{1}{d}$ $/m$	C $/F$
1	1	312.02	1.00E+03	3.1202E-10
2	2	152.70	5.00E+02	1.5270E-10
3	3	111.35	3.33E+02	1.1135E-10
4	4	82.40	2.50E+02	8.2400E-11
5	5	66.00	2.00E+02	6.6000E-11
6	6	56.95	1.67E+02	5.6950E-11
7	7	49.10	1.43E+02	4.9100E-11
8	8	44.00	1.25E+02	4.4000E-11
9	9	41.40	1.11E+02	4.1400E-11
10	10	39.20	1.00E+02	3.9200E-11

TABLE 1. *Recorded capacitance values for varying plate separations. The table presents the measured capacitance (C) in picofarads (pF) and farads (F) for different plate distances (d) in millimeters. The inverse plate separation (1/d) is also calculated to facilitate the linear relationship analysis used to determine the vacuum permittivity* ε_0.



Graph 1. *Capacitance C vs. Inverse plate separation 1/d. The graph illustrates the expected linear relationship between capacitance and 1/d, confirming the theoretical equation* $\varepsilon_0 = \frac{C \times d}{A}$*. The slope m = 3E-13 of the best-fit line y = 3E-13x + 7E-12, when divided by the plate area, provides an experimental value for the vacuum permittivity* $\mathcal{E}_0$*. The high* R^2 *value of 0.9991 indicates strong agreement with the theoretical model.*

Radius of the plate $/m$	Area of the plate $/m^2$	Experimental ε_0 $/F$	Standard ε_0 $/F$	Error %
0.088	0.024328	1.25E-11	8.85E-12	41%

TABLE 2. *Calculation of the experimental permittivity of free space* $\mathcal{E}_0$*. The table summarizes the measured radius and calculated area of the capacitor plates, along with the experimentally determined value of* $\mathcal{E}_0$*. The standard accepted value of* $\mathcal{E}_0$ *is* $8.85 \times 10^{-12}\ F/m$*, while the experimentally obtained value is* $1.25 \times 10^{-11}\ F/m$*, resulting in a 41% error.*

DISCUSSION

Several factors contributed to 41% error. Firstly, the small plate separations (***starting at just 1 mm***) introduced significant sensitivity to measurement inaccuracies. Small variations in plate alignment or tiny deviations in distance measurements could result in **substantial percentage** errors in capacitance readings. Additionally, the **capacitance values themselves were extremely small *(on the order of $\mathbf{10^{-12}}$ $\boldsymbol{F}$***), making them highly susceptible to external interference, slight imperfections in the setup, or limitations in the capacitance meter's precision.

The experimental setup required ensuring that the plates remained perfectly parallel throughout the process. Misalignment, even by a **fraction of a millimeter**, would have led to **deviations from the expected theoretical capacitance values**. Furthermore, the **grey rubber spacer** on one of the plates prevented direct contact between them but could have **slightly affected the uniformity** of the spacing at smaller distances.

Despite the high error percentage, the experiment successfully demonstrated the fundamental relationship between capacitance and plate separation in a parallel plate capacitor. The observed trend confirmed that capacitance is inversely proportional to distance and directly proportional to plate area, in agreement with theoretical predictions.

CONCLUSION

This experiment successfully applied the fundamental capacitance formula to determine an experimental value of ε_0 . While the calculated value deviated **significantly** from the accepted standard, the error **can largely be attributed** to the challenges associated with measuring extremely **small distances** and **capacitance values**. Nonetheless, the results validated the expected proportional relationships, that **capacitance** is **inversely** proportional to **distance** and **directly proportional** to **plate area**, and provided insight into the precision required for accurate electrostatic measurements.

ACKNOWLEDGMENTS

I would like to acknowledge my lab partner Jonah Villafan and Jabir Rahman for his assistance in data collection. I also appreciate Dr. Ray D. Sameshima's guidance during the lab.

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FIGURES

Figure 1. Schematic of a parallel plate capacitor setup. *Physics Bootcamp*. Retrieved from https://www.physicsbootcamp.org/external/images/capacitors/parallel-cap.png.

Figure 2. Commercial capacitors used in this experiment. *Photograph by Zhasmin Tuiachieva*.

Figure 3. Capacitance meter. *Photograph by Zhasmin Tuiachieva*.

Figure 4. Capacitor 1: 470 μF (labeled) vs. 535 μF (measured). *Photograph by Zhasmin Tuiachieva*.

Figure 5. Capacitance meter readings for a 330 μF capacitor. *Photograph by Zhasmin Tuiachieva*.

Figure 6. Capacitance meter readings for a 1000 μF capacitor. *Photograph by Zhasmin Tuiachieva*.

Figure 7. Capacitor meter with connecting cables. *Photograph by Zhasmin Tuiachieva*.

Figure 8. Circular conductive metal plates used to form a parallel plate capacitor. *Photograph by Zhasmin Tuiachieva*.

TABLES

Table 1. *Recorded capacitance values for varying plate separations. By Zhasmin Tuiachieva, Jonah Villafan, and Jabir Rahman.*

Table 2. Summarization of the measured radius, calculated area, and the experimentally determined value of ε_0. *By Zhasmin Tuiachieva, Jonah Villafan, and Jabir Rahman.*

GRAPHS

Graph 1. Measured capacitance values for varying plate separations. *Graph created by Zhasmin Tuiachieva, Jonah Villafan, and Jabir Rahman*.