Capacitors

PURPOSE

In this experiment, you will investigate fundamental properties of capacitors, which is a device that stores charge (energy) and you will study capacitors connected in series and in parallel.

THEORY

A capacitor is a device that stores electrical energy in an electric field. A capacitor consists of two parallel isolated conductors (the plates) with charges +q and -q. The charge of the capacitor C is given by:

\[ q = CV \]  \hspace{1cm} (1)

Where \( V \) is the potential difference between the plates. The capacitance of the parallel-plates capacitor is calculated using:

\[ C = \frac{\kappa \varepsilon_0 A}{d} \]  \hspace{1cm} (2)

where \( \kappa \) is the relative permittivity of the dielectric material between the plates, \( \varepsilon_0 = 8.85 \times 10^{-12} \text{ F}\cdot\text{m}^{-1} \) is the vacuum permittivity, \( A \) is the area of the plates, and \( d \) is the separation between the plates. The electric field magnitude between the parallel plates of the capacitor is given by:

\[ E = \frac{V}{d} \]  \hspace{1cm} (3)

The electric potential energy \( U \) of a charged capacitor is given by:

\[ U = \frac{q^2}{2C} \text{ or } U = \frac{1}{2} CV^2 \]  \hspace{1cm} (4)

The equivalent capacitor \( C_{eq} \) of \( n \) capacitors in parallel is given by:

\[ C_{eq} = \sum_{i=1}^{n} C_i \]  \hspace{1cm} (5)

The equivalent capacitor \( C_{eq} \) of \( n \) capacitors in series is given by:

\[ \frac{1}{C_{eq}} = \sum_{i=1}^{n} \frac{1}{C_i} \]  \hspace{1cm} (6)

EXPERIMENTAL SETUP

One or more parallel plate capacitor(s); Battery; Voltmeter and two probes; Dielectric: Teflon, Paper, Glass and custom (with adjustable dielectric constant).
PROCEDURE
In this experiment, you will investigate the fundamental properties of a parallel plate capacitor. You should run the simulation from the site below:
https://phet.colorado.edu/en/simulation/legacy/capacitor-lab

1. Charging a Capacitor
In this part, you will be using a capacitor with air as a dielectric ($\kappa = 1.000$).
- Disconnect the battery (click on the control Disconnect Battery).
- Check all the boxes including Capacitance, Plate Charges, Storage Energy, Electric field lines and Voltmeter.
- Attach the red probe (positive) of the voltmeter to the connector attached to the positive terminal of the battery and the black probe (common) to the connector attached to the negative terminal of the battery.
- Slide the slider on the battery to have a maximum voltage of $+1.5$ V, verified by the voltmeter reading.
- Connect the battery (click on the box labeled Disconnect Battery).
- You should see the picture shown in Figure 2.

Note: If your meter bars are saturated (maximum reading), click on $\times$ to scale them back.

- For the plate separation of 10.0 mm and the capacitor plate area of 100.0 mm$^2$, record the measured values of voltage, capacitance, plate charge, and stored energy in the table below.

| Area $A$ (mm$^2$) | Plate Separation $d$ (mm) | Capacitance $C$ (pF) | Voltage $|V|$ (V) | Charge $|Q|$ (pC) | Calculated Electric Field $|E|$ (V/m) | Energy $U$ (pJ) |
|-------------------|---------------------------|-----------------------|-----------------|-----------------|--------------------------------------|----------------|
| 100.0             | 10.0                      |                       |                 |                 |                                      |                |

Table 1
2. Changing Capacitor Area
In this part, you will be using a capacitor with air as a dielectric (κ = 1.000).
- Slide the slider on the battery to have a maximum voltage of +1.5 V, verified by the voltmeter reading.
- Check all the boxes including Capacitance, Plate Charges, Storage Energy, Electric field lines and Voltmeter.
- Fix the separation between the plates as per your instructor recommendation, in the range between 5 and 10 mm.
- Slowly increase the area of the plates by dragging the little double arrow away from the plates. The range of area is between 100 and 400 mm².
- Make sure that the voltmeter probes stay connected to the wires as shown in Figure 1.
- Fill your results in the table 2.

| Area $A$ (mm²) | Plate Separation $d$ (mm) | Capacitance $C$ (pF) | Voltage $|V|$ (V) | Charge $|Q|$ (pC) | Calculated Electric Field $|E|$ (V/m) | Energy $U$ (pJ) |
|----------------|--------------------------|----------------------|----------------|---------------|---------------------------------|----------------|
| 100            |                          |                      |                |               |                                 |                |
| 200            |                          |                      |                |               |                                 |                |
| 300            |                          |                      |                |               |                                 |                |
| 400            |                          |                      |                |               |                                 |                |

Table 2

- Discuss your observations on the change of capacitance, charge, potential energy, and calculated electric field magnitude with increasing capacitor plate area.

3. Changing Capacitor Plate Separation
In this part, you will be using a capacitor with air as a dielectric (κ = 1.000).
- Slide the slider on the battery to have a maximum voltage of +1.5 V, verified by the voltmeter reading.
- Check all the boxes including Capacitance, Plate Charges, Storage Energy, Electric field lines and Voltmeter.
- Fix the area of the plates as per your instructor recommendation (range of area is between 100 and 400 mm²).
- Slowly change the separation between the plates by dragging the little double arrow down (or up). The range of plate separation is between 5 and 10 mm.
- Make sure that the voltmeter probes stay connected to the wires as shown in Figure 1.
- Fill you results in the table 3 below.

| Area $A$ (mm²) | Plate Separation $d$ (mm) | Capacitance $C$ (pF) | Voltage $|V|$ (V) | Charge $|Q|$ (pC) | Calculated Electric Field $|E|$ (V/m) | Energy $U$ (pJ) |
|----------------|--------------------------|----------------------|----------------|---------------|---------------------------------|----------------|
| 5              |                          |                      |                |               |                                 |                |
| 6              |                          |                      |                |               |                                 |                |
| 8              |                          |                      |                |               |                                 |                |
| 10             |                          |                      |                |               |                                 |                |

Table 3

- Discuss your observations on the change of capacitance, charge, potential energy, and calculated electric field magnitude with increasing plate separation.
4. Changing the Dielectric Material
- Click on the Dielectric tab to switch to another window as shown in Figure 2. In this part, you will be using a dielectric material including Teflon, glass, paper or custom with dielectric constant between 1 and 5.

Figure 2

- Slide the slider on the battery to have a maximum voltage of +1.5 V, verified by the voltmeter reading.
- Check all the boxes including Capacitance, Plate Charges, Storage Energy, Electric field lines and Voltmeter.
- Fix the area of the plates as per your instructor recommendation (range of area is between 100 and 400 mm²).
- Fix the separation between the plates as per your instructor recommendation, in the range between 5 and 10 mm.
- Select the dielectric as per your instructor recommendation (Custom, Teflon, Paper, Glass).
- Insert the dielectric all the way between the plates by dragging the little double arrow to the left (labeled offset) as shown in Figure 2.
- Fill your results in table 4 below.

<table>
<thead>
<tr>
<th>Area A (mm²)</th>
<th>Separation d (mm)</th>
<th>Dielectric Material</th>
<th>Dielectric Constant κ</th>
<th>Capacitance C (pF)</th>
<th>Voltage</th>
<th>Charge</th>
<th>Calculated Electric Field</th>
<th>U (pJ)</th>
<th>Energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Custom (air)</td>
<td></td>
<td></td>
<td>1.000</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Teflon</td>
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<tr>
<td>Paper</td>
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<td></td>
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<tr>
<td>Glass</td>
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<td></td>
</tr>
</tbody>
</table>

- Discuss your observations on the change of capacitance, charge, potential energy, and calculated electric field magnitude with increasing dielectric constant.
5. Capacitors Connected in Series
- Click on the Multiple Capacitors tab to switch to another window and choose “2 in series” for capacitors connected in series as shown in Figure 3.

- Slide the slider on the battery to have a maximum voltage of +1.5 V, verified by the voltmeter reading.
- Check all the boxes including Capacitance, Plate Charges, Storage Energy, Electric field lines and Voltmeter.
- Use the values of the capacitor \( C_1 \) and \( C_2 \) as per your instructor recommendation. The capacitance is in the range of 0.1 to 0.3 pF.
- Fill table 5 below including the experimental equivalent capacitance, voltage, charge and potential energy of the equivalent capacitance.

| Capacitance \( C_1 \) (pF) | Capacitance \( C_2 \) (pF) | Equivalent Capacitance \( C_{exp} \) (pF) | Voltage \( |V| \) (V) | Charge \( |Q| \) (pC) | Energy \( U \) (pJ) |
|--------------------------|--------------------------|---------------------------------|----------------|----------------|----------------|
|                          |                          |                                 |                |                |                |

- How do the experimental and theoretical values of equivalent capacitances compare? Show the details of your calculation.
6. Capacitors Connected in Parallel

- Click on the Multiple Capacitors tab to switch to another window and choose “2 in Parallel” for capacitors connected in parallel as shown in Figure 4.

- Slide the slider on the battery to have a maximum voltage of +1.5 V, verified by the voltmeter reading.
- Check all the boxes including Capacitance, Plate Charges, Storage Energy, Electric field lines and Voltmeter.
- Use the values of the capacitor $C_1$ and $C_2$ as per your instructor recommendation. The capacitance is in the range of 0.1 to 0.3 pF.
- Fill table 6 below including the experimental equivalent capacitance, voltage, charge and potential energy of the equivalent capacitance.

| Capacitance $C_1$ (pF) | Capacitances $C_2$ (pF) | Equivalent Capacitance $C_{\text{eq}}$ (pF) | Voltage $|V|$ (V) | Charge $|Q|$ (pC) | Energy $U$ (pJ) |
|-------------------------|-------------------------|------------------------------------------|----------------|--------------|----------------|
|                         |                         |                                          |                |              |                |

Table 6

- How do the experimental and theoretical values of equivalent capacitances compare? Show the details of your calculation.
QUESTIONS
1) If a capacitor is connected to the battery and you double the area of the capacitor, what happens to the capacitor voltage, charge, electric field and potential energy? Verify you answer theoretically (show equations).

2) If a capacitor is connected to the battery and you double the capacitor plate separation, what happens to the capacitor voltage, charge, electric field, and potential energy? Verify you answer theoretically (show equations).

3) If a capacitor is connected to the battery and you replace the air by a dielectric with dielectric constant $\kappa$, what happens to the capacitor voltage, charge, electric field, and potential energy? Verify you answer theoretically (show equations).

4) If a capacitor $C_1$, is connected to the battery and you disconnect the capacitor from the battery, what happens to the capacitor voltage, charge, electric field, and potential energy? Verify you answer experimentally.

5) If a capacitor $C_1$, is connected to the battery and you connect a similar capacitor $C_2$ in parallel with it, what happens to the capacitor $C_1$ voltage, charge, electric field, and potential energy? Verify your answer theoretically (show equations).

CONCLUSION: What did you learn from this experiment?