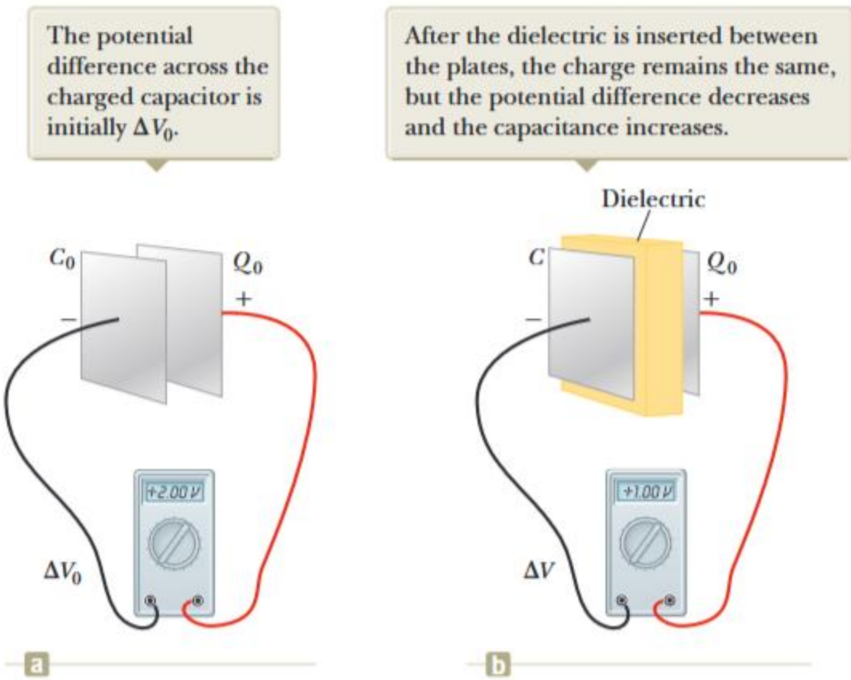
25.5 Capacitor with Dielectric



1. Introduction to Dielectrics

- A **dielectric** is an insulating material (nonconducting material) placed between the plates of a capacitor.
- It **increases the capacitance** of a capacitor without conducting electricity.
- Examples: Glass, plastic, mica, paper, and ceramic.

2. Effect of Dielectrics on Capacitance

- When a dielectric is inserted, the capacitance increases by a factor **k**, called the **dielectric constant**.
- From the experiments and as shown in the figure, the new potential difference after adding the dielectric materials is less than the initial potential before adding the dielectric material:

$$(\Delta \boldsymbol{V} = \frac{\Delta \boldsymbol{V_0}}{\mathbf{k}};\ \mathbf{k} > \mathbf{1}\ ;\ \Delta \boldsymbol{V_0} > \Delta \boldsymbol{V})$$

- The new capacitance is: $C=\kappa C_{0;}$ where $\mathbf{C_0}$ is the capacitance without the dielectric, and **k** is the dielectric constant for the material and a dimensionless factor.
- The capacitance of a parallel-plate capacitor filled with a dielectric is given by:

$$C = kC_0 = k\frac{\varepsilon_0 A}{d}$$

3. Polarization in Dielectrics

- When a dielectric is placed in an electric field:
    1. Molecules in the dielectric **polarize**, creating an internal field.
    2. This reduces the **net electric field (E')** inside the capacitor.
    3. As a result, the voltage **decreases**, and the capacitance increases.

4. Energy Stored in a Capacitor with a Dielectric

- The energy stored in a capacitor with a dielectric is:

$$U = \frac{1}{2}CV^2$$

Since C increases with a dielectric, the energy stored also increases.

5. Dielectrics in a Capacitor: Two Cases

Case 1: Battery Connected (Constant Voltage)

- When a dielectric is inserted while the battery is connected:
    - **Voltage remains constant**.
    - **Capacitance increases** by a factor k.
    - **Charge (Q) increases** since Q=CV➔ $(Q = kQ_0)$
    - **Energy (U) increases**.

Case 2: Battery Disconnected (Constant Charge)

- When a dielectric is inserted after disconnecting the battery:
    - **Charge remains constant**.
    - **Capacitance increases**.
    - **Voltage decreases** (since V=Q/C)➔$(V = \frac{V_0}{k})$
    - **Energy decreases**.

6. Dielectric Breakdown

- If the electric field is too strong, the dielectric **breaks down**, becoming conductive.
- The maximum electric field a dielectric can withstand is called the **dielectric strength**.
- Exceeding this leads to electrical discharge (like in lightning or spark gaps).

7. Applications of Dielectrics in Capacitors

- Used in **electronic circuits**, power supply units, and memory storage devices.
- Dielectrics improve **energy storage** and allow capacitors to be more compact.

TABLE 25.1 Approximate Dielectric Constants and Dielectric Strengths of Various Materials at Room Temperature

Material	Dielectric Constant κ	Dielectric Strength[a] (10^6 V/m)
Air (dry)	1.000 59	3
Bakelite	4.9	24
Fused quartz	3.78	8
Mylar	3.2	7
Neoprene rubber	6.7	12
Nylon	3.4	14
Paper	3.7	16
Paraffin-impregnated paper	3.5	11
Polyethylene	2.30	18
Polystyrene	2.56	24
Polyvinyl chloride	3.4	40
Porcelain	6	12
Pyrex glass	5.6	14
Silicone oil	2.5	15
Strontium titanate	233	8
Teflon	2.1	60
Vacuum	1.000 00	—

[a]The dielectric strength equals the maximum electric field that can exist in

Example-1:

A parallel-plate capacitor is charged with a battery to a charge Q_0. The battery is removed, and a slab of material with a dielectric constant k is inserted between the plates. Identify the system as the capacitor and the dielectric. Find the energy stored in the system before and after the dielectric is inserted.

- Think about the energy stored if the battery is CONNECTED and the voltage between the capacitor is constant!!

• Electrostatic energy in a capacitor: $U = \frac{1}{2} C V^2 = \frac{1}{2} Q^2 / C$

• Capacitance with dielectric filling the gap: $C = \kappa C_0$ (C_0 is the capacitance without dielectric).

1) Before Insertion (no dielectric; charge Q_0)

Capacitance: C_0

Energy: $U_0 = (1/2)\, Q_0^2 / (C_0)$

2) After Insertion (battery disconnected; charge remains Q_0)

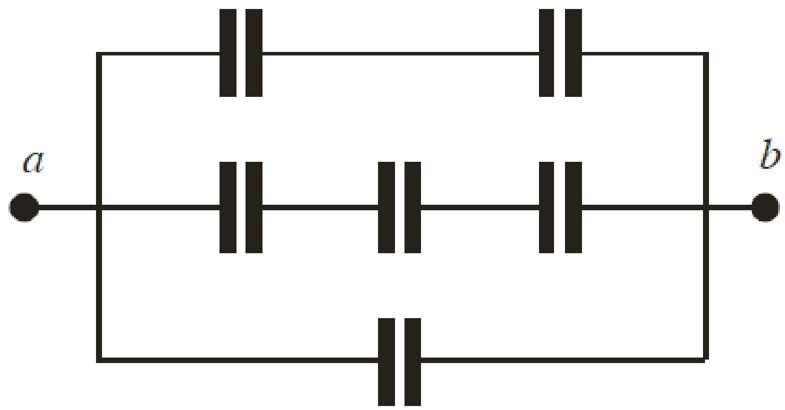
Capacitance becomes: $C = \kappa\, C_0$

Energy: $U_f = (1/2)\, Q_0^2 / (C) = (1/2)\, Q_0^2 / (\kappa\, C_0) = U_0 / \kappa$

Think about it, what would be the energy if the voltage is constant?

Extra Exercises:

1- What is the equivalent capacitance of the combination of the capacitors in the drawing below, knowing that the capacitance of each is C?



2- When an insulating material, with a dielectric constant K=3, is inserted between the plates of a capacitor whose capacitance equals C_o, what is the new capacitance, C?

3- If the stored energy of a capacitor, disconnected from the electric circuit, equals U_o, what is its stored energy, U, after inserting a dielectric material, whose K = 5, between its plates?

4- For a capacitor having $C = 6\ \mu F$, $d = 0.07\ mm$, and a dielectric material with $E_{max} = 14 \times 10^6\ V/m$, what is the maximum charge that can accumulate on its plate?

5- Find the equivalent capacitance between points a and b in the combination of capacitors shown in the Figure. (Answer: 12.9 µF)