Quick Quiz 26.1 A capacitor stores charge Q at a potential difference ΔV. What happens if the voltage applied to the capacitor by a battery is doubled to $2\,\Delta V$? **(a)** The capacitance falls to half its initial value, and the charge remains the same. **(b)** The capacitance and the charge both fall to half their initial values. **(c)** The capacitance and the charge both double. **(d)** The capacitance remains the same, and the charge doubles.

$$C \equiv \frac{2Q}{2\Delta V}$$

Quick Quiz 26.4 You have three capacitors and a battery. In which of the following combinations of the three capacitors is the maximum possible energy stored when the combination is attached to the battery? **(a)** series **(b)** parallel **(c)** no difference because both combinations store the same amount of energy

26.5: Capacitors with Dielectrics

A dielectric is a nonconducting material that, when placed between the plates of a capacitor, increases the capacitance.

- Dielectrics include rubber, glass, and waxed paper

Two important Notes:

$\Delta V \rightarrow$ same

If the capacitor remains connected to a battery, the voltage across the capacitor necessarily remains the same.

If the capacitor is disconnected from the battery, the capacitor is an isolated system and the charge remains the same.

$Q \rightarrow$ same

Now, we need to investigate the effect of inserting a dielectric material between the plates of a capacitor.

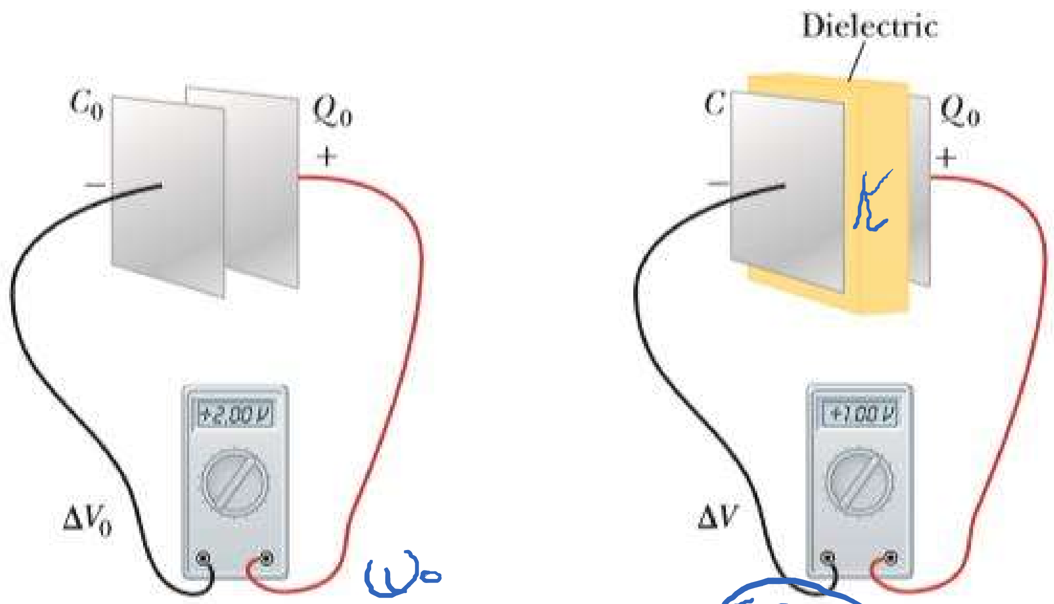
Assume a charged capacitor (disconnected from the battery!) without dielectric that has a charge Q_0 as shown.

After inserting the dielectric:

- the charge remains unchanged. $\rightarrow Q_0$
- The potential difference becomes $\Delta V = \dfrac{\Delta V_0}{\kappa}$

where ΔV_0 is the potential difference without dielectric

and κ is the dielectric constant, where $\kappa > 1$ ➔ $\Delta V < \Delta V_0$



The capacitance without dielectric is $C_0 = \dfrac{Q_0}{\Delta V_0}$

$$C = \frac{Q_0}{\frac{\Delta V_0}{\kappa}} = \kappa \frac{Q_0}{\Delta V_0} \quad C_0$$

Since the charge remains unchanged ➔ the capacitance with dielectric becomes:

$$C = \frac{Q_0}{\Delta V} = \frac{Q_0}{\Delta V_0/\kappa} = \kappa \frac{Q_0}{\Delta V_0} \quad ➔ \quad \boxed{C = \kappa C_0}$$

with without

$\Rightarrow \kappa > 1 \Rightarrow C > C_0$

- Because $\kappa > 1$, the capacitance increases by the factor κ when the dielectric completely fills the region between the plates.

For a parallel-plate capacitor, $C = \kappa \dfrac{\epsilon_0 A}{d}$ ← $C = K C_0$ ← $C_0 = \dfrac{\varepsilon_0 A}{d}$

ΔV - E

In theory, *d* could be made very small to create a very large capacitance.

In practice, there is a limit to *d.*

- *d* is limited by the electric discharge that could occur though the dielectric medium separating the plates.

For a given *d*, the maximum voltage that can be applied to a capacitor without causing a discharge depends on the **dielectric strength** (maximum electric field) of the dielectric.

If the magnitude of the electric field in the dielectric exceeds the dielectric strength, the insulating properties break down and the dielectric begins to conduct.

Dielectrics provide the following advantages:

- Increase in capacitance
- Increase the maximum operating voltage
- Possible mechanical support between the plates
  - This allows the plates to be close together without touching.
  - This decreases *d* and increases *C.*

d

Table 26.1 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
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	—
Water	80	—

[a]The dielectric strength equals the maximum electric field that can exist in a dielectric without electrical breakdown.

Example 26.5 Energy Stored Before and After **AM**

i f

A parallel-plate capacitor is charged with a battery to a charge Q_0. The battery is then removed, and a slab of material that has a dielectric constant κ 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.

The energy stored without dielectric is $U_0 = \dfrac{Q_0^{\,2}}{2C_0}$

The energy stored with dielectric is $U = \dfrac{Q_0^{\,2}}{2C}$ ➔ $U = \dfrac{Q_0^{\,2}}{2\kappa C_0} = \dfrac{U_0}{\kappa}$

But since $\kappa > 1$ ➔ $U < U_0$: the final energy is less than the initial energy!

$U_i \to U_0$, $U_f \to U$

$U_f = U = \dfrac{Q^2}{2C} = \dfrac{Q_0^2}{2\kappa C_0} = \dfrac{1}{\kappa}\dfrac{Q_0^2}{2C_0} = \dfrac{U_0}{\kappa}$

$W = \Delta U = U_f - U_i = U - U_0 = U_0\left(\frac{1}{\kappa} - 1\right) < 0$

Note that the work done needed to insert the dielectric is $W = \Delta U$ ➔ $W < 0$: negative work. Why?

When the dielectric is inserted, it is pulled into the device. To keep the dielectric from accelerating, an external agent must do negative work on the dielectric. Therefore W is negative!

Think about W needed to remove the dielectric!

$i \to$ with, $f \to$ without $\rightarrow W > 0$