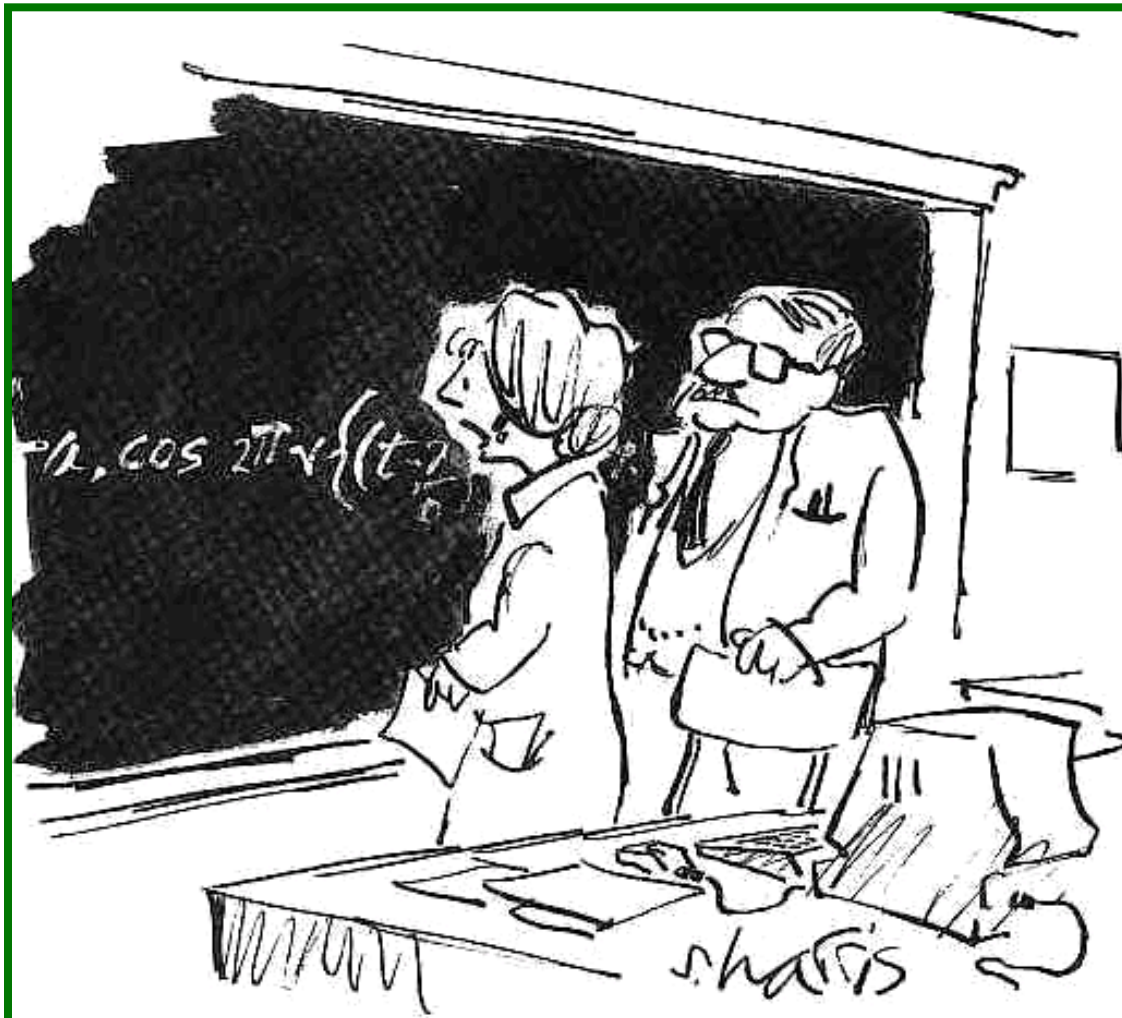
Dielectrics



"IT'S AN EXCELLENT PROOF, BUT IT LACKS WARMTH AND FEELING."

- **A dielectric** is an insulator, & is characterized by a dielectric constant ***K*** (or ***Kappa***).
- The capacitance of a parallel-plate capacitor filled with a dielectric is:

$$\boxed{C = K\epsilon_0 \frac{A}{d}.}$$

- Using the dielectric constant, ***the permittivity is defined as***:

$$\boxed{\epsilon = K\epsilon_0.}$$

- For a parallel-plate capacitor filled with a dielectric

$$\boxed{C = K\epsilon_0 \frac{A}{d}.}$$

The permittivity is: $\boxed{\epsilon = K\epsilon_0.}$

- Dielectrics in capacitors **provide the following advantages:**

  a. Increase in capacitance

  b. Increase the maximum operating voltage

- This allows the plates to be close together without touching. This decreases **d** and increases **C**.

Dielectric Constants & Dielectric Strengths

TABLE 24–1
Dielectric Constants (at 20°C)

Material	Dielectric constant K	Dielectric strength (V/m)
Vacuum	1.0000	
Air (1 atm)	1.0006	3×10^6
Paraffin	2.2	10×10^6
Polystyrene	2.6	24×10^6
Vinyl (plastic)	2–4	50×10^6
Paper	3.7	15×10^6
Quartz	4.3	8×10^6
Oil	4	12×10^6
Glass, Pyrex	5	14×10^6
Porcelain	6–8	5×10^6
Mica	7	150×10^6
Water (liquid)	80	
Strontium titanate	300	8×10^6

The ***dielectric strength*** is the maximum electric field a dielectric can experience without breaking down.

Dielectric Constants & Dielectric Strengths

TABLE 26.1 *Approximate Dielectric Constants and Dielectric Strengths of Various Materials at Room Temperature*

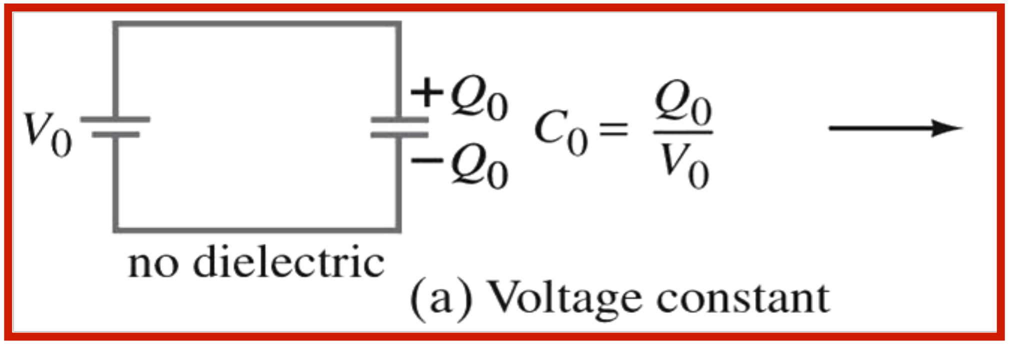
Material	Dielectric Constant κ	Dielectric Strength[a] (10^6 V/m)
Air (dry)	1.000 59	3
Bakelite	4.9	24
Fused quartz	3.78	8
Mylar	3.2	7
Neoprene rubber	6.7	12
Nylon	3.4	14
Paper	3.7	16
Paraffin-impregnated paper	3.5	11
Polystyrene	2.56	24
Polyvinyl chloride	3.4	40
Porcelain	6	12
Pyrex glass	5.6	14
Silicone oil	2.5	15
Strontium titanate	233	8
Teflon	2.1	60
Vacuum	1.000 00	—
Water	80	—

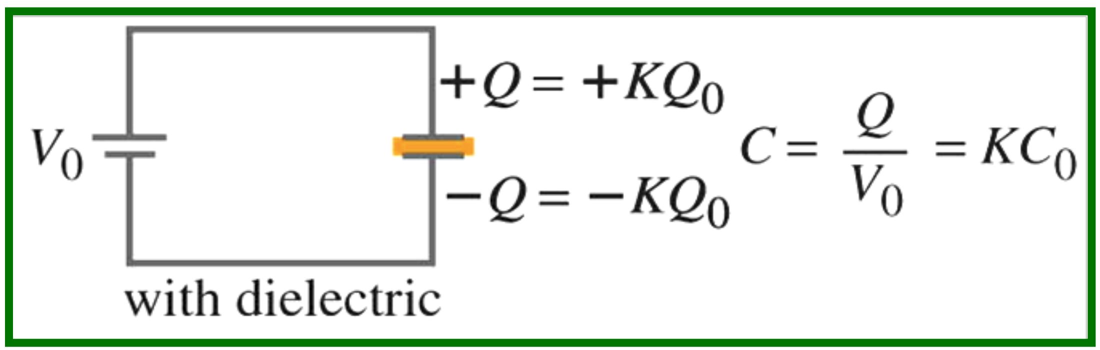
[a]The dielectric strength equals the maximum electric field that can exist in a dielectric without electrical breakdown. These values depend strongly on the presence of impurities and flaws in the materials.

- Consider *two experiments* where a dielectric is inserted & removed a from a capacitor.

Experiment #1

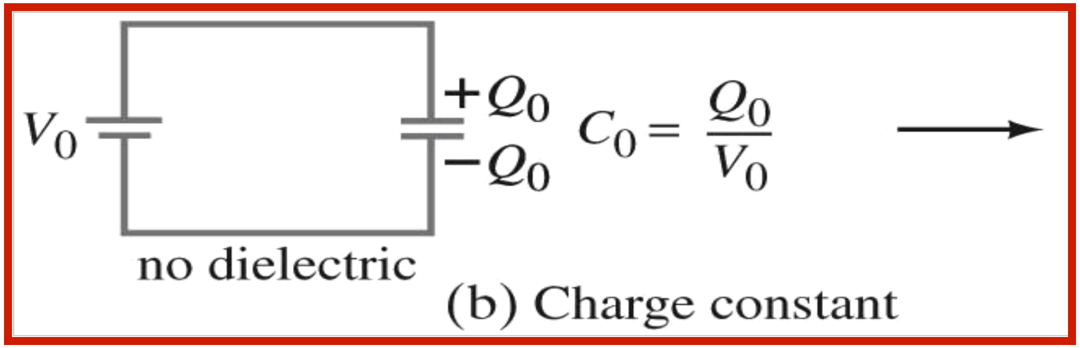
- The capacitor is connected to a battery, so the voltage $\mathbf{V_0}$ remains constant. See figures below.
- When the dielectric is inserted, the capacitance **C** increases.
- So, the charge **Q** on the plates must also increase.

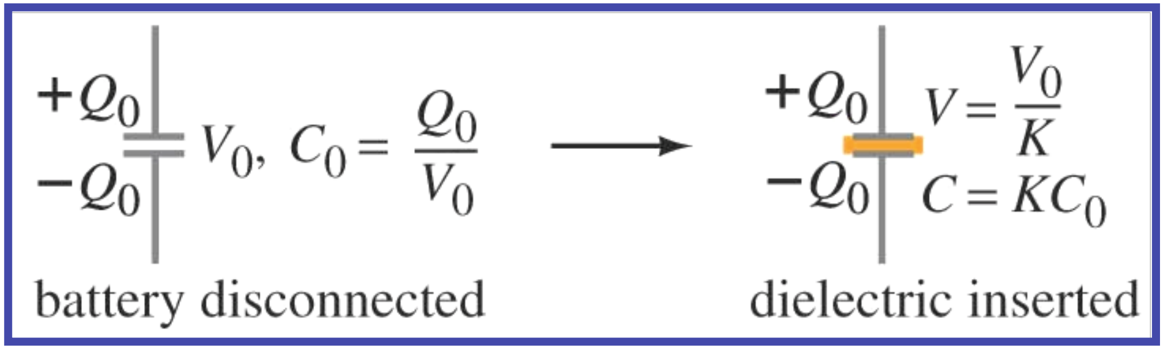




Experiment #2:

- A capacitor is charged & then disconnected from the battery. Then, a dielectric is inserted. In this case, the charge remains constant. See figures below.
- Since the dielectric increases the capacitance, the potential across the capacitor must drop.

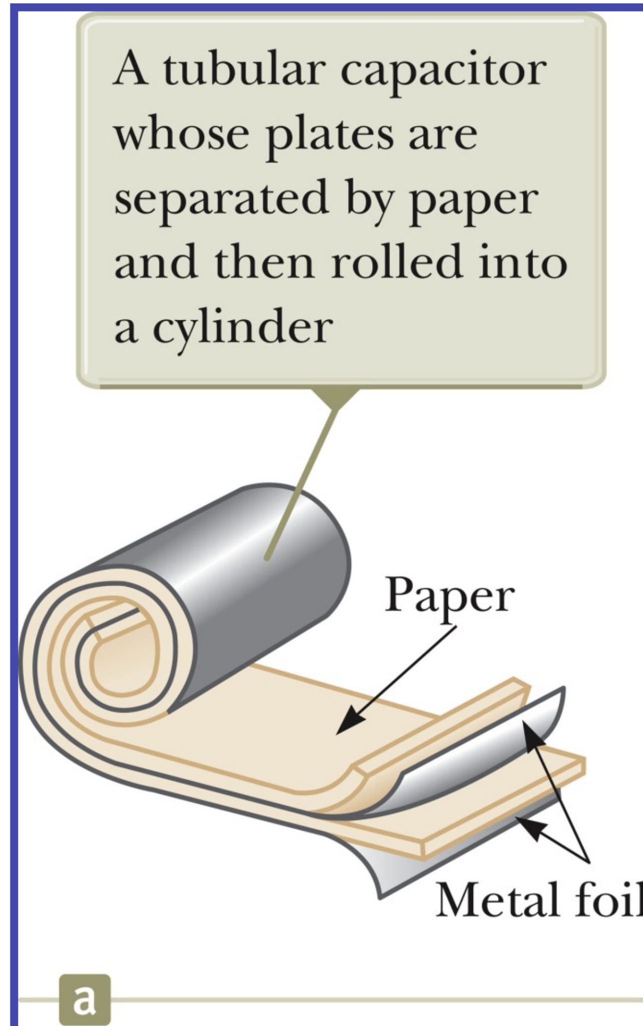




There are Many Types of Capacitors

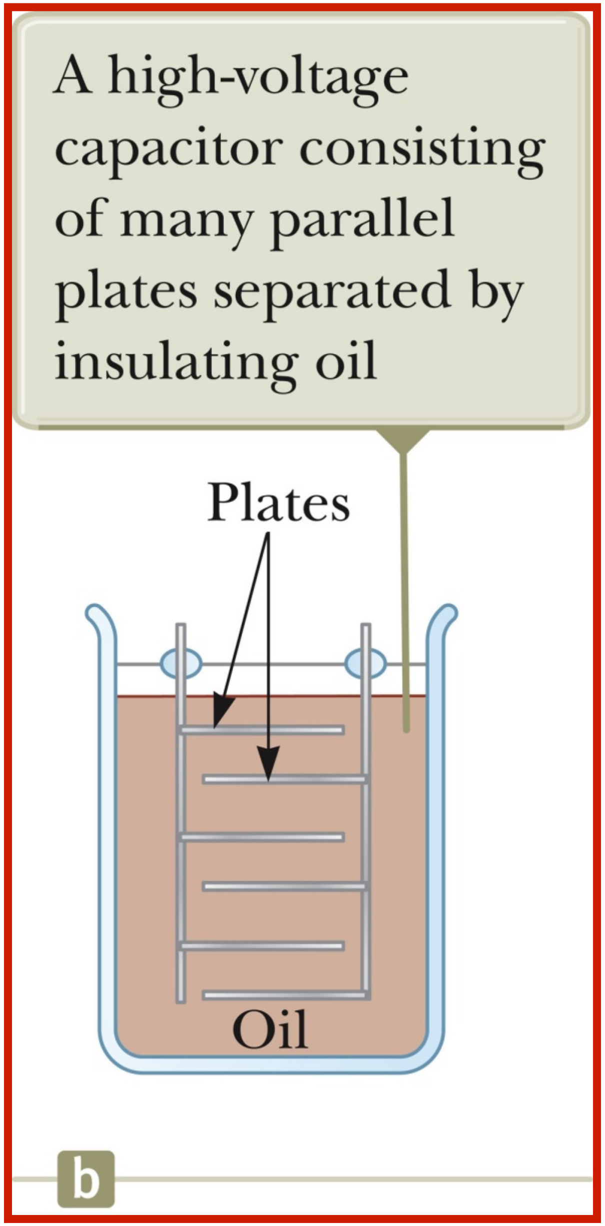
Example: Tubular Capacitors

- Metallic foil may be interlaced with thin sheets of paraffin impregnated paper or Mylar.
- The layers are rolled into a cylinder to form a small package for the capacitor.



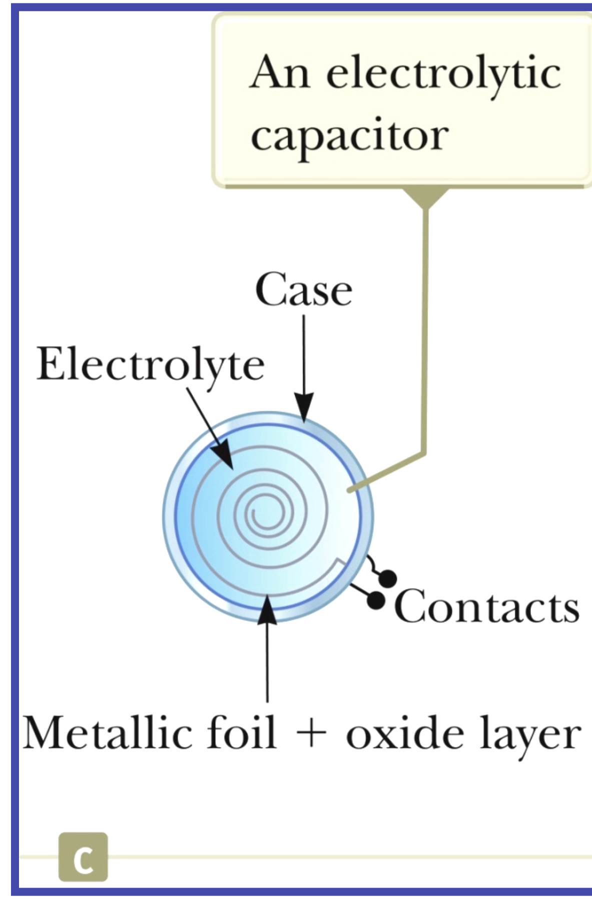
Example: An Oil Filled Capacitor

- These are commonly used for high-voltage capacitors
- They consist of a number of interwoven metallic plates immersed in silicon oil.



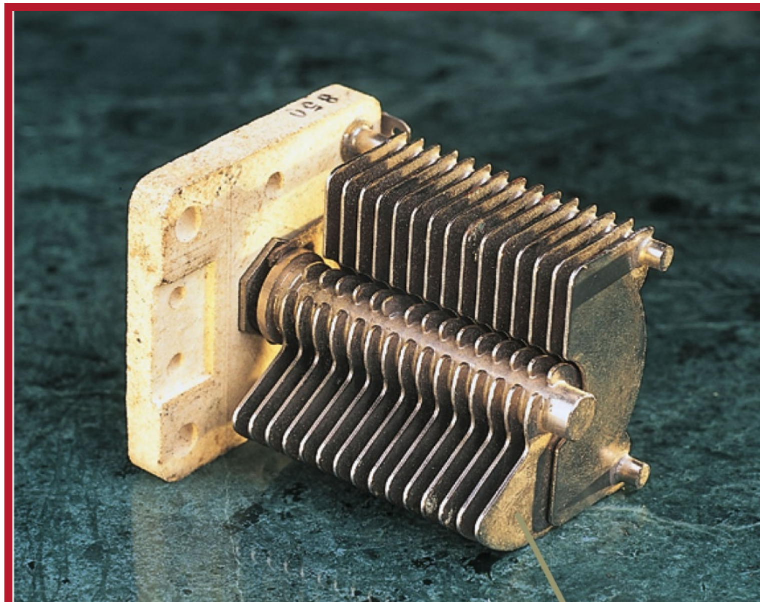
Example: An Electrolytic Capacitor

- These are commonly used to store large amounts of charge at relatively low voltages
- The electrolyte is a solution that conducts electricity by virtue of motion of ions contained in the solution.
- When a voltage is applied between the foil & the electrolyte, a thin layer of metal oxide is formed on the foil.
- This layer serves as a dielectric.
- Large values of capacitance can be obtained because the dielectric layer is very thin & the plate separation is very small.



Example: Variable Capacitors

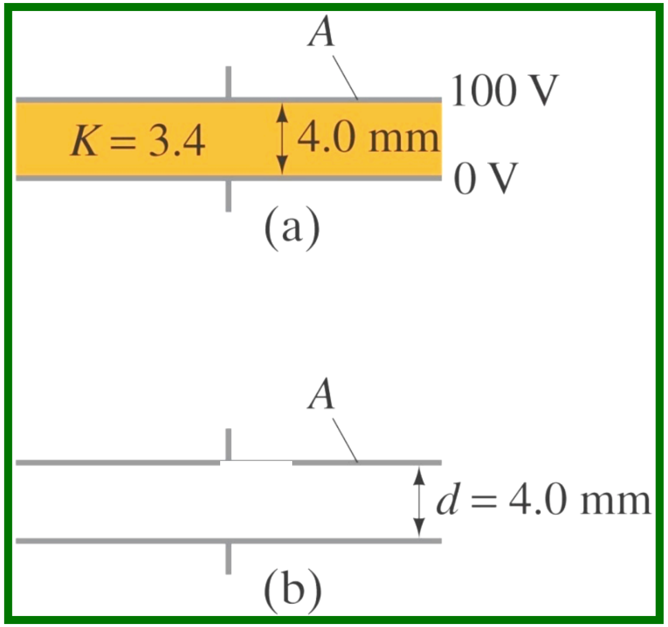
- Variable capacitors consist of 2 interwoven sets of metallic plates.
- One plate is fixed & the other is movable.
- Air is contained as the dielectric.
- These capacitors generally vary between **10 & 500 pF**.
- They are commonly used in radio tuning circuits



When one set of metal plates is rotated so as to lie between a fixed set of plates, the capacitance of the device changes.

Example: Dielectric Removal.

- A parallel-plate capacitor, filled with a dielectric (**K = 3.4**) is connected to a **100-V** battery. After it is fully charged, the battery is disconnected. Plate area **$A = 4.0\ m^2$**. Separation **d = 4.0 mm.**



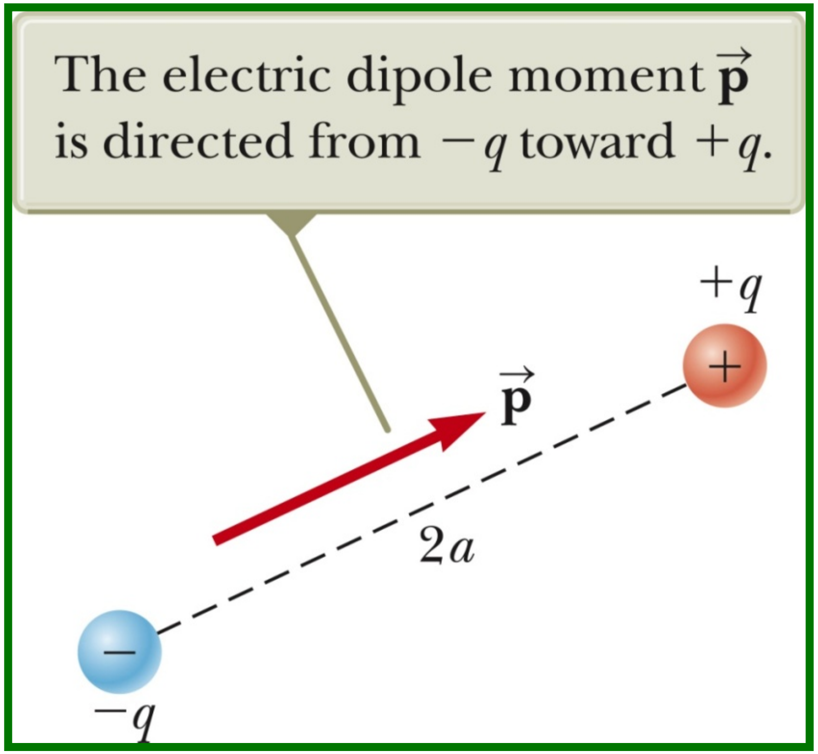
(a) Find the capacitance, the charge on the capacitor, the electric field strength, & the energy stored in the capacitor.

(b) The dielectric is carefully removed, without changing the plate separation nor does any charge leave the capacitor. Find the new values of capacitance, electric field strength, voltage between the plates, and the energy stored in the capacitor.

Section D:
Molecular Description of Dielectrics

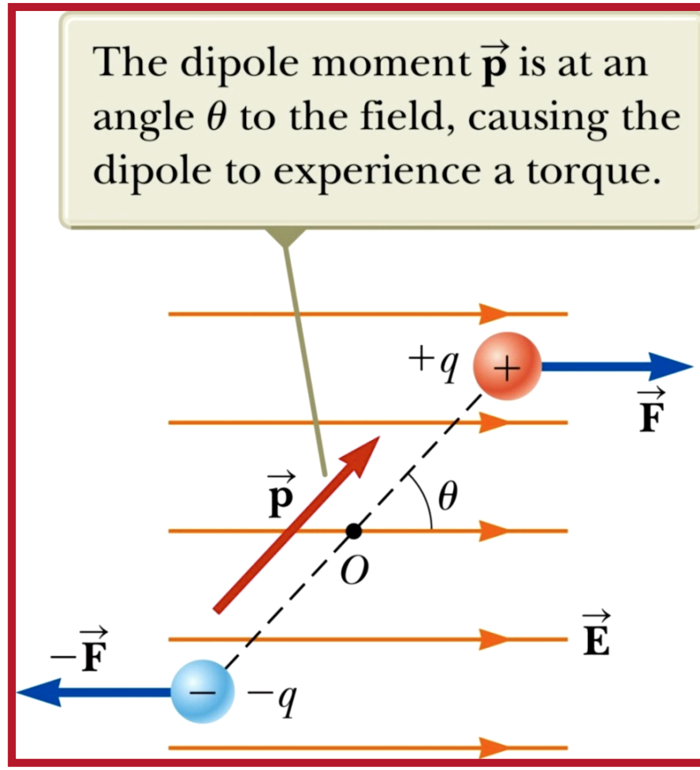
Electric Dipole

- An electric dipole consists of 2 charges of equal magnitude & opposite sign.
- Charge separation is **2a**.
- The **electric dipole moment p** is directed along the line joining the charges from **–q** to **+q**.



Electric Dipole

- The electric dipole moment has magnitude **p ≡ 2aq**.
- Assume the dipole is placed in a uniform external field, **E** external to the dipole; not the field produced by the dipole.
- Assume the dipole makes an Angle **θ** with the field **E**



- Each charge experiences a force **F = Eq** acting on it.
- The net force on the dipole is zero, but

<u>the forces produce a net torque on the dipole</u>.

- So, treat the dipole as a rigid object under a net torque.

- The magnitude of the torque is:

$$\tau = 2Fa \sin\theta = pE \sin\theta$$

- This can also be expressed as the cross product of the dipole moment & the field:

$$\boxed{\vec{\tau} = \vec{\mathbf{p}} \times \vec{\mathbf{E}}}$$

- The potential energy of the dipole in the external electric field can written as:

$$U_f - U_i = pE(\cos\theta_i - \cos\theta_f)$$

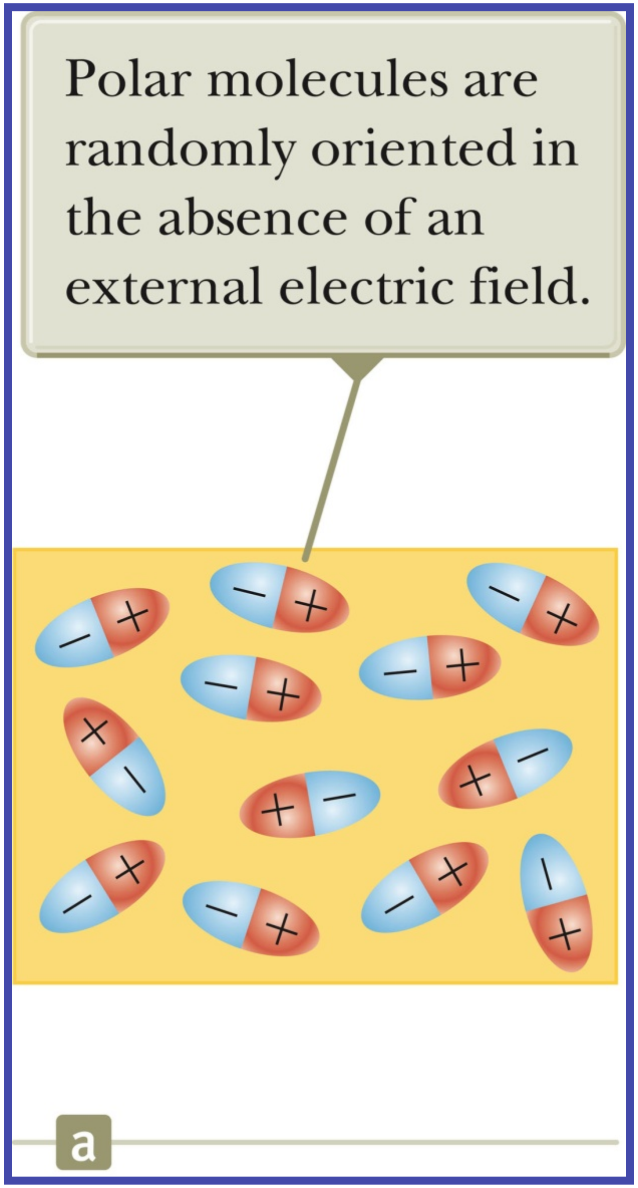
$$\Delta U = -\, pE \cos\theta$$

- This can also be written as a dot product.

$$\boxed{U = \vec{\mathbf{p}} \cdot \vec{\mathbf{E}}}$$

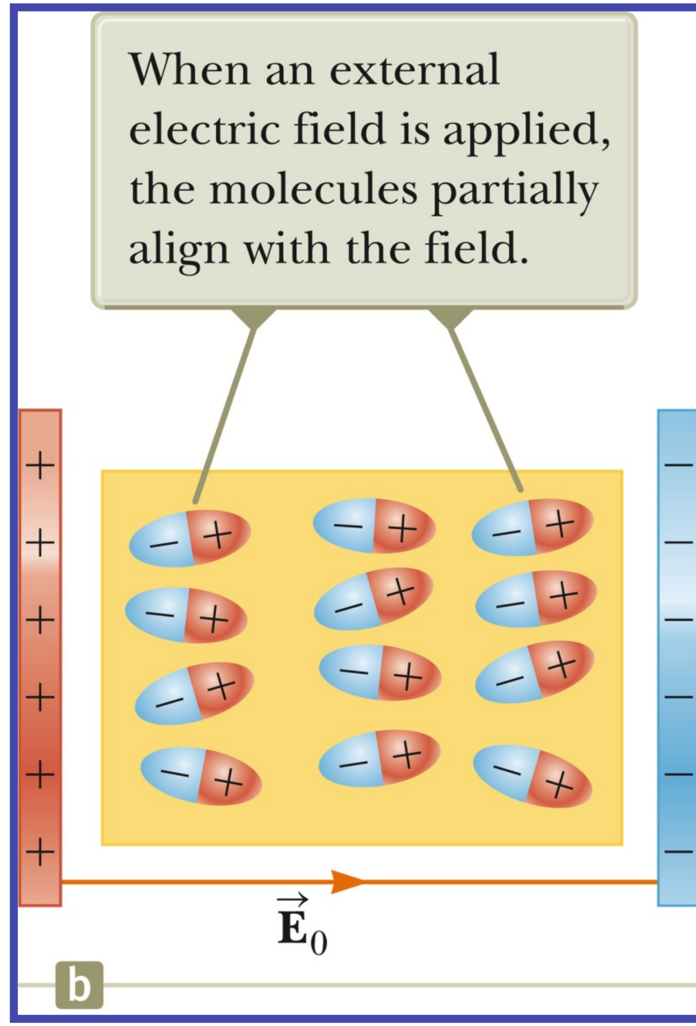
Dielectrics – An Atomic View

The molecules that make up the dielectric are modeled as dipoles. The molecules are randomly oriented in the absence of an electric field.



Dielectrics

An external electric field is applied. This produces a torque on the molecules. The molecules partially align with the electric field. The degree of alignment depends on temperature and the magnitude of the field. In general, the alignment increases with decreasing temperature and with increasing electric field.

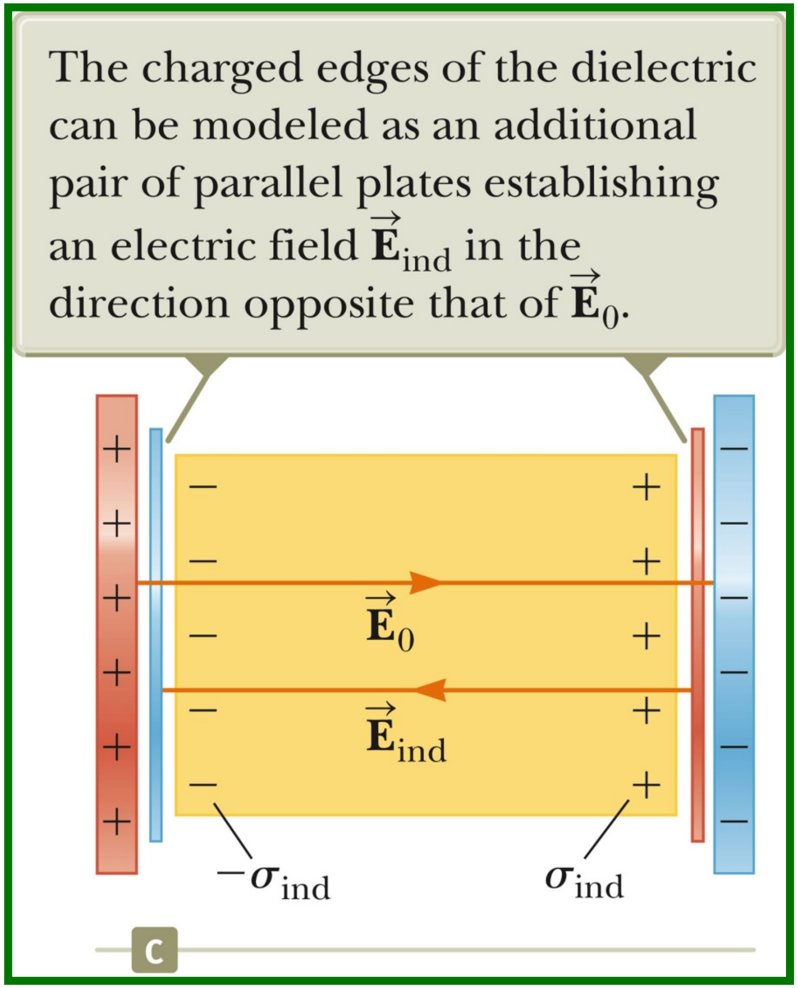


If the molecules of the dielectric are nonpolar molecules, the electric field produces some charge separation. This produces an

induced dipole moment.

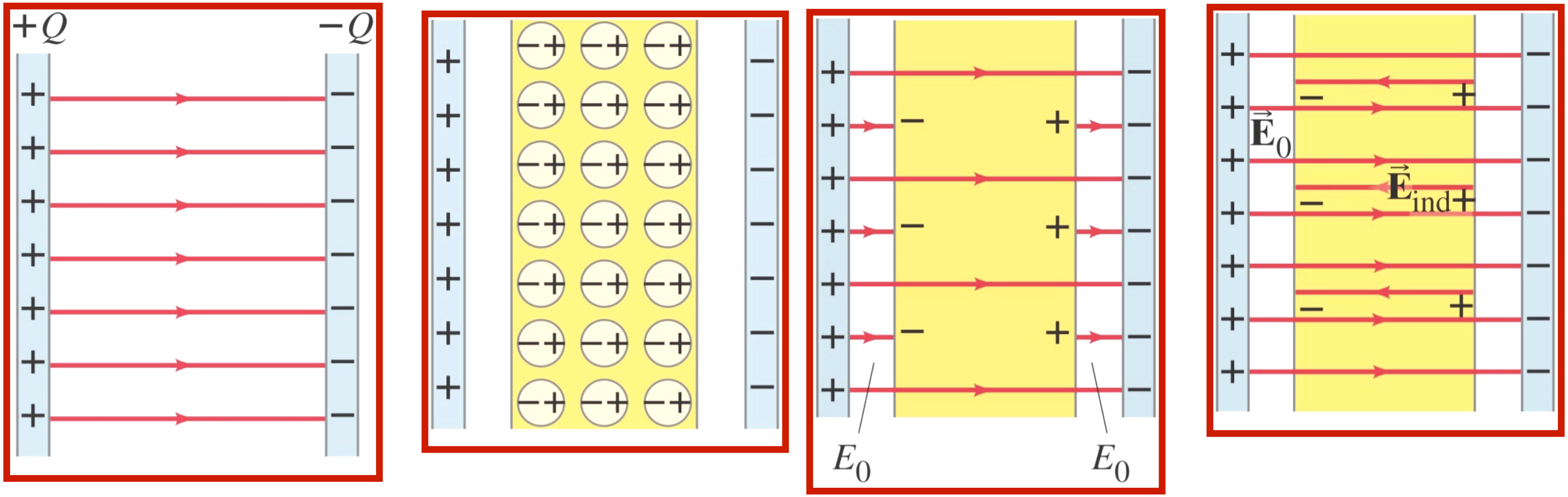
The effect is then the same as if the molecules were polar.

An external field can polarize the dielectric whether the molecules are polar or nonpolar. The charged edges of the dielectric act as a second pair of plates producing an induced electric field in the direction opposite the original electric field.



Molecular Description of Dielectrics

The molecules in a dielectric, when in an external electric field, tend to become oriented in a way that reduces the external field.



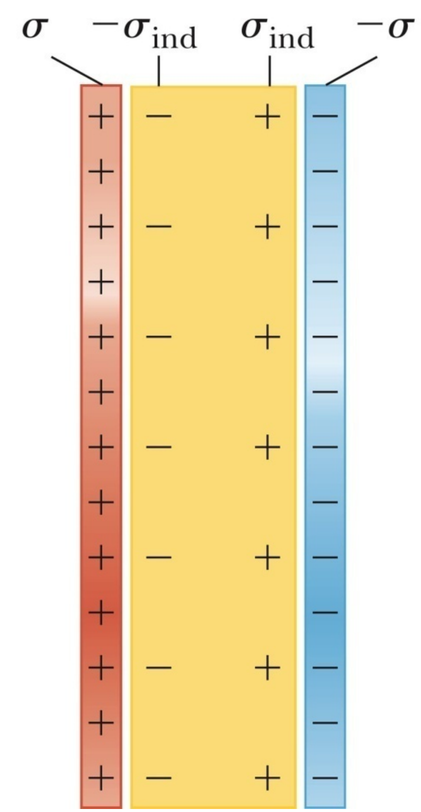
This means that the electric field within the dielectric is less than it would be in air, allowing more charge to be stored for the same potential. This reorientation of the molecules results in an induced charge – there is no net charge on the dielectric, but the charge is asymmetrically distributed. The magnitude of the induced charge depends on the dielectric constant:

$$\boxed{Q_{\text{ind}} = Q\left(1 - \frac{1}{K}\right).}$$

Induced Charge and Field

The electric field due to the plates is directed to the right and it polarizes the dielectric.
The net effect on the dielectric is an induced surface charge that results in an induced electric field.
If the dielectric were replaced with a conductor, the net field between the plates would be zero.

The induced charge density σ_{ind} on the dielectric is *less* than the charge density σ on the plates.



Summary of Chapter

- **Capacitor:** nontouching conductors carrying equal & opposite charge.

  Capacitance:

$$\boxed{Q = CV.}$$

$$\boxed{C = \frac{Q}{V} = \epsilon_0 \frac{A}{d}. \qquad \text{[parallel-plate capacitor]}}$$

- **Capacitors** in **parallel & series:**

$$\boxed{C_{\text{eq}} = C_1 + C_2 + C_3. \qquad \text{[parallel]}}$$

$$\boxed{\frac{1}{C_{\text{eq}}} = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3}. \qquad \text{[series]}}$$

- **Energy density** in **electric field:**

$$u = \text{energy density} = \tfrac{1}{2}\epsilon_0 E^2.$$

- A **dielectric** is an insulator.

- **Dielectric constant K** gives the ratio of the total field to the external field.

- For a **parallel-plate capacitor:**

$$C = K\epsilon_0 \frac{A}{d}. \qquad \text{[parallel-plate capacitor]}$$