PHYS2326
Lecture #11

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Goals for this lecture

- Summary of Lecture 10
- Quantify the energy stored in capacitors
- Understand the role of dielectrics in capacitors

Chapter 24

Capacitors

- A capacitor is an electrical device capable of storing electric charge and electric potential energy.

- The quantity called capacitance (C) indicates the ability of a capacitor to store energy.

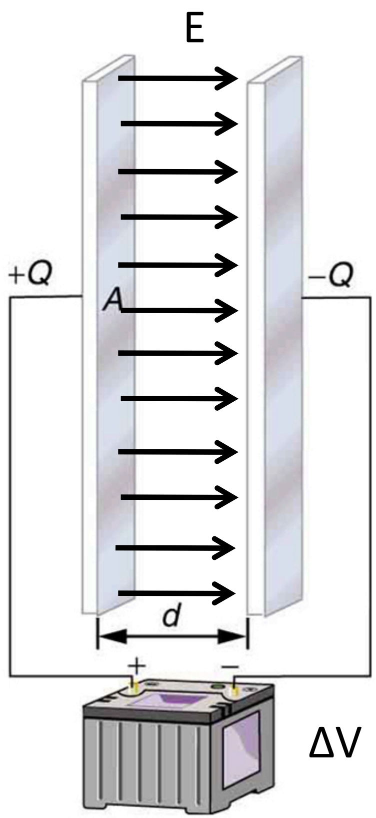
$$C = \frac{Q}{V}$$

$$Unit: \frac{C}{V} = Farad = F$$

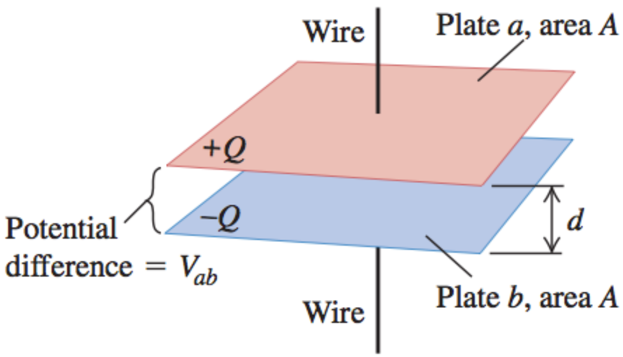
Capacitance

- The capacitance (C) tells how much charge Q (or electric field) can be stored for a given potential difference V (we start dropping the Δ).

$$Q = CV$$



Parallel-Plate Capacitor



$$C = \frac{Q}{V_{ab}} = ?$$

$$V_{ab} = Ed = \frac{\sigma}{\epsilon_0} d$$

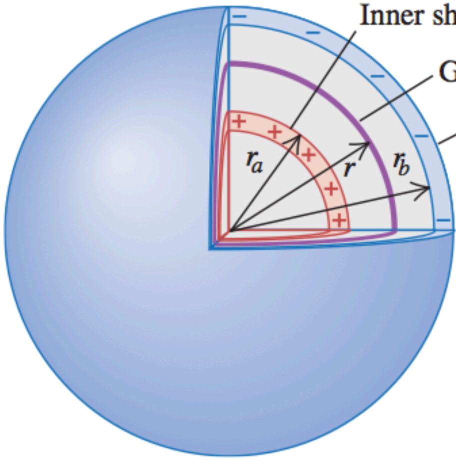
$$Q = \sigma A$$

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

Depends only on:

- Shape and size of plates
- Insulating material between them

Spherical Capacitor



$$C = \frac{Q}{V_{ab}} = ?$$

$$Q = Q$$

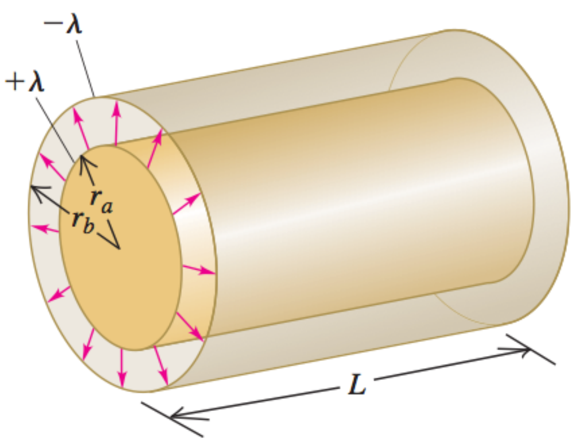
$$V_{sphere}(r) = \frac{Q}{4\pi\epsilon_0 r}$$

$$V_{ab} = V_a - V_b = \frac{Q}{4\pi\epsilon_0}\left[\frac{1}{r_a} - \frac{1}{r_b}\right]$$

$$V_{ab} = \frac{Q}{4\pi\epsilon_0}\left[\frac{r_b - r_a}{r_a r_b}\right]$$

$$\boxed{C = 4\pi\epsilon_0\left[\frac{r_a r_b}{r_b - r_a}\right]}$$

Cylindrical Capacitor



$$C = \frac{Q}{V_{ab}} = ?$$

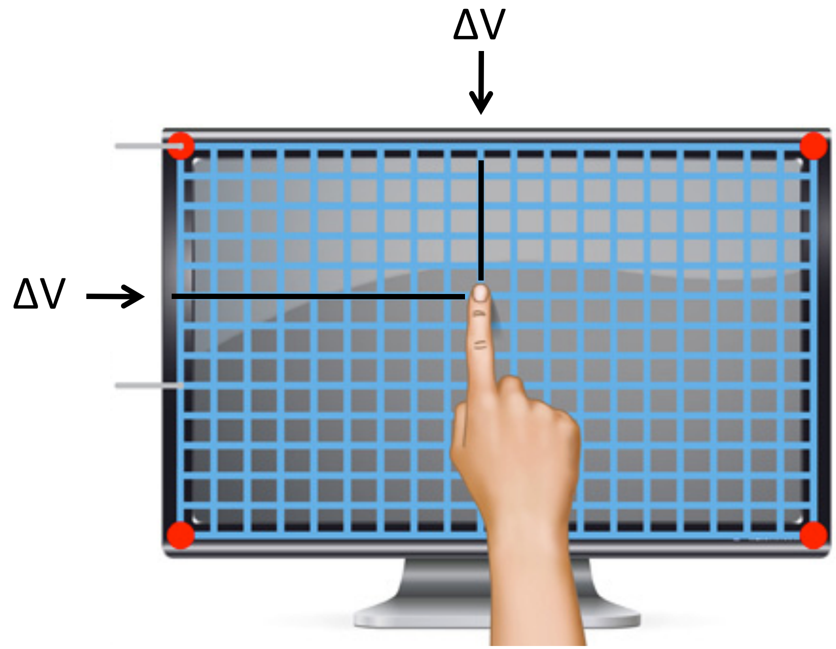
$$Q = \lambda L$$

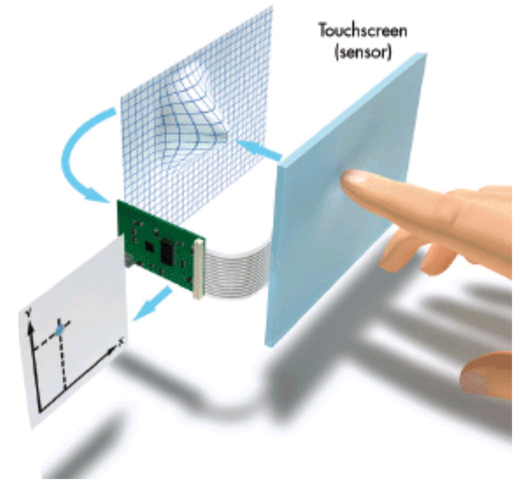
$$V_{cylinder}(r) = \frac{\lambda}{2\pi\epsilon_0} ln\left[\frac{r_0}{r}\right]$$

$$V_{ab} = V_a - V_b = \frac{\lambda}{2\pi\epsilon_0} ln\left[\frac{r_b}{r_a}\right]$$

$$\boxed{C = \frac{2\pi\epsilon_0 L}{\ln[r_b/r_a]}}$$

Application: Capacitive touchscreen panel

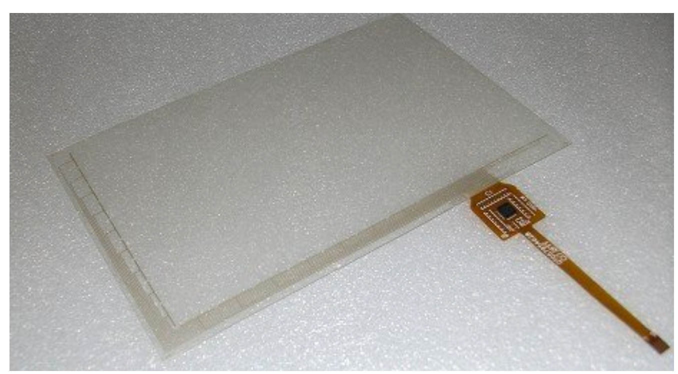




$$C = \frac{Q}{V}$$

$$C = \frac{A}{d}\epsilon_0 \quad Parallel\,plate$$

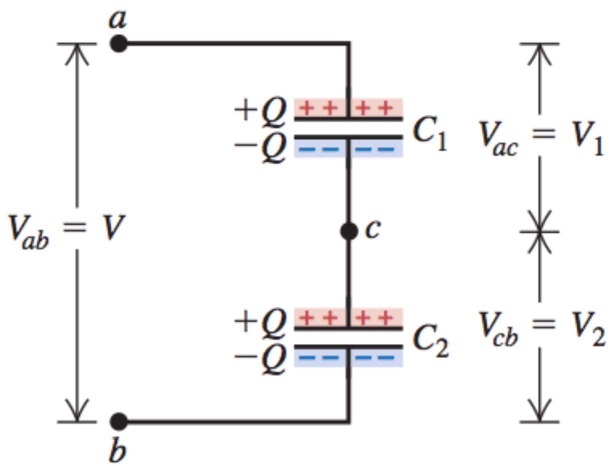
$$V = \left(\frac{Q}{A\epsilon_0}\right)d$$



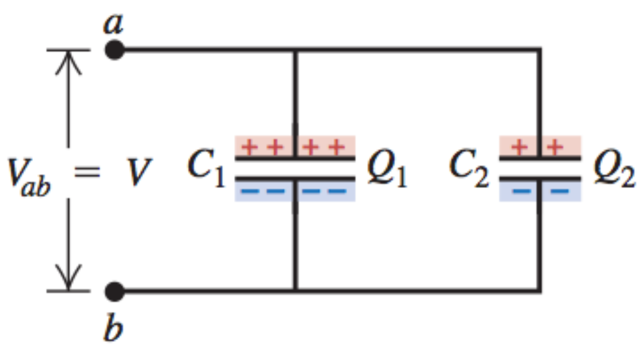
Capacitors in series and parallel

- Capacitors are made for a few specific capacitance and voltage values.
- A lot of times, these values do not meet the requirements of our projects.
- By combining capacitors in series and/or parallel connections we can obtain the capacitance values needed.

Capacitors in series and parallel

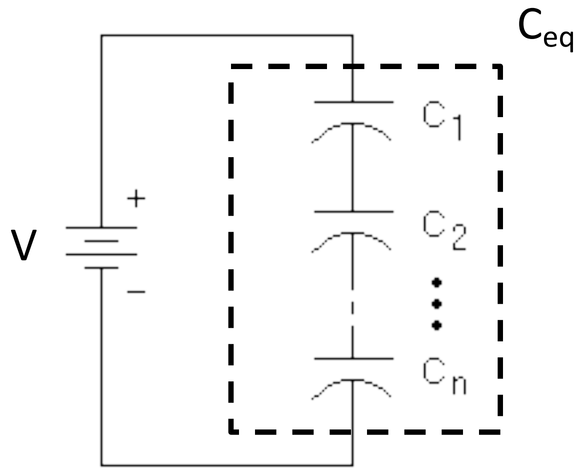


Capacitors in Series: Same Q



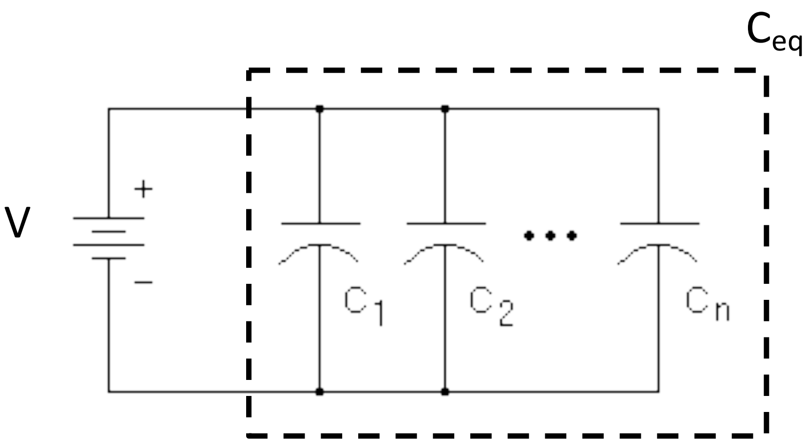
Capacitors in Parallel: Same V

Capacitors in series



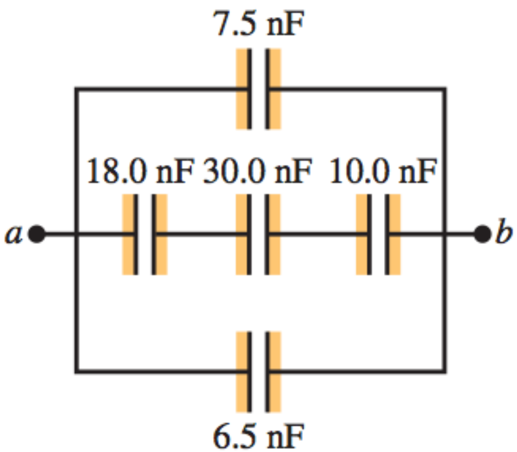
$$\frac{1}{C_{eq}} = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3} + \ldots + \frac{1}{C_n}$$

Capacitors in parallel



$$C_{eq} = C_1 + C_2 + C_3 + \ldots + C_n$$

Example: (a) What is the equivalent capacitance between a and b? (b) How much charge is stored in this system? (c) How much does the 6.5 nF capacitor store? (d) What is the voltage across the 7.5 nF capacitor?



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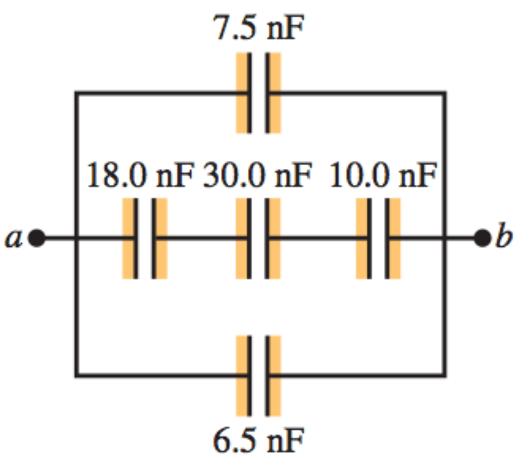
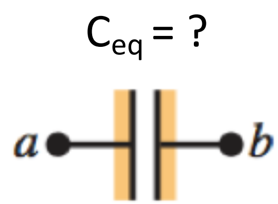
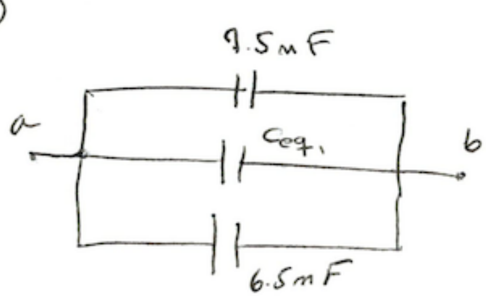




(a)



C_{eq1} = ?

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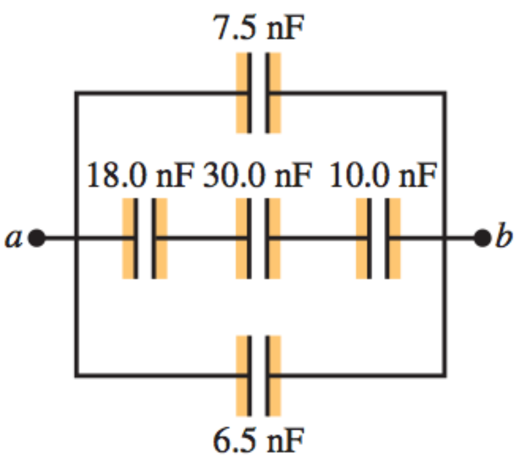
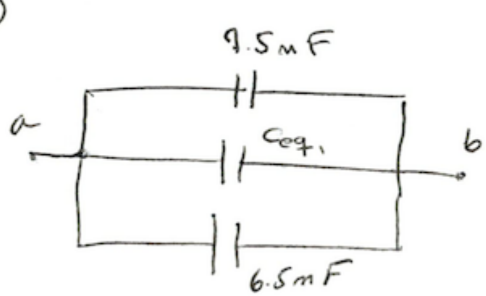


$C_{eq} = ?$

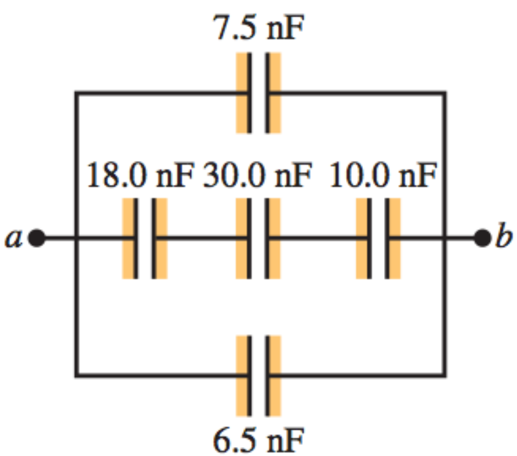
(a)



$C_{eq_1} = ?$

$$\frac{1}{C_{eq_1}} = \frac{1}{18\times10^{-9}} + \frac{1}{30\times10^{-9}} + \frac{1}{10\times10^{-9}}$$

Example: (a) What is the equivalent capacitance between a and b? (b) How much charge is stored in this system? (c) How much does the 6.5 nF capacitor store? (d) What is the voltage across the 7.5 nF capacitor?



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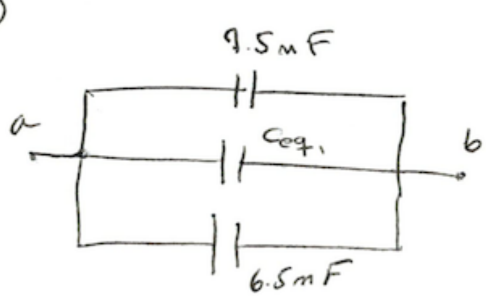

$C_{eq_1} = ?$

$$\frac{1}{C_{eq_1}} = \frac{1}{18\times10^{-9}} + \frac{1}{30\times10^{-9}} + \frac{1}{10\times10^{-9}}$$

$$C_{eq_1} = 5.3\times10^{-9}\ F$$

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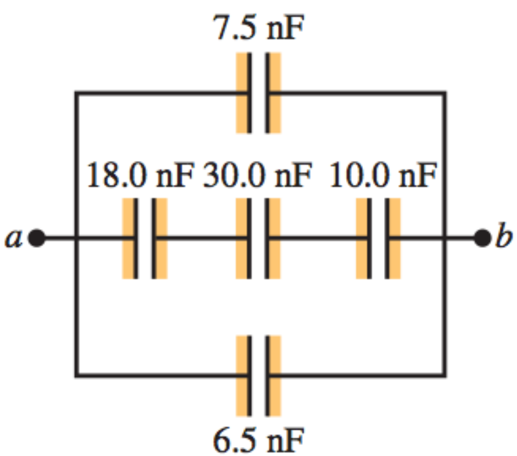
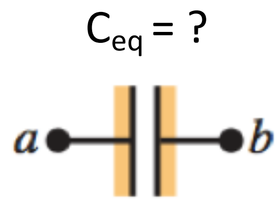
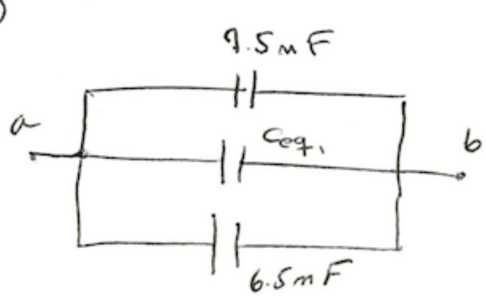
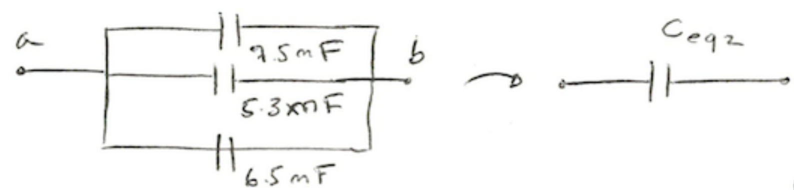




(a)





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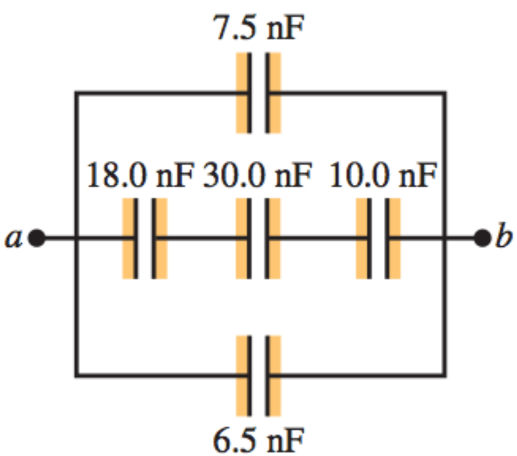
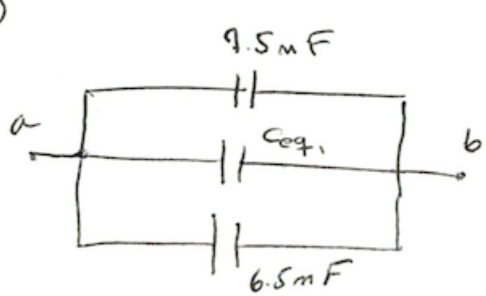
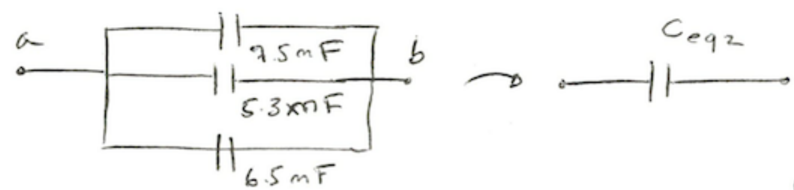


$C_{eq} = ?$

(a)





$C_{eq_2} = ?$

$C_{eq_1} = ?$

$$\frac{1}{C_{eq_1}} = \frac{1}{18\times10^{-9}} + \frac{1}{30\times10^{-9}} + \frac{1}{10\times10^{-9}}$$

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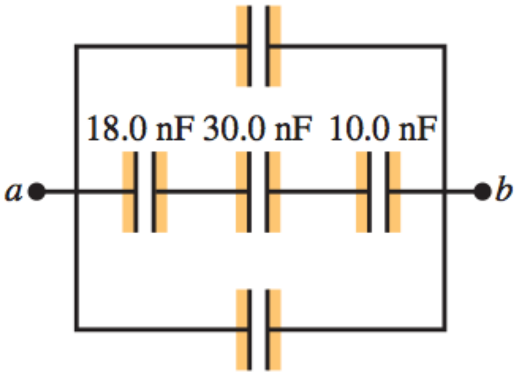

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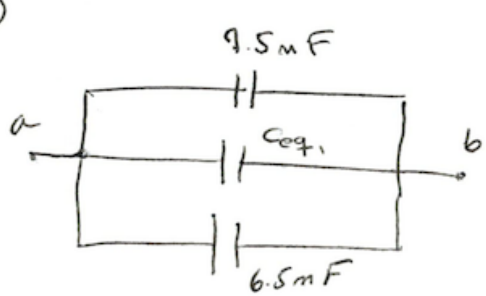

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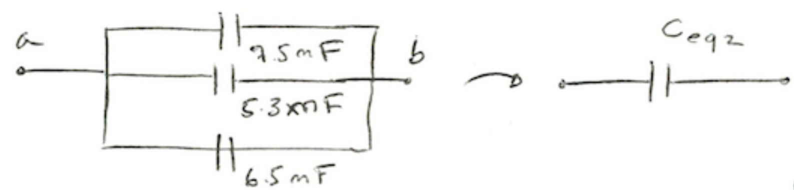
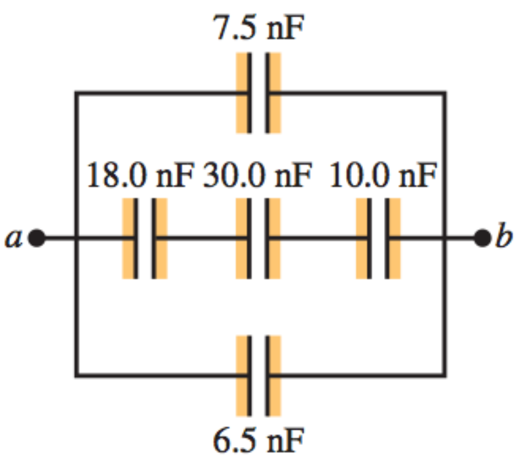
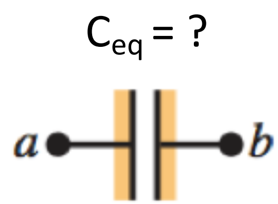


$C_{eq_2} = ?$

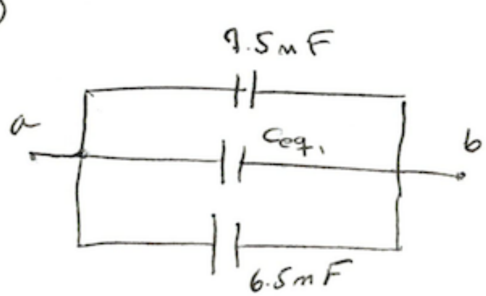
$C_{eq_2} = 7.5\times10^{-9} + 5.3\times10^{-9} + 6.5\times10^{-9}$

Example: (a) What is the equivalent capacitance between a and b? (b) How much charge is stored in this system? (c) How much does the 6.5 nF capacitor store? (d) What is the voltage across the 7.5 nF capacitor?





(a)



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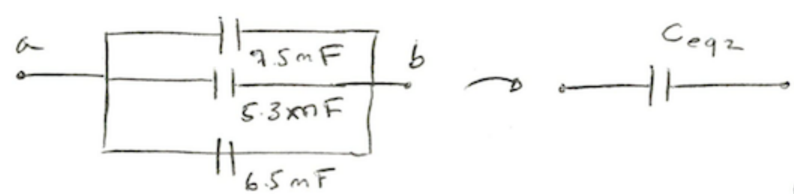
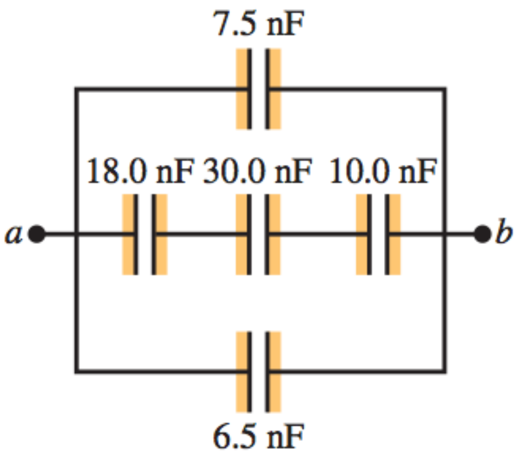


$C_{eq_2} = ?$

$C_{eq_2} = 7.5\times10^{-9} + 5.3\times10^{-9} + 6.5\times10^{-9}$

$C_{eq} = 19.3\times10^{-9}\,F = \underline{19.3\,mF}$

Example: Assume V_{ab} = 25 V: (a) What is the equivalent capacitance between a and b? **(b) How much charge is stored in this system?** (c) How much does the 6.5 nF capacitor store? (d) What is the voltage across the 7.5 nF capacitor?



(b)

Q = ?

C_{eq} = 19.3 nF

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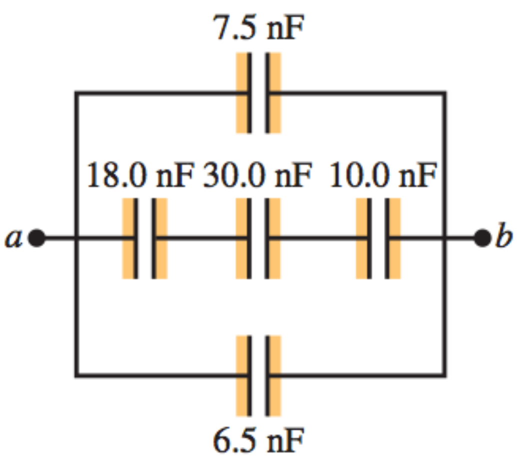

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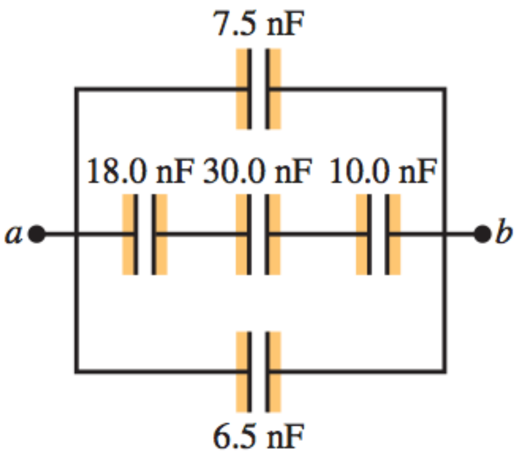

(b)

$Q = ?$

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

$Q = CV = (19.3 \times 10^{-9})(25)$

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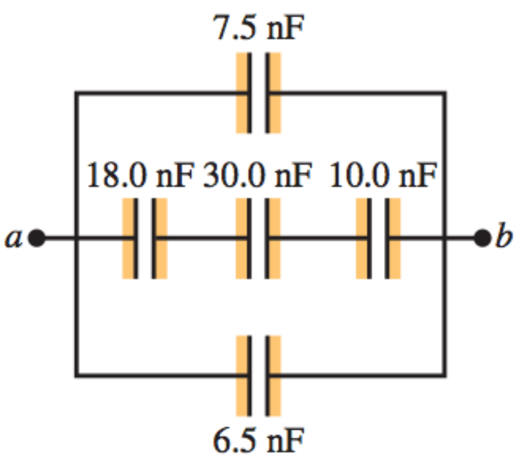

(b)

$Q = ?$

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

$Q = CV = (19.3 \times 10^{-9})(25)$

$Q = 482.5 m\ C$

C_{eq} = 19.3 nF

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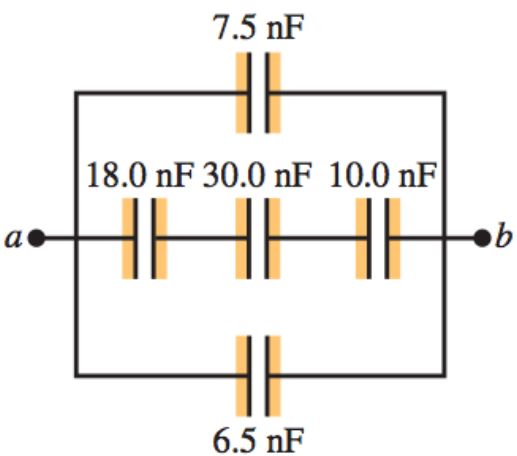

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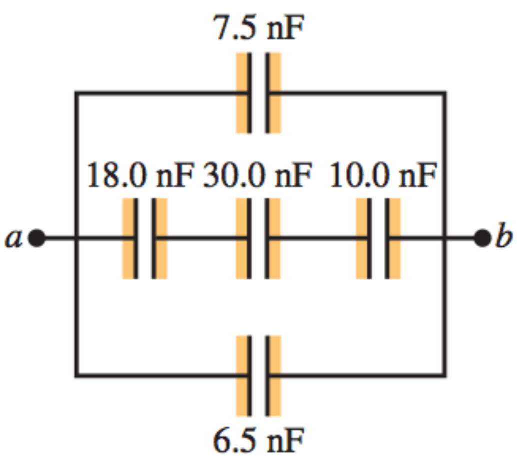

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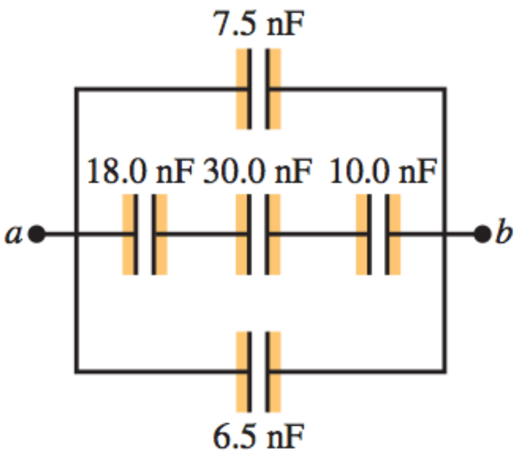
Example: Assume V_{ab} = 25 V: (a) What is the equivalent capacitance between a and b? (b) How much charge is stored in this system? **(c) How much does the 6.5 nF capacitor store?** (d) What is the voltage across the 7.5 nF capacitor?



C_{eq} = 19.3 nF

(b)

$Q = ?$

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

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$Q = 482.5 m\ C$

(c) $Q = ?$

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

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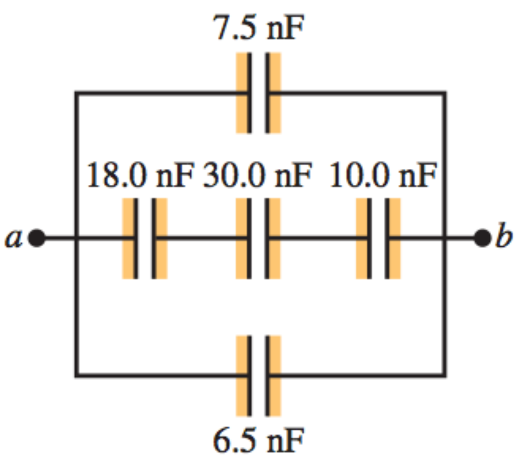


C_{eq} = 19.3 nF

(b)

$Q = ?$

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

$Q = CV = (19.3\times10^{-9})(25)$

$Q = 482.5\text{m C}$

(c)

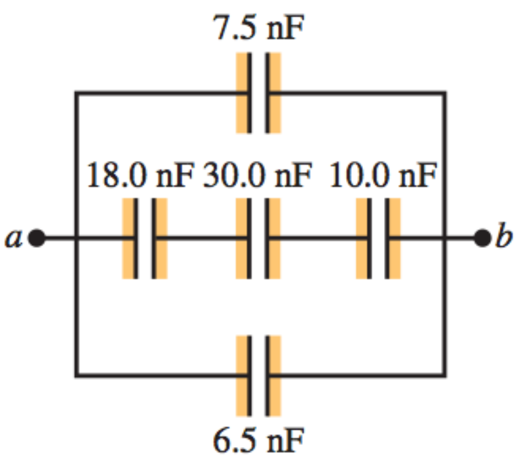
$Q = ?$

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

$Q = CV = (6.5\times10^{-9})(25)$

$Q = 162.5\text{ m C}$

Example: Assume V_{ab} = 25 V: (a) What is the equivalent capacitance between a and b? (b) How much charge is stored in this system? (c) How much does the 6.5 nF capacitor store? **(d) What is the voltage across the 7.5 nF capacitor?**



(b)

$Q = ?$

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

$Q = CV = (19.3 \times 10^{-9})(25)$

$Q = 482.5 m\ C$

C_{eq} = 19.3 nF

(c) $Q = ?$

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

$Q = CV = (6.5 \times 10^{-9})(25)$

$Q = 162.5\ m\ C$

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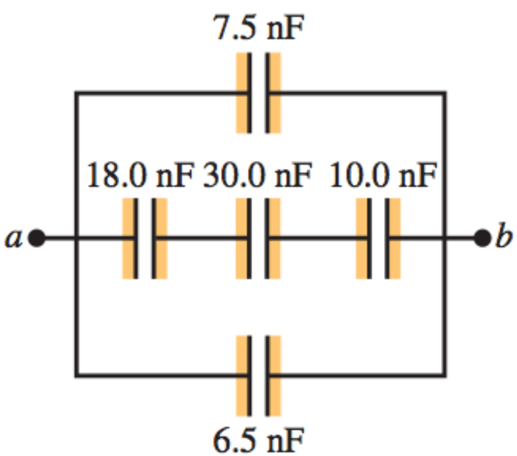


(b)

$Q = ?$

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

$Q = CV = (19.3 \times 10^{-9})(25)$

$Q = 482.5 m\,C$

C_{eq} = 19.3 nF

(c)

$Q = ?$

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

$Q = CV = (6.5 \times 10^{-9})(25)$

$Q = 162.5\ m\,C$

(d)

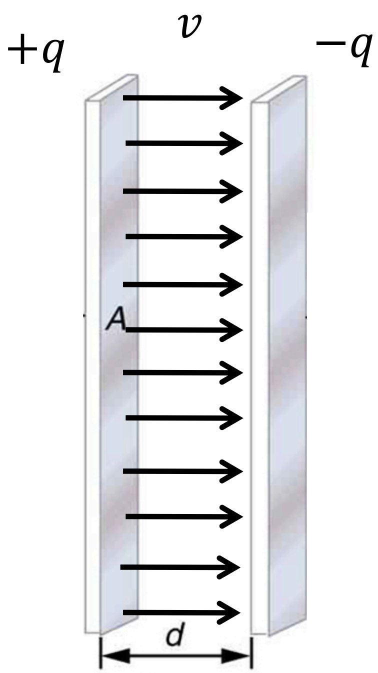
$V = 25$ V

Energy stored in capacitors

Energy stored in capacitors

- How much energy does a capacitor store?
  - Well, it should equal the work done to charge your capacitor

Energy stored in capacitors

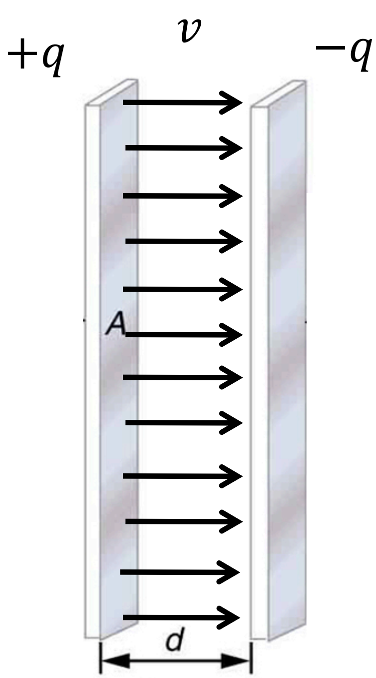


$At\ any\ given\ time\ during\ charging$:

$$U = W = \int_0^Q v\,dq$$

$v = instantaneous\ potential$
$q = instantaneous\ charge$
$V = final\ potential$
$Q = final\ charge$

Energy stored in capacitors

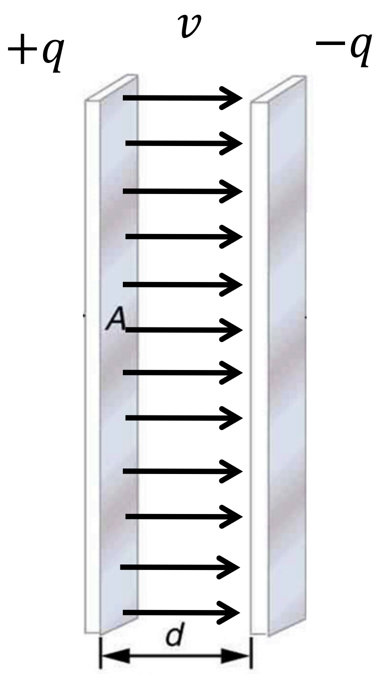


$At\ any\ given\ time\ during\ charging:$

$$U = W = \int_0^Q v\,dq$$

$$\rightarrow\ C = \frac{q}{v} \longrightarrow v = \frac{q}{C}$$

Energy stored in capacitors



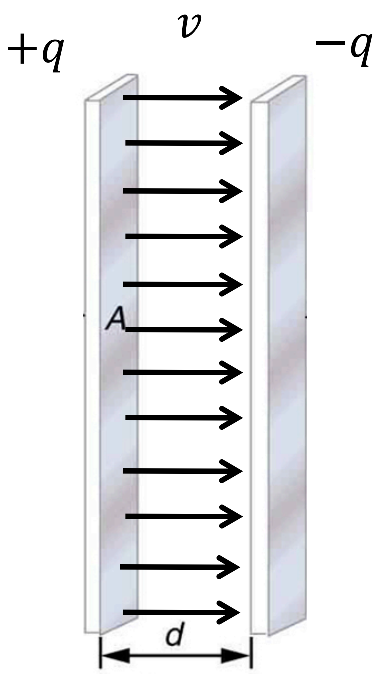
$At\ any\ given\ time\ during\ charging$:

$$U = W = \int_0^Q v dq$$

$$\rightarrow\ C = \frac{q}{v} \longrightarrow v = \frac{q}{C}$$

$$U = W = \int_0^Q \left(\frac{q}{C}\right) dq$$

Energy stored in capacitors



$At\ any\ given\ time\ during\ charging:$

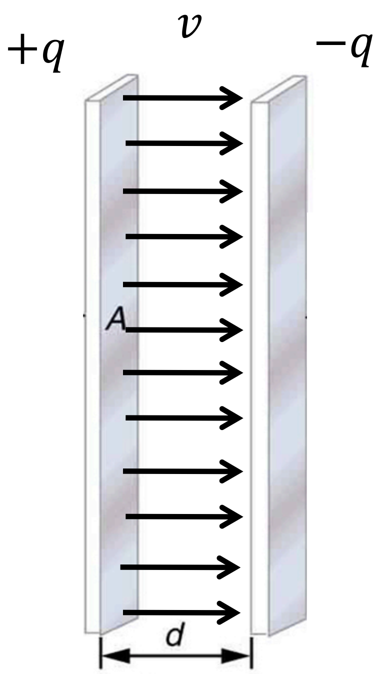
$$U = W = \int_0^Q v\,dq$$

$$\rightarrow\ C = \frac{q}{v} \longrightarrow v = \frac{q}{C}$$

$$U = W = \int_0^Q \left(\frac{q}{C}\right) dq$$

$$U = W = \frac{Q^2}{2C}$$

Energy stored in capacitors



$At\ any\ given\ time\ during\ charging:$

$$U = W = \int_0^Q v\,dq$$

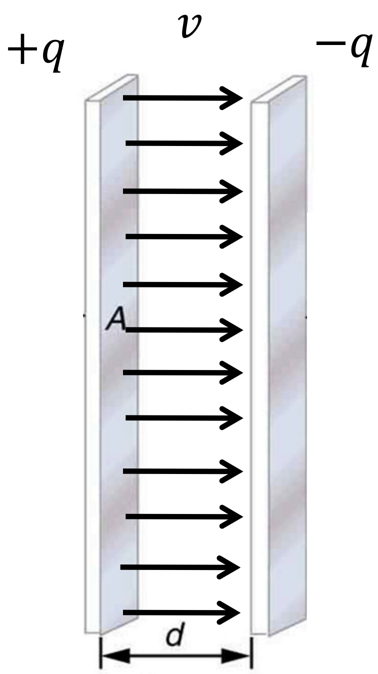
$$\rightarrow\ C = \frac{q}{v} \longrightarrow v = \frac{q}{C}$$

$$U = W = \int_0^Q \left(\frac{q}{C}\right) dq$$

$$U = W = \frac{Q}{2C}^{2}$$

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

Energy stored in capacitors



$At\ any\ given\ time\ during\ charging:$

$$U = W = \int_0^Q v\,dq$$

$$\rightarrow\ C = \frac{q}{v} \longrightarrow v = \frac{q}{C}$$

$$U = W = \int_0^Q \left(\frac{q}{C}\right) dq$$

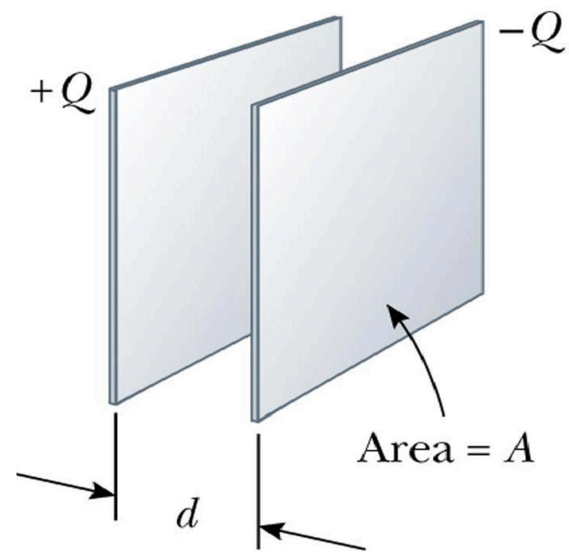
$$U = W = \frac{Q^2}{2C}$$

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

$$U = \frac{Q^2}{2C} = \frac{QV}{2} = \frac{CV^2}{2}$$

Energy Density (u)

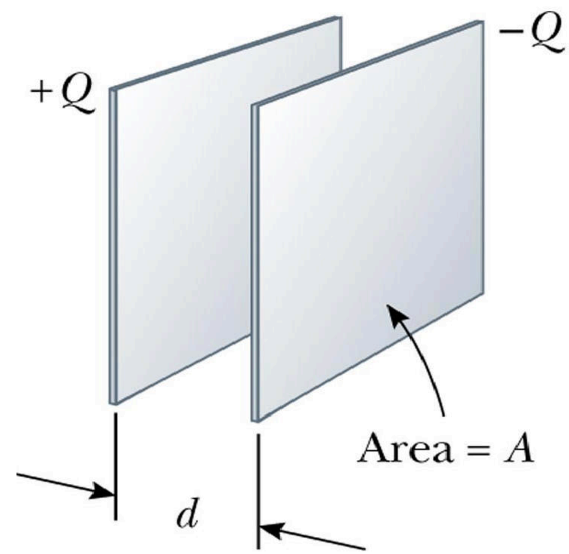
$$u = \frac{Energy}{Volume}$$



Energy Density (u)

$$u = \frac{Energy}{Volume}$$

$$u = \frac{\frac{1}{2}CV^2}{Ad}$$



Energy Density (u)

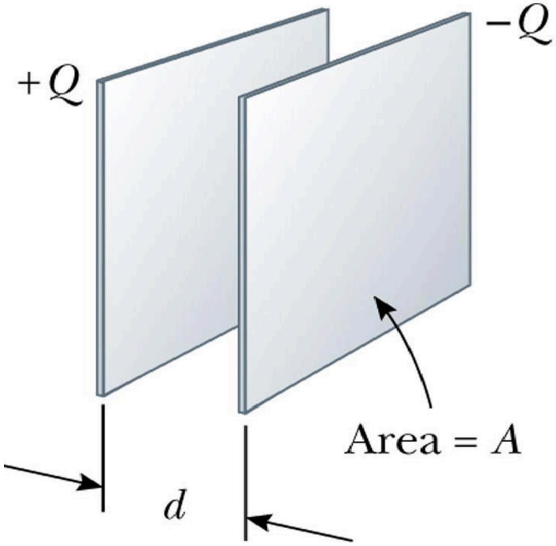
$$u = \frac{Energy}{Volume}$$

$$u = \frac{\frac{1}{2}CV^2}{Ad}$$

But:

$$C = \frac{A}{d}\epsilon_0$$
$$V = Ed$$

$$\boxed{u = \frac{1}{2}E^2\epsilon_0}$$



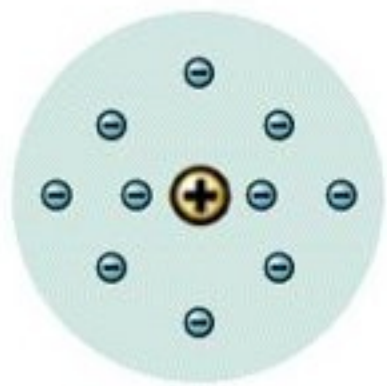
Derived assuming E-field created by parallel plates but works for any E-field configuration

The role of dielectrics on capacitors

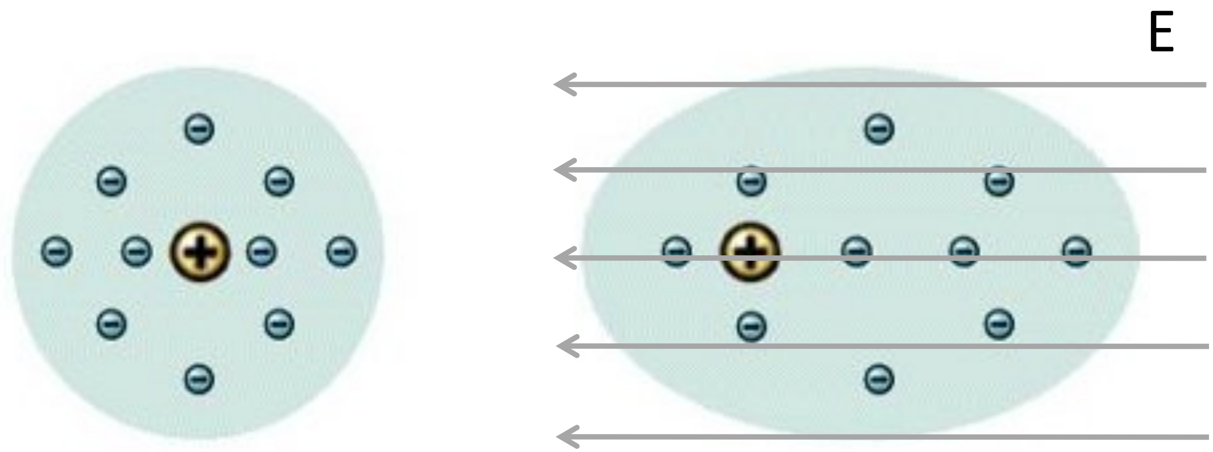
The role of dielectrics on capacitors

- Conductors:
  - Electrons are free to move (free charges)
  - Electrons redistribute to cancel any E-field inside conductor
- Dielectrics:
  - Electrons are not free to move (bound charges)
  - An external electric field will distort the electron distribution around the nucleus or align polar molecules

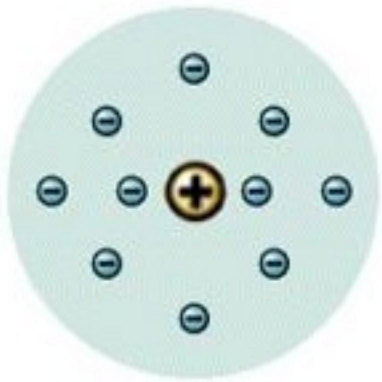
Dielectrics: Polarization

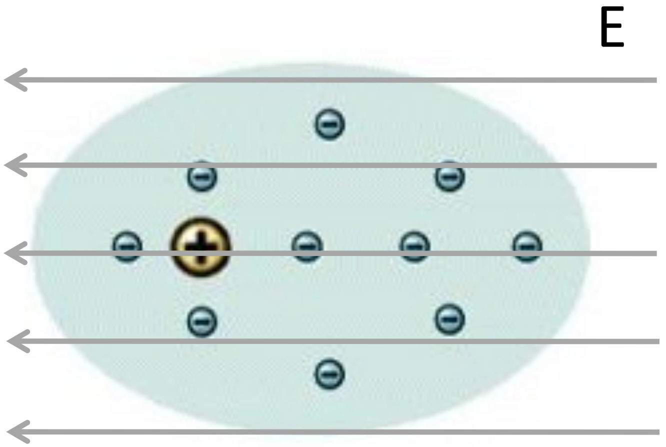


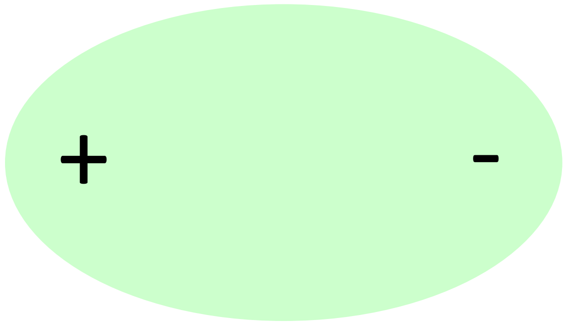
Dielectrics: Polarization



Dielectrics: Polarization



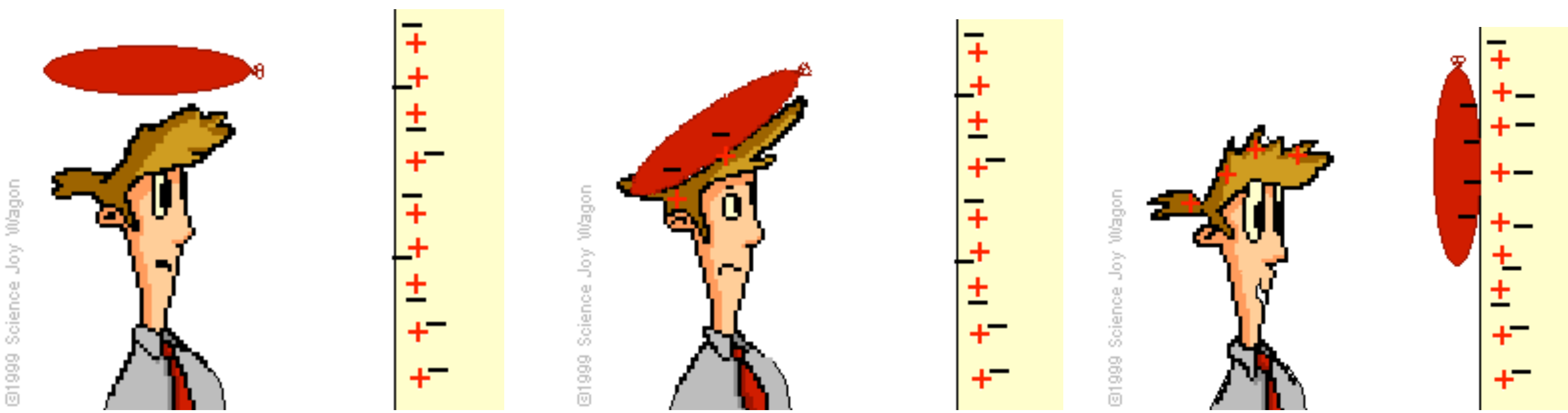




Polarized atom

Dielectrics

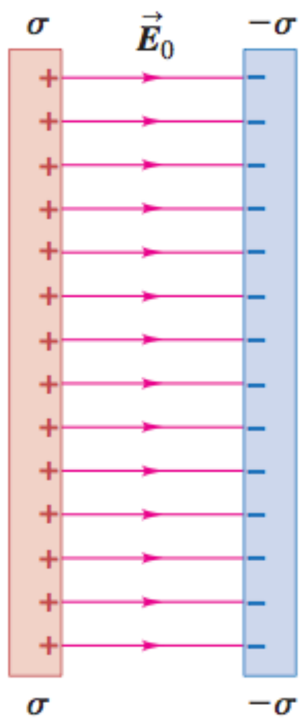
Dielectrics



The role of dielectrics in capacitors

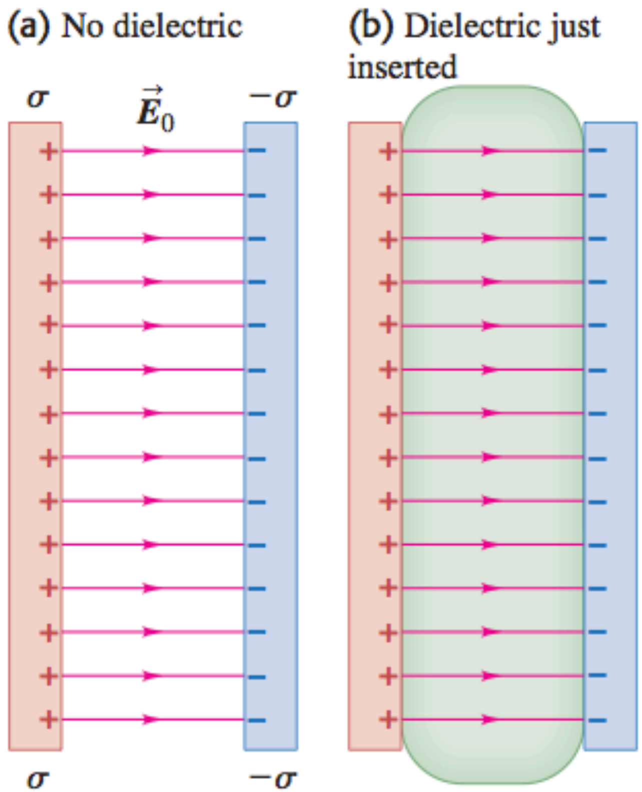
The role of dielectrics in capacitors

(a) No dielectric



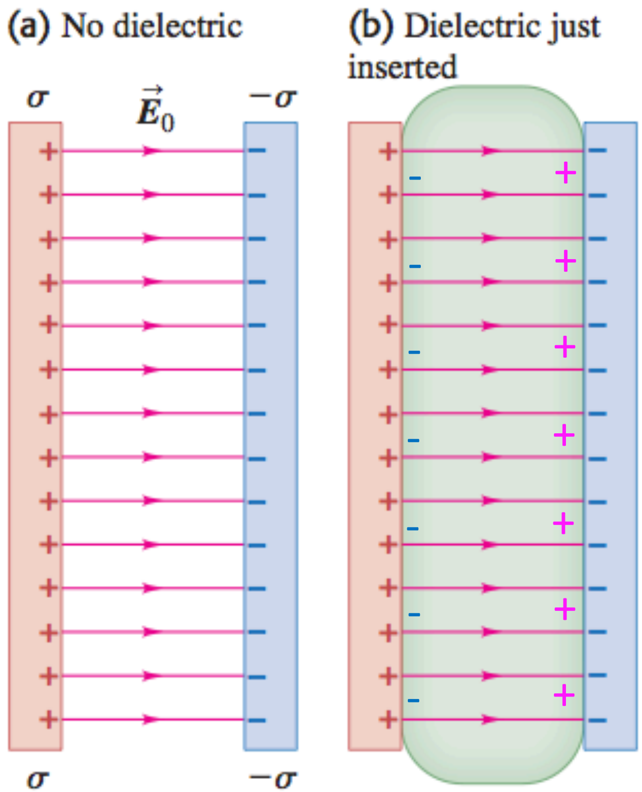
σ = surface charge density

The role of dielectrics in capacitors



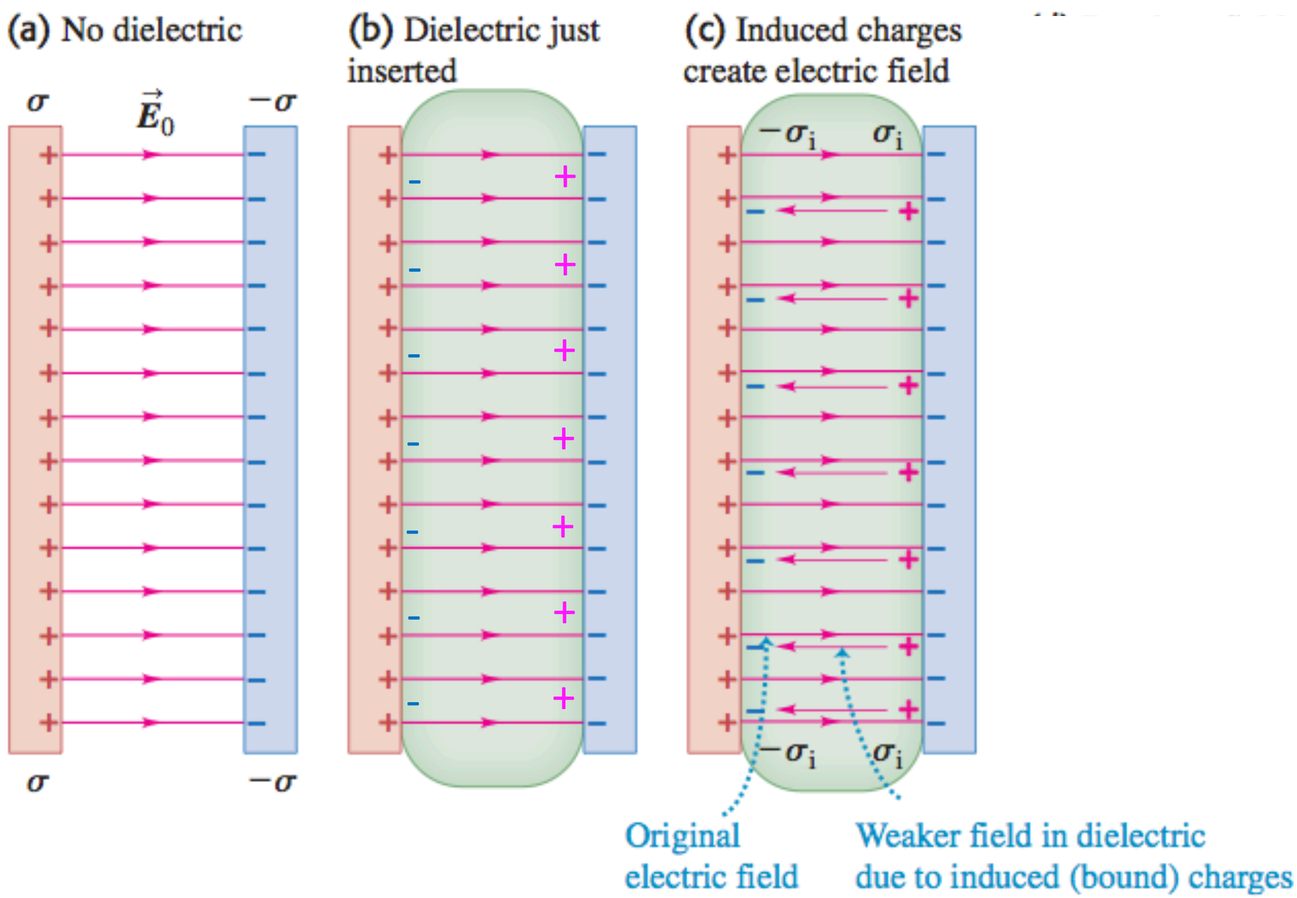
σ = surface charge density

The role of dielectrics in capacitors



σ = surface charge density

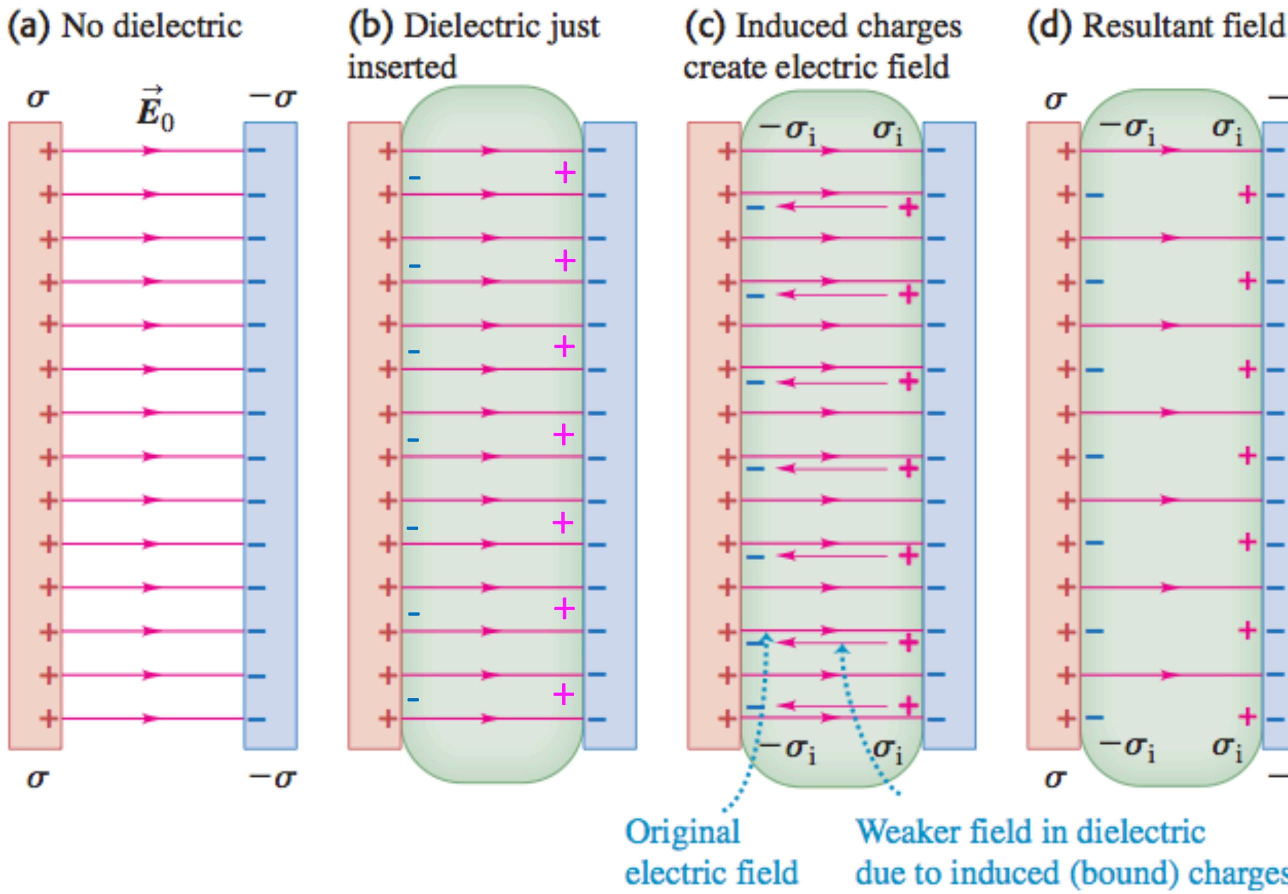
The role of dielectrics in capacitors



σ = surface charge density

σ_i = induced surface charge density

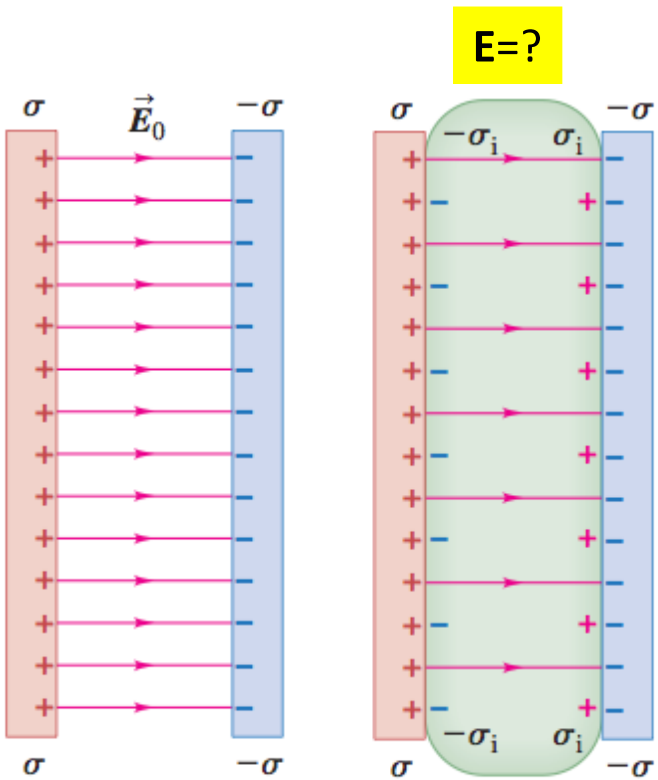
The role of dielectrics in capacitors



σ = surface charge density

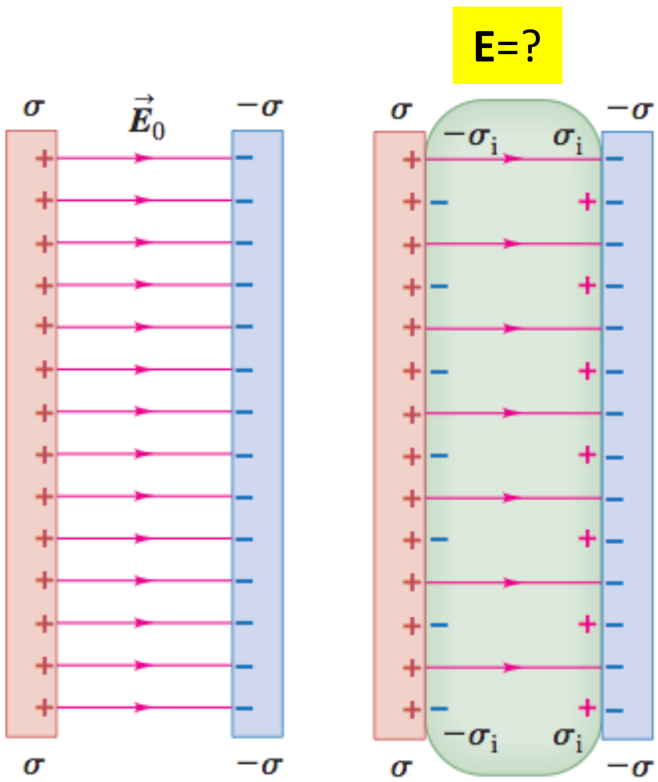
σ_i = induced surface charge density

How strong is the E-field now?

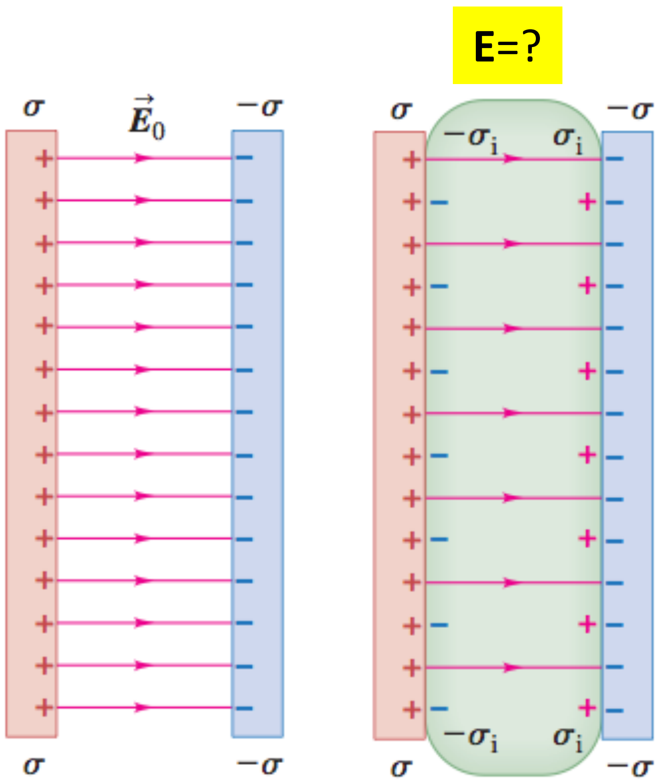


How strong is the E-field now?

$$Originally: \; E_0 = \frac{\sigma}{\epsilon_0}$$



How strong is the E-field now?

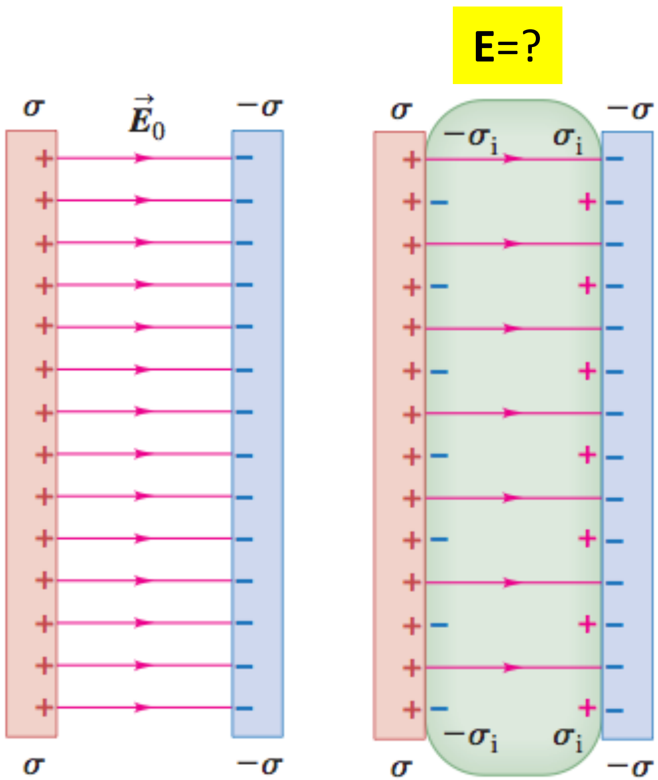


$Originally$: $E_0 = \dfrac{\sigma}{\epsilon_0}$

$With\ dielectric$:

$$E = \frac{\sigma - \sigma_i}{\epsilon_0}$$

How strong is the E-field now?



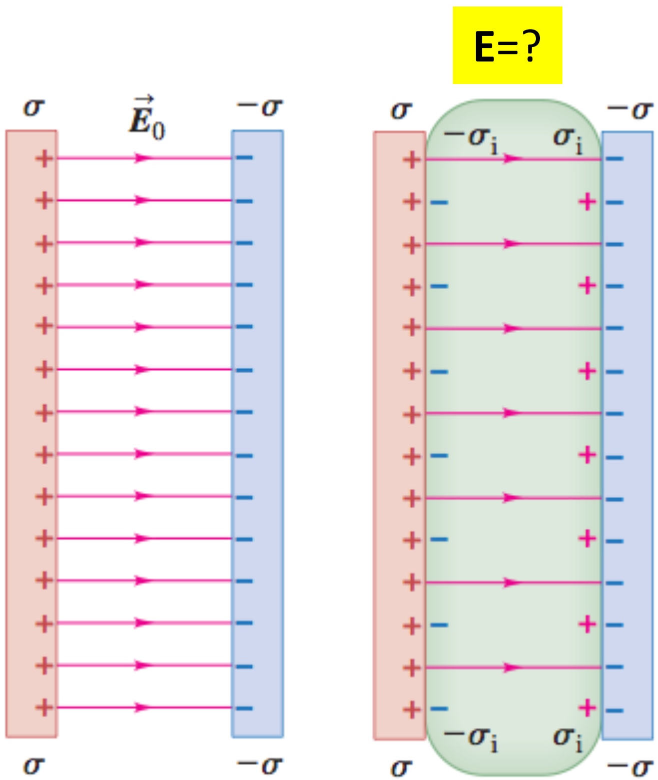
$Originally$: $E_0 = \dfrac{\sigma}{\epsilon_0}$

$With\ dielectric$:

$$E = \frac{\sigma - \sigma_i}{\epsilon_0}$$

$$E = \frac{\sigma}{\epsilon_0}\left[\frac{\sigma - \sigma_i}{\sigma}\right]$$

How strong is the E-field now?



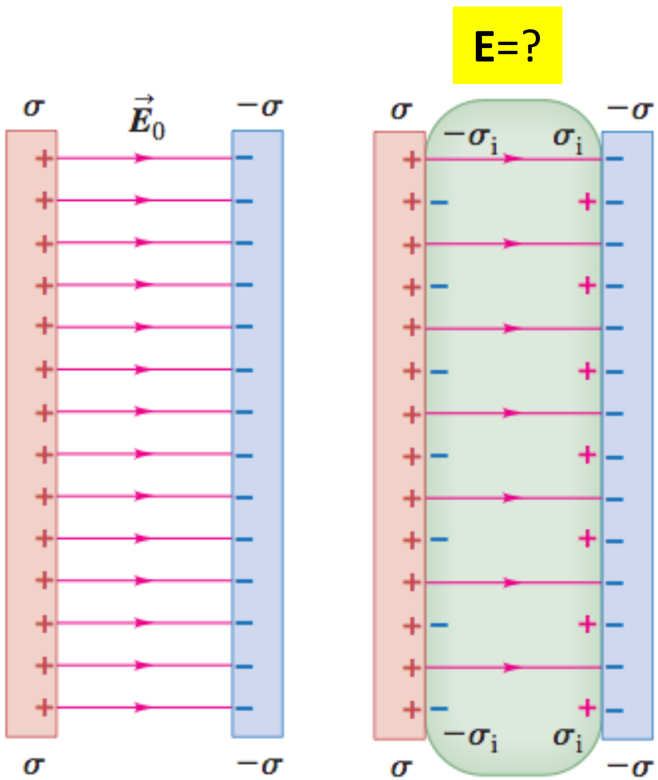
$$Originally: \;\; E_0 = \frac{\sigma}{\epsilon_0}$$

$$With\ dielectric:$$

$$E = \frac{\sigma - \sigma_i}{\epsilon_0}$$

$$E = \frac{\sigma}{\epsilon_0}\left[\frac{\sigma - \sigma_i}{\sigma}\right] = \frac{\sigma}{\epsilon_0\left[\frac{\sigma}{\sigma - \sigma_i}\right]}$$

How strong is the E-field now?



$$Originally: \; E_0 = \frac{\sigma}{\epsilon_0}$$

$$With\ dielectric:$$

$$E = \frac{\sigma - \sigma_i}{\epsilon_0}$$

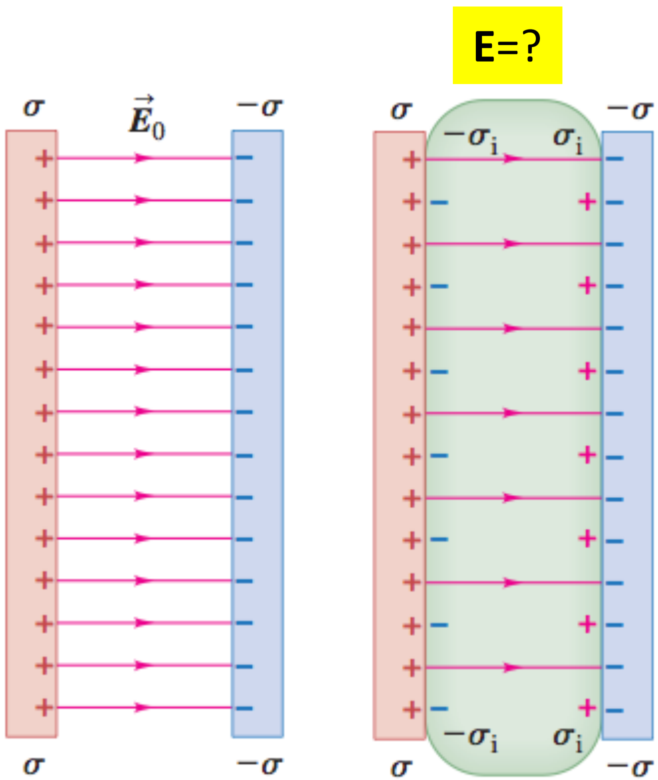
$$E = \frac{\sigma}{\epsilon_0}\left[\frac{\sigma - \sigma_i}{\sigma}\right] = \frac{\sigma}{\epsilon_0\left[\frac{\sigma}{\sigma - \sigma_i}\right]}$$

$$E = \frac{\sigma}{\epsilon_0 K}$$

$$Where:$$

$$K = \frac{\sigma}{\sigma - \sigma_i} \qquad (Dieletric\ constant)$$

How strong is the E-field now?



$$Originally: \; E_0 = \frac{\sigma}{\epsilon_0}$$

$$With\ dielectric:$$

$$E = \frac{\sigma - \sigma_i}{\epsilon_0}$$

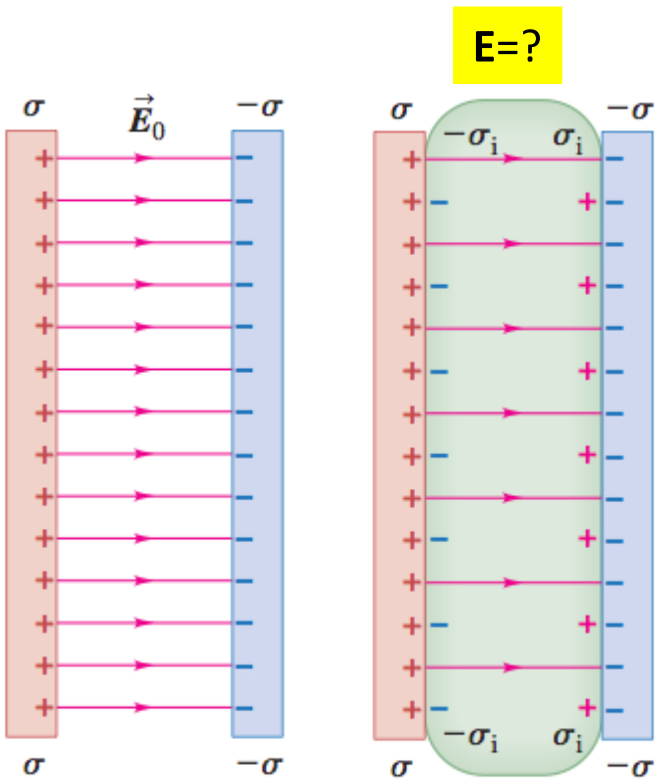
$$E = \frac{\sigma}{\epsilon_0}\left[\frac{\sigma - \sigma_i}{\sigma}\right] = \frac{\sigma}{\epsilon_0\left[\frac{\sigma}{\sigma - \sigma_i}\right]}$$

$$E = \frac{\sigma}{\epsilon_0 K} = \frac{E_0}{K}$$

$$Where:$$

$$K = \frac{\sigma}{\sigma - \sigma_i} \qquad (Dieletric\ constant)$$

How strong is the E-field now?



$$Originally: \; E_0 = \frac{\sigma}{\epsilon_0}$$

$$With\ dielectric:$$

$$E = \frac{\sigma - \sigma_i}{\epsilon_0}$$

$$E = \frac{\sigma}{\epsilon_0}\left[\frac{\sigma - \sigma_i}{\sigma}\right] = \frac{\sigma}{\epsilon_0\left[\frac{\sigma}{\sigma - \sigma_i}\right]}$$

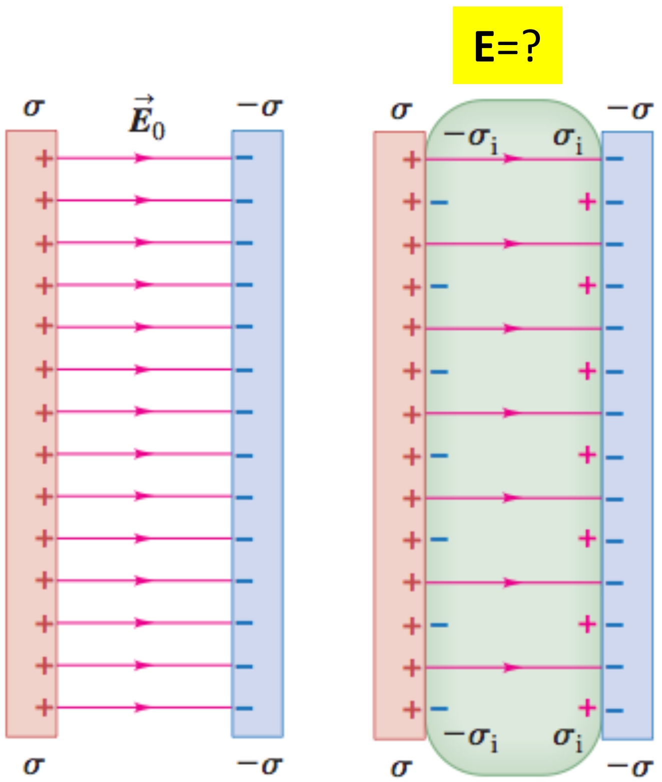
$$E = \frac{\sigma}{\epsilon_0 K} = \frac{E_0}{K} = \frac{\sigma}{\epsilon}$$

$$Where:$$

$$K = \frac{\sigma}{\sigma - \sigma_i} \qquad (Dieletric\ constant)$$

$$\epsilon = K\epsilon_0 \qquad (Dieletric\ permittivity)$$

How strong is the E-field now?



$$Originally: \; E_0 = \frac{\sigma}{\epsilon_0}$$

$$With\ dielectric:$$

$$E = \frac{\sigma - \sigma_i}{\epsilon_0}$$

$$E = \frac{\sigma}{\epsilon_0}\left[\frac{\sigma - \sigma_i}{\sigma}\right] = \frac{\sigma}{\epsilon_0\left[\frac{\sigma}{\sigma - \sigma_i}\right]}$$

$$E = \frac{\sigma}{\epsilon_0 K} = \frac{E_0}{K} = \frac{\sigma}{\epsilon}$$

$$Where:$$

$$K = \frac{\sigma}{\sigma - \sigma_i} \quad (Dieletric\ constant)$$

$$\epsilon = K\epsilon_0 \quad (Dieletric\ permittivity)$$

- How does the dielectric affect the capacitor besides making it more expensive?

Dielectrics

Capacitor without dielectric:

$$C_0 = \frac{Q}{V_0}$$
$$V_0 = E_0 d$$

Dielectrics

Capacitor without dielectric:

$$C_0 = \frac{Q}{V_0}$$
$$V_0 = E_0 d$$

Capacitor with dielectric:

$$V = Ed$$

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

Dielectrics

Capacitor without dielectric:

$$C_0 = \frac{Q}{V_0}$$
$$V_0 = E_0 d$$

Capacitor with dielectric:

$$V = Ed = \frac{E_0}{K} d$$

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

Dielectrics

Capacitor without dielectric:

$$C_0 = \frac{Q}{V_0}$$
$$V_0 = E_0 d$$

Capacitor with dielectric:

$$V = Ed = \frac{E_0}{K} d = \frac{V_0}{K}$$

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

Dielectrics

Capacitor without dielectric:

$$C_0 = \frac{Q}{V_0}$$
$$V_0 = E_0 d$$

Capacitor with dielectric:

$$V = Ed = \frac{E_0}{K} d = \frac{V_0}{K}$$

$$C = \frac{Q}{V} = \frac{QK}{V_0}$$

Dielectrics

Capacitor without dielectric:

$$C_0 = \frac{Q}{V_0}$$
$$V_0 = E_0 d$$

Capacitor with dielectric:

$$V = Ed = \frac{E_0}{K} d = \frac{V_0}{K}$$

$$C = \frac{Q}{V} = \frac{QK}{V_0} = KC_0$$

Dielectrics

Capacitor without dielectric:

$$C_0 = \frac{Q}{V_0}$$
$$V_0 = E_0 d$$

Capacitor with dielectric:

$$V = Ed = \frac{E_0}{K} d = \frac{V_0}{K}$$

$$C = \frac{Q}{V} = \frac{QK}{V_0} = KC_0$$

The dielectric increases the capacitance by a factor of K:

$$C = KC_0$$

Dielectrics

Capacitor without dielectric:

$$C_0 = \frac{Q}{V_0}$$
$$V_0 = E_0 d$$

Capacitor with dielectric:

$$V = Ed = \frac{E_0}{K} d = \frac{V_0}{K}$$

$$C = \frac{Q}{V} = \frac{QK}{V_0} = KC_0$$

The dielectric increases the capacitance by a factor of K:

$C = KC_0$

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

For a given voltage V, energy will increase with C

Dielectrics

Capacitor without dielectric:

$$C_0 = \frac{Q}{V_0}$$
$$V_0 = E_0 d$$

Capacitor with dielectric:

$$V = Ed = \frac{E_0}{K} d = \frac{V_0}{K}$$

$$C = \frac{Q}{V} = \frac{QK}{V_0} = KC_0$$

Summary of relationships:

$$K = \frac{\sigma}{\sigma - \sigma_i} = \frac{E_0}{E} = \frac{V_0}{V} = \frac{C}{C_0}$$

The dielectric increases the capacitance by a factor of K:

$C = KC_0$

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

For a given voltage V, energy stored will increase with C

Dielectrics

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

$$\boxed{C = KC_0}$$

Table 24.1 Values of Dielectric Constant K at 20°C

Material	K	Material	K
Vacuum	1	Polyvinyl chloride	3.18
Air (1 atm)	1.00059	Plexiglas®	3.40
Air (100 atm)	1.0548	Glass	5–10
Teflon	2.1	Neoprene	6.70
Polyethylene	2.25	Germanium	16
Benzene	2.28	Glycerin	42.5
Mica	3–6	Water	80.4
Mylar	3.1	Strontium titanate	310