18.7 Capacitors

19.1 Electric Current

19.2. Batteries and emf

Review

In uniform electric field:

$$\Delta V = -E\Delta r \cos(\measuredangle(\vec{E}, \Delta\vec{r}))$$

Capacitance

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

Capacitor with a dielectric:

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

Review

Capacitance:

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

$$Q = \eta A$$

where η is the surface charge density.

Electric field inside the capacitor

$$E = \frac{\eta}{\varepsilon_0} = \frac{Q}{A\varepsilon_0} \rightarrow Q = EA\varepsilon_0$$

$$C = \frac{Q}{\Delta V} = \frac{EA\varepsilon_0}{Ed} = \frac{\varepsilon_0 A}{d}$$

$$C_{dielectric} = \kappa C_{vacuum}$$

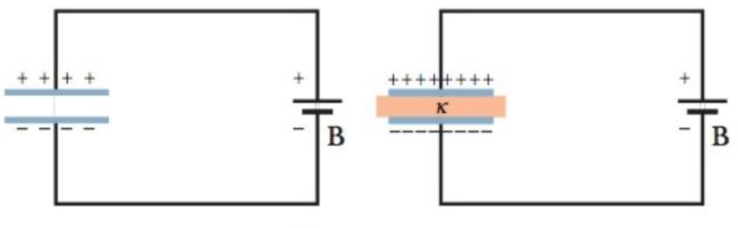
Dielectric constants of some dielectrics

Material	Dielectric Constant κ
Vacuum	1
Air [1 atm]	1.00054
Polystyrene	2.6
Paper	3.5
Porcelain	6.5
Silicon	12
Water	75-80
Titania ceramic	130
Strontium titanite	310
Calcium copper titanite	>250000

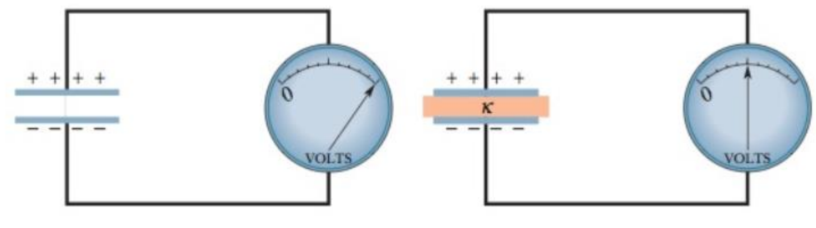
CAPACITOR WITH DIELECTRIC – ELECTRIC FIELD

$$C = \kappa C_0$$

Capacitor is charged and connected to a battery.
Dielectric is entered between the plates of the capacitor.



Capacitor is charged and not connected to the battery.
Dielectric is entered between the plates of the capacitor.



Maintaining potential difference with increasing C means the **amount of charge on the capacitor increases** as $C = \frac{Q}{V} \rightarrow V = \frac{Q}{C}$.

Increasing C by κ means that **the amount of charge stored on the plates can increase κ fold for the same potential difference.**

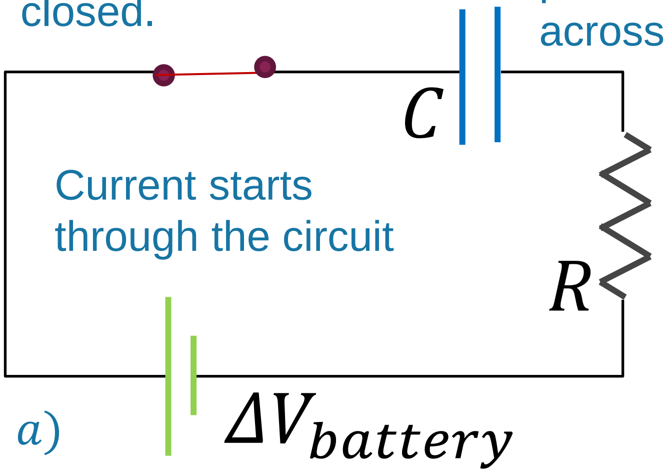
Keeping constant charge with increasing C means **the potential difference between the plates decreases** as $C = \frac{Q}{V} \rightarrow Q = CV$.

Increasing C by κ means **the potential difference drops κ times for the same charge.** This also means the electric field in the dielectric decreases

CHARGING A CAPACITOR

The switch is closed.

Initially there is no potential difference across the capacitor

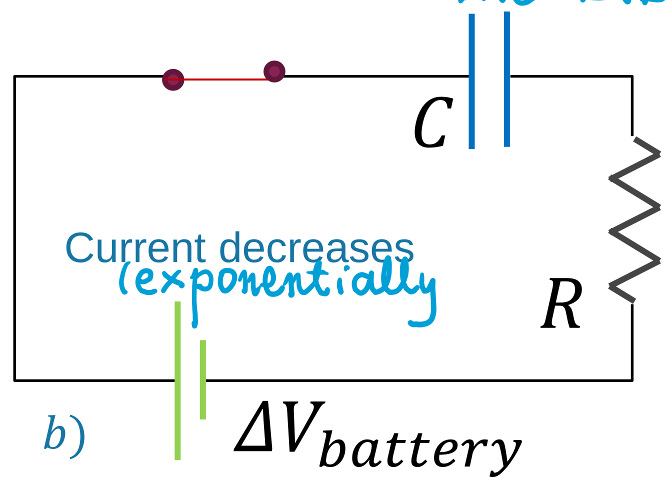


Current starts through the circuit

→ current is maximum at first, $\frac{\Delta V}{R}$

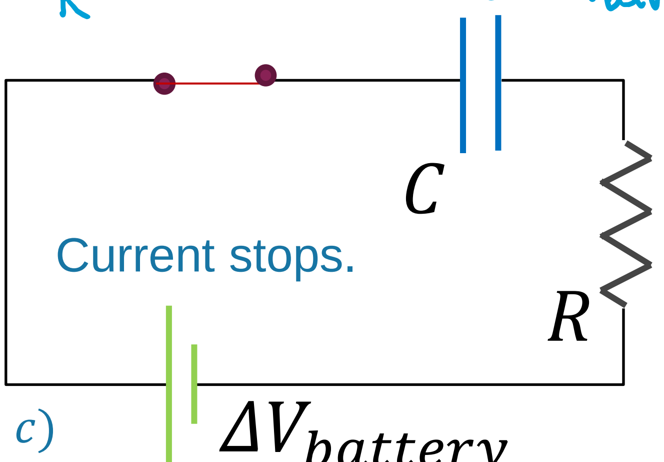
After some time charge gathers on the plates of the capacitor creating a potential difference $\Delta V_C < \Delta V_{battery}$

$\Delta V_C < \Delta V_B$



Current decreases (exponentially

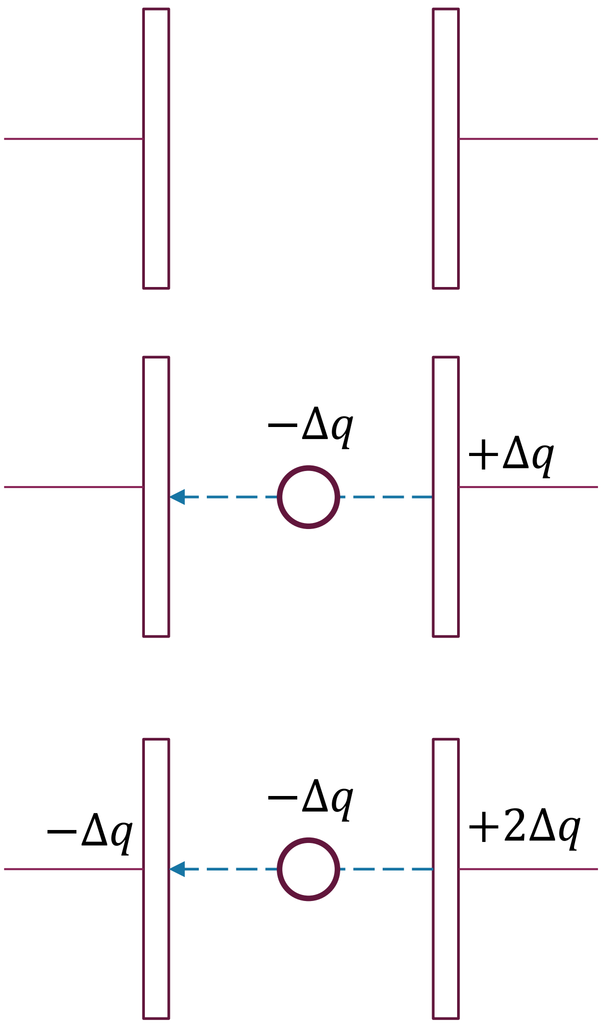
$\Delta V_C = \Delta V_{bat}$



Current stops.

Capacitor is fully charged $\Delta V_C = \Delta V_{battery}$. The charge on the plates is $Q = \pm C\Delta V$

18.7 ENERGY STORED IN A CAPACITOR



Every time small amount of charge $-\Delta q$ is moved from one plate to another, the potential difference between the plates gets larger.

To move the charge, the battery needs to do work

$$W_{battery} = \Delta q \Delta V_{average} = \Delta U_q$$

It turns out that the total change in potential energy (so the energy stored in the capacitor once it is charged) is

$$\boxed{U_C = \frac{1}{2} C \Delta V^2}$$

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

$$\Delta V = \frac{Q}{c}$$

$$U_c = \frac{1}{2} \frac{Q}{\Delta V} (\Delta V)^2 = \frac{1}{2} Q \Delta V$$

$$U_c = \frac{1}{2} C \cdot \left(\frac{Q}{c}\right)^2 = \frac{1}{2}$$

Learning Catalytics

Which of these expressions can be used to calculate the electric potential energy stored in a capacitor of capacitance C that is charged using a battery ΔV and stores charge $\pm Q$ on the plates?

Choose ALL correct answers

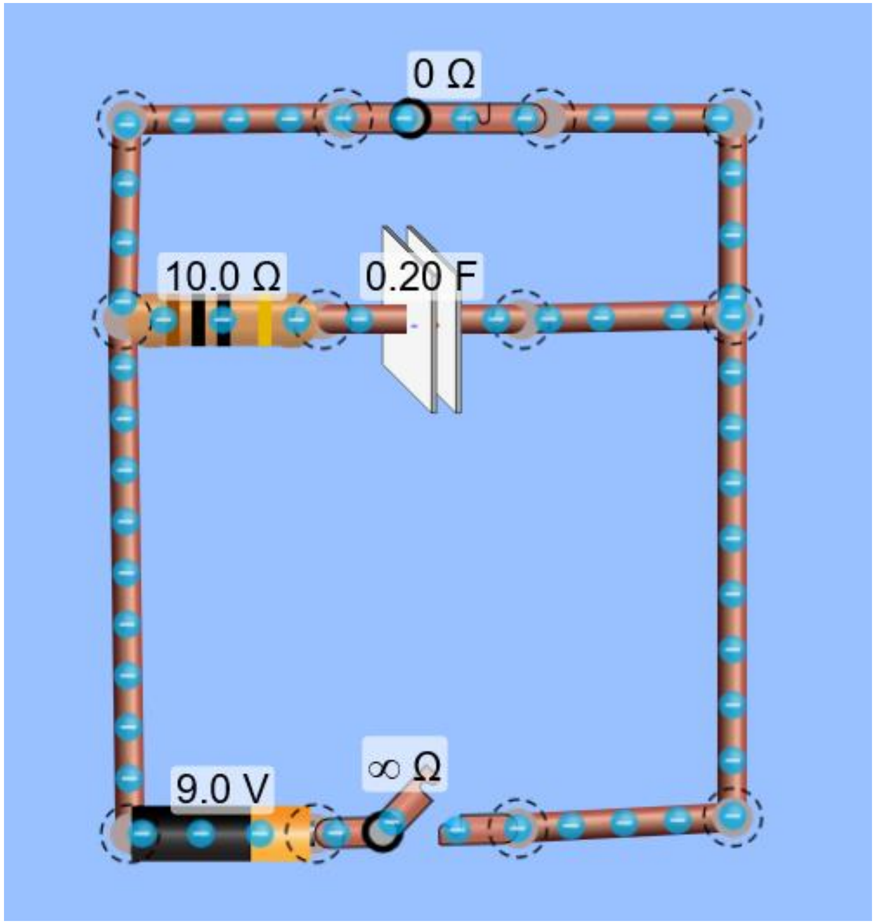
$$a)\ U_C = \frac{1}{2} C \Delta V^2$$

$$b)\ U_C = \frac{Q^2}{2C}$$

$$c)\ U_C = \frac{1}{2} Q \Delta V$$

$$d)\ U_C = \frac{Q}{2\Delta V^2}$$

Learning Catalytics



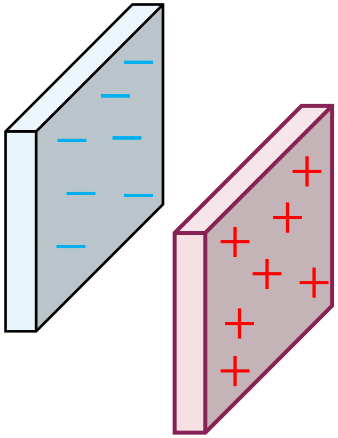
Looking at the circuit analyzed in class determine:

a) The potential difference across the capacitor once it is fully charged.

b) The energy stored in the capacitor when it is fully charged.

NOTE:
the answer should be in JOULES

19.1 The Electron Current

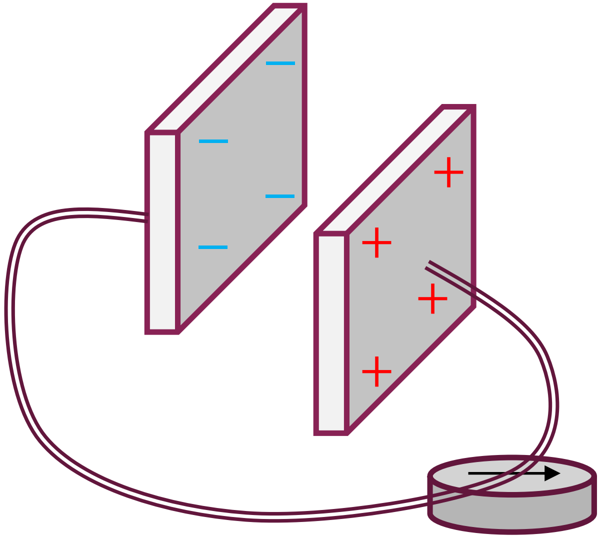


Isolated electrodes stay charged indefinitely.

If a wire is connected to them, the capacitor will be quickly discharged.

Current is the motion of charges.

The net charge of each plate is decreasing.

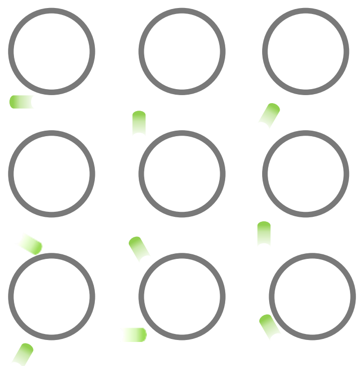


Moving charges (current) are causing the wire to heat up…

… while deflecting the needle of the compass placed nearby.

Charge Carriers

The charges that move in a conductor are called ***charge carriers***.

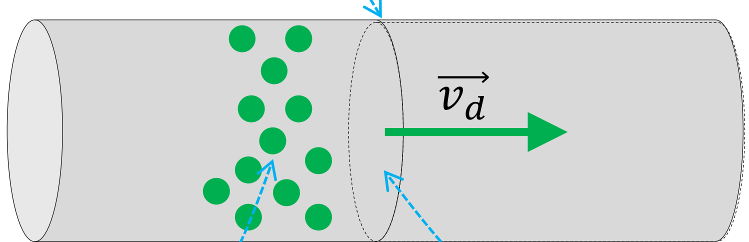


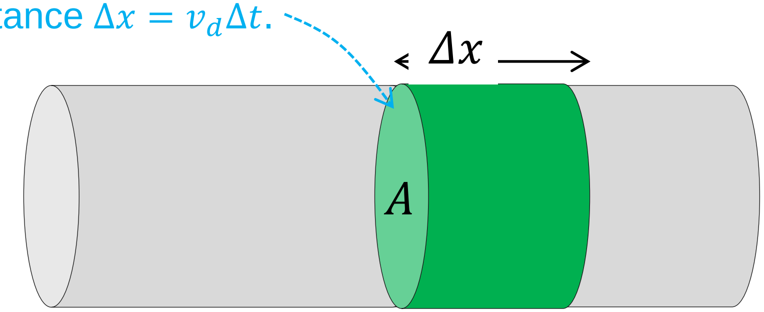
The conduction electrons in metal, like molecules in a gas, undergo random thermal motions, but there is no *NET* motions.

If electric field is applied, there will be net motion, at ***drift speed*** $\vec{v}_d$, superimposed over the random motion

A cross section of the wire

In time Δt, the sea of electrons moved forward distance $\Delta x = v_d \Delta t$.

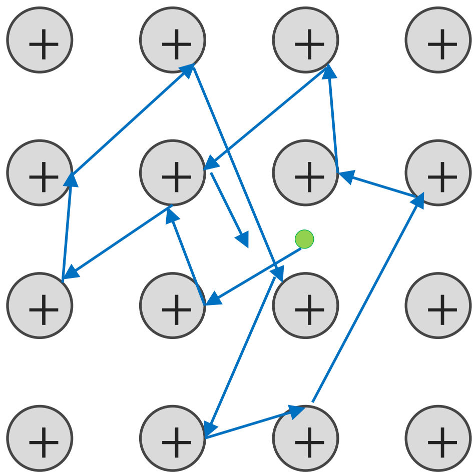


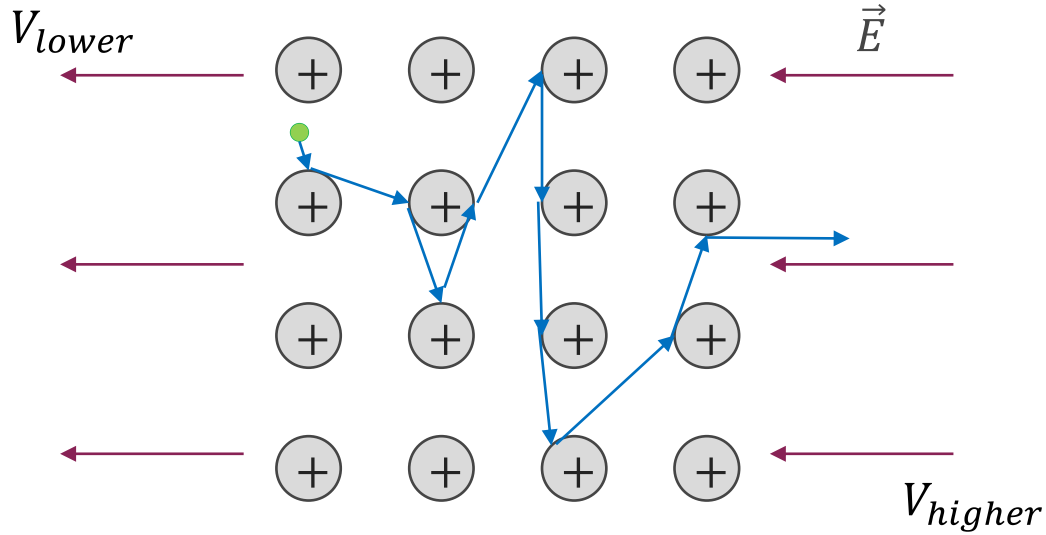


Sea of electrons, containing n_e electrons per cubic meter of wire.

Sea of electrons is moving to the right with drift speed $\overrightarrow{v_d}$. Number of electrons passing through the cross section in one second is defined as **electric current** $\boldsymbol{i_e}$.

A MODEL OF CONDUCTION





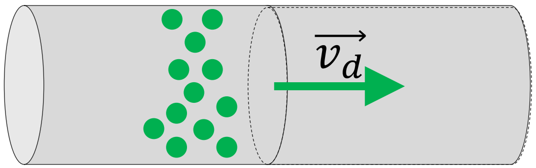
In the absence of an electric field, the electrons move randomly within the wire.

In the presence of an electric field, the electrons drift **toward higher $\boldsymbol{V}$ region.**

Inside the batter the electrons do move from + to –, but it requires work done by the battery (electrochemical/ mechanical/…)

ELECTRIC CURRENT

$$N_e = electron\ density \times volume$$



METAL	ELECTRON DENSITY $[\mathrm{m}^{-3}]$
Al	$6.0 \cdot 10^{28}$
Cu	$8.5 \cdot 10^{28}$
Fe	$8.5 \cdot 10^{28}$
Au	$5.9 \cdot 10^{28}$
Ag	$5.8 \cdot 10^{28}$

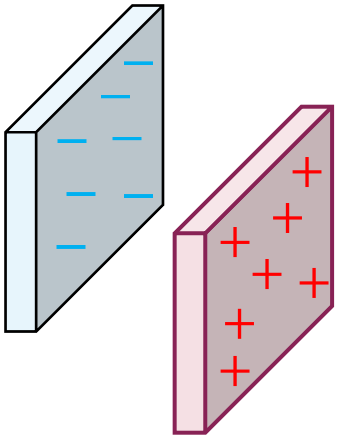
ELEMENT	CARRIER DENSITY $[\mathrm{m}^{-3}]$
Ge	$2.02 \cdot 10^{13}$
Si	$8.72 \cdot 10^{9}$
Ga-Ar	$2.03 \cdot 10^{6}$

Electric current is defined as a magnitude of the electric charge that passes through the cross section of a wire divided by the time interval needed for the charge to pass:

$$I = \frac{|q|}{\Delta t}$$

Number of available carriers depends on the material.

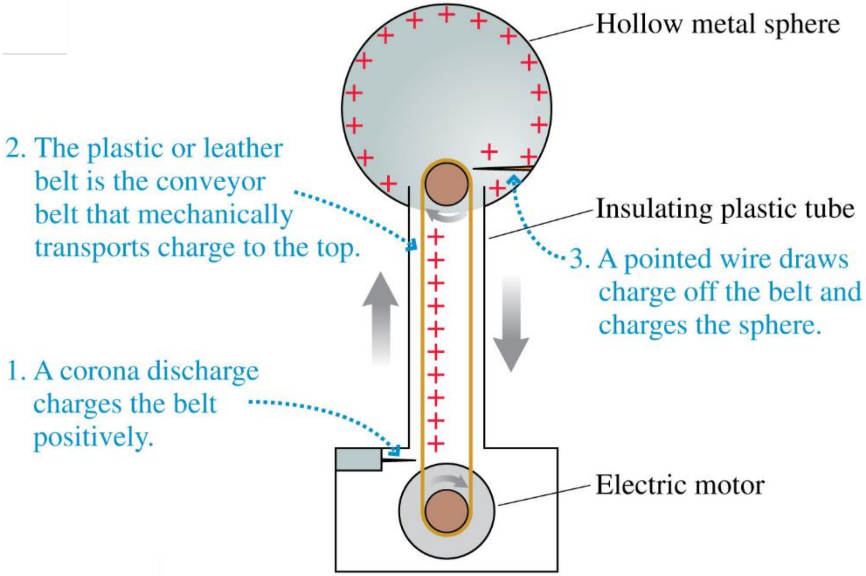
19.2 BATTERIES AND EMF



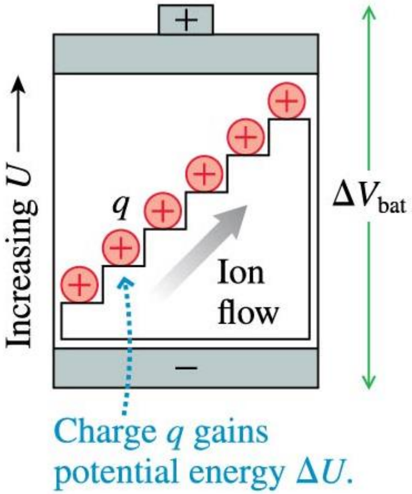
Electric potential difference is created by the **separation** of the electric charges.

Sources of the electric potential:

VAN DER GRAAF GENERATOR



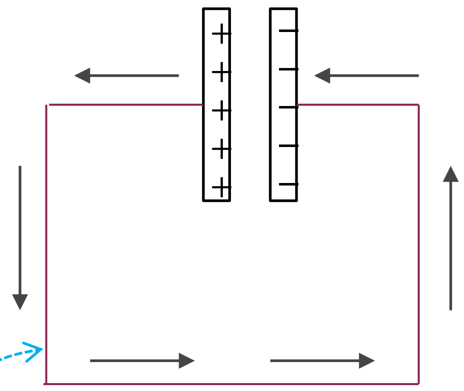
BATTERIES



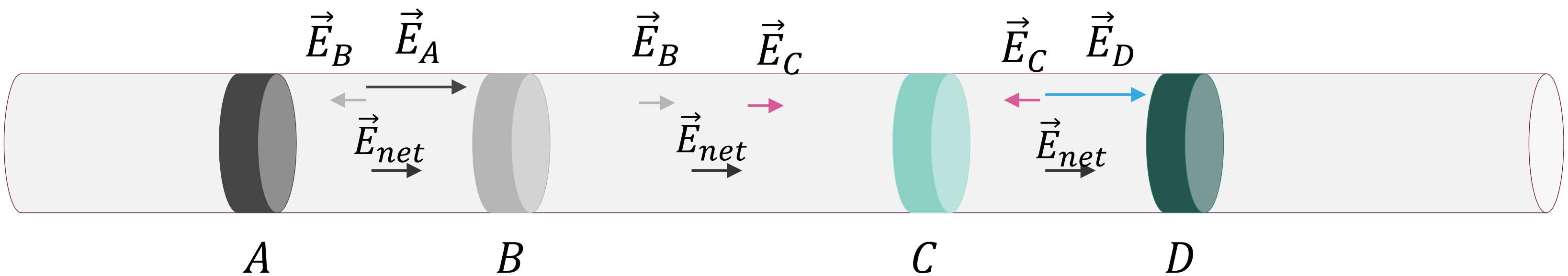
$\epsilon = W_{\text{chem}}/q$

CREATING A CURRENT

An electron current is an nonequilibrium motion of charges sustained by internal electric field.



The surface charge density varies along the wire. The nonuniform surface charge density creates electric field inside the wire.



Internal electric field, created by non-uniform charge distribution, moves charge carriers through the wire.

Most important points:

- inserting dielectric (insulator) into capacitor increases its capacitance

→ if capacitor is still connected to a battery ΔV_c will drop initially and capacitor will continue charging until

$$\Delta V_c = \Delta V_{bat}$$

This means more charge can be stored

$$Q = C\boxed{\Delta V} \qquad Q_\kappa = \kappa C\boxed{\Delta V}$$

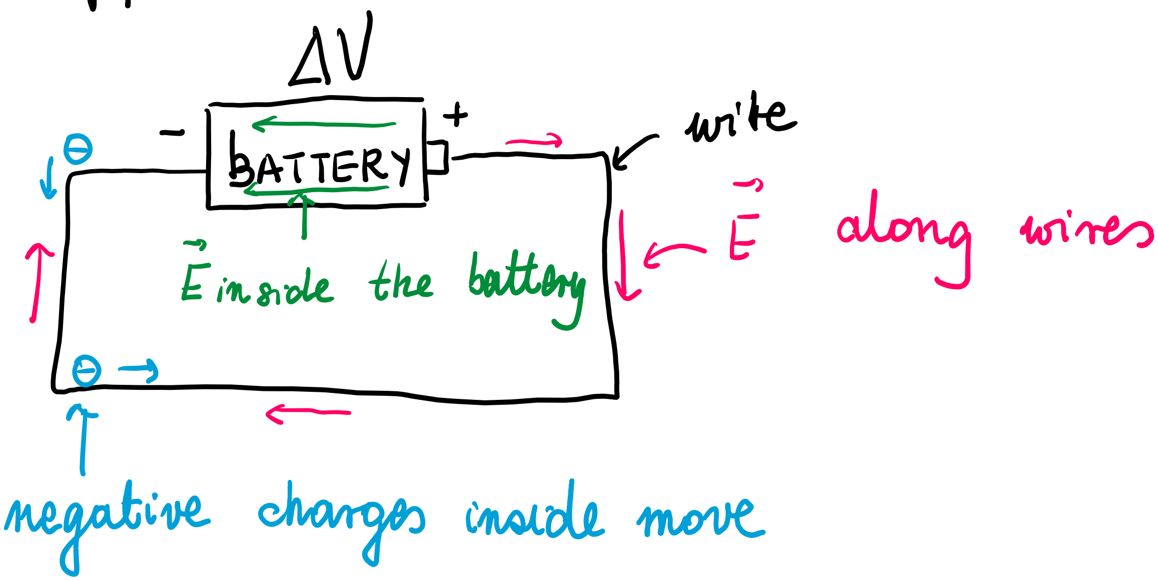
$\kappa > 1$

- if capacitor is disconnected,

ΔV_c drops and stays there. Q is constant

$$\boxed{Q} = C\Delta V \qquad Q_\kappa = \boxed{Q} = \kappa C \Delta V_\kappa \rightarrow \Delta V_\kappa = \frac{\boxed{Q}}{\kappa C}$$

- When electric potential (from a battery or capacitor) is applied across a wire, charges move



$$I = \frac{Q}{\Delta t}$$

Q ← amount of charge moving through a cross section of a wire

units I : amperes (A)