Review 1

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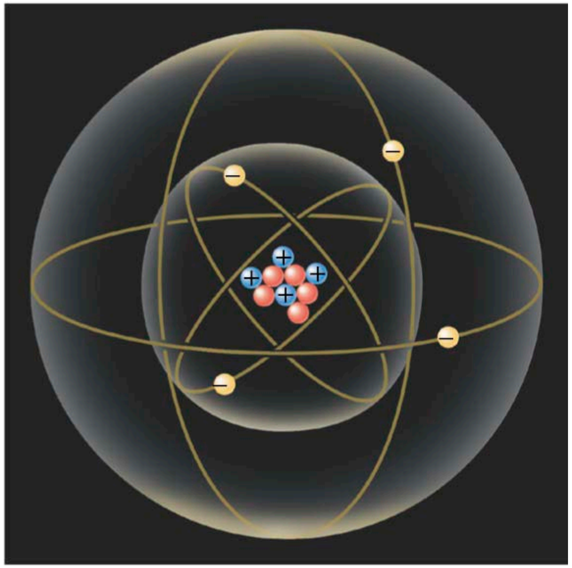
Thanks to: Dr. Rich Vallery, Physics, GVSU

Electrostatics, Coulomb's law, and Electric Field

Fundamentals of Matter

The electrical nature of matter is inherent in atomic structure.



•Atoms are normally found with equal numbers of protons and electrons, so they are electrically neutral.

•By adding or removing *electrons* from matter it will acquire a net electric charge with magnitude equal to *e* times the number of electrons added or removed, *N*.

$$m_p = 1.673\times10^{-27}\,\text{kg}$$

$$m_n = 1.675\times10^{-27}\,\text{kg}$$

$$m_e = 9.11\times10^{-31}\,\text{kg}$$

•The charge on an electron is called *e* and is:

$$e = 1.602\times10^{-19}\,\mathbf{C}$$

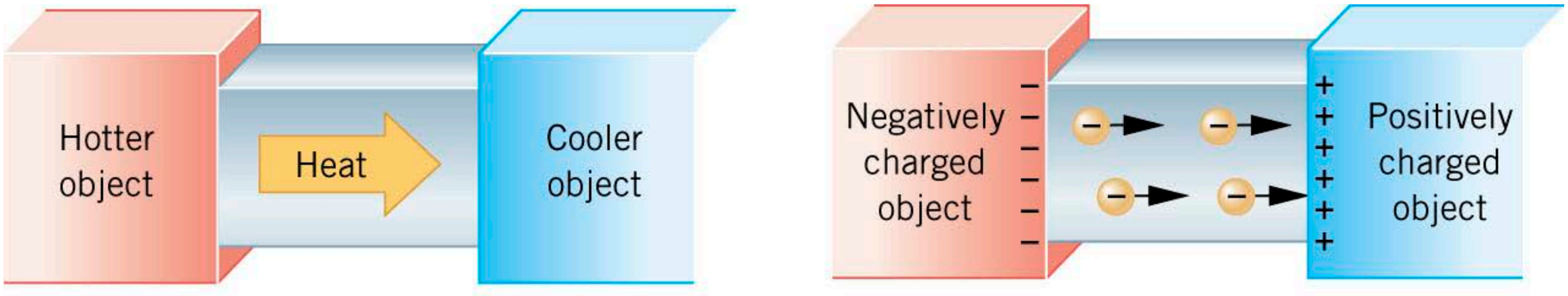
Coulombs

•Total charge is:

$$q = Ne$$

6.25×10^{18} electrons in 1 coulomb

Insulators and Conductors



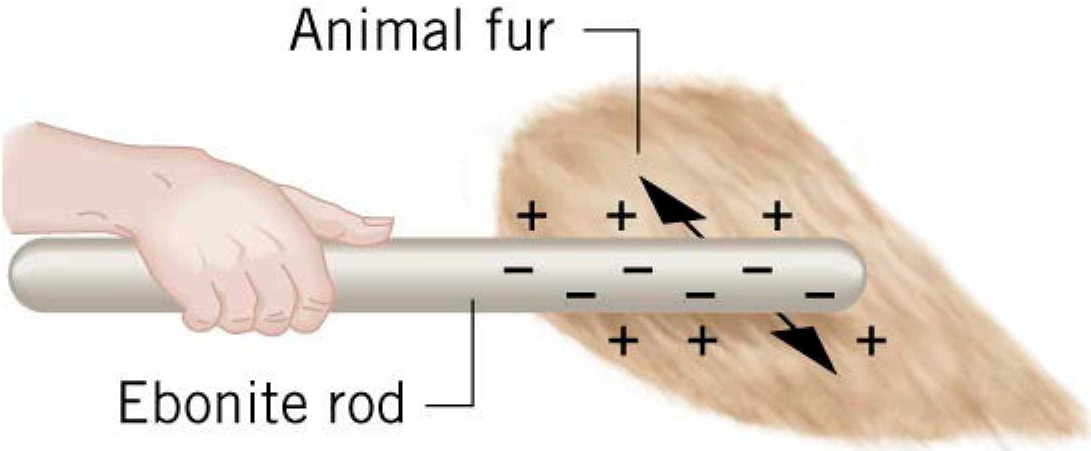
Not only can electric charge exist *on an object,* but it can also move *through and object*.

Conductors (electrical): Substances that readily conduct electric charge.

Insulators (electrical): Materials that conduct electric charge poorly.

Semiconductors: Conduct charge under certain conditions.

Charging Up



LAW OF CONSERVATION OF ELECTRIC CHARGE

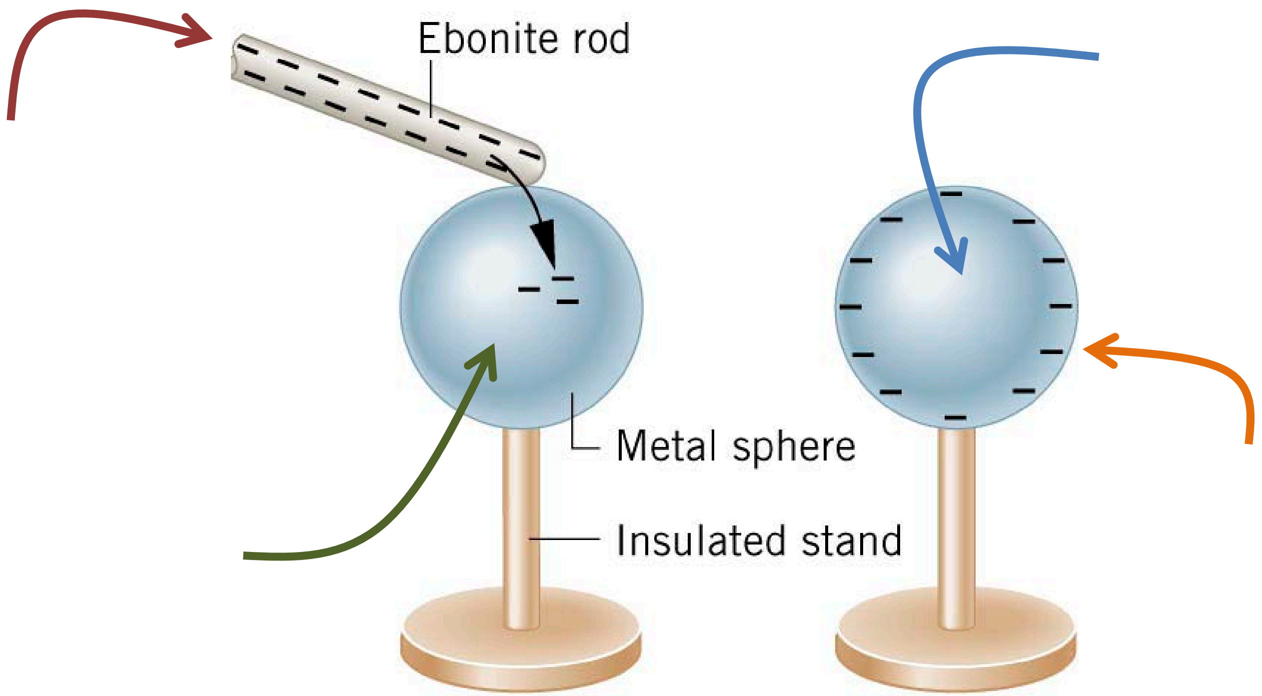
During any process, the net electric charge of an isolated system remains constant (is conserved).

It is possible to *transfer* electric charge from one object to another.

→ The body that loses electrons has an excess of ***positive charge***.

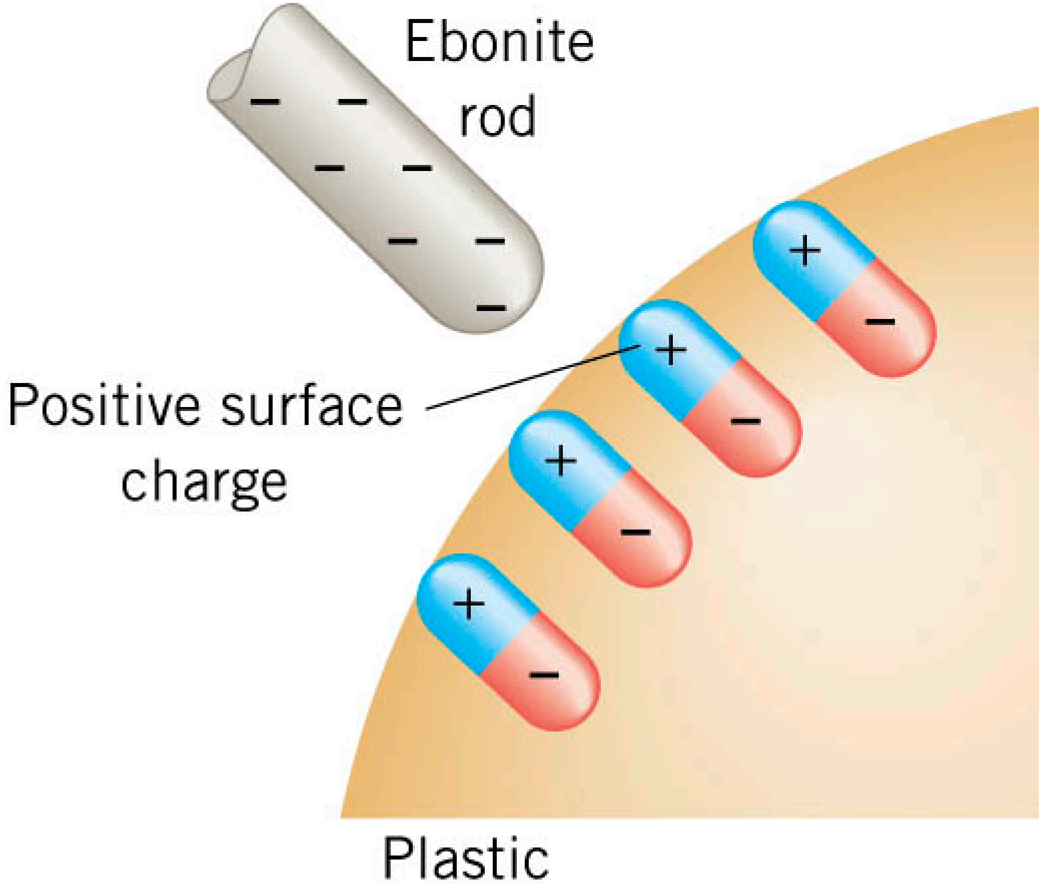
→ The body that gains electrons has an excess of ***negative charge***.

Charging by Contact

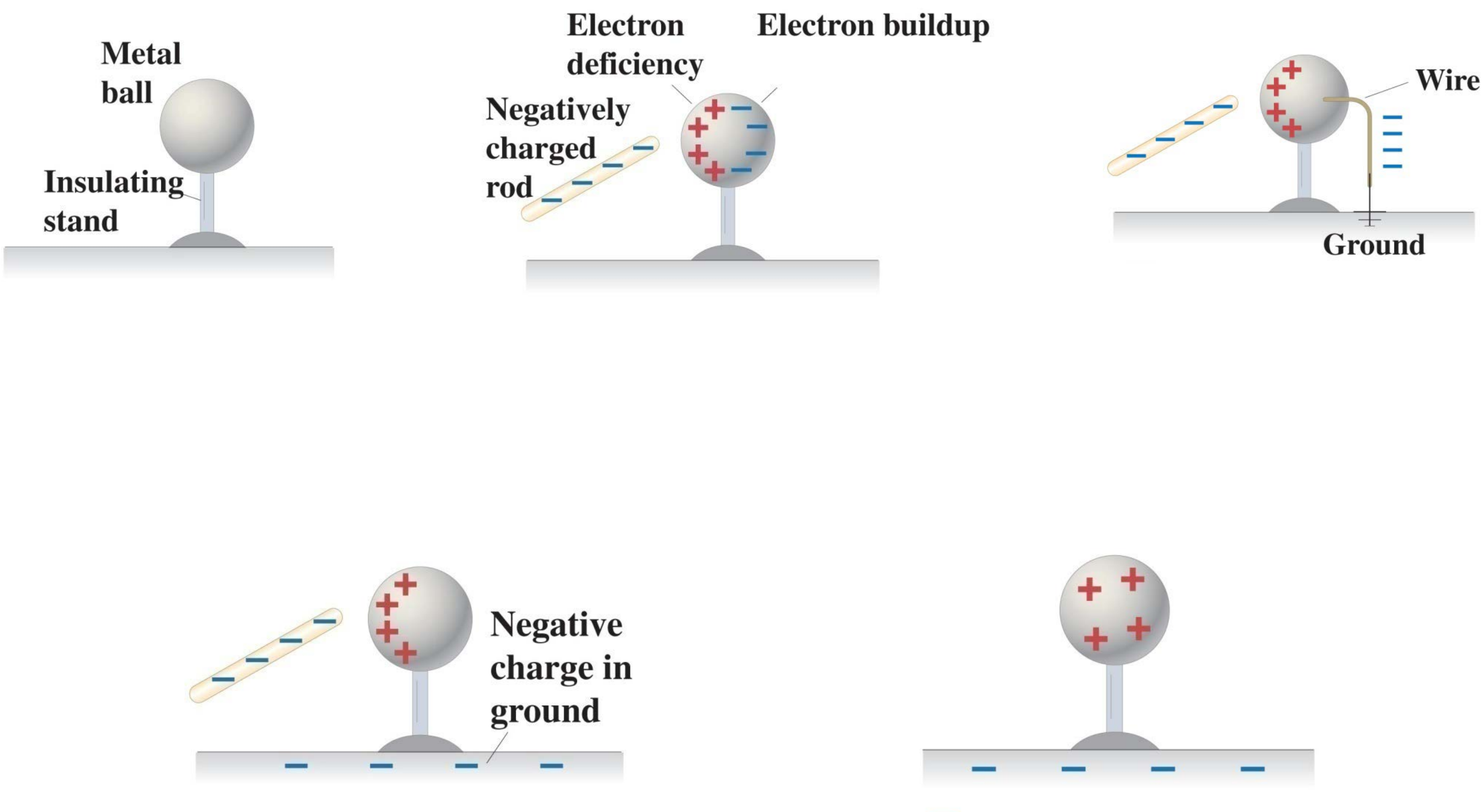


What happens if two equal sized conductors (one charged and the other uncharged are touched together?

Polarization



Charging by Induction

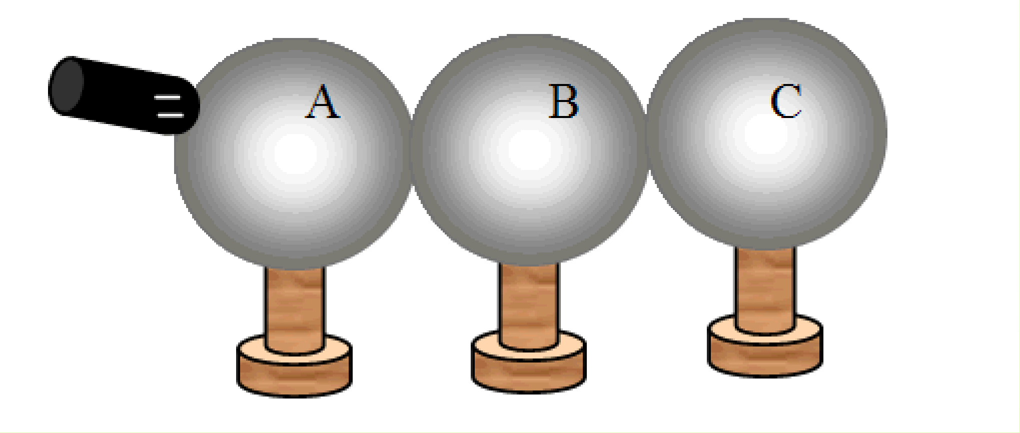


How is this different than if we directly touched the sphere?

Concept Test #1

Three identical conducting spheres on individual insulating stands are initially electrically neutral. The three spheres are arranged so that they are in a line and touching as shown. A negatively-charged conducting rod is brought into contact with sphere A. Subsequently, someone takes sphere C away. Then, someone takes sphere B away. Finally, the rod is taken away. What is the sign of the final charge, if any, of the three spheres?

	A	B	C
a)	+	+	–
b)	+	–	+
c)	+	0	–
d)	–	+	0
e)	–	–	–



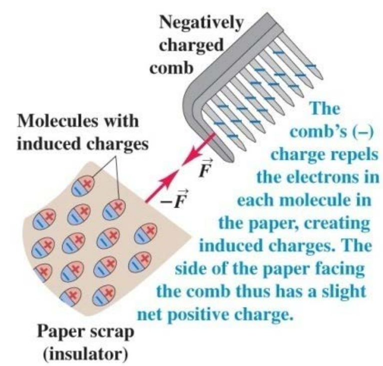
"Observing" Charge

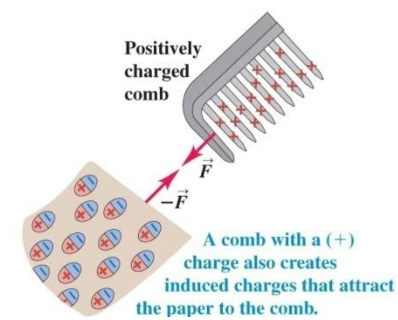
We don't see charge directly but rather observe its effects on the surrounding environment

Observed effects of charge:

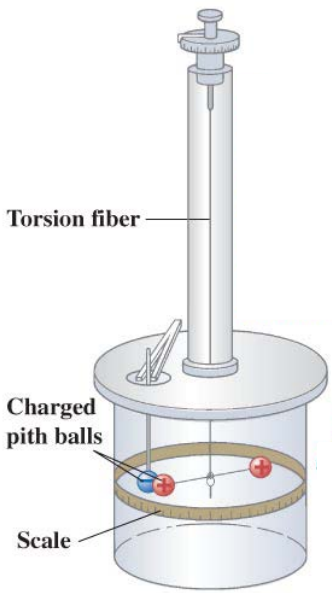
- ➢ **Sparks**
- ➢ **Shocks**
- ➢ ***Force***

Charles Coulomb



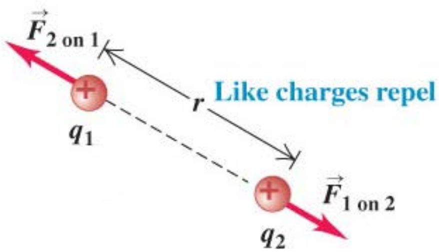


Coulomb's Law



The magnitude of the electrostatic force exerted by one point charge on another point charge:

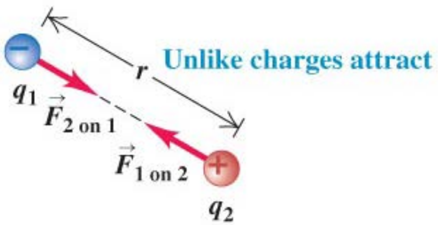
- is proportional to the magnitudes of the charges interacting
- inversely proportional to the distance between the charges squared



$$\varepsilon_o = 8.85\times10^{-12}\ \mathrm{C^2/(N\cdot m^2)}$$

$$|F| = k\frac{|q_1||q_2|}{r^2}$$

$$k = 1/(4\pi\varepsilon_o)$$
$$= 8.99\times10^{9}\ \mathbf{N\cdot m^2/C^2}$$



Direction:

➢ Like charges ***repel.***

➢ Unlike charges ***attract.***

Coulomb's Law and Gravity

One of Newton's crowning achievements was a law that described the way two bodies interacted gravitationally:

$$F_{\mathbf{g}} = \frac{\mathbf{G} m_1 m_2}{r^2}$$

G = 6.67×10^{-11} Nm^2/kg^2

Attractive ONLY

Coulombs law similarly describes the way two bodies interact electrostatically:

$$F_{\mathbf{C}} = \frac{\mathbf{k} q_1 q_2}{r^2}$$

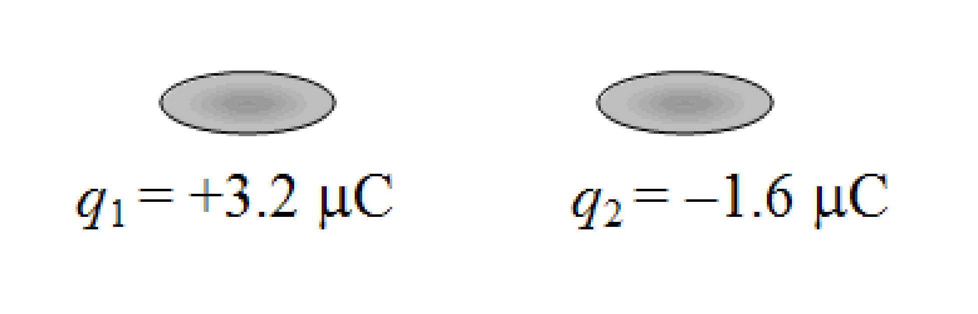
k = 8.99×10^{9} Nm^2/C^2

Attractive OR repulsive

Both are inverse <u>square</u> laws

Concept Test #2

Consider the two charges shown in the drawing. Which of the following statements correctly describes the direction of the electric force acting on the two charges?



a) The force on q_1 points to the left and the force on q_2 points to the left.

b) The force on q_1 points to the right and the force on q_2 points to the left.

c) The force on q_1 points to the left and the force on q_2 points to the right.

d) The force on q_1 points to the right and the force on q_2 points to the right.

Example: Charges in a Line

We have three charges in a line as shown:

$$F_{12} = k\frac{|q_1||q_2|}{r^2} = \frac{\left(8.99\times10^{9}\,\mathbf{N\cdot m^2/C^2}\right)\left(3.0\times10^{-6}\,\mathbf{C}\right)\left(4.0\times10^{-6}\,\mathbf{C}\right)}{\left(0.20\mathbf{m}\right)^2} = 2.7\mathbf{N}$$

$$F_{13} = k\frac{|q_1||q_3|}{r^2} = \frac{\left(8.99\times10^{9}\,\mathbf{N\cdot m^2/C^2}\right)\left(3.0\times10^{-6}\,\mathbf{C}\right)\left(7.0\times10^{-6}\,\mathbf{C}\right)}{\left(0.15\mathbf{m}\right)^2} = 8.4\mathbf{N}$$

Net Force:

$$\vec{\mathbf{F}} = \vec{\mathbf{F}}_{12} + \vec{\mathbf{F}}_{13} = -2.7\text{N} + 8.4\text{N} = +5.7\text{N}$$

Concept Test #3

Two point charges are stationary and separated by a distance *R*. Which one of the following pairs of charges would result in the largest repulsive force?

a) $-2q$ and $+4q$

b) $-3q$ and $-2q$

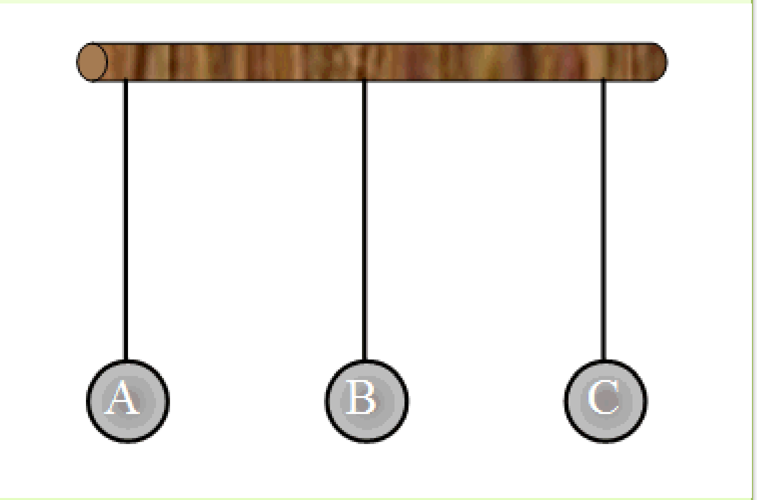
c) $+3q$ and $-2q$

d) $+2q$ and $+4q$

e) $-3q$ and $-q$

Concept Test #4

Three insulating balls are hung from a wooden rod using thread. The three balls are then individually charged via induction. Subsequently, balls A and B are observed to attract each other, while ball C is repelled by ball B. Which one of the following statements concerning this situation is correct?



a) A and B are charged with charges of opposite signs; and C is charged with charge that has the same sign as B.

b) A and B are charged with charges of the same sign; and C is electrically neutral.

c) A is electrically neutral; and C is charged with charge that has the same sign as B.

d) B is electrically neutral; and C is charged with charge that has the same sign as A.

e) Choices a and c are both possible configurations.

The Electric Field

The *electric field* that exists at a point is the electrostatic force experienced by a small test charge placed at that point divided by the charge itself:

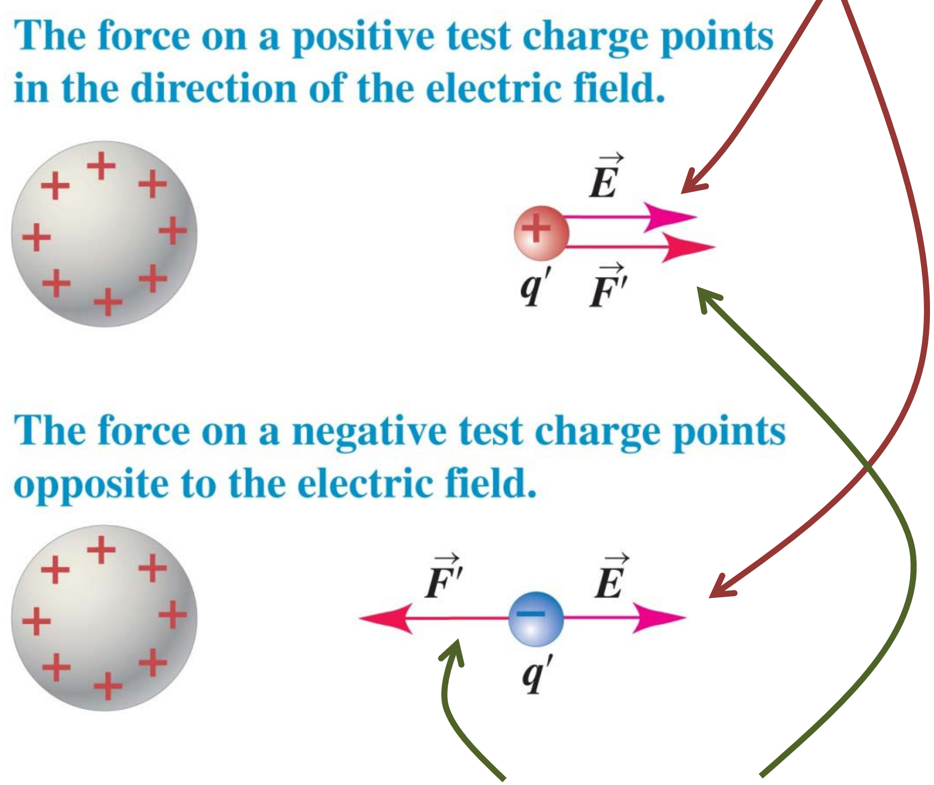
$$\vec{\mathbf{E}} = \frac{\vec{\mathbf{F}}}{q_o}$$

SI Units of Electric Field: newton per coulomb (N/C)

Point charge q:

$$E = k\frac{|q|}{r^2}$$

Electric field to the right

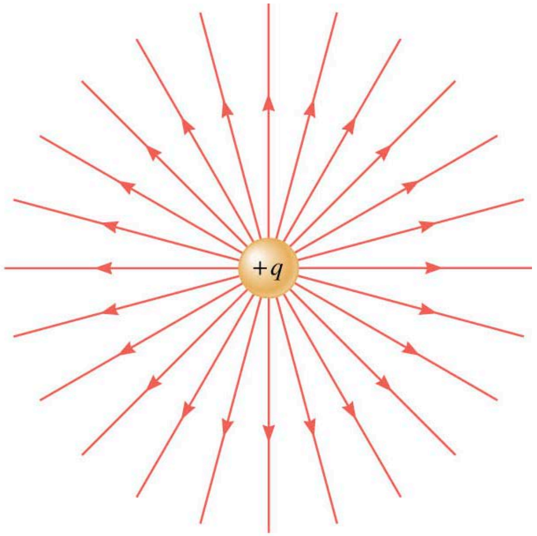


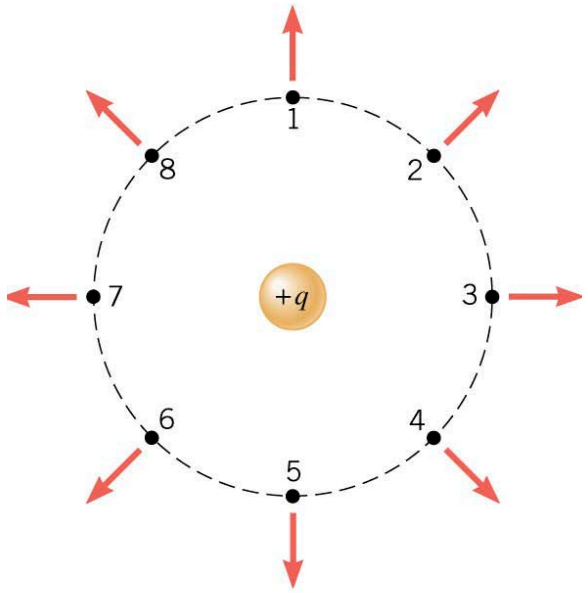
Force in opposite directions

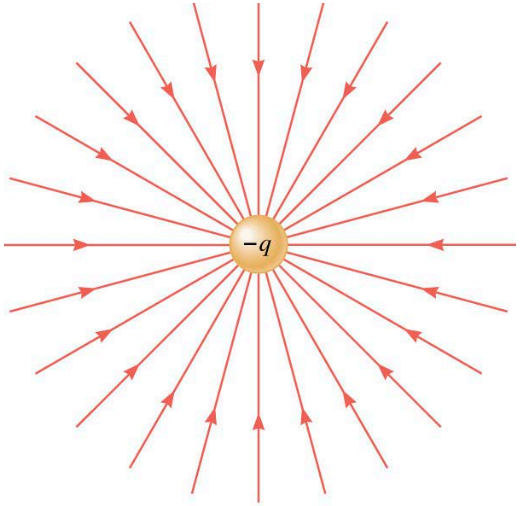
Electric Fields

Electric field lines **or** ***lines of force*** **provide a map of the electric field in the space surrounding electric charges**

Draw the map by imaging the direction a positive test charge would feel a force for all points in space

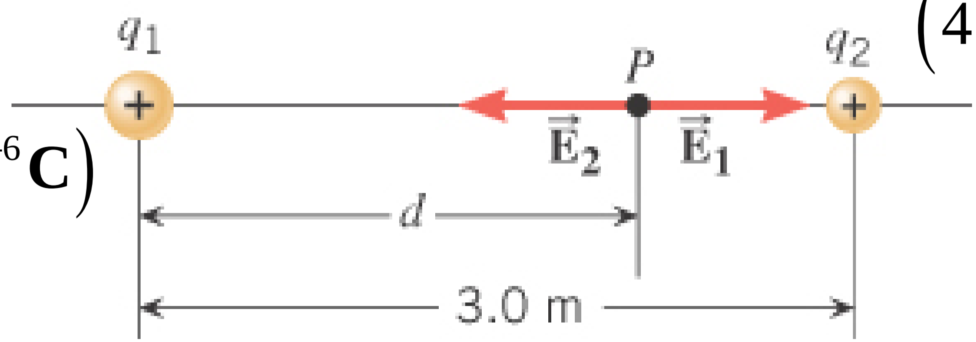






Electric field lines are always directed away from positive charges and toward negative charges.

Example: Superposition of Electric Fields



$(4.0\times10^{-6}\,\mathbf{C})$

$(16\times10^{-6}\,\mathbf{C})$

Where must q_1 be placed for the electric field at *P* to be zero?

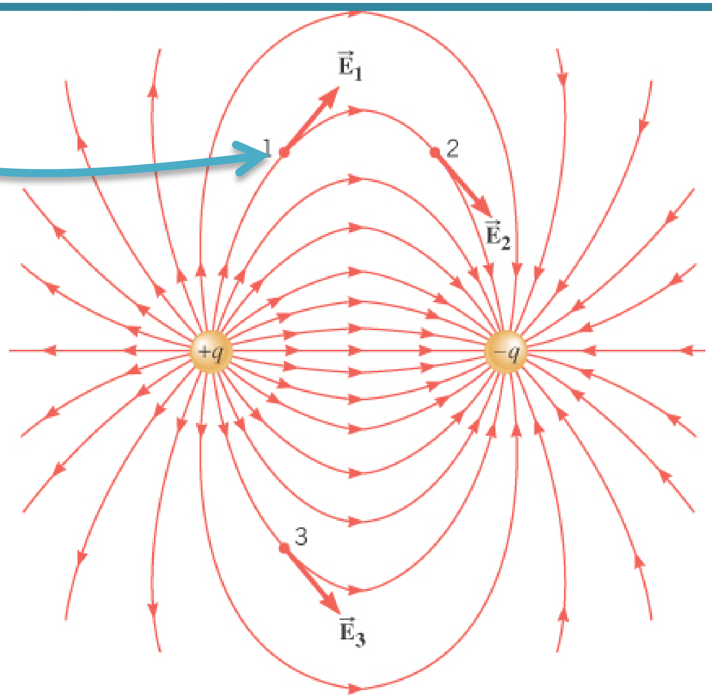
$$E = k\frac{|q|}{r^2} \Rightarrow -k\frac{(16\times10^{-6}\,\mathbf{C})}{d^2} + k\frac{(4.0\times10^{-6}\,\mathbf{C})}{(3.0\mathbf{m}-d)^2} = 0 \Rightarrow$$

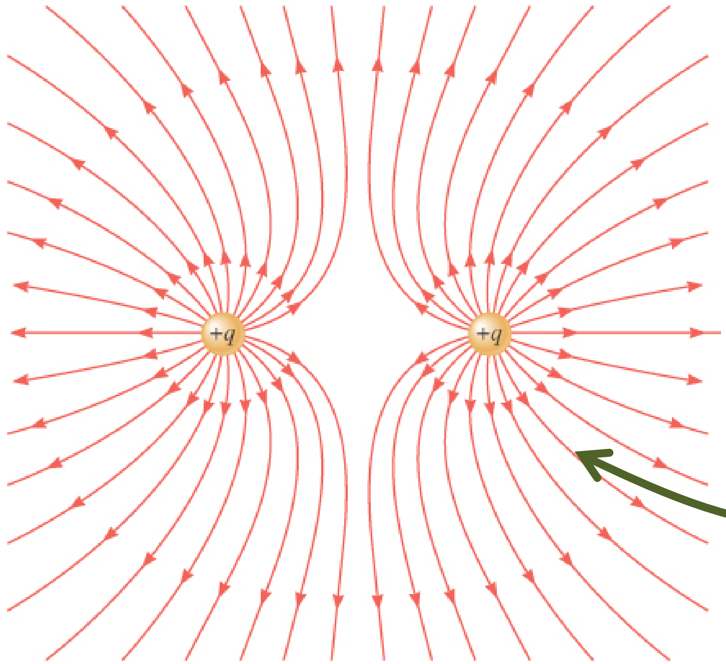
$$k\frac{(16\times10^{-6}\,\mathrm{C})}{d^2} = k\frac{(4.0\times10^{-6}\,\mathrm{C})}{(3.0\mathrm{m}-d)^2} \Rightarrow 2.0(3.0\mathrm{m}-d)^2 = d^2$$

$$d = +2.0\,\mathrm{m}$$

Reading Electric Field Maps

Electric field at a **point** is *tangent* to the electric field line



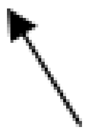


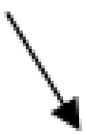
Electric field lines can never cross! (superposition)

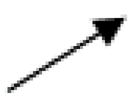
Concept Test #5

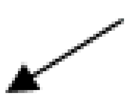
Consider the drawing, where the solid lines with arrows represent the electric field due to the charged object. An electron is placed at the point P and released at rest. Which of the following vectors represents the direction of the force, if any, on the electron?

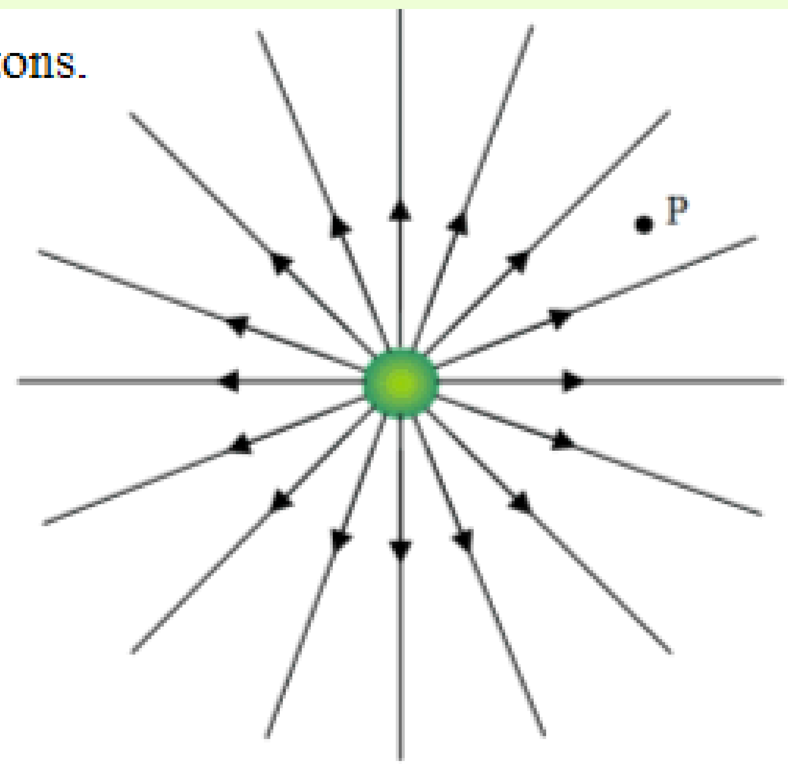
a) The electric force will be zero newtons.

b) 

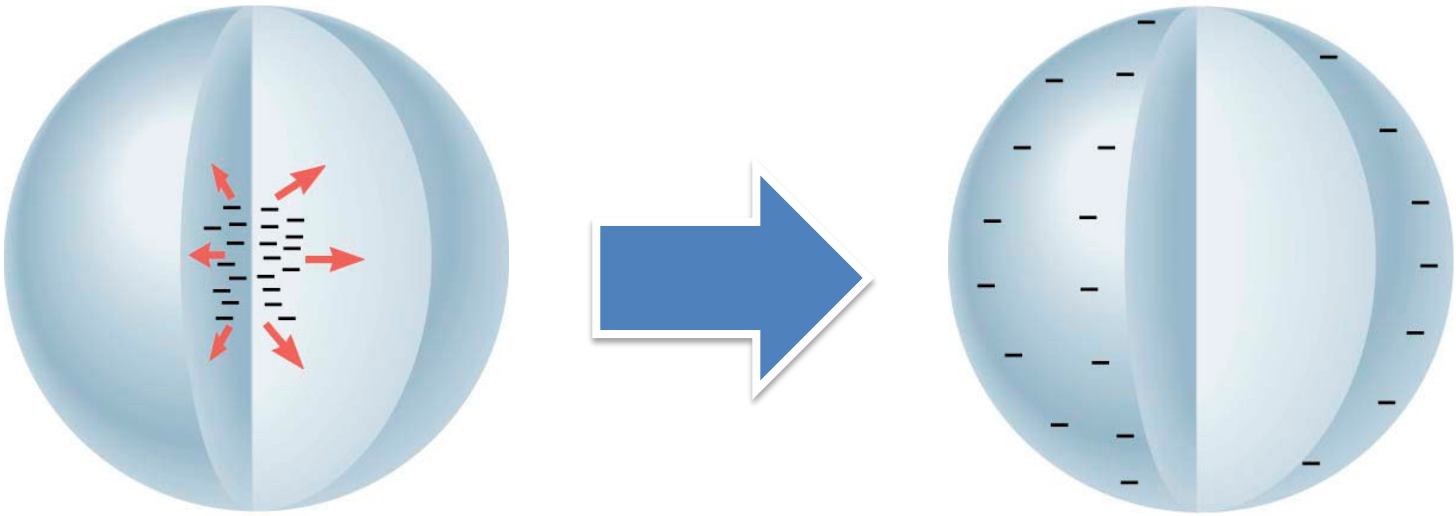
c) 

d) 

e) 



Electric Fields and Conductors



•Recall: In a conductor charge is free to move around → the charge in a conductor will try to get as far away as possible.

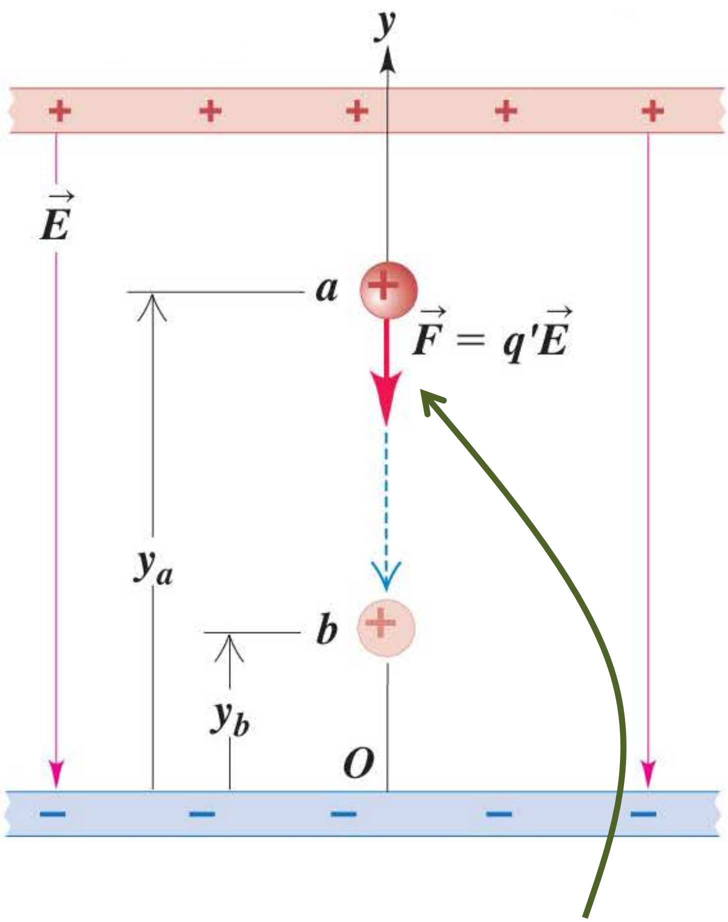
•Result: At equilibrium under electrostatic conditions, any excess charge resides on the surface of a conductor.

•At equilibrium under electrostatic conditions, the electric field is zero at any point within a conducting material.

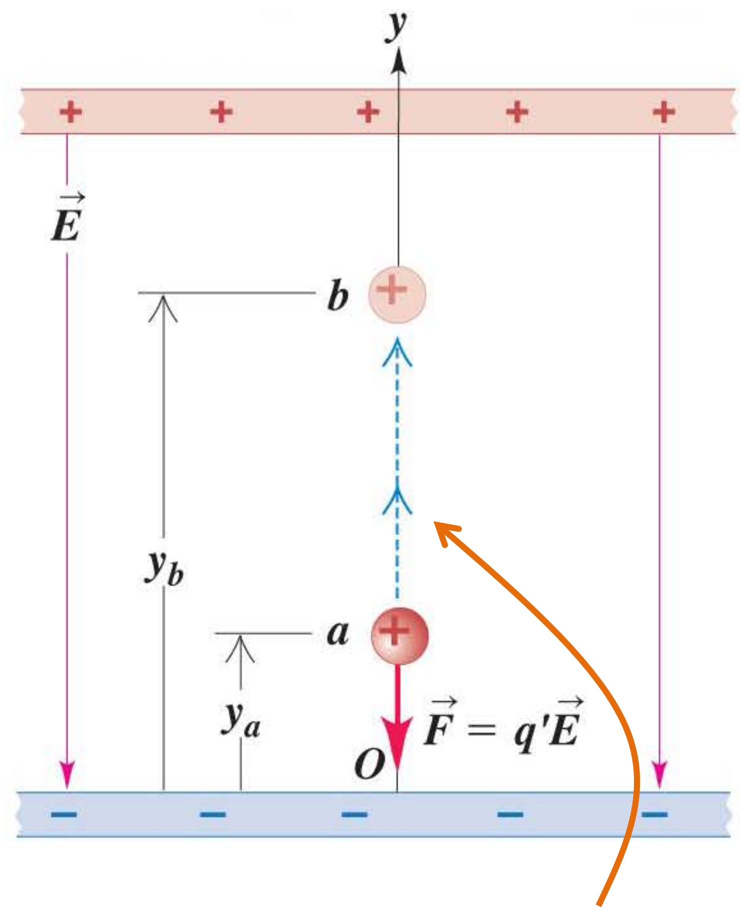
•The conductor shields any charge within it from electric fields created outside the conductor.

Electric Energy and Potential

Moving Charges in an Electric Field

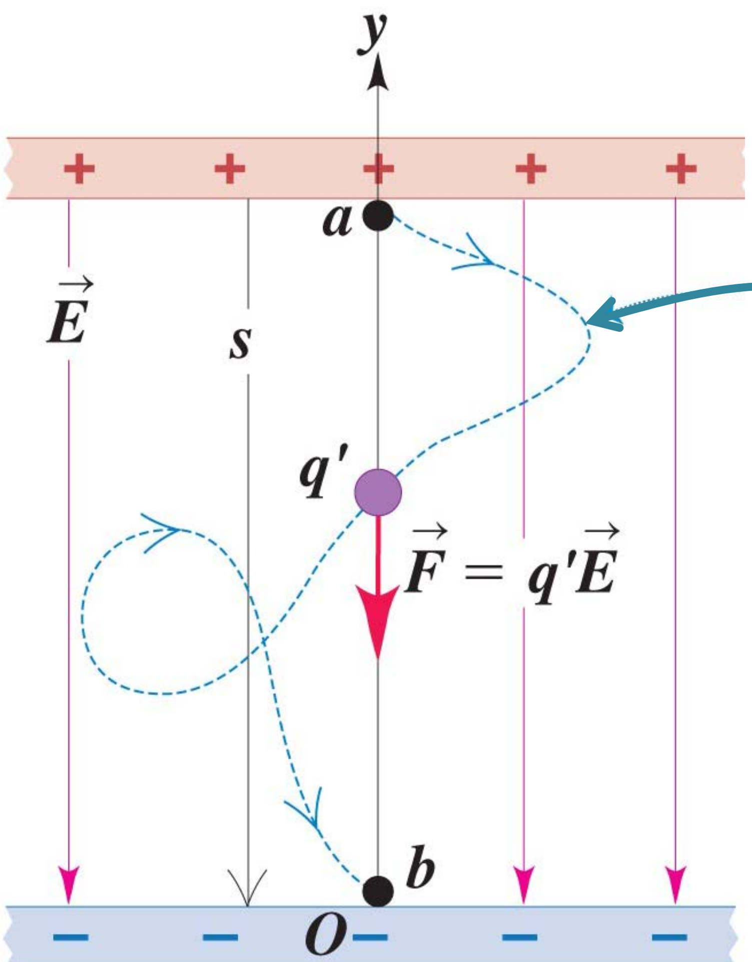


The electric field does ***positive work*** on the positive charge when it moves *with* the field line



The electric field does ***negative work*** on the positive charge when it moves *against* the field line

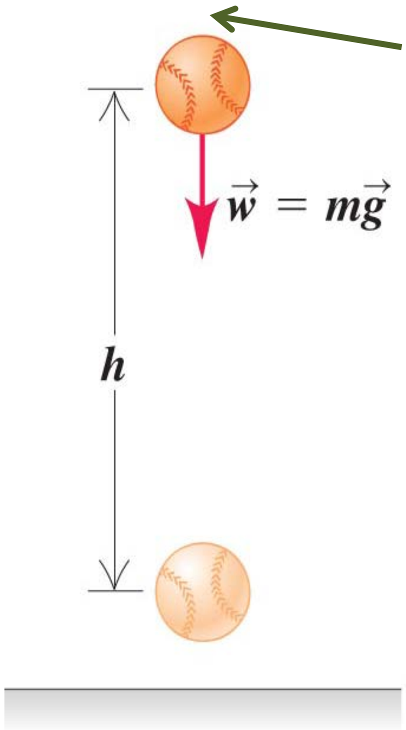
Conservative Forces and the Electric Field



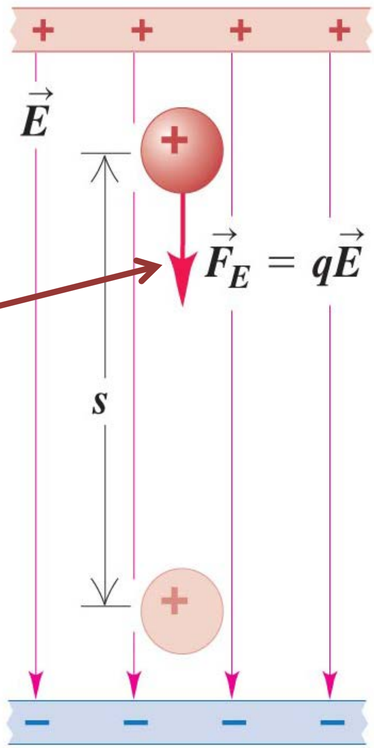
Since moving perpendicular to the electric field doesn't do any work, it doesn't matter if we follow this path or move straight down from a to b

<u>Same work is done!</u>

Energy and the Electric Field



$$W_{AB} = mgh_A - mgh_B = \mathrm{GPE}_A - \mathrm{GPE}_B$$



$$W_{AB} = \mathrm{EPE}_A - \mathrm{EPE}_B$$

$$\frac{W_{AB}}{q_o} = \frac{\mathrm{EPE}_A}{q_o} - \frac{\mathrm{EPE}_B}{q_o}$$

The potential energy per unit charge is called the *electric potential*, V [volt].

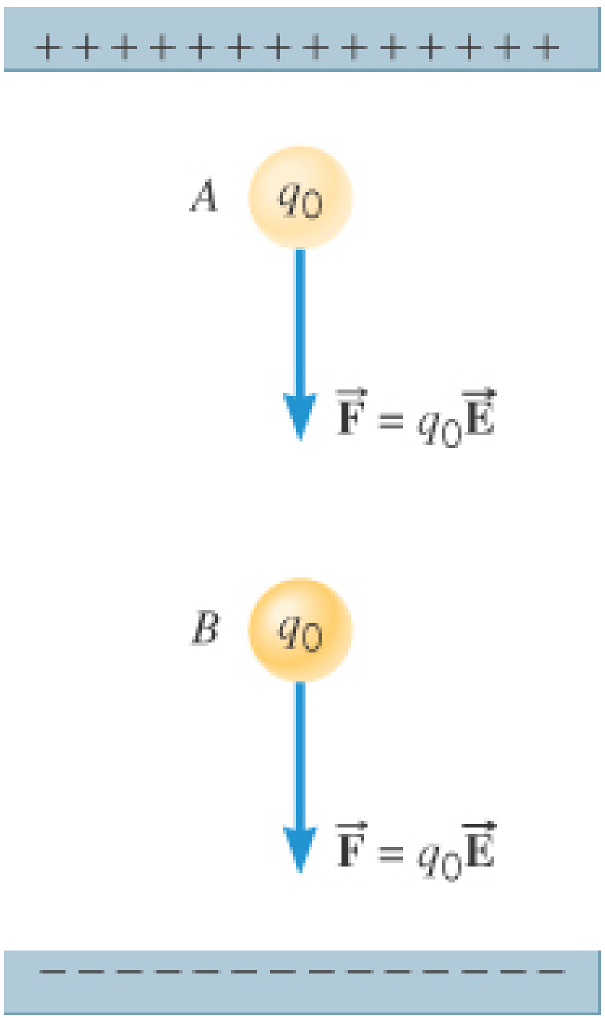
The Electric Potential

The electric potential at a given point is the electric potential energy of a small test charge divided by the charge itself:

$$V = \frac{\text{EPE}}{q_o}$$

SCALAR

SI Unit of Electric Potential:
joule/coulomb = volt (V)



We reference the potential relative to another point → *potential difference ΔV*:

$$V_B - V_A = \frac{\text{EPE}_B}{q_o} - \frac{\text{EPE}_A}{q_o} = \frac{-W_{AB}}{q_o}$$

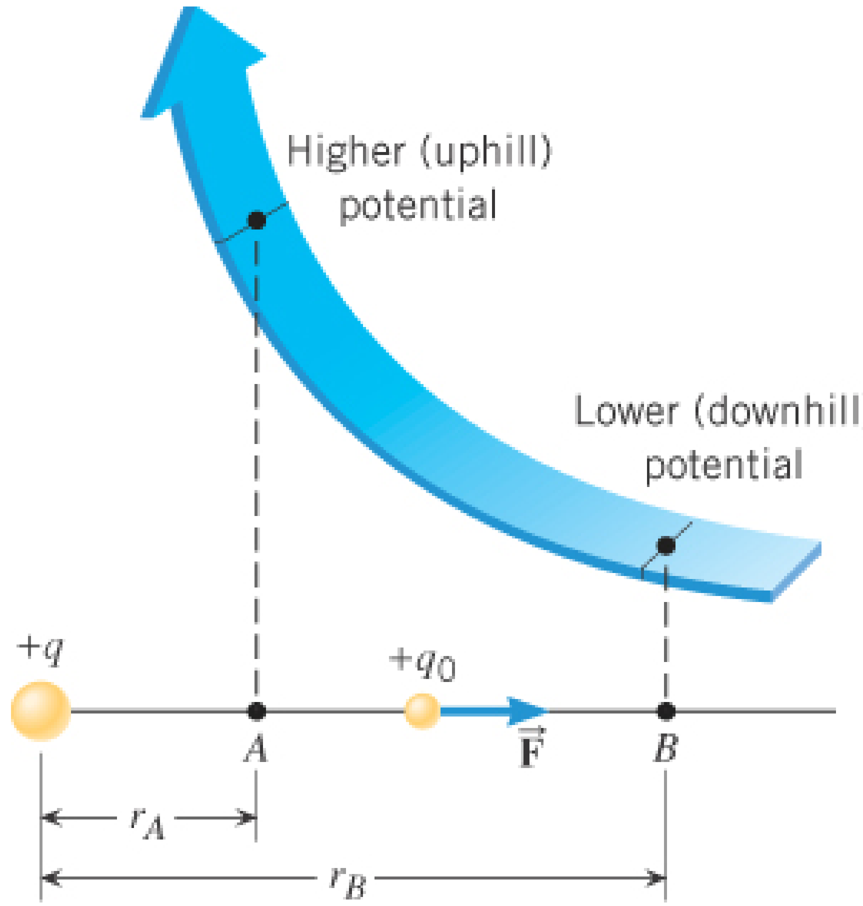
$$\Delta V = \frac{\Delta(\text{EPE})}{q_o} = \frac{-W_{AB}}{q_o}$$

Electric Potential: Point Charge

Up to this point we've talked about potential in a generic sense. Now we look at potential for a *point charge*:

$$W_{AB} = \frac{kqq_o}{r_A} - \frac{kqq_o}{r_B}$$

$$V_B - V_A = \frac{-W_{AB}}{q_o} = \frac{kq}{r_A} - \frac{kq}{r_B}$$

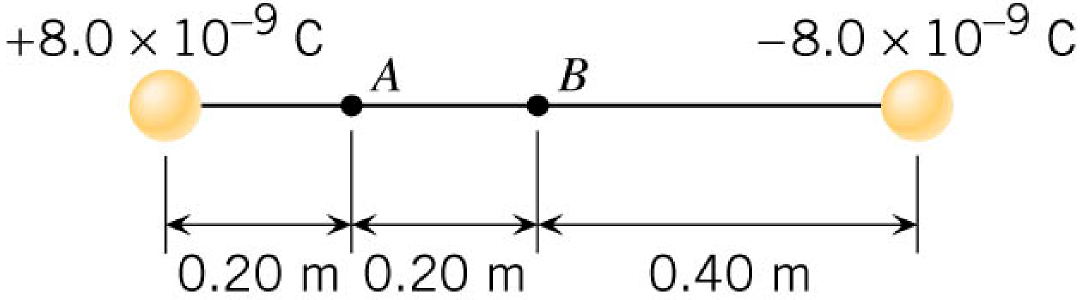


Potential of a point charge:

$$V = \frac{kq}{r}$$

At infinity, potential is zero.

Example: Potential and Point Charges



Recall that potential is a scalar quantity → potentials simply "add"

Here we make ground at infinity

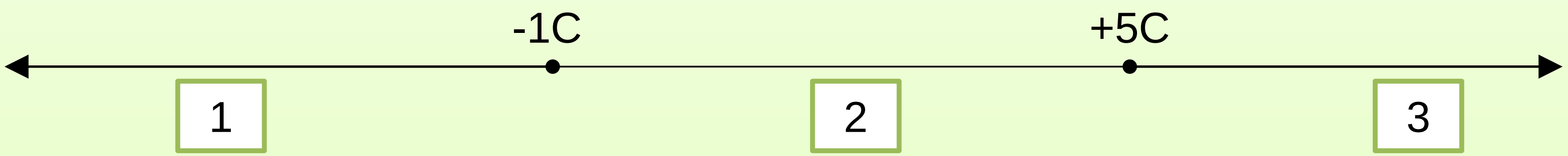
- ***positive*** **charges produce positive potentials (above ground)**
- ***negative*** **charges produce negative potentials (below ground)**

$$V_A = \frac{\left(8.99\times10^{9}\ \mathrm{N\cdot m^2/C^2}\right)\left(+8.0\times10^{-8}\,\mathrm{C}\right)}{0.20\ \mathrm{m}} + \frac{\left(8.99\times10^{9}\ \mathrm{N\cdot m^2/C^2}\right)\left(-8.0\times10^{-8}\,\mathrm{C}\right)}{0.60\ \mathrm{m}} = +240\ \mathrm{V}$$

$$V_B = \frac{\left(8.99\times10^{9}\ \mathrm{N\cdot m^2/C^2}\right)\left(+8.0\times10^{-8}\,\mathrm{C}\right)}{0.40\ \mathrm{m}} + \frac{\left(8.99\times10^{9}\ \mathrm{N\cdot m^2/C^2}\right)\left(-8.0\times10^{-8}\,\mathrm{C}\right)}{0.40\ \mathrm{m}} = 0\ \mathrm{V}$$

Concept Question #6

We have a -1C pt charge and +5C pt charge located on the x-axis as shown. If V(∞)=0 what regions along the axis might have V=0 and E=0?



	V=0	E=0
A.	1,2	1
B.	2	2
C.	never	1
D.	2	never
E.	2,3	3

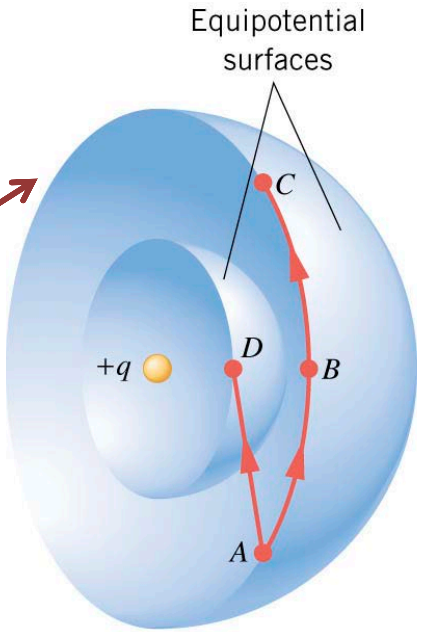
Note that the collection of all points with V=0 is a *surface* surrounding the -1C charge

The Electric Field and Potential

An *equipotential surface* is a surface on which the electric potential is the same everywhere.

$$V = \frac{kq}{r}$$

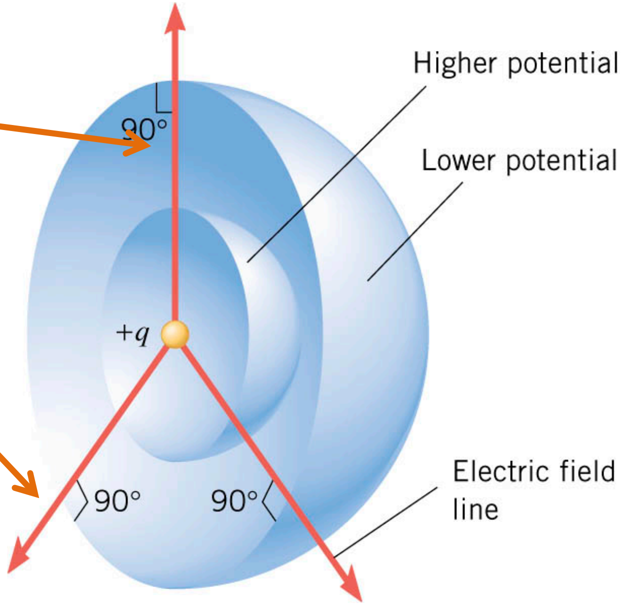
For a p.c. equipotential surfaces occur at fixed radii



The net electric force does no work on a charge as it moves on an equipotential surface.

The electric field created by any charge or group of charges is *everywhere perpendicular* to the associated equipotential surfaces and *points in the direction of decreasing potential*.

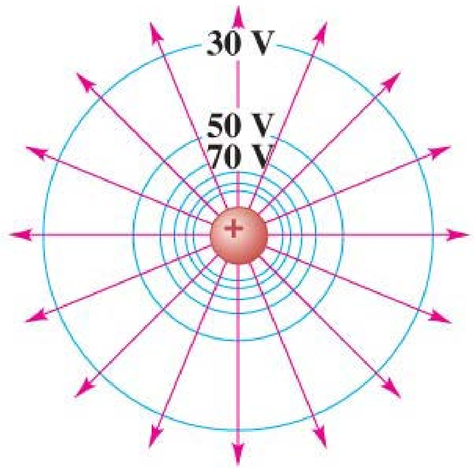
$$E = -\frac{\Delta V}{\Delta s}$$



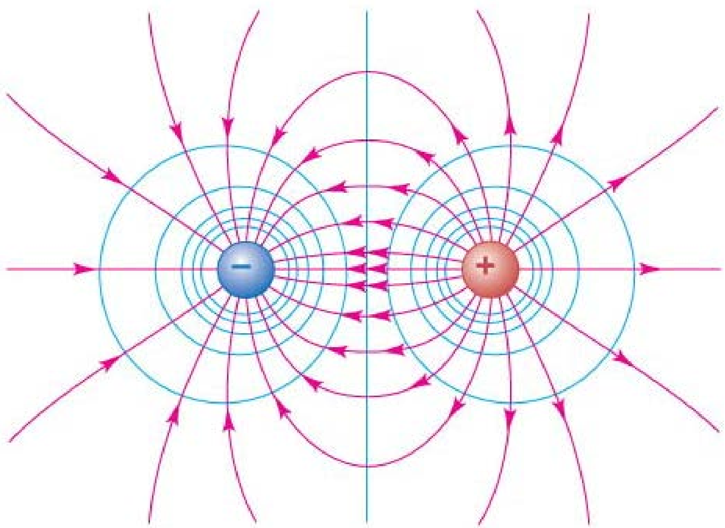
The Electric Field and Potential Maps

Electric field lines

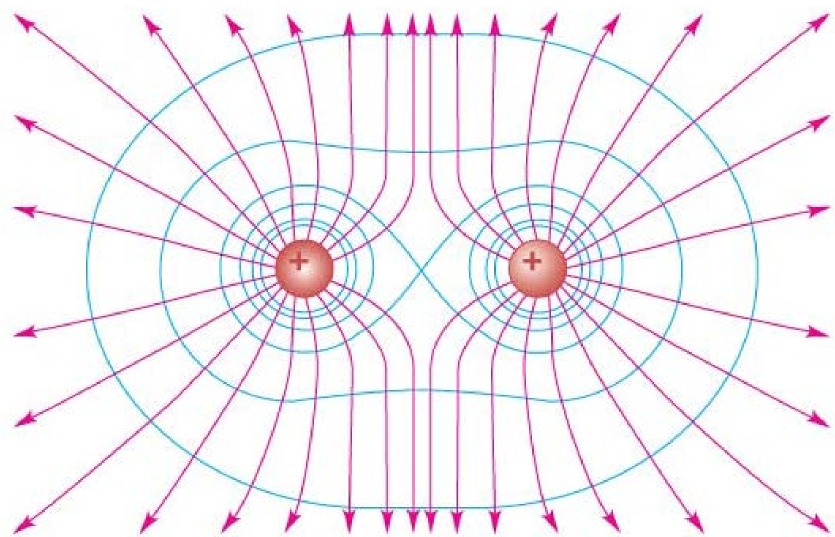
Cross sections of equipotential surfaces at 20 V intervals



Positive Point Charge



Dipole



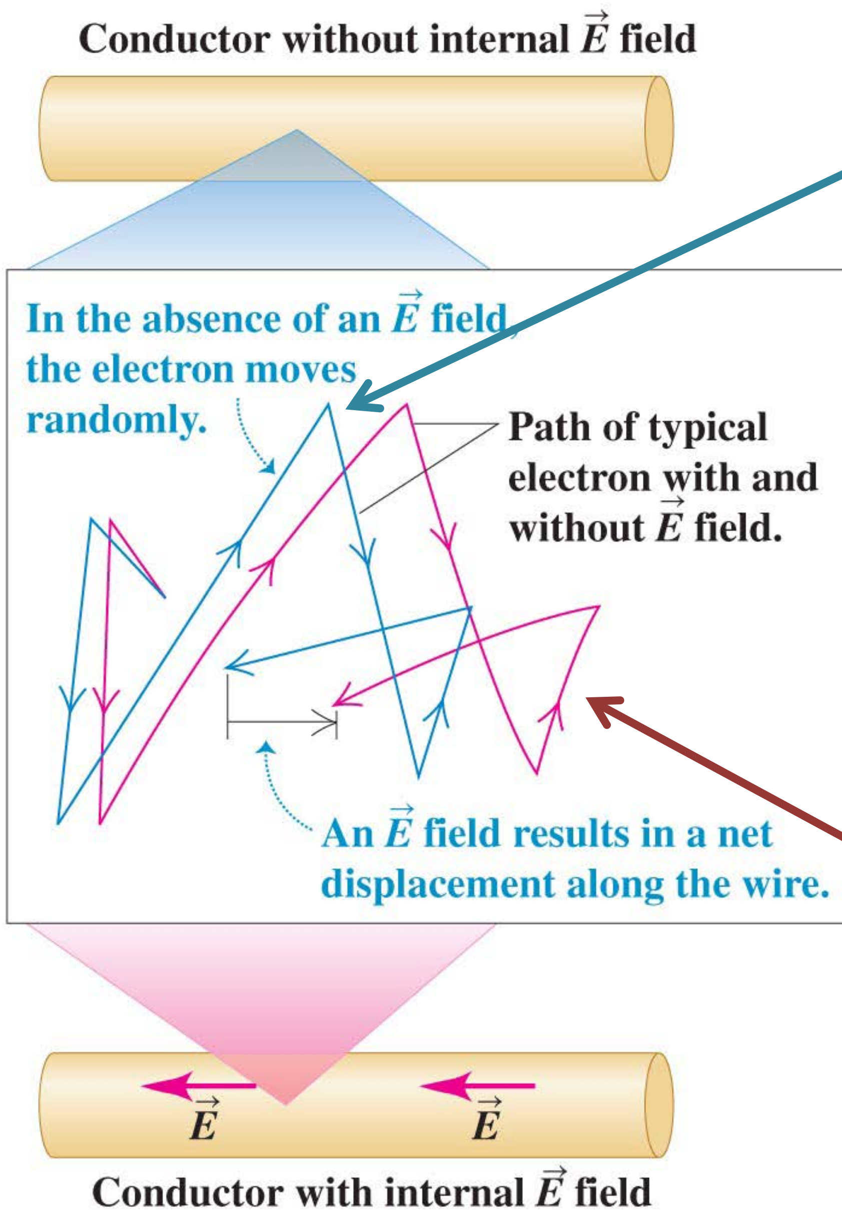
Two Positive Charges

Summary

	General	Point Charge
Electric Field (vector)	$\vec{\mathbf{E}} = \dfrac{\vec{\mathbf{F}}}{q_o}$; $E = -\dfrac{\Delta V}{\Delta s}$	$E = k\dfrac{\lvert q \rvert}{r^2}$
Force (vector)	$\vec{\mathbf{F}} = \vec{\mathbf{E}} q_o$	$F_C = \dfrac{\mathbf{k} q_1 q_2}{r^2}$
Electric PE (scalar)	$\Delta\mathbf{EPE} = q_o \Delta V$	$\Delta\mathbf{EPE} = q_o \Delta V$
Potential (scalar)	$V = \dfrac{\mathrm{EPE}}{q_o}$	$V = \dfrac{kq}{r}$

Resistance and Ohm's Law

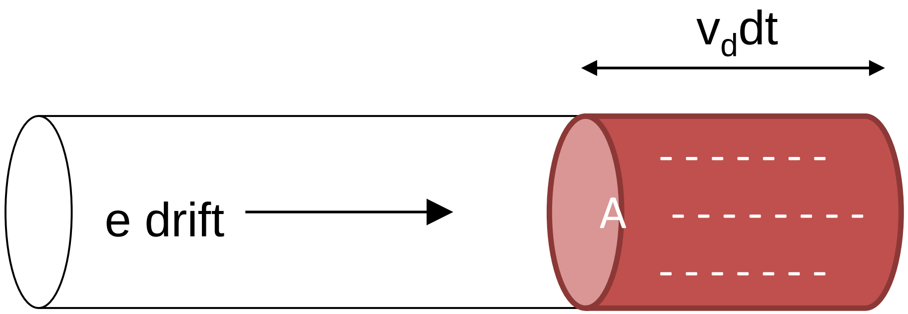
Moving Charge Around



In the absence of an applied electric field charges move around randomly

When an electric field is applied there is a net force on the charges causing them to drift along the wire

Electron Drift Velocity



<u>Shaded volume has dQ</u>

$dQ = q\ N_e$

$dQ = qndV = qnAv_d dt$

Where "n" is free electron density

$$I = dQ/dt = qnv_d A$$

$$J = I/A = qnv_d$$

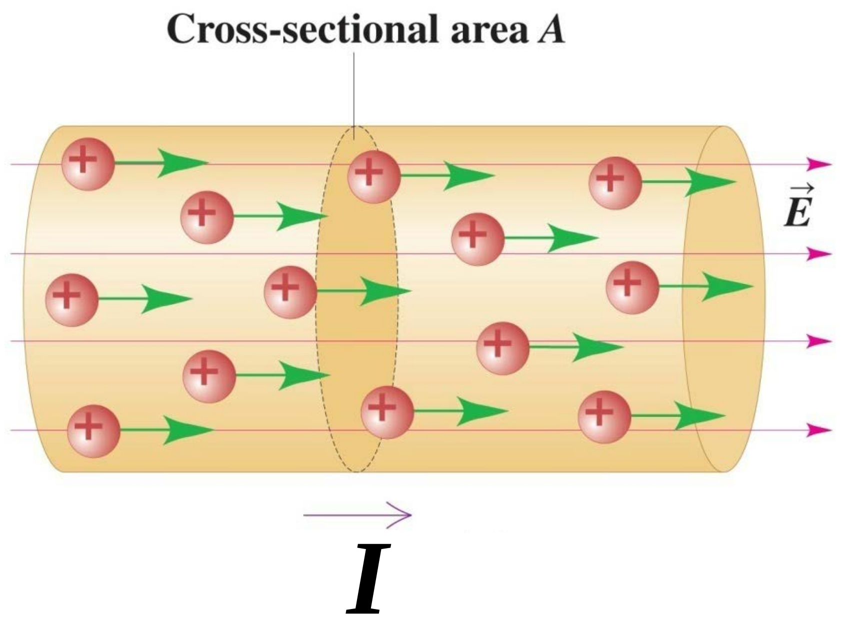
n is huge! ~10^{29} electrons/m^3

Hence nq ~ 10^{10} C/m^3

Current

The electric current is the amount of charge per unit time that passes through a surface that is perpendicular to the motion of the charges.

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



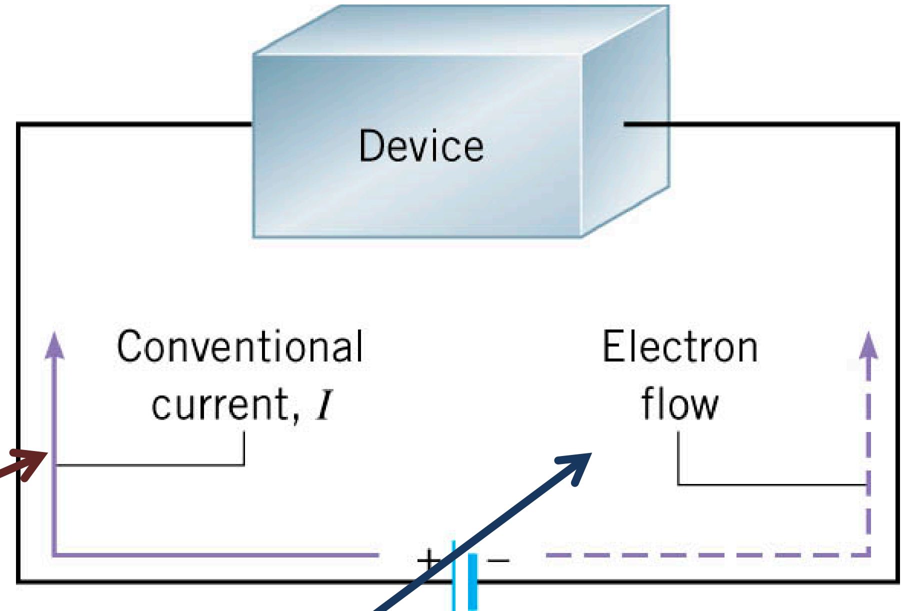
One coulomb per second equals one ampere (A).

If the charges move around the circuit in the same direction at all times, the current is said to be *direct current (dc)*.

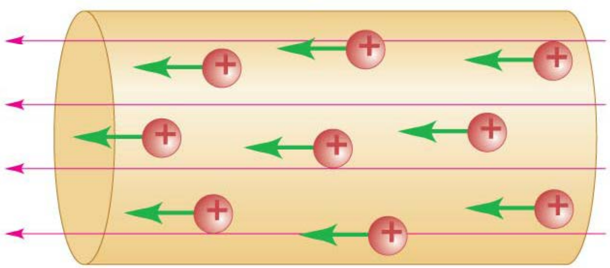
If the charges move first one way and then the opposite way, the current is said to be *alternating current (ac)*.

Conventional Current

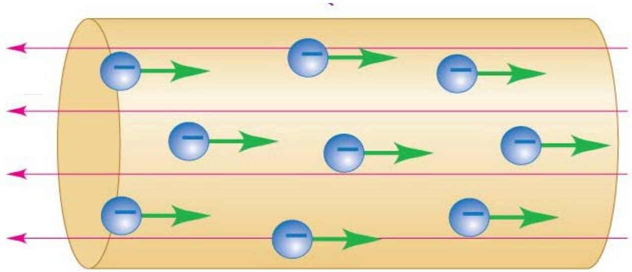
Conventional current is the hypothetical flow of *positive charges* that would have the same effect in the circuit as the movement of *negative charges* that actually does occur.



CURRENT DEFINED



ACTUAL CHARGE FLOW



Benjamin Franklin

Ohm's Law

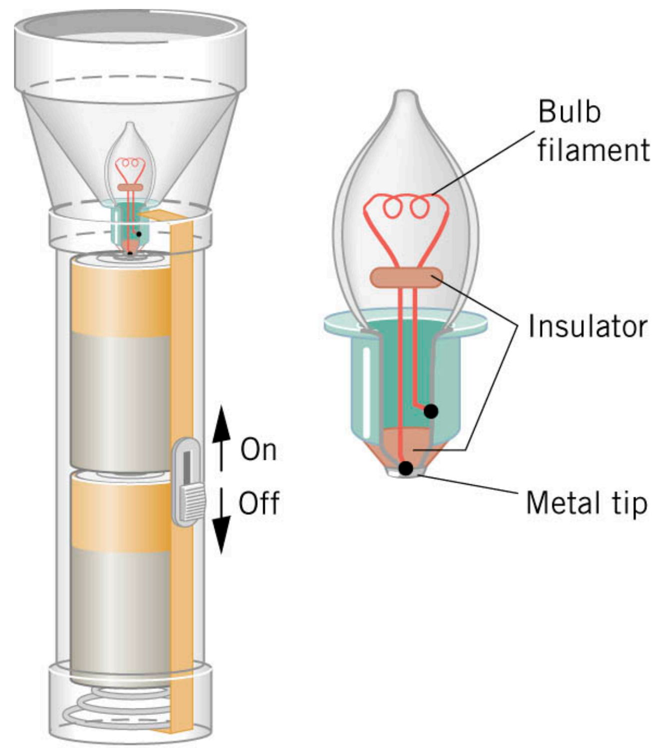
The resistance (R) is defined as the ratio of the voltage V applied across a piece of material to the current I through the material.

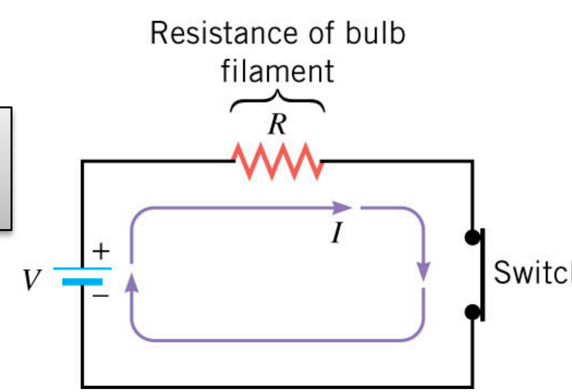
OHM'S LAW

The ratio V/I is a constant, where V is the voltage applied across a piece of material and I is the current through the material:

$$\frac{V}{I} = R = \text{constant} \qquad \text{or} \qquad V = IR$$

SI Unit of Resistance:
volt/ampere (V/A) = ohm (Ω)

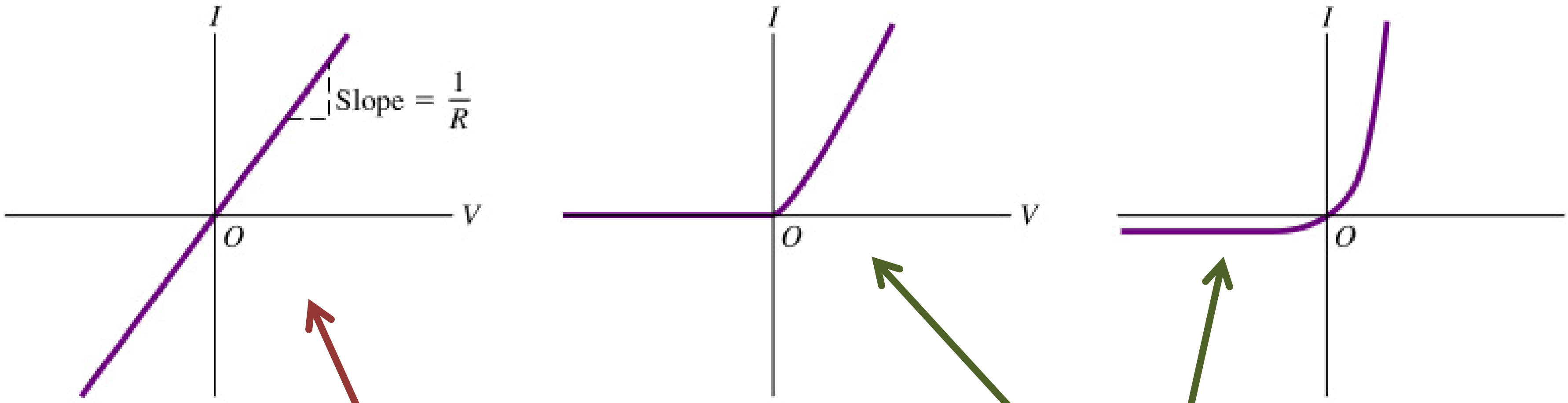




To the extent that a wire or an electrical device offers resistance to electrical flow, it is called a resistor.

Graphical Ohm's Law

If we plot voltage versus current:



(a) Resistor that obeys Ohm's law

(b) Vacuum diode (does not obey Ohm's law)

(c) Semiconductor diode (does not obey Ohm's law)

Ohmic: slope of line is resitance

Non-Ohmic

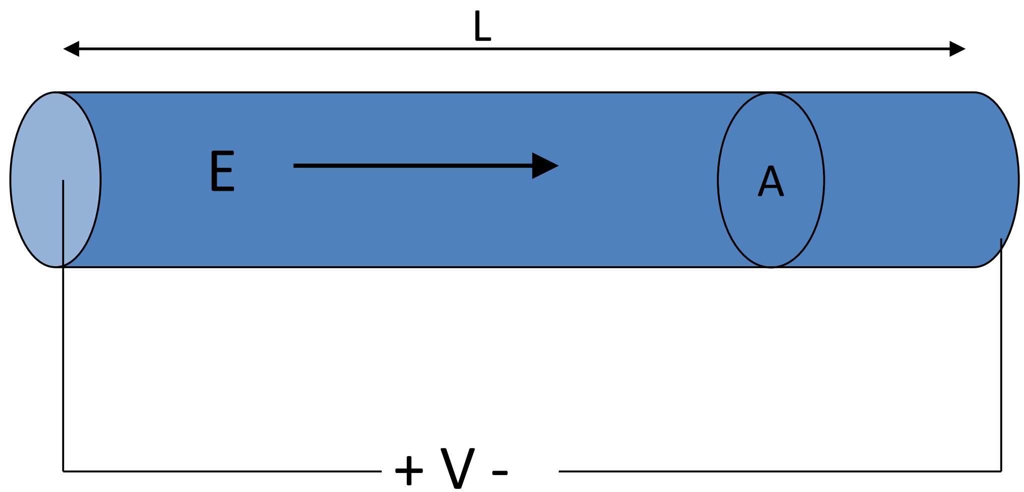
Georg Ohm

Resistance and Resistivity

For a wide range of materials, the resistance of a piece of material of length L and cross- sectional area A is:

$$R = \rho \frac{L}{A}$$

resistivity in units of ohm·meter



The resistivity, ρ, is a fundamental property of the material.

Low resistivity materials make good conductors.

Table 20.1 Resistivities[a] of Various Materials

Material	Resistivity ρ ($\Omega \cdot$ m)	Material	Resistivity ρ ($\Omega \cdot$ m)
Conductors		***Semiconductors***	
Aluminum	2.82×10^{-8}	Carbon	3.5×10^{-5}
Copper	1.72×10^{-8}	Germanium	0.5[b]
Gold	2.44×10^{-8}	Silicon	20–2300[b]
Iron	9.7×10^{-8}	***Insulators***	
Mercury	95.8×10^{-8}	Mica	10^{11}–10^{15}
Nichrome (alloy)	100×10^{-8}	Rubber (hard)	10^{13}–10^{16}
Silver	1.59×10^{-8}	Teflon	10^{16}
Tungsten	5.6×10^{-8}	Wood (maple)	3×10^{10}

[a] The values pertain to temperatures near 20 °C.
[b] Depending on purity.

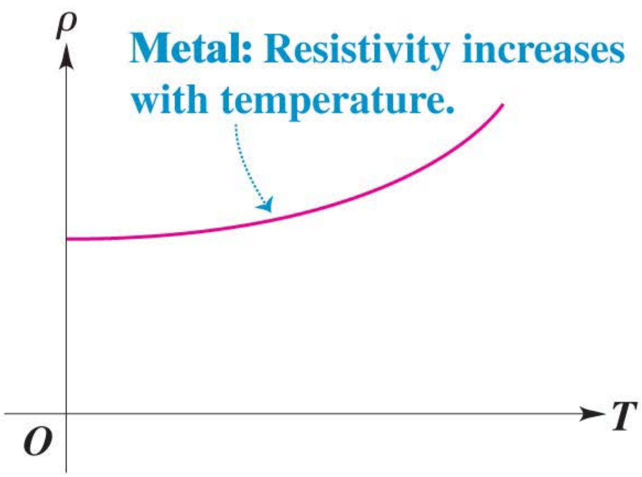
Resistivity and Temperature

As metals heat their resistivity changes:

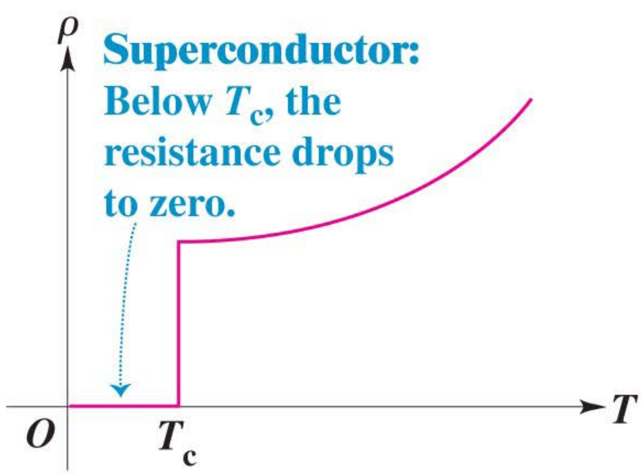
$$\rho = \rho_o\left[1+\alpha\left(T-T_o\right)\right]$$

temperature coefficient of resistivity

$$R = R_o\left[1+\alpha\left(T-T_o\right)\right]$$



(a)



(b)

Power in Resistors

When there is current in a circuit as a result of a voltage, the *electric power* delivered to the circuit is:

$$P = \frac{(\Delta q)V}{\Delta t} = \frac{\Delta q}{\Delta t}V = IV$$

SI Unit of Power: watt (W)

If this power is delivered to a resistor it is dissipated (usually as heat):

$$P = I(IR) = I^2 R$$

$$P = \left(\frac{V}{R}\right)V = \frac{V^2}{R}$$

Concept Question #8

Which of the following would cause the resistance of a wire to *double*?

a) **Doubling the wire's length and area**
b) **Halving the wire's length and area**
c) **Halving the wire's length, area, and resistivity**
d) **Doubling the wire's length, area, and resistivity**
e) **Doubling the wire's length and halving the area**

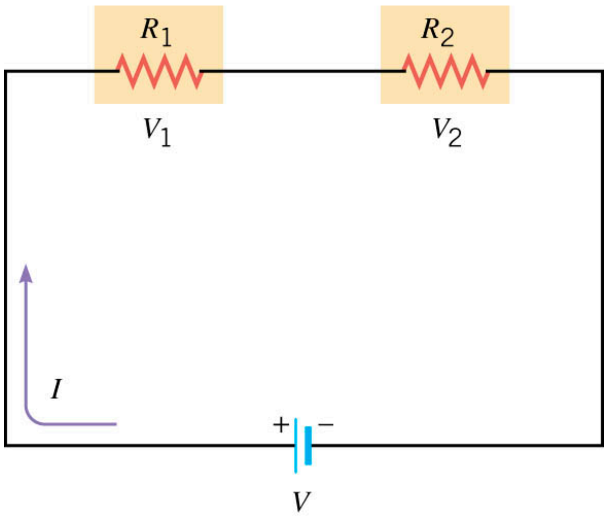
Concept Question #9

You are presented with a box of assorted copper wires that come in different lengths and thicknesses. To get a wire with the *largest* possible resistance, you should pick the

a) **thickest, longest wire.**
b) **thickest, shortest wire.**
c) **thinnest, longest wire.**
d) **thinnest, shortest wire.**

Resistors in Series

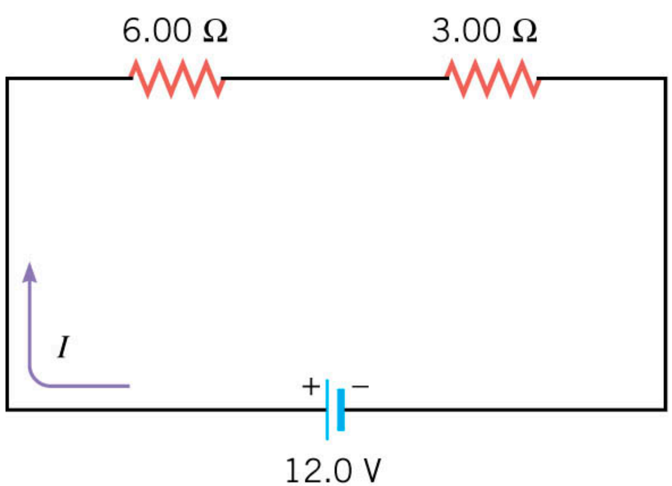
Series wiring means that the devices are connected in such a way that there is the *<u>same electric current through</u>* each device.



$$V = V_1 + V_2 = IR_1 + IR_2 = I\left(R_1 + R_2\right) = IR_S$$

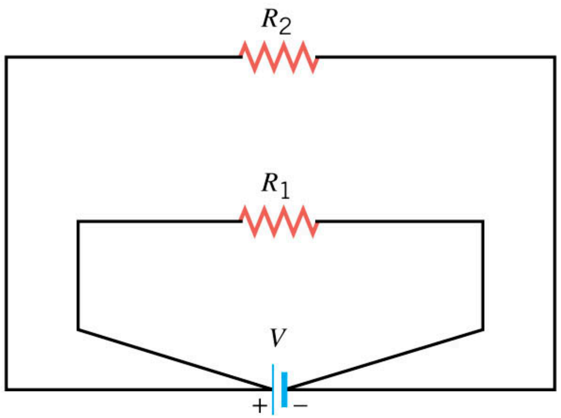
$$R_S = R_1 + R_2 + R_3 + \cdots$$

Series resistors

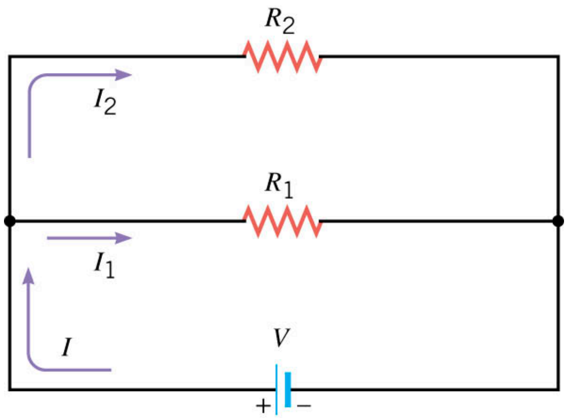


Resistors in Parallel

Parallel wiring means that the devices are connected in such a way that the *same voltage is applied across* each device.



When two resistors are connected in parallel, each receives current from the battery as if the other was not present.



Therefore the two resistors connected in parallel *draw more current than does either resistor alone*.

$$I = I_1 + I_2 = \frac{V}{R_1} + \frac{V}{R_2} = V\left(\frac{1}{R_1} + \frac{1}{R_2}\right) = V\left(\frac{1}{R_P}\right)$$

$$\boxed{\frac{1}{R_P} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \cdots}$$

parallel resistors

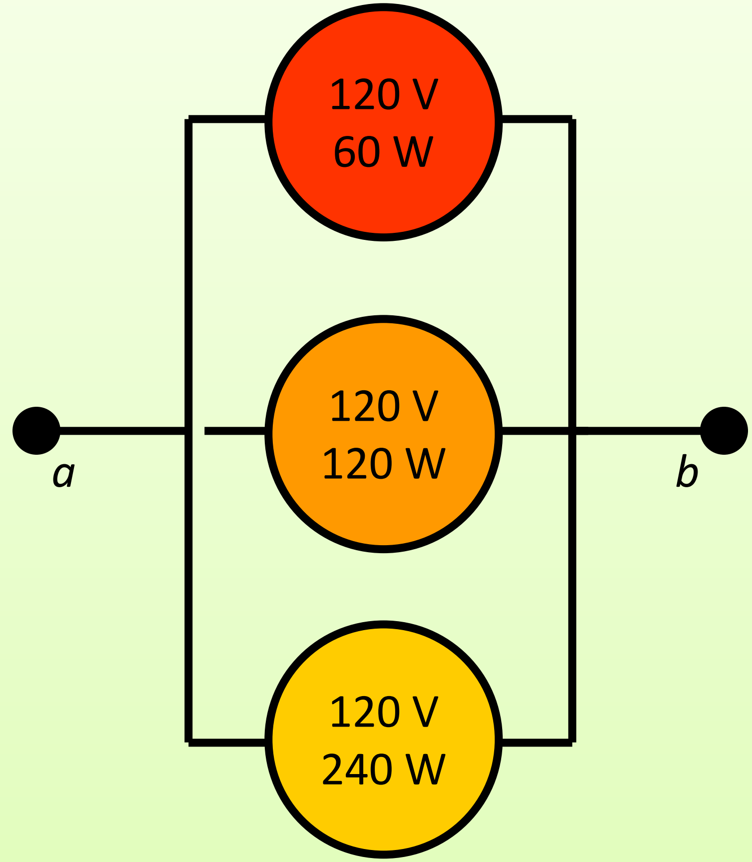
Concept Question #10

Consider a resistor connected in series to a few batteries. If we double the voltage (by adding batteries) and double the resistance (by replacing the wire,) the current through the circuit will

a) decrease by a factor of 4.
b) decrease by a factor of 2.
c) remain the same.
d) increase by a factor of 2.
e) increase by a factor of 4.

Concept Question #11

A 120-V, 60-W light bulb, a 120-V, 120-W light bulb, and a 120-V, 240-W light bulb are connected in parallel as shown.



The voltage between points *a* and *b* is 120 V. Which bulb glows the brightest?

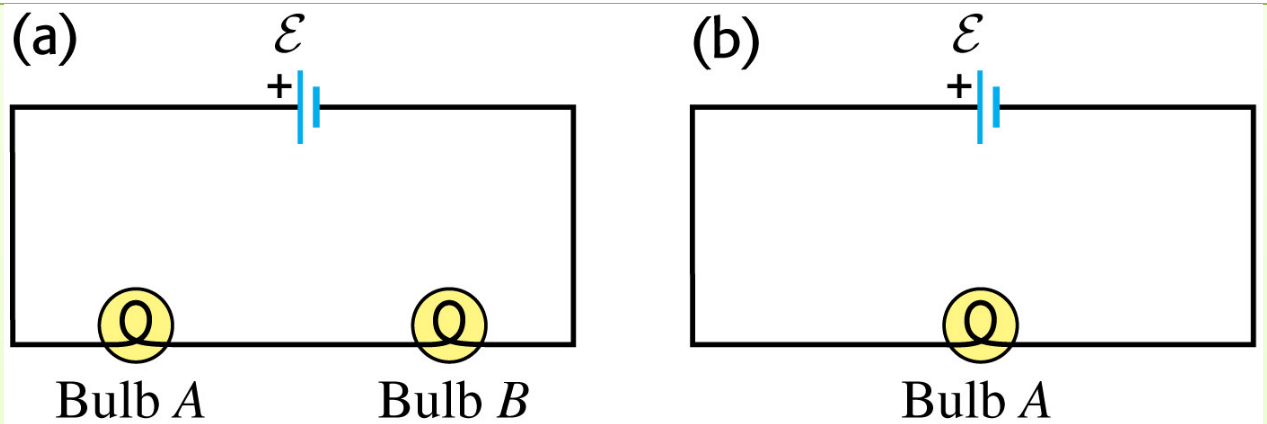
A. the 120-V, 60-W light bulb

B. the 120-V, 120-W light bulb

C. the 120-V, 240-W light bulb

D. All three light bulbs glow with equal brightness.

Concept Question #12



In the circuit shown in (a), the two bulbs *A* and *B* are identical. Bulb *B* is removed and the circuit is completed as shown in (b). Compared to the brightness of bulb *A* in (a), bulb *A* in (b) is:

A. brighter.

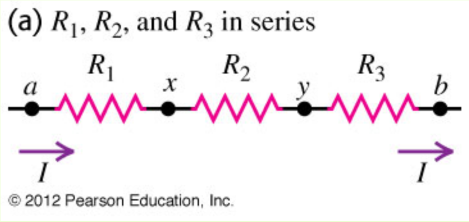
B. B. less bright.

C. C. just as bright.

D. Any of the above, depending on the rated wattage of the bulb.

Concept Question #13

Which of the two arrangements shown has the *smaller* equivalent resistance between points *a* and *b*?

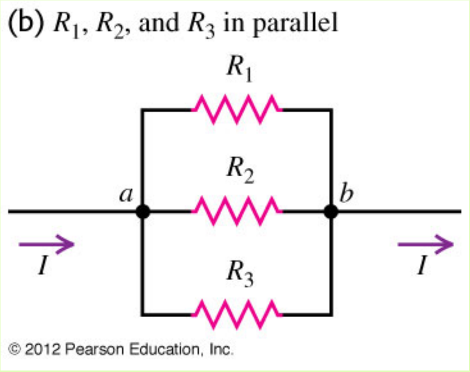


A. the series arrangement

B. the parallel arrangement

C. The equivalent resistance is the same for both arrangements.

D. The answer depends on the values of the individual resistances R_1, R_2, and R_3.



Concept Question #14

Three identical light bulbs are connected to a source of emf as shown. Which bulb is brightest?

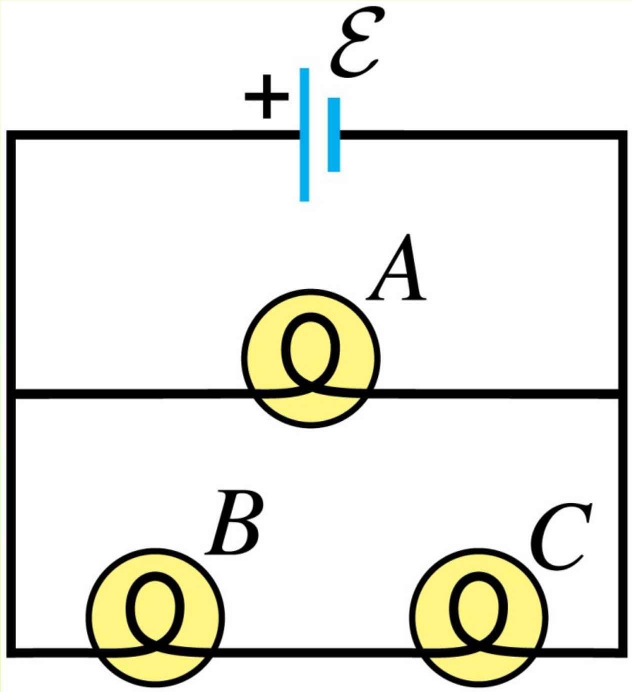
A. light bulb *A*

B. light bulb *B*

C. light bulb *C*

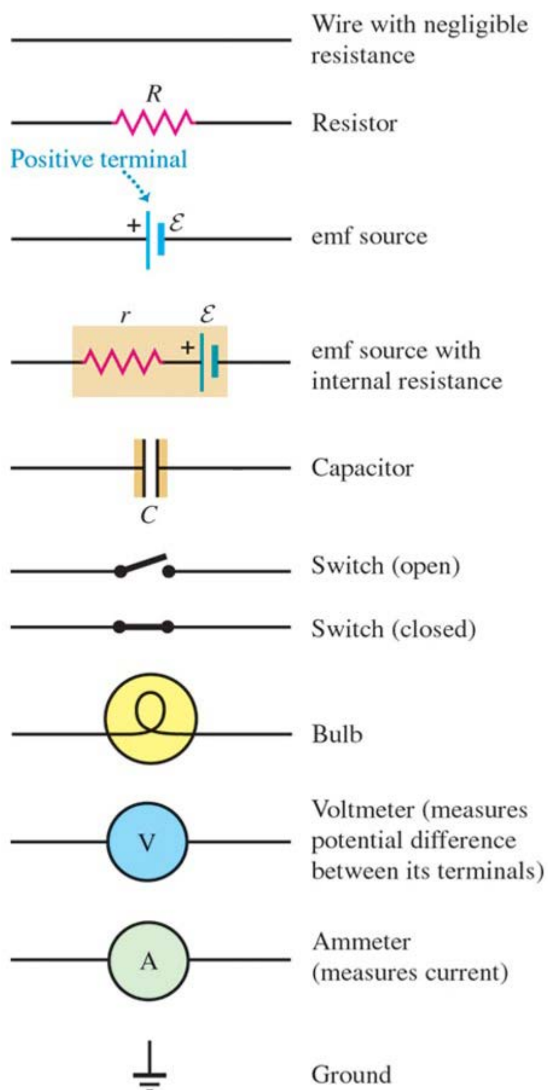
D. both light bulbs *B* and *C* (Both are equally bright and are brighter than light bulb *A*.)

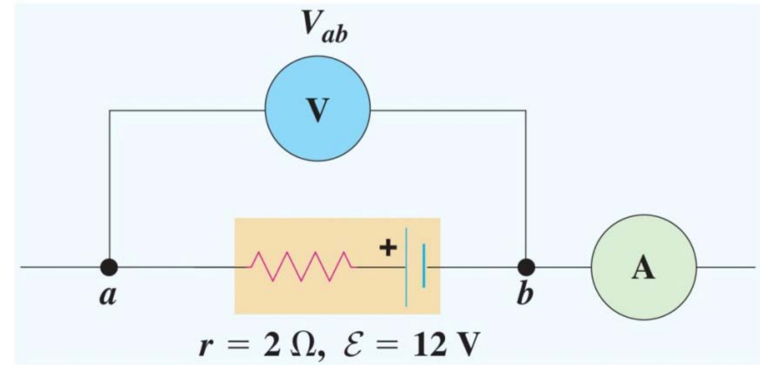
E. All bulbs are equally bright.

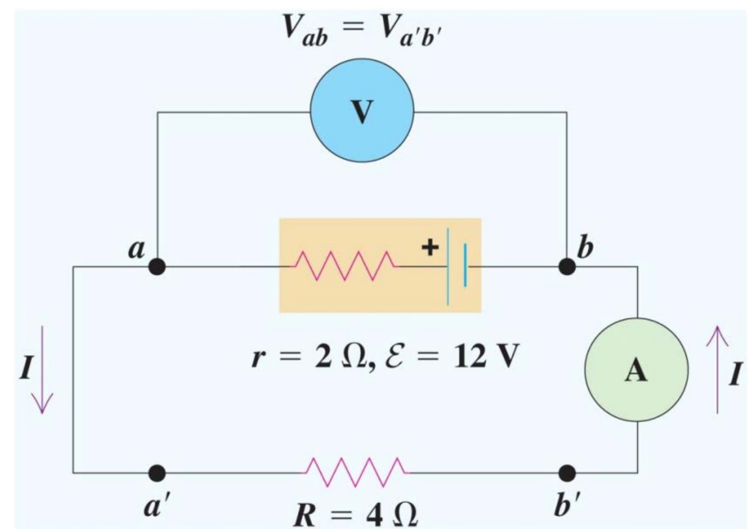


Circuits

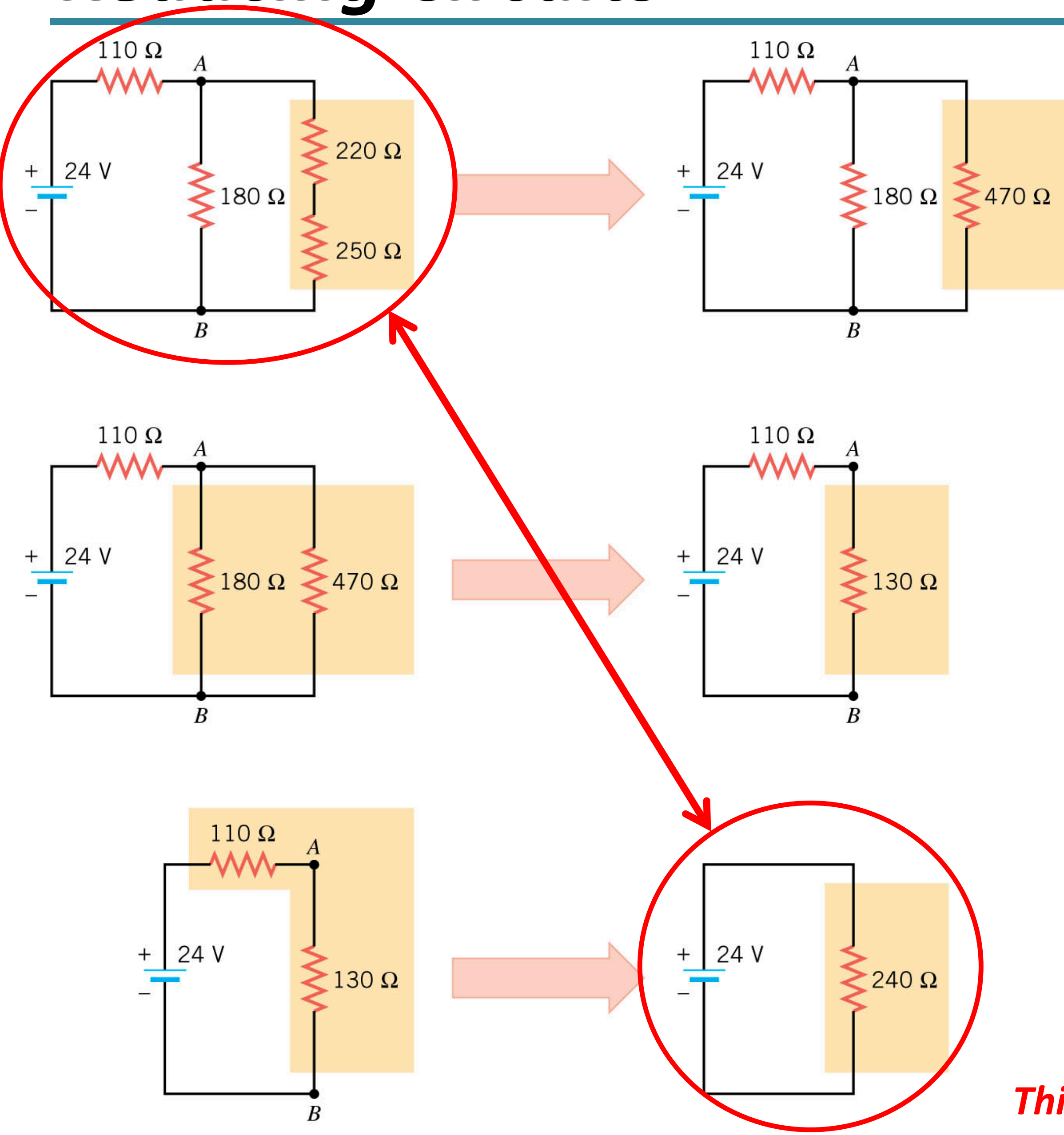
Each device will be represented by brief symbols. The utility of the method becomes clear as soon as soon as you must represent a car or a blender. There are too many parts to draw them as they actually appear.







Reducing Circuits



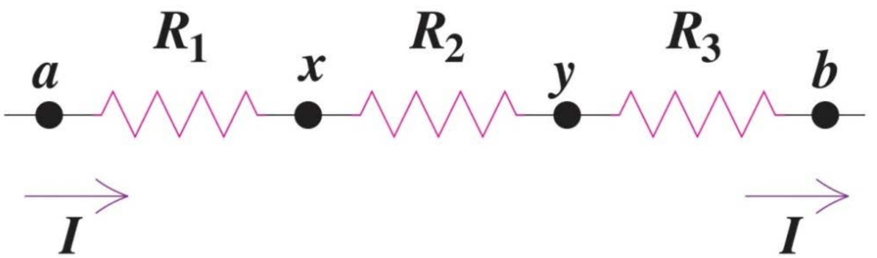
Step 1: Replace two *series* resistors with a single equivalent resistor

Step 2: Replace two *parallel* resistors with a single equivalent resistor

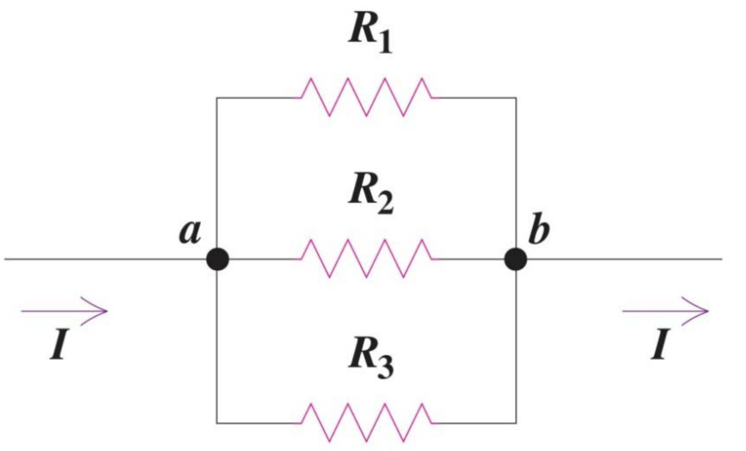
Step 3: Replace two *series* resistors with a *final* single equivalent resistor

This single resistor draws the same <u>total</u> current

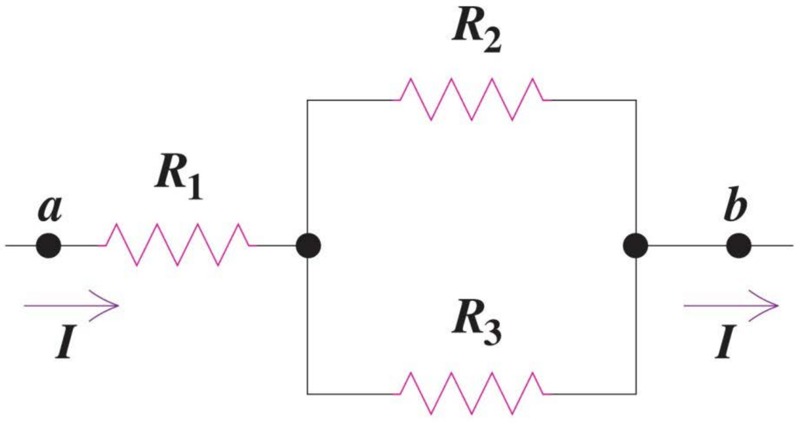
Resistors Summary



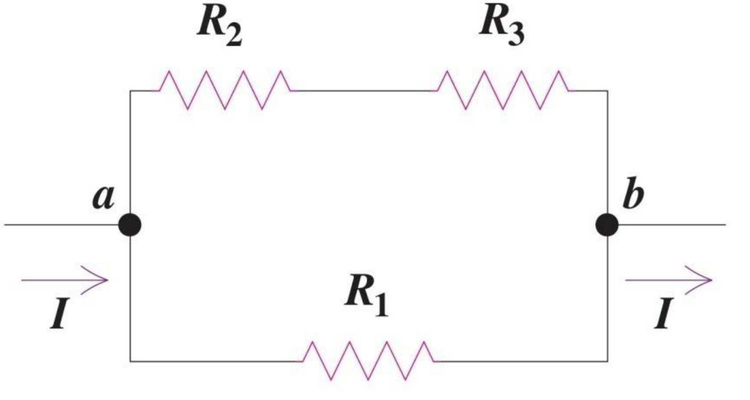
Three resistors in series



Three resistors in parallel



R_2 and R_3 in parallel → in series with R_1

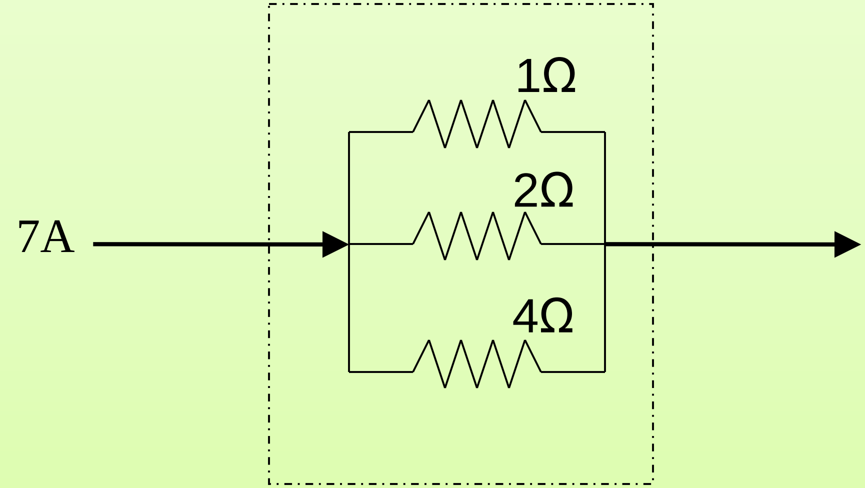


R_2 and R_3 in series → in parallel with R_1

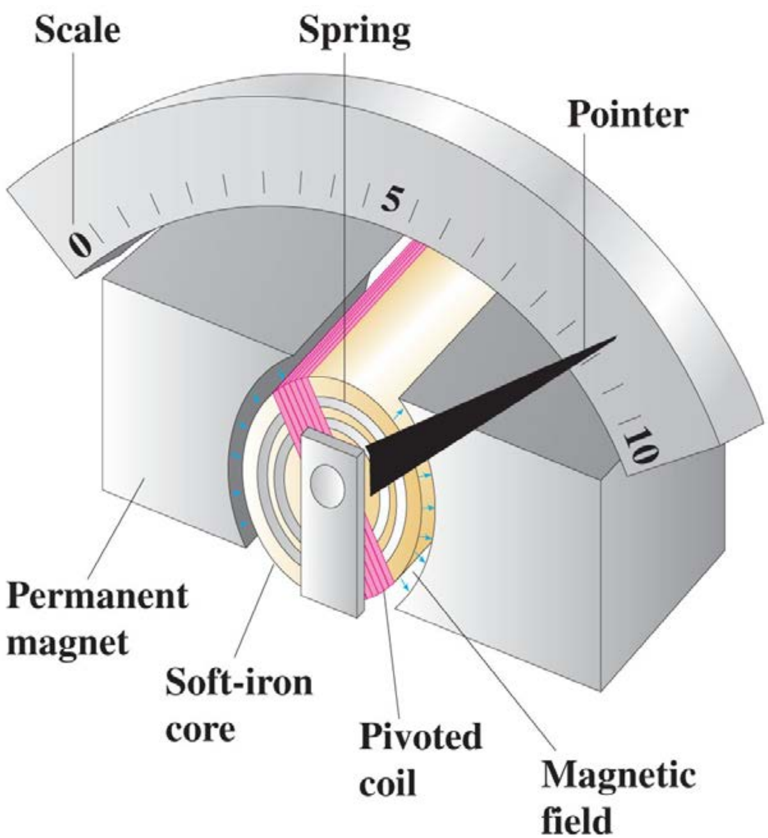
Concept Question #15

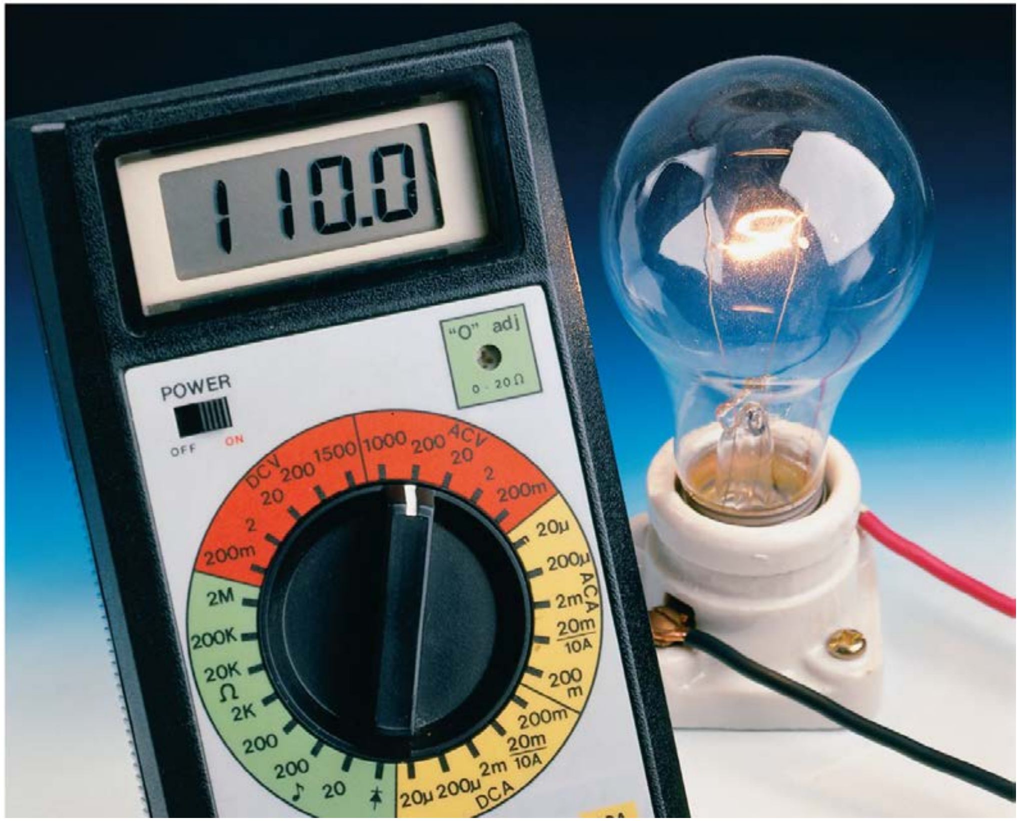
3 Resistors in Parallel have resistances of 1, 2, and 4 Ω. A current of 7 A is flowing into the parallel combination. The current in each resistor is, respectively:

- **A. 1, 2, and 4 A**
- **B. 4, 2, and 1 A**
- **C. 3, 2, and 2 A**
- **D. 7, 7, and 7 A**
- **E. 2.33, 2.33, 2.33A**



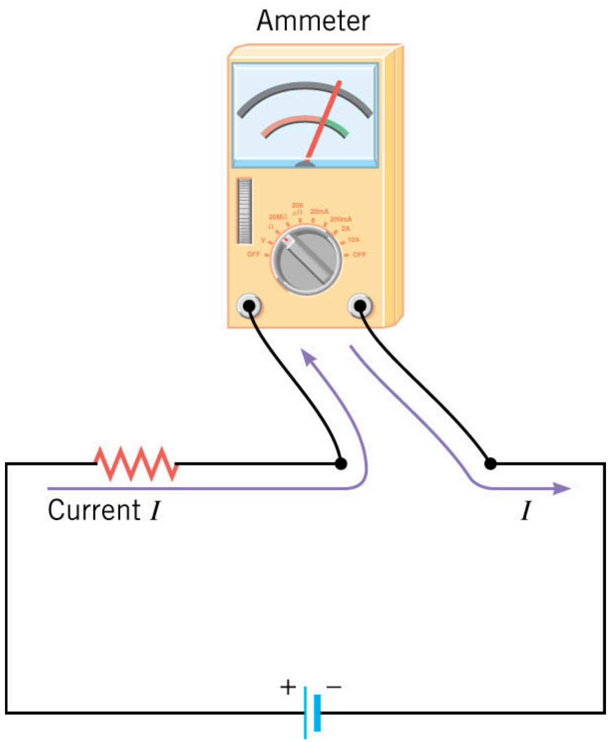
Measurement of Current and Voltage

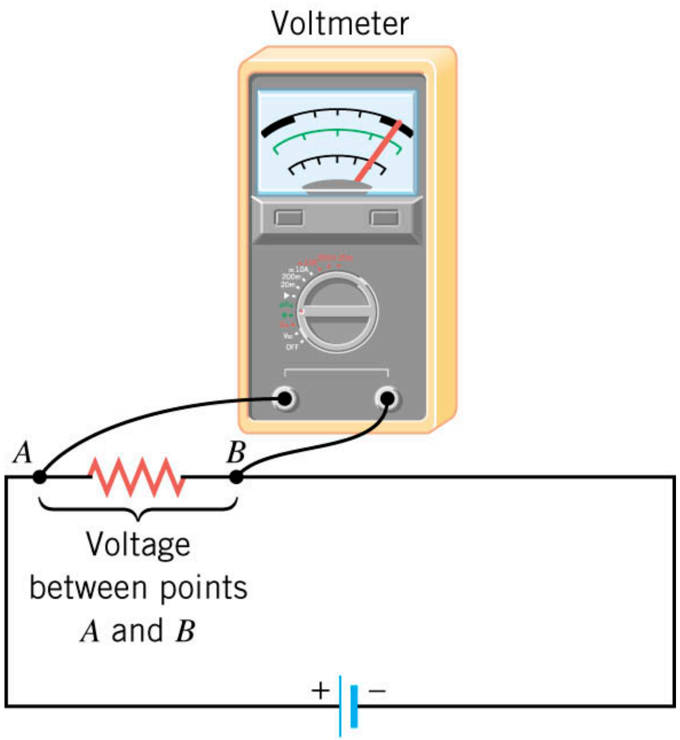




Voltmeters, ammeters, resistance gauges, digital multimeters are all at our disposal. Some are more traditional like the generic galvanometer at left; some are newer and digital, like the multimeter on the right.

Digital Multimeters (DMM)





- ***Ammeters*** are used to measure ***current***.
- An ammeter must be inserted into a circuit so that the current passes directly through it.
- Ammeters need a *small internal resistance* to not affect the circuit.

- ***Voltmeters*** are used to measure ***voltage*** (potential difference).
- To measure the voltage between two points in a circuit, a voltmeter is connected between the points (in parallel).
- Voltmeters need a *large internal resistance* to not affect the circuit.