Physics 2B: Electricity and Magnetism

Part I: Electricity

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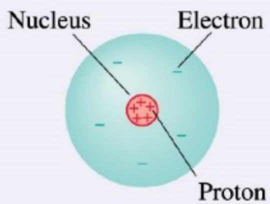
Including E. Michelsen's and Oleg Shpyrko course material

Slightly tailored for Randall Knight's
Physics for Scientists and Engineers

Ch. 22: Electric Charges and Forces

What is electric charge?

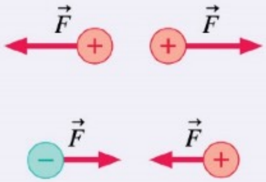
Electric phenomena depend on charge.



- There are two kinds of charge, called positive and negative.
- Electrons and protons—the constituents of atoms—are the basic charges of ordinary matter.
- Charging is the transfer of electrons from one object to another.

What is Coulomb's law?

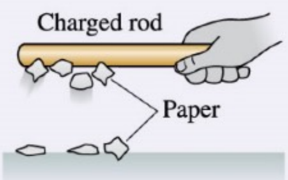
Coulomb's law is the fundamental law for the electric force between two charged particles. Coulomb's law, like Newton's law of gravity, is an inverse-square law: The electric force is inversely proportional to the *square* of the distance between charges.



« LOOKING BACK Sections 3.2–3.4 Vector addition
« LOOKING BACK Sections 13.2–13.4 Gravity

How do charges behave?

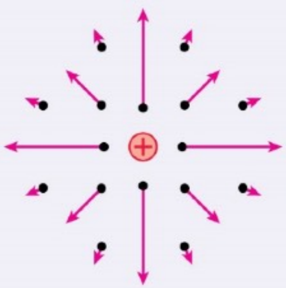
Charges have well-established behaviors:



- Two charges of the same kind repel; two opposite charges attract.
- Small neutral objects are attracted to a charge of either sign.
- Charge can be transferred from one object to another.
- Charge is conserved.

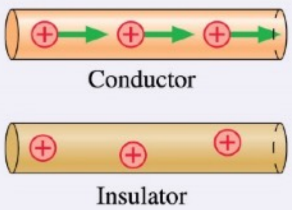
What is an electric field?

How is a long-range force transmitted from one charge to another? We'll develop the idea that charges create an electric field, and the electric field of one charge is the agent that exerts a force on another charge. That is, charges interact via electric fields. The electric field is present at all points in space.



What are conductors and insulators?

There are two classes of materials with very different electrical properties:



- Conductors are materials through or along which charge moves easily.
- Insulators are materials on or in which charge is immobile.

Why are electric charges important?

Computers, cell phones, and optical fiber communications may seem to have little in common with the fact that you can get a shock when you touch a doorknob after walking across a carpet. But the physics of electric charges—how objects get charged and how charges interact with each other—is the foundation for all modern electronic devices and communications technology. Electricity and magnetism is a very large and very important topic, and it starts with simple observations of electric charges and forces.

First review concepts, then move quickly to solve problems

Electrical Charge

- Charge is defined in a similar manner to mass.
- Charge is something an object inherently has (like mass).
- Be careful!!!! Many homework problems have statements like "a charge of 4.5 μC."
- They really mean to say "a small point particle has a charge of 4.5 μC." They are just being lazy.

Electrical Charge

- The modern names for the two types of charge, coined by Benjamin Franklin, are

  positive charge and *negative charge.*

- Franklin established the convention that **a glass rod that has been rubbed with silk is *positively* charged**.

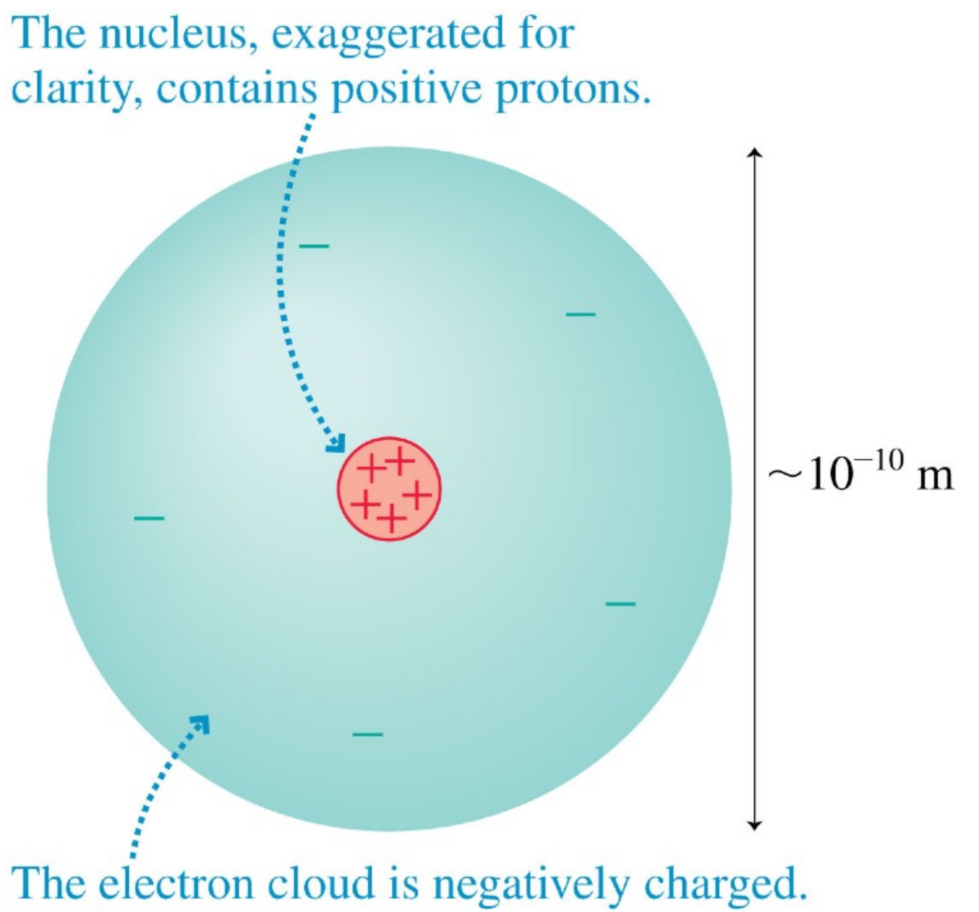
- Any other object that repels a charged glass rod is also positively charged, and any charged object that attracts a charged glass rod is negatively charged.
- Thus **a plastic rod rubbed with wool is negative**.
- This convention was established long before the discovery of electrons and protons.

Electrical Charge

- Many subatomic objects can carry positive charge: protons, pions, positrons, quarks.
- Many subatomic objects can carry negative charge: electrons, pions, anti-protons, quarks.
- In the early 1900's, Robert Millikan performed an experiment that showed that **all charge is a multiple of one fundamental unit.**
- This fundamental unit was the charge of the electron, symbolized by e.
- As it turns out, **there is one exception to this rule**, *quarks* have either a charge of (1/3)*e* or (2/3)*e*.
- But for historical reasons, we still consider *e* the fundamental unit of charge.

Atoms and Electricity

- An atom consists of a very small and dense *nucleus*, surrounded by much less massive orbiting *electrons*.
- The nucleus contains both *protons* and *neutrons*.



Electrical Charge

- The SI unit of charge is the Coulomb (C).
- e = 1.602 x 10^{-19} Coulombs.
- Electrons have a charge of –e.
- Protons have a charge of +e.
- Neutrons have no charge.

TABLE 15.1

Charge and Mass of the Electron, Proton, and Neutron

Particle	Charge (C)	Mass (kg)
Electron	-1.60×10^{-19}	9.11×10^{-31}
Proton	$+1.60 \times 10^{-19}$	1.67×10^{-27}
Neutron	0	1.67×10^{-27}

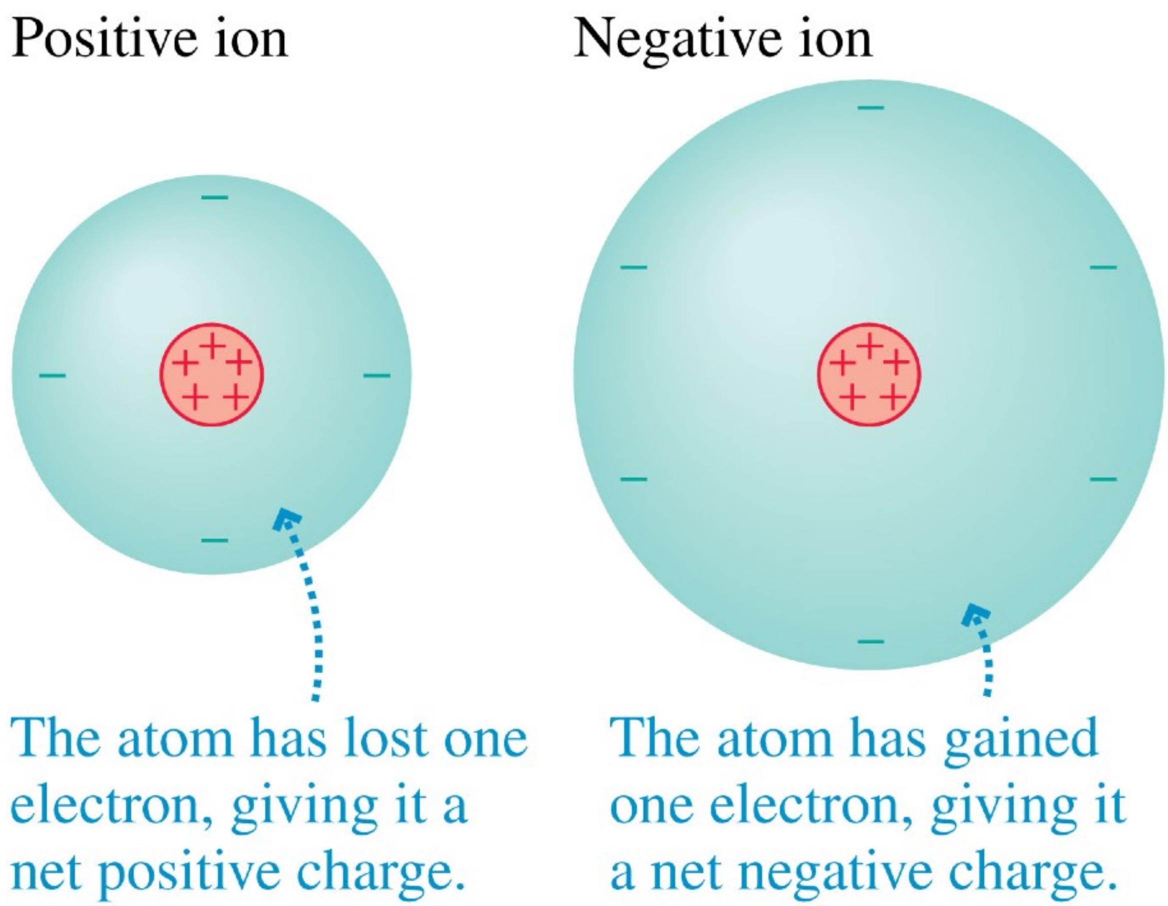
Charge Quantization

- A macroscopic object has net charge:

$$q = N_{\mathrm{p}}e - N_{\mathrm{e}}e = (N_{\mathrm{p}} - N_{\mathrm{e}})e$$

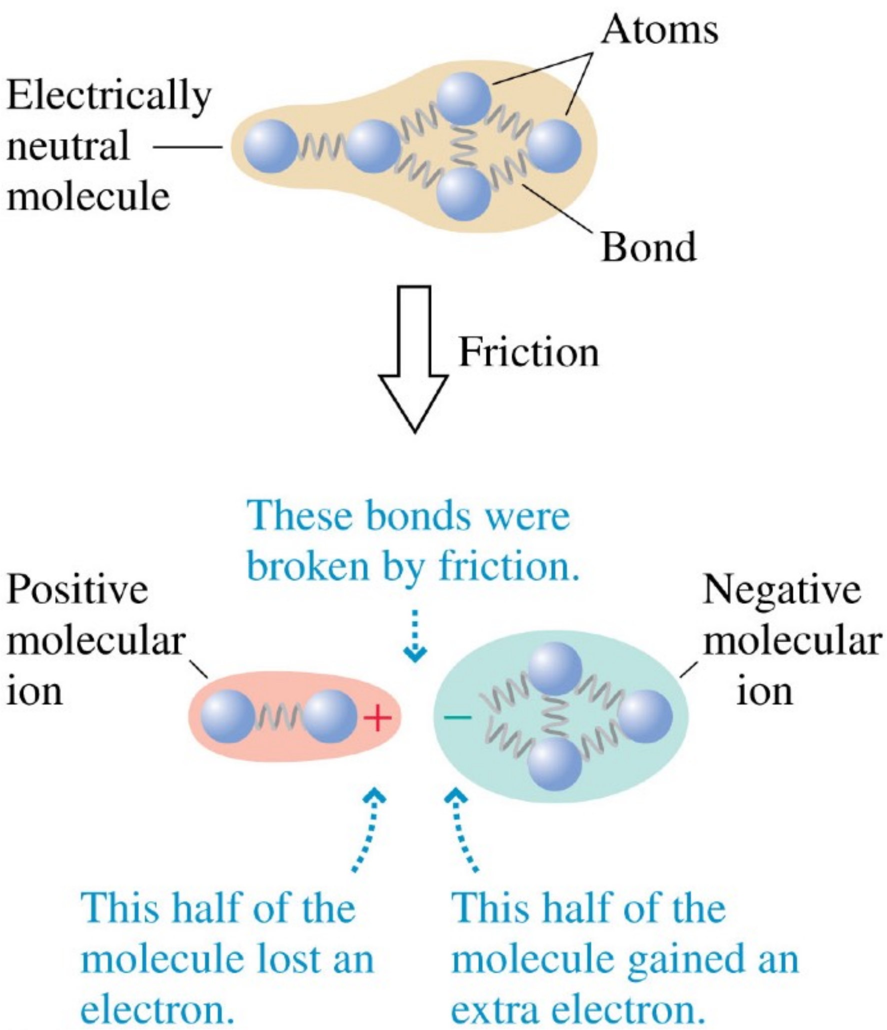
  where N_{p} and N_{e} are the number of protons and electrons contained in the object.
- Most macroscopic objects have an *equal number* of protons and electrons and therefore have $q = 0$.
- A charged object has an unequal number of protons and electrons.
- Notice that an object's charge is always an integer multiple of e.
- This is called **charge quantization**.

- The process of removing an electron from the electron cloud of an atom, or adding an electron to it, is called **ionization**.



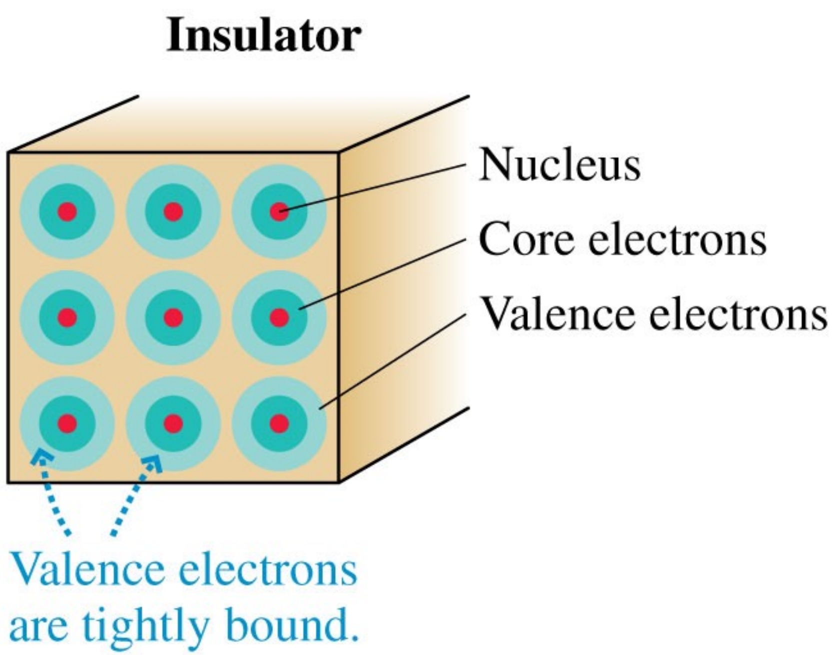
Atoms and Electricity

- *Molecular ions* can be created when one of the bonds in a large molecule is broken.
- This is the way in which a plastic rod is charged by rubbing with wool or a comb is charged by passing through your hair.



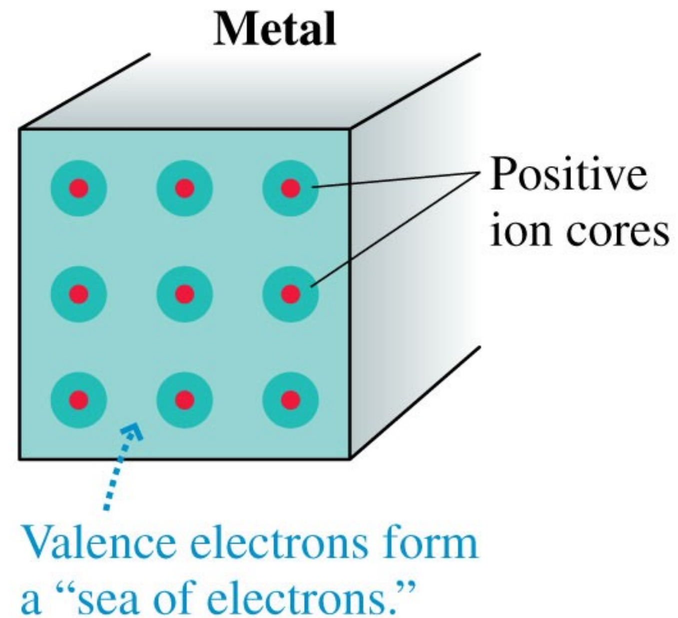
Insulators

- The electrons in an **insulator** are all tightly bound to the positive nuclei and not free to move around.
- Charging an insulator by friction leaves patches of molecular ions on the surface, but these patches are immobile.



Conductors

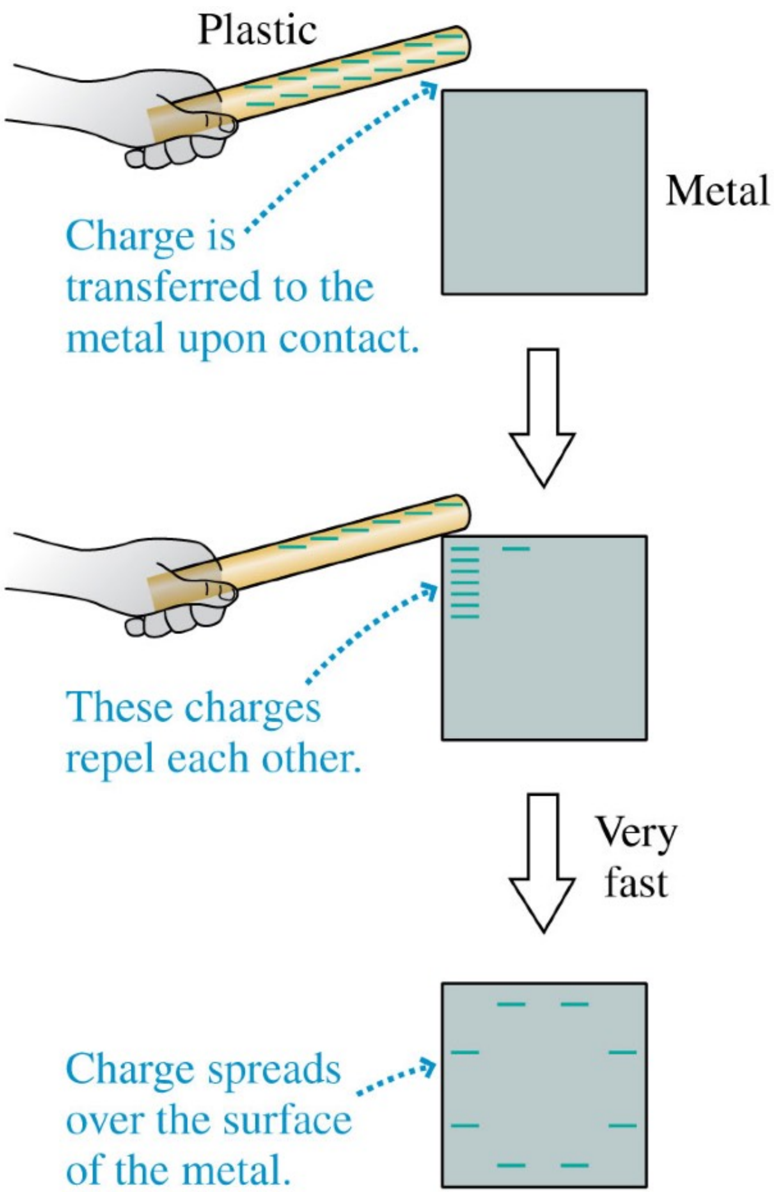
- In metals, the outer atomic electrons are only weakly bound to the nuclei.
- These outer electrons become detached from their parent nuclei and are free to wander about through the entire solid.



- The solid *as a whole* remains electrically neutral, but the electrons are now like a negatively charged liquid permeating an array of positively charged **ion cores**.

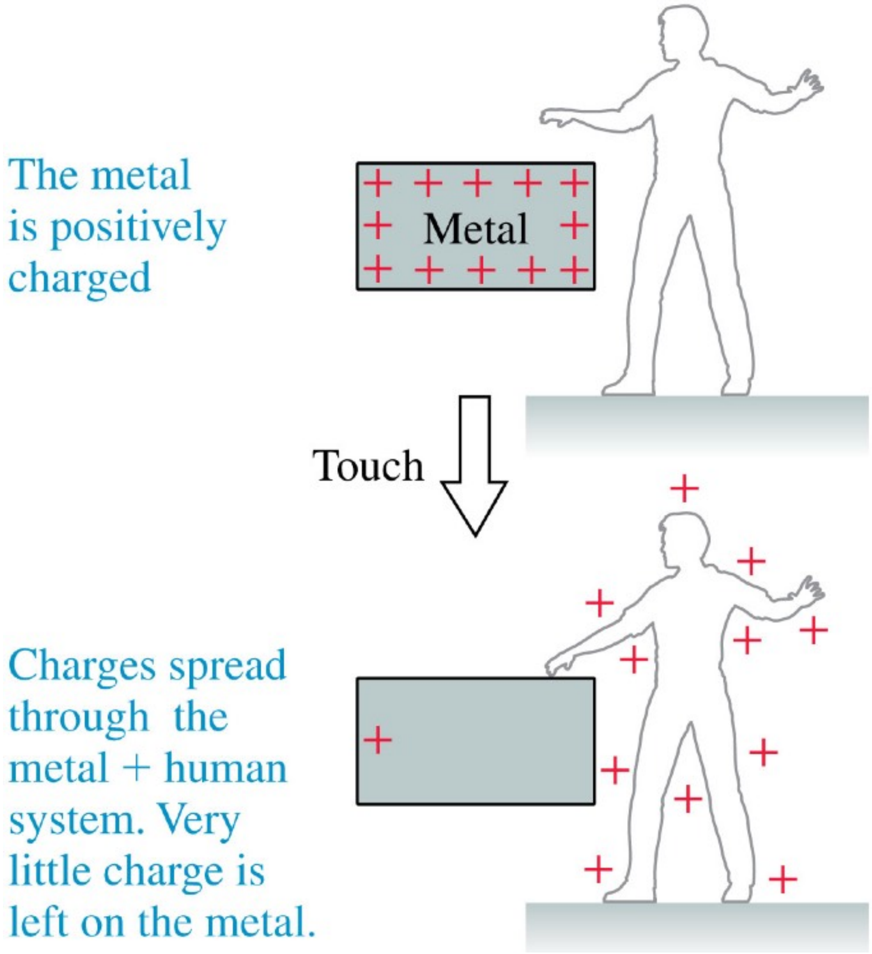
Charging

- The figure shows how a conductor is charged by contact with a charged plastic rod.
- Electrons in a conductor are free to move.
- Once charge is transferred to the metal, repulsive forces between the electrons cause them to move apart from each other.



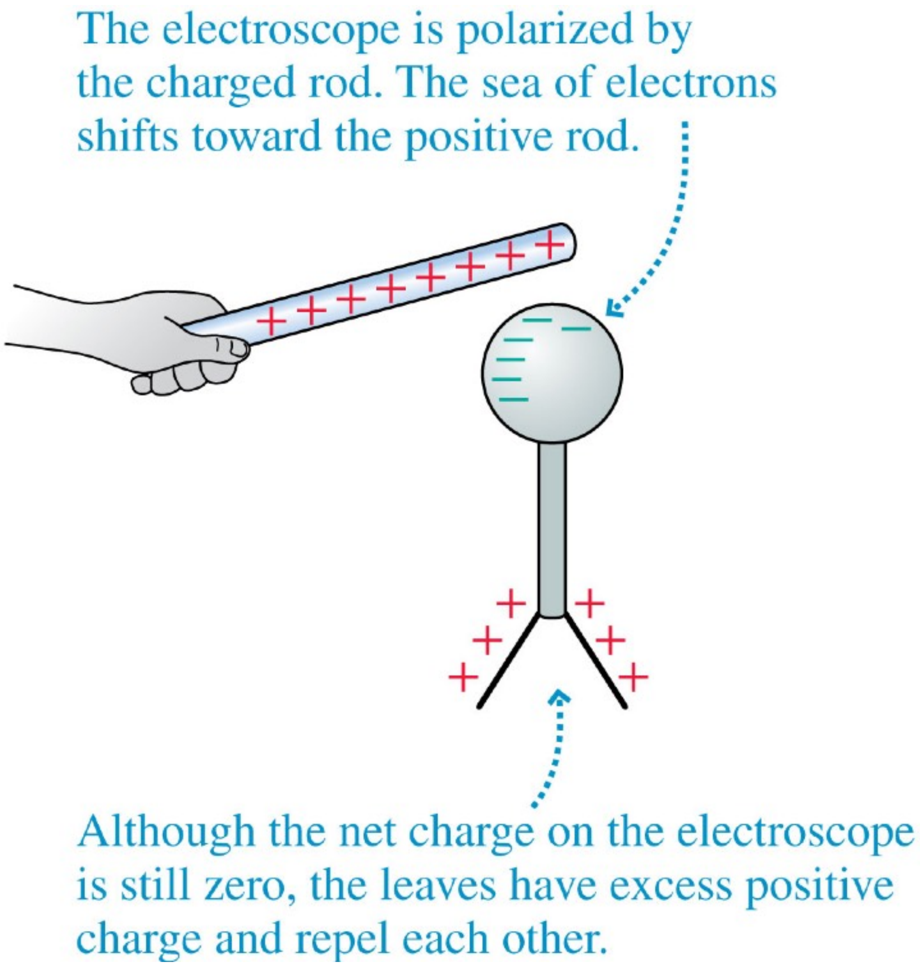
Discharging

- The figure shows how touching a charged metal discharges it.
- Any excess charge that was initially confined to the metal can now spread over the larger metal + human conductor.



Charge Polarization

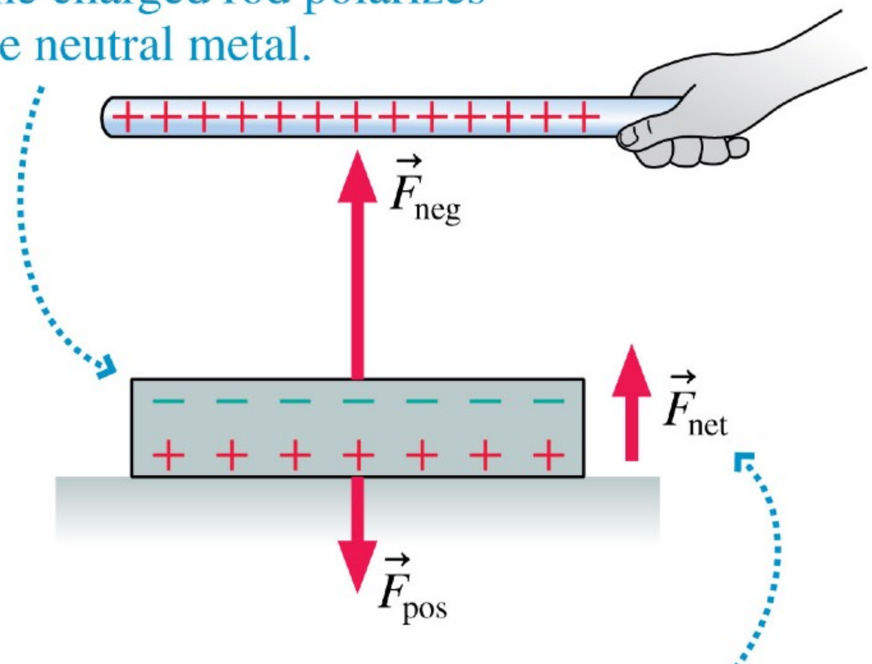
- The figure shows how a charged rod held close to an electroscope causes the leaves to repel each other.
- How do charged objects of either sign exert an attractive force on a *neutral* object?



Charge Polarization

- Although the metal as a whole is still electrically neutral, we say that the object has been *polarized*.
- **Charge polarization** is a slight separation of the positive and negative charges in a neutral object.

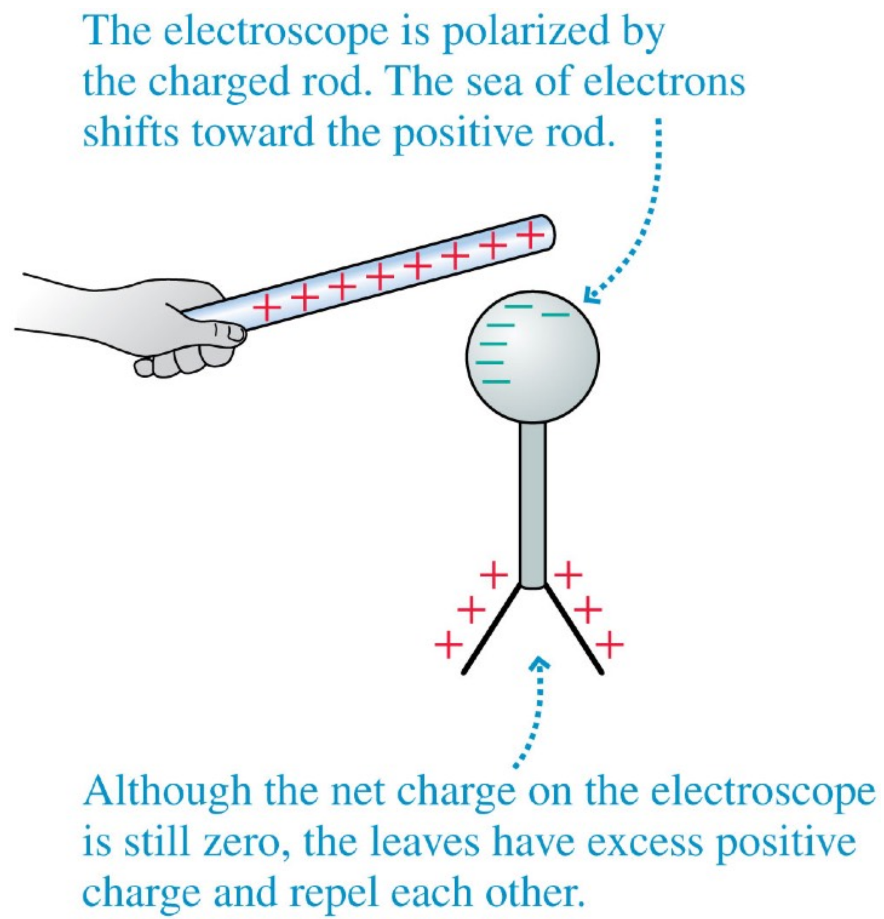
1. The charged rod polarizes the neutral metal.



2. The nearby negative charge is attracted to the rod more strongly than the distant positive charge is repelled, resulting in a net upward force.

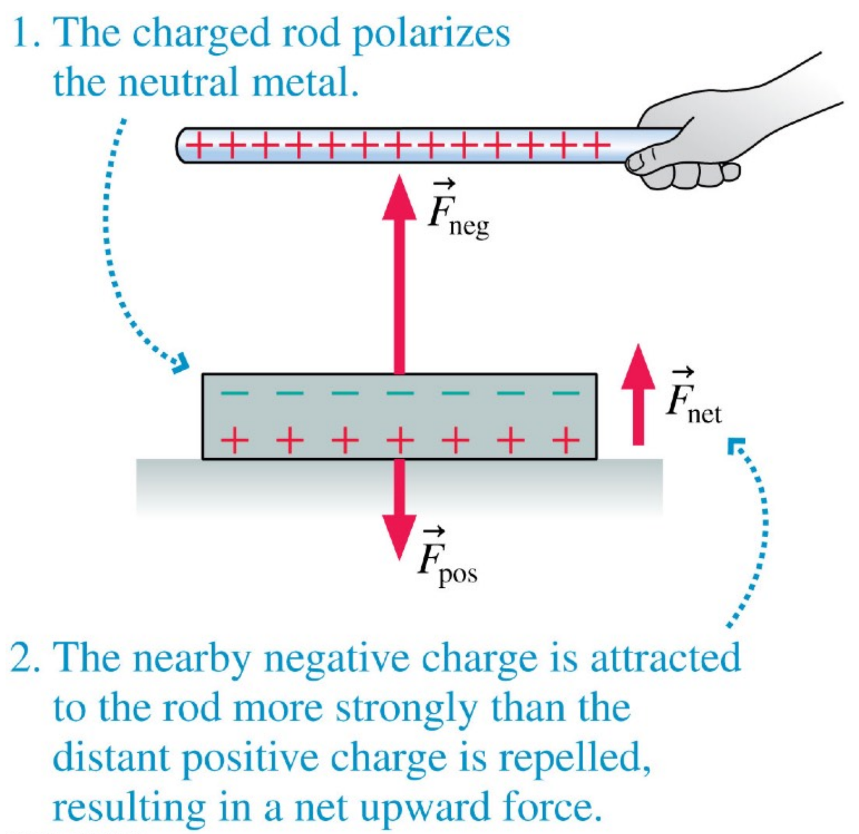
Charge Polarization

- Charge polarization produces an excess positive charge on the leaves of the electroscope, so they repel each other.
- Because the electroscope has no *net* charge, the electron sea quickly readjusts once the rod is removed.



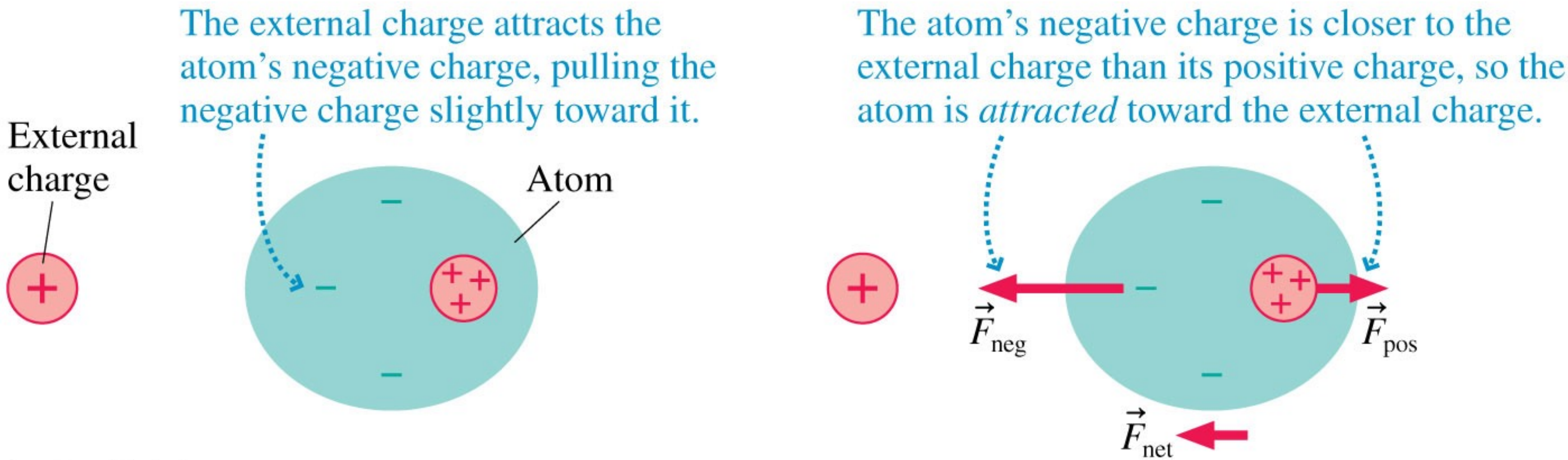
Polarization Force

- The figure shows a positively charged rod near a neutral piece of metal.
- Because the electric force decreases with distance, the attractive force on the electrons at the top surface is *slightly greater* than the repulsive force on the ions at the bottom.
- The net force toward the charged rod is called a **polarization force**.

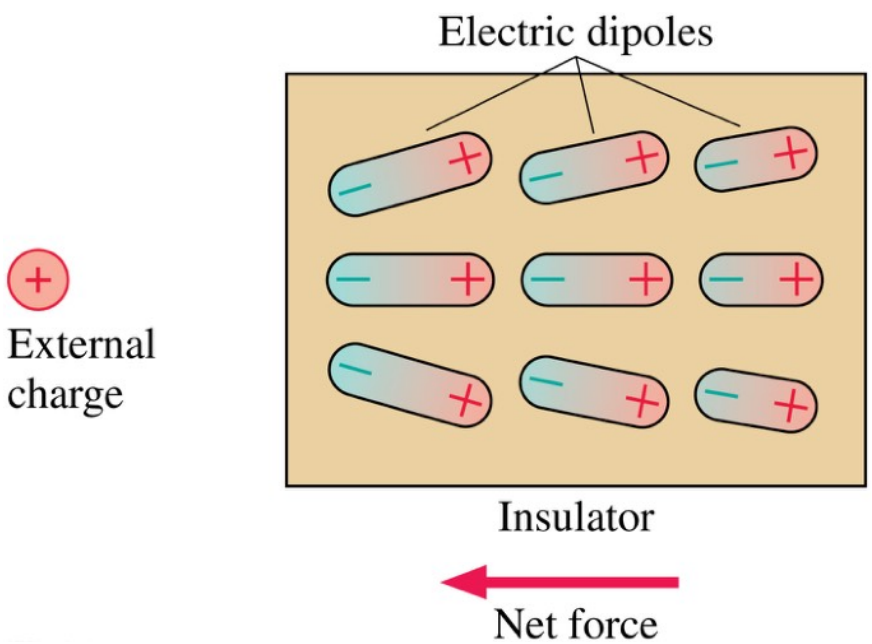


The Electric Dipole

- The figure below shows how a neutral atom is polarized by an external charge, forming an **electric dipole**.

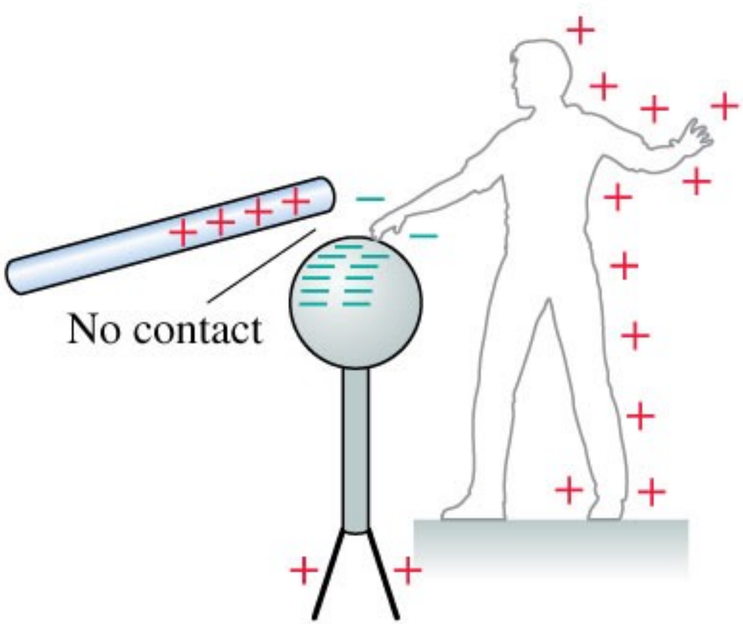


The Electric Dipole



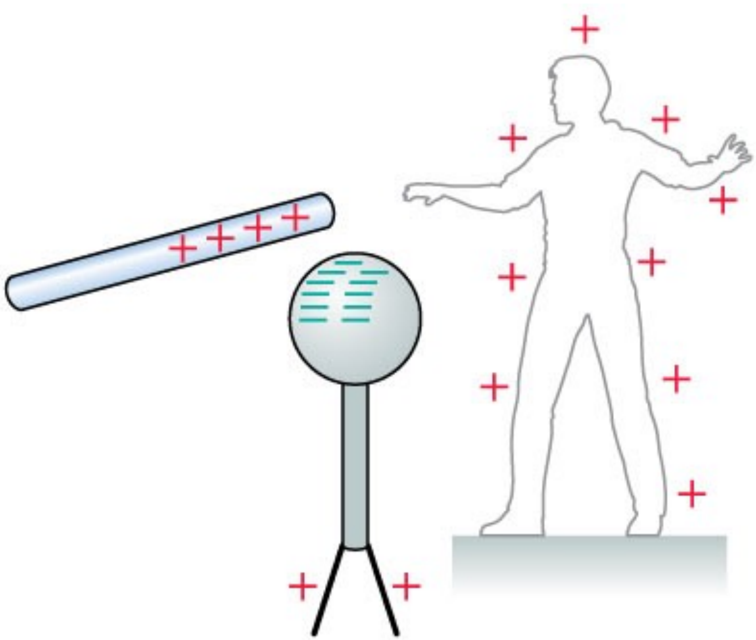
- When an insulator is brought near an external charge, all the individual atoms inside the insulator become polarized.
- The polarization force acting *on each atom* produces a net polarization force toward the external charge.

Charging by Induction: Step 1



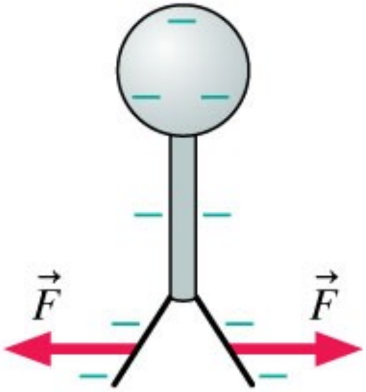
1. The charged rod polarizes the electroscope + person conductor. The leaves repel slightly due to polarization.

Charging by Induction: Step 2



2. The negative charge on the electroscope is isolated when contact is broken.

Charging by Induction: Step 3



3. When the rod is removed, the leaves first collapse as the polarization vanishes, then repel as the excess negative charge spreads out.

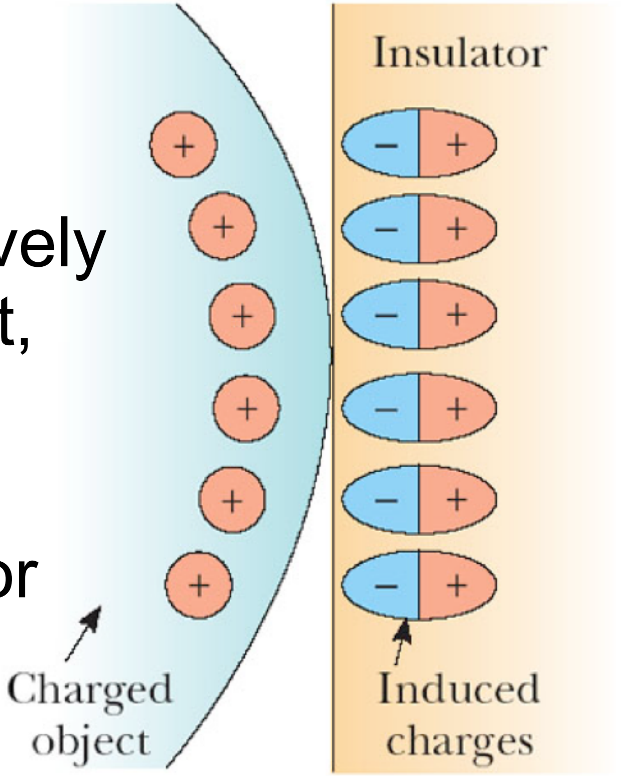
Charging (1)


"Electric Slide"
(Source: Ken Bosma)
http://www.flickr.com/photos/evdg/304764153/

Charging
Discharging

Induction

- In addition to adding or removing electrons, you can rearrange the electrons present in the object.
- For example, when you place a positively charged object next to a neutral object, the protons will be repulsed and the electrons will be attracted.
- This will lead to an overall attraction for the neutral object to the positively charged object.



Polarization

"Cooper and Styrofoam"
(Source: Sean McGrath)
http://www.flickr.com/photos/mcgraths/235112299/

Set subfrequency code 1/2 = C/A for York 2722.

Have you used iClickers before?

A Yes, and I have mine with me.

B Yes, but I don't have mine with me now. I promise to bring it every day from now on.

C I don't know what iClickers are.

D I don't know how to spell iClicker.

E I don't know what class I'm in.

Coulomb's Law

- Charles Coulomb was the first to establish the amount of electric force between charged objects.
- He experimentally determined that the magnitude of the electric force between two point charges (q_1 and q_2) separated by a distance r is given by:

Force is proportional to *both* charges:

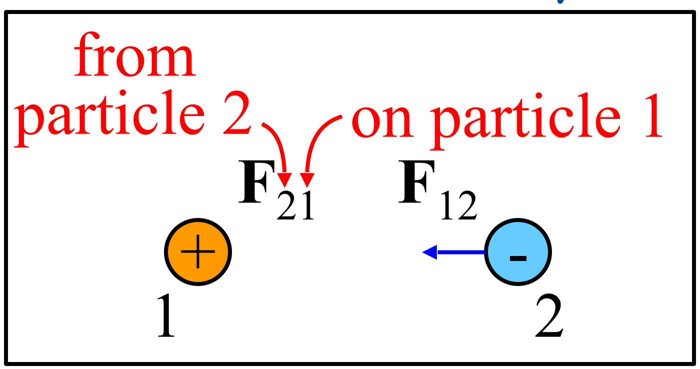
$$|\mathbf{F}| = k_e\, |q_1 q_2| \,/\, r^2$$

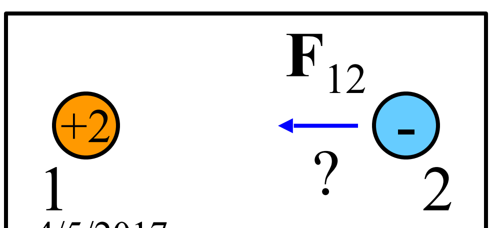
- where k_e is the proportionality constant with a value of: $k_e = 8.99\times10^9$ N m^2/C^2.
-

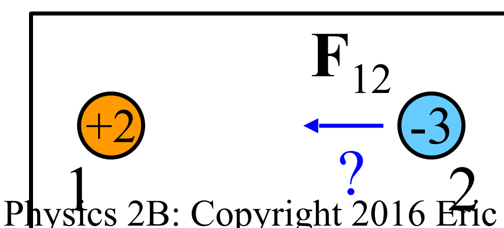
More on charges

- Again, charge is measured in **Coulombs** (C)
  - A coulomb is like a "dozen," only bigger: 6.242e18 electrons-worth of charge
    - ≈10^{-5} moles of electrons
  - Or, an electron has -1.602e-19 C of charge

~0.0001e-4 femto Coulombs (Very small in these units)







Force is proportional to *both* charges:
$|\mathbf{F}| = k_e\, |q_1 q_2| \,/\, r^2$

Coulomb's Law

$[N]$

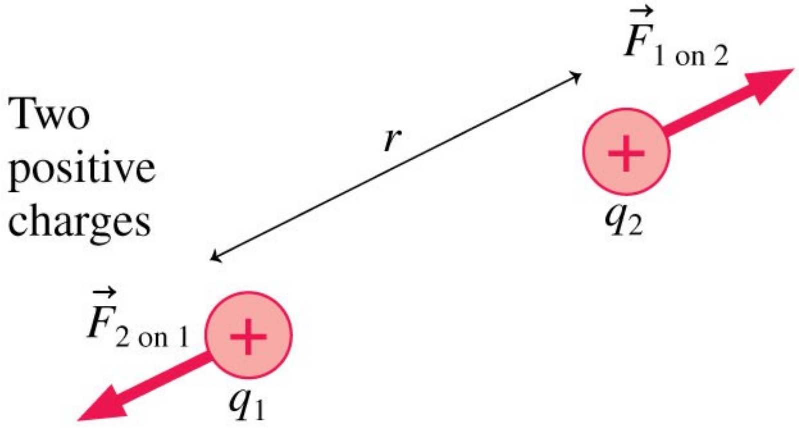
$$\boxed{F = k\frac{|q_1||q_2|}{r^2}}$$

$$\frac{[\cancel{C}][\cancel{C}]}{[\cancel{m^2}]}$$

$$8.99\times10^9\ \frac{N\cdot\cancel{m^2}}{\cancel{C^2}}$$

Coulomb's Law

- When two positively charged particles are a distance, r, apart, they each experience a repulsive force.

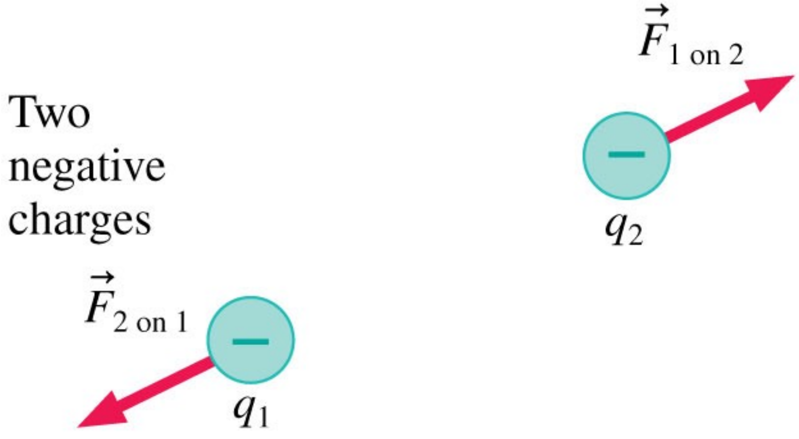


$$F_{1\text{ on }2} = F_{2\text{ on }1} = \frac{K|q_1||q_2|}{r^2}$$

- In SI units $K = 8.99 \times 10^9\ \mathrm{N\ m^2/C^2}$

Coulomb's Law

- When two negatively charged particles are a distance, r, apart, they each experience a repulsive force.

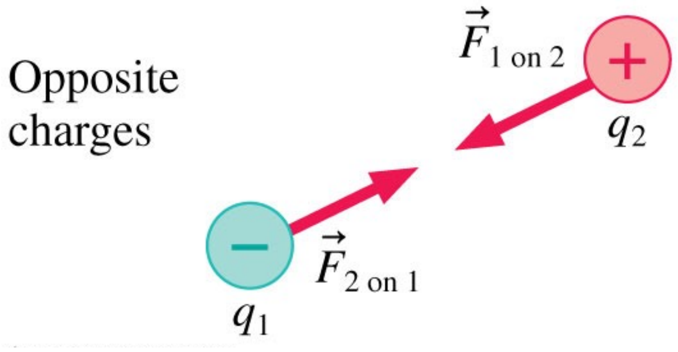


$$F_{1\text{ on }2} = F_{2\text{ on }1} = \frac{K|q_1||q_2|}{r^2}$$

- In SI units $K = 8.99 \times 10^9\ \text{N m}^2/\text{C}^2$

Coulomb's Law

- When two oppositely charged particles are a distance, r, apart, they each experience an attractive force.



$$F_{1\text{ on }2} = F_{2\text{ on }1} = \frac{K|q_1||q_2|}{r^2}$$

- In SI units $K = 8.99 \times 10^9 \text{ N m}^2/\text{C}^2$

Coulomb’s Law

When performing a Coulomb’s Law problem make sure you:

1) Define a coordinate system.

2) Make a clear diagram of the situation (if one is not given).

3) List the quantities known.

4) Calculate the magnitude from the equation for Coulomb’s Law.

5) Determine the direction (maybe using the fact that “like charges repel, and opposites attract.”)

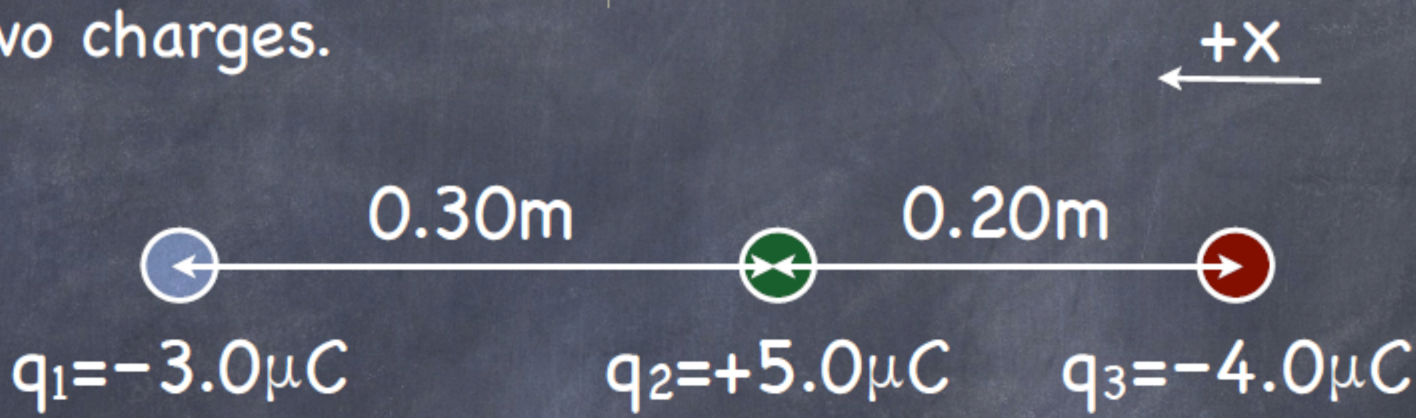
6) Potentially incorporate force diagrams and Newton’s Laws.

Coulomb's Law: superposition

- Calculating the force on one charge due to another charge via Coulomb's Law is quite simple, the issue becomes when you have multiple charges present.
- If you have more than two charges present you must use vector superposition.
- This means you calculate each force separately and then add them together under the rules of vector addition.
- You have to take both magnitude and direction into account.

Superposition

- Example
- Calculate the net electric force on the rightmost particle (q_3) in the figure below due to the other two charges.



- Answer
- First, you must define a coordinate system.
- Let's say that the rightmost particle is located at $x = 0$ and that the left direction is positive.

Superposition

- Answer

Next, let's list the quantities that we know:

$q_1 = -3.0\times10^{-6}$Coul

$q_2 = +5.0\times10^{-6}$Coul

$q_3 = -4.0\times10^{-6}$Coul

$r_{23} = 0.20$m

$r_{13} = 0.50$m

Let's calculate each force separately. First, let's start the force between particles 2 and 3.

$$F_{23} = k_e \frac{|q_2||q_3|}{r_{23}^2}$$

$$F_{23} = \left(8.99\times10^9 \,{}^{\mathrm{N\cdot m^2}}\!/_{\mathrm{C^2}}\right)\frac{|+5.0\times10^{-6}\mathrm{C}||-4.0\times10^{-6}\mathrm{C}|}{(0.20\mathrm{m})^2} = 4.5\mathrm{N}$$

Superposition

- Answer

Next, let's calculate the force between particles 1 and 3.

$$F_{13} = k_e \frac{|q_1||q_3|}{r_{13}^2}$$

$$F_{13} = \left(8.99 \times 10^9 \, \mathrm{N \cdot m^2}/\mathrm{C^2}\right) \frac{|-3.0 \times 10^{-6}\mathrm{C}||-4.0 \times 10^{-6}\mathrm{C}|}{(0.50\mathrm{m})^2} = 0.43\mathrm{N}$$

- What about direction?
- Since particles 2 and 3 are oppositely charged, they will be attractive => F_{23} is in +x direction.
- Since particles 1 and 3 are like charged, they will be repulsive => F_{13} is in the -x direction.

Superposition

- <u>Answer</u>

- Next, we add the two forces (via superposition).
- $\sum F_{elec} = F_{23} + F_{13} = 4.5\text{N} + -0.43\text{N} = +4.1\text{N}$
- Where the positive sign indicates that the force points to the left (since we chose left as +).
- The answer is the net electric force will have a magnitude of 4.1N and point to the left.
- Note: The middle charge q_2 in no way blocks the effect of q_1. If q_2 did not exist q_1 would still contribute the same amount.

Superposition

- <u>Example</u>
- In the figure below, particles 1 and 2 are fixed in place on the x-axis at a separation of 8.00 cm. Their charges are $q_1 = +e$ and $q_2 = -27e$. Particle 3 with charge $q_3 = +4e$ is to be placed on the line between particles 1 and 2, so that they produce a net electrostatic force on it. At what coordinate should particle 3 be placed to minimize the magnitude of that force?

- <u>Answer</u>
- The coordinate system is already defined for us.

Superposition

- Answer

Next, let's list the quantities that we know:

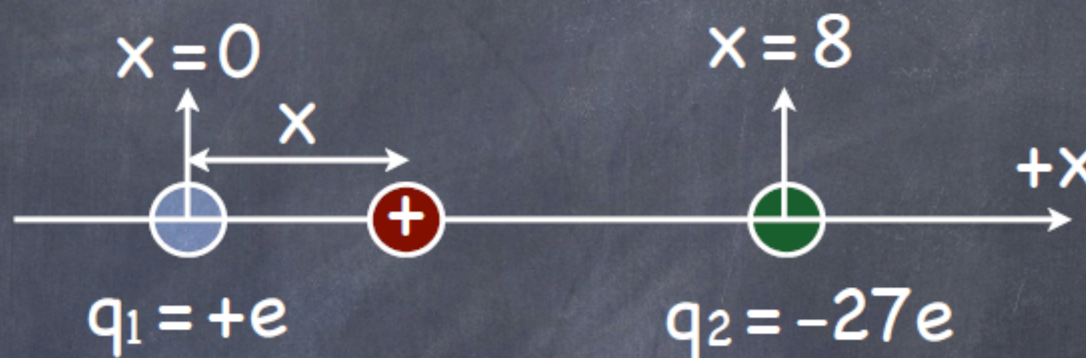
$q_1 = +e$

$q_2 = -27e$

$q_3 = +4e$

$r_{23} = ?$

$r_{13} = ?$



Let's alter the diagram of the situation by placing q_3 somewhere; call it a distance x from q_1.

This means that we now have a value for r_{13} (x) and a value for r_{23} (8-x)

What will the direction of q1 on q3 be? To the right.

What will the direction of q2 on q3 be? To the right.

Superposition

- Answer

Since both forces point in the same direction, we just need to add the absolute values of the forces involved.

$$F_{net} = |F_{13}| + |F_{23}|$$

$$F_{net} = k\frac{|q_1\, q_3|}{x^2} + k\frac{|q_2\, q_3|}{(8\text{ cm} - x)^2}$$

Putting in the values gives us: $$F_{net} = 4ke^2\left(\frac{1}{x^2} + \frac{27}{(8\text{ cm} - x)^2}\right)$$

In order to minimize this force, we need to take a derivative with respect to x and set it equal to zero.

$$\frac{dF_{net}}{dx} = 4ke^2\left(\frac{-2}{x^3} + \frac{-1(-2)(27)}{(8\text{ cm} - x)^3}\right) = 0$$

Superposition

- Answer

The only part that can go to zero is inside the parenthesis, so we can set that to zero:

$$\left(\frac{-2}{x^3}+\frac{54}{(8\,\mathrm{cm}-x)^3}\right)=0$$

$$\frac{2}{x^3}=\frac{54}{(8\,\mathrm{cm}-x)^3}$$

Eliminating the denominators yields:

$$(8\,\mathrm{cm}-x)^3=\frac{54x^3}{2}=27x^3$$

Taking a cube root of both sides gives us:

$$(8\,\mathrm{cm}-x)=3x$$

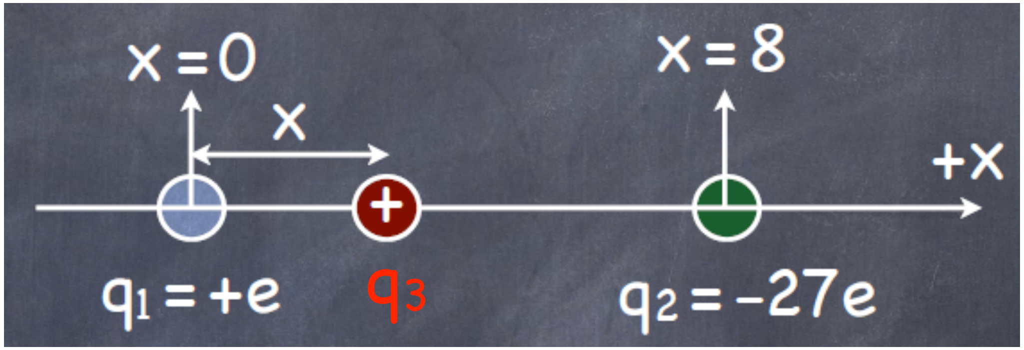
$$8\,\mathrm{cm}=4x$$

$$x=2.00\,\mathrm{cm}$$

This means particle 3 is placed 2.00 cm from particle 1 to minimize the force on it.

Coulomb's Law: superposition

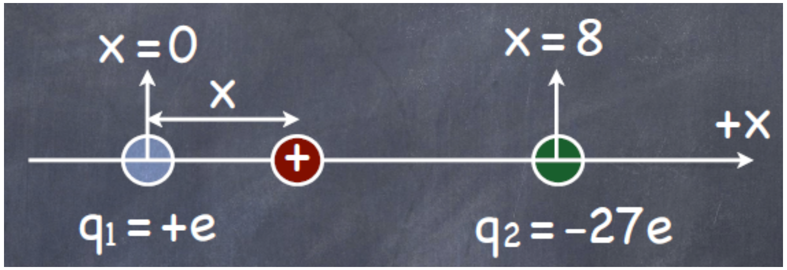
- Last time we were asked to find the position of charge q_3 (red charge below) where the force due to charges q_1 and q_2 would be a minimum.



- Note that the force there from both charges is to the right, so the minimum cannot be zero!
- Where would it be zero?
- Somewhere to the right or the left?

Let's quickly plot in google

$$F_{net} = k\frac{|q_1\ q_3|}{x^2} + k\frac{|q_2\ q_3|}{(8\text{ cm} - x)^2}$$

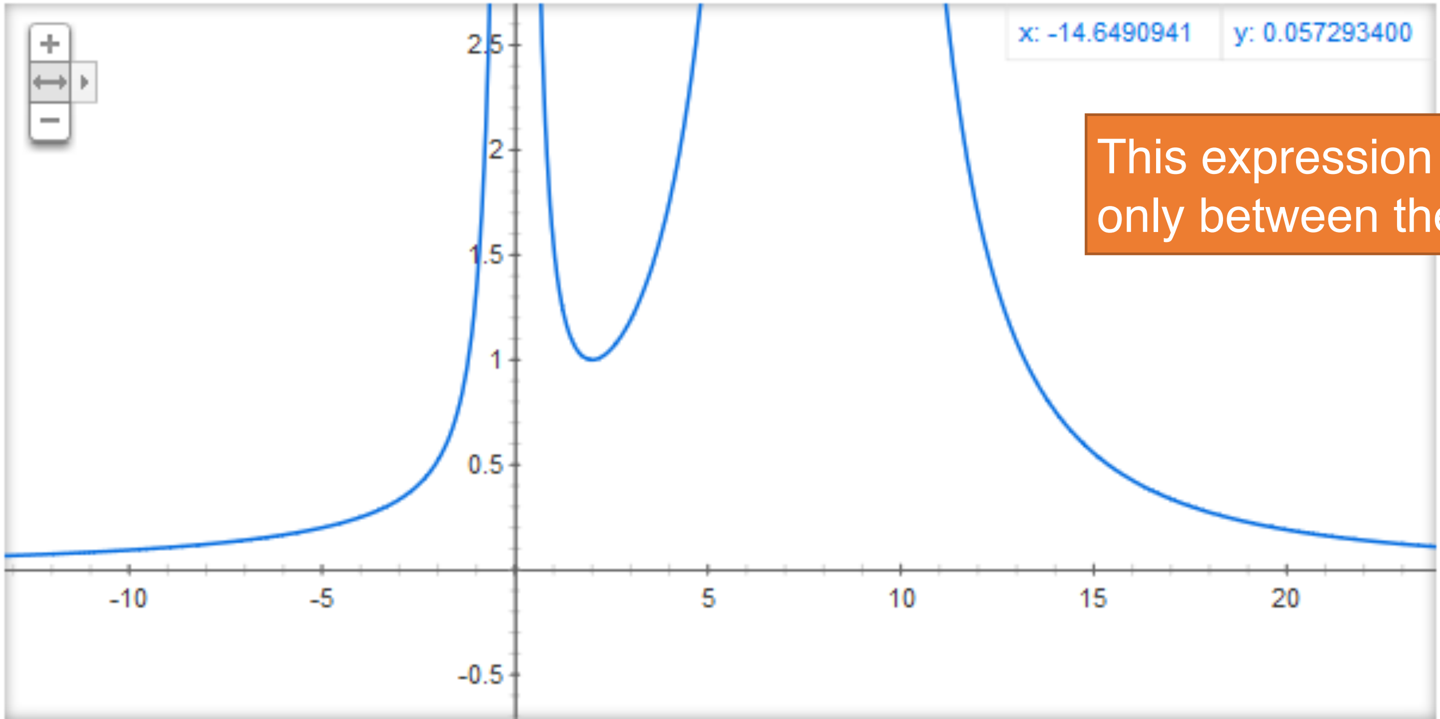


- Note that k and q_3 are common factors

Google

plot(1/x^2 +27/(8-x)^2)

Graph for 1/x^2+27/(8-x)^2

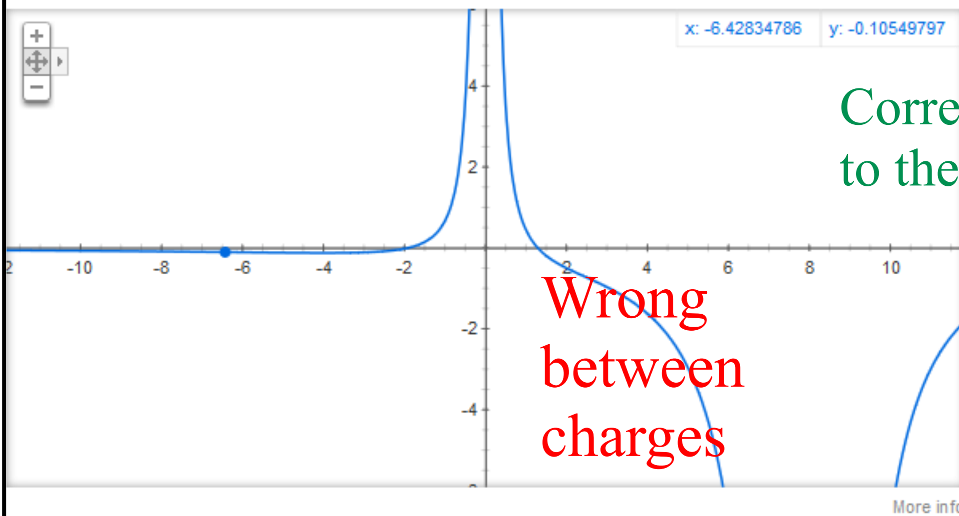


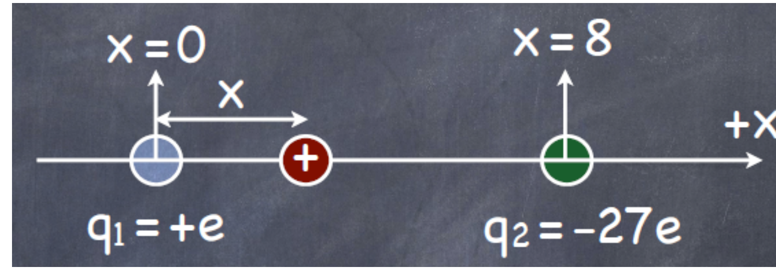
This expression is valid only between the charges!

Wait, how about writing the charges' signs

$$F_{net} = k\frac{|q_1\, q_3|}{x^2} - k\frac{|q_2\, q_3|}{(8\text{ cm} - x)^2}$$

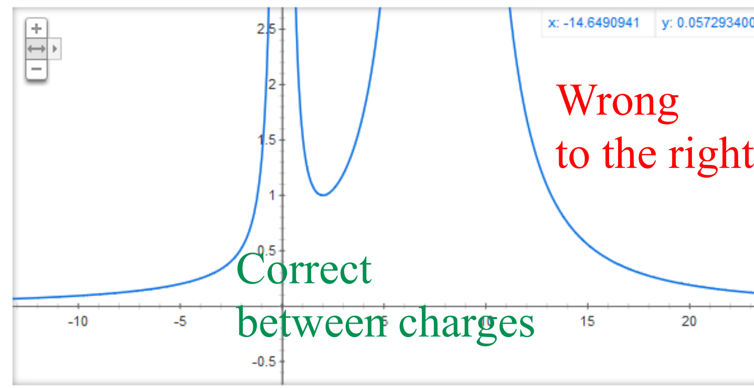
Graph for 1/x^2-27/(8-x)^2





$$F_{net} = k\frac{|q_1\, q_3|}{x^2} + k\frac{|q_2\, q_3|}{(8\text{ cm} - x)^2}$$

Graph for 1/x^2+27/(8-x)^2



$|\mathbf{F}| = k_e\, |q_1 q_2| / r^2$ only tells us about the magnitude,
we do the "direction by hand", we'll see a more useful expression

iClicker question 3-1:

The direction of the force on charge $-q$ is

A. Up.
B. Down.
C. Right.
D. Left.
E. The force on $-q$ is zero.