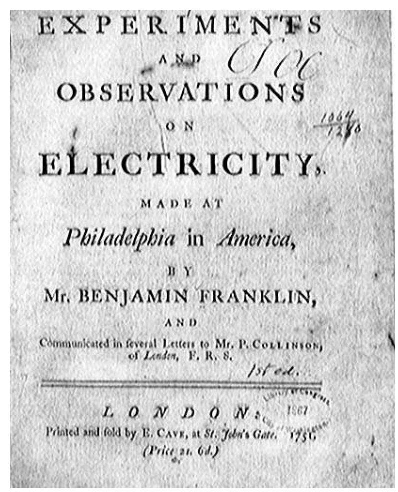
AP* Physics 1
ELECTROSTATICS

As early as the fourth century B.C., Plato noted that a yellow substance then known as *elektron* attracted lightweight objects when rubbed against a piece of fur. This material is now known as *amber*, and it has been shown to be the fossilized resin from pine trees which occasionally trapped ancient insects. (Yes, just like in *Jurassic Park.*)

In 1733 Charles Francois de Cisternay du Fay noticed that objects that had been rubbed sometimes attracted and sometimes repelled each other. He explained this by proposing two different kinds of electricity. Vitreous electricity (from the Latin for "glass") is produced when glass or gems were rubbed. Resinous electricity (from the Latin for "resin," or "amber") is obtained by rubbing amber, silk, or paper. Du Fay argued that objects with different kinds of electricity attract each other, whereas those with the same kind of electricity repel.

Du Fay's discovery led to a theory of electricity that assumed the existence of two fluids. Objects that are not electrified were assumed to have equal amounts of these fluids, which neutralize each other. Rubbing an object was assumed to remove one of the fluids, leaving an excess of the other.



EXPERIMENTS AND OBSERVATIONS ON ELECTRICITY, MADE AT *Philadelphia* in *America*, BY Mr. BENJAMIN FRANKLIN, AND Communicated in several Letters to Mr. P. COLLINSON, of *London*, F. R. S.

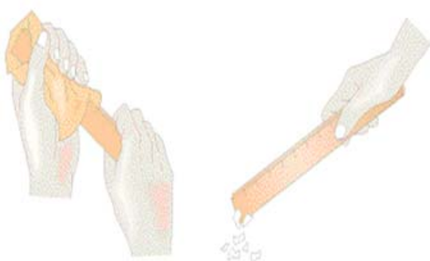
LONDON: Printed and sold by E. CAVE, at *St. John's Gate.* 1751. (Price 2s. 6d.)

In June of 1752, Benjamin Franklin flew his famous kite in a lightning storm (fool that he was). Franklin suspected that lightning was an electrical current in nature, and he wanted to see if he was correct. One way to test his idea would be to see if the lightning would pass through metal. He decided to use a metal key and looked around for a way to get the key up near the lightning. As you probably already know, he used a child's toy, a kite, to prove that lightning is really a stream of electrified air, known today as *plasma*. His famous stormy kite flight in June of 1752 led him to develop many of the terms that we still use today when we talk about electricity: *battery, conductor, condenser, charge, discharge, uncharged, negative, minus, plus, electric shock,* and even *electrician*.

In 1780 an Italian anatomist Luigi Galvani while experimenting with static ‘electricity’ and dissected frogs stumbled upon what is today known as ‘electric current’. In 1791 he published a paper regarding the presence of a continuous flow of electricity, at the time referring to it as ‘animal electricity’. In 1800 Italian Alessandro Guiseppe Antonio Anastasio Volta’s experiments lead to the first version of the battery. It would not be until 1807 in London that Sir Humphrey Davy’s discovery of the ‘electric arc’ during experiments with a 2,000-cell battery, would lead to the beginning stages of incandescent lighting.

Static Electricity; Electric Charge & Its Conservation

The word *electricity* comes from the Greek word *elektron* as coined by Plato. Static electricity is literally "electricity at rest." Static electricity is an electrical charge that builds up due to friction between two dissimilar materials. Friction removes some electrons from one object and deposits them on the other. Each object is said to be *charged*. The one acquiring e^- is said to be *negative*, while the one that lost electrons is said to be *positive*.



Pieces of paper can be picked up with a plastic ruler that you have just vigorously rubbed with cloth or paper towel. You've probably experienced static electricity when combing your hair or taking a piece of clothing from the dryer that is made of a synthetic fabric. You may also have felt a shock when touching something metal, such as a car door latch, after sliding across a cloth car seat.

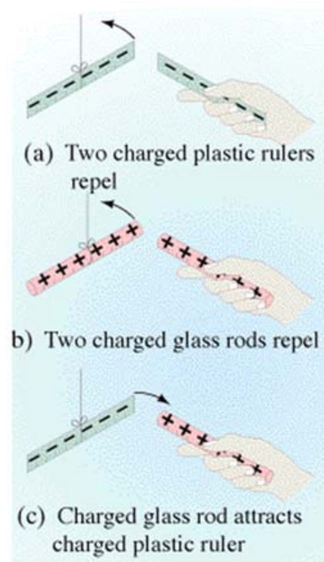
Like charges repel and unlike or opposite charges attract.

A simple demonstration proves there are indeed two different kinds of electric charge. You can even try this one yourself!

Part (a)
A plastic ruler is suspended with a thread and rubbed vigorously with a cloth to charge it. When a second ruler that has been charged the same way approaches the suspended ruler, it is found that the rulers *repel*.

Part (b)
Similarly, if a rubbed glass rod is brought close to a second charged glass rod, they also repel each other.

Part (c)
However, if the charged glass rod is brought close to the charged plastic ruler, they *attract* each other.

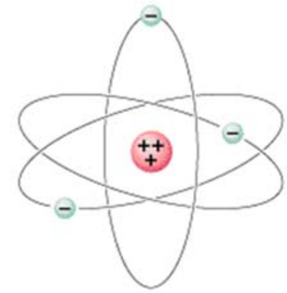


Therefore, there are two types of electric charge. Further experimentation shows that there are two and *only* two types of charge and Ben Franklin named them *positive* and *negative.* His choice of which name went with which charge was arbitrary, but he called the rubbed glass rod positive and physicists still follow that convention today. Franklin proposed that when a certain amount of charge is produced on one body (by rubbing), then an equal amount of the opposite type of charge is produced on another body.

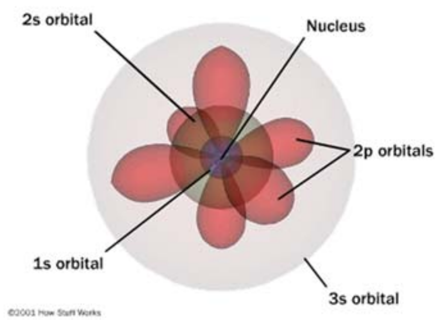
The Law of Conservation of Electric Charge
The net amount of electric charge produced in any process is zero.

Sound familiar? This law is a companion to the conservation laws we've studied such as energy and momentum.

Electric Charge in the Atom



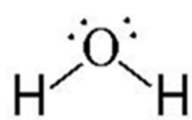
Only within the past century has it become clear that electricity starts inside the atom itself. Recall that it was June, 1752 that Ben Franklin flew his kite. It would be another 145 years before J.J. Thomson would discover the electron!



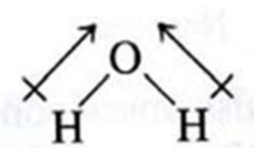
Recall that atoms are neutral having equal numbers of p^+ and e^-. The p^+ and n^0 are packed into a very dense nucleus. The electrons are in constant motion in the electron cloud. The picture you see above is not the best representation of this arrangement. It implies that the e^- have fixed orbits which is simply incorrect! The representation at left, while not as adorable, is far more accurate since it depicts the *probability regions* in which electrons are most likely found.

Isotopes have *differing numbers of neutrons*, therefore different masses, but it is the number of *protons* that determines an isotope's "identity" such as the common isotopes of uranium: ${}^{238}_{92}U$ & ${}^{235}_{92}U$. Also recall that *ions* have gained e^- to form negative anions, or lost e^- to form positive cations.

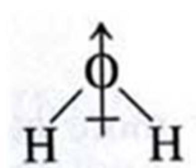
Now we can better explain this whole "rubbing" or "charging" concept. When a plastic ruler is charged by rubbing it with a cloth, electrons are transferred from the cloth to the plastic, so the cloth is positively charged and the ruler is negatively charged. Furthermore, once the ruler is charged, it can't hold its charge forever.



So, where does the charge go? It "leaks" away by colliding with oppositely charged ions in the air [rare], or by colliding with water molecules in the air [far more common, think "humidity"].



Recall water is a neutral but polar molecule. Its shape it determined by the repulsions between electron pairs. The lone pairs repel with more force than the shared pairs. We use vectors, called *dipole moments*, to indicate the direction of the uneven charge distribution as well as the signs of the charges. The cross-hatch on the arrow indicates the positive end of the dipole moment.



Since these are **vectors**, we can use vector addition to solve for the *net* moment on the water molecule, which is shown as the final drawing at left. Thus (+) charges are neutralized by colliding with the "oxygen-end" or negative end of the water molecule. And (–) charges are neutralized by collisions with the "hydrogen-end", since it is the positive end of the water molecule.

Insulators and Conductors

To conduct or not to conduct? [Apologies to Shakespeare]

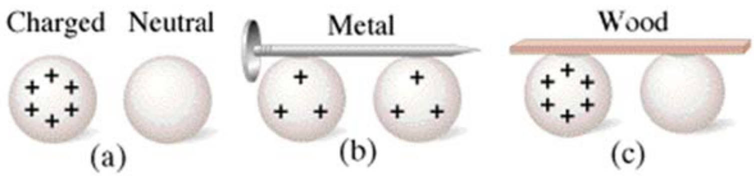


Image (a): Start with two metal spheres, one highly charged and the other electrically neutral.

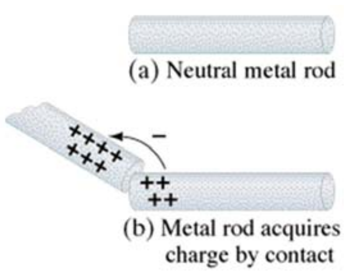
Image (b): Place an iron nail so that it touches both spheres, it is found that the uncharged sphere now becomes charged *and* that the charge is *evenly* distributed between both spheres.

Image (c): Start again with the spheres in Part (a) and repeat the experiment with a piece of dry wood and the spheres remain unaffected. *Why*?

We're back to atomic structure again. Metals exist as cations surrounded by delocalized electrons.
In English, that means positive ions surrounded by a "sea" of electrons that are mobile and free to move about. However, don't be misled; these electrons don't leave the metal easily.

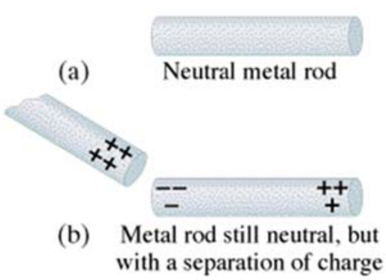
Insulators on the other hand are nonmetals that have their electrons bound tightly to the nucleus.
No free moving electrons, means no conduction of electricity. However, there are some elements such as silicon, carbon and germanium that have an intermediate electron situation and are referred to as *semiconductors*.

Induced Charge: the Electroscope



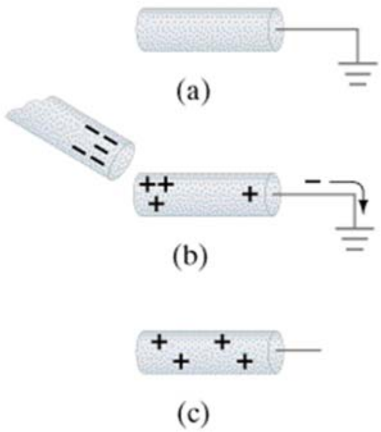
A positively charged metal rod is brought in contact with an uncharged or neutral metal rod (a). Electrons will pass over to the charged rod, leaving the once uncharged rod electron deficient and thus positively charged (b).

(Note the quantity of charge is not necessarily equal.) This process is called charging by *contact* or *conduction*.



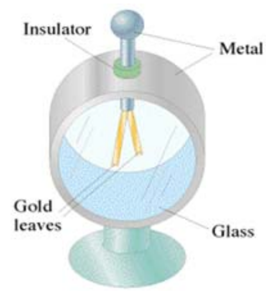
Next, suppose we bring a positively charged metal rod near a neutral metal rod but we DO NOT allow them to touch. What happens now?

The delocalized electrons in the neutral rod (b) are attracted to the positive charge. Their movement causes a *surplus of electrons* (–) at the end closest to the charged rod and leaves a *deficiency of electrons* (+) at the opposite end. Note that no electrons were transferred! Therefore, no net charge has been created; charges have been simply separated. A charge was *induced* at each end of the rod. This process is called charging by *induction*.

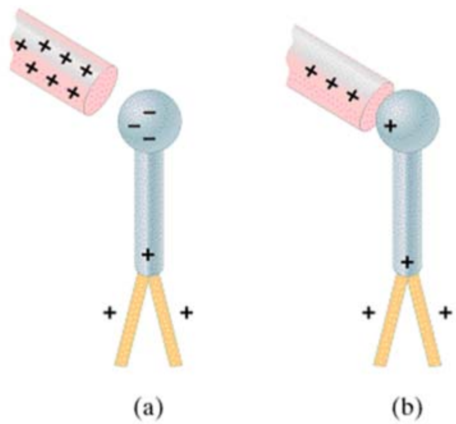


Yet another way to induce a net charge on a metal object is to connect it with a wire to the ground (a). The object is said to be “grounded” which is indicated by this symbol: ⏚

Earth provides an excellent sink for electrons since it conducts well and is so large. If a negatively charged rod approaches a neutral grounded rod, then e^- are repelled and conducted down the wire to Earth, leaving the metal positively charged (b). If you cut the wire now, before moving the negative rod away, the rod will have lost its e^- to Earth, thus a positive induced charge remains on the rod (c). IF you move the negative rod away before cutting the wire, the e^- would have moved back into the rod through the wire and the rod would once again be neutral.



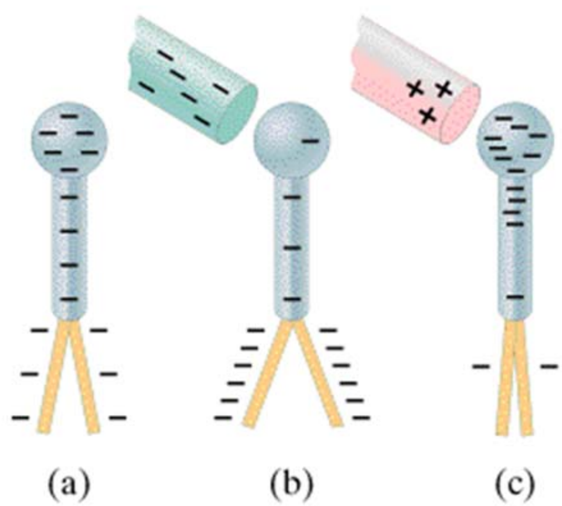
An **electroscope** is used to detect charge. It consists of two movable leaves (often gold) connected by a conductor to a metal ball on the outside of the case, but insulated from the case itself.



If you bring a positively charged rod near (induction) the metal ball, electrons from the leaves migrate to the ball (a) and the leaves separate since a (+) charge is induced on each leaf and like charges repel. If you remove the rod, the electrons return and the leaves fall back to their original position.

If you touch (conduction) a positively charged rod to the metal ball (b), the entire device acquires a positive charge and the leaves *stay* separated, and the greater the charge, the greater the separation. The trouble is… a negatively charged rod produces the same result!

If you wish to determine the sign of the charge the electroscope must first be charged by conduction. The one pictured at right (a) has been charged negatively and has a slight separation between its leaves.

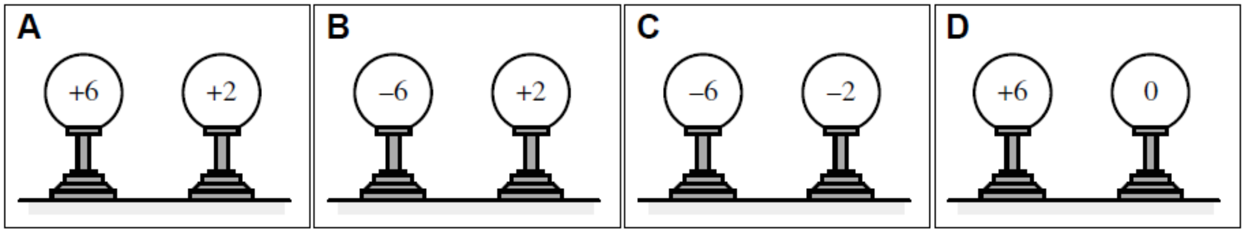


IF the rod approaching is negative, then electrons in the ball are repelled and run down the leaves, increasing the separation (b).

IF the rod approaching is positive, then electrons in the ball are attracted and even more electrons leave the leaves to enter the ball, thus reducing the initial amount of negative charge on the leaves which causes less separation between the leaves (c).

Example 1

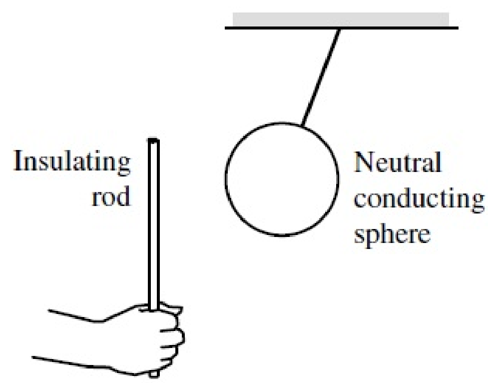
Two identical conducting spheres are shown with an initial given number of units of charge. The two spheres are brought into contact with each other. After several moments the two spheres are separated.



Rank the charge on the left sphere from the highest positive charge to the lowest negative charge after they have been separated. (Remember that –6 is lower than –2)

Example 2

A student observes a demonstration involving an interaction between a neutral metallic sphere suspended from a string and a negatively charged insulating rod.

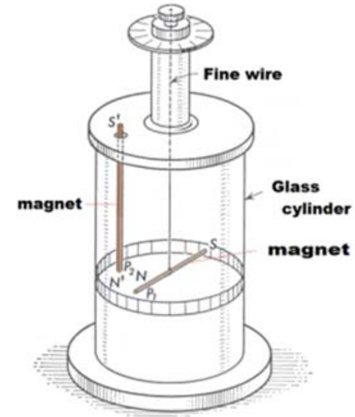


The student makes the following observation:

"As the negatively charged rod nears the sphere, it causes the electrons in the sphere to move away from the rod. The side of the sphere nearest to the rod becomes positively charged while the other side becomes negatively charged. So the sphere will be attracted toward the rod. If they touch, the sphere will swing back since they will both become neutral."

What, if anything, is wrong with this statement?
If something is wrong, *explain* the error and how to correct it.
If the statement is valid, *explain* why it is valid.

Coulomb's Law



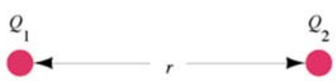
Coulomb type torsion balance

Magnet NS of pole strength P_1 and magnet N'S' of pole strength P_2

By now you probably have the hang of the *qualitative* relationships between electric charges and forces. Now, it's time to *quantify* those forces. The French physicist Charles Coulomb (1736-1806) investigated electric forces in the 1780s using a torsion balance (similar to what Cavendish used for the gravitational force) which is an instrument for measuring *very weak* forces by their effect on a system of fine twisted wire. Thus, he had no fancy equipment, but was able to produce charged spheres whose ratio of charge was known. He studied the effect of changing the charges on spheres and the effect of changing the distance between them. The SI unit for charge, the **coulomb** (C), is named in his honor.

- He discovered that there was a direct relationship between the charges of the spheres and how they affected each other. Keeping the distance between the spheres the same and doubling the charge on one sphere, doubled the force. Tripling the charge on one sphere tripled the force, etc. Doubling the charge on both spheres, quadrupled the force, and so on.

- He found that *increasing the distance* between the spheres of equal charge, *decreased the force* with the ***square** of the distance* between them. If he doubled the distance, the force fell to $\frac{1}{4}$ of its original value. If he tripled the distance, the force fell to $\frac{1}{9}$ of its original value, and so on.



Mathematically stated Coulomb's Law is: $F \propto \frac{Q_1 Q_2}{r^2}$

Insert a proportionality constant and equal sign and you have a much more useful version of Coulomb's Law!

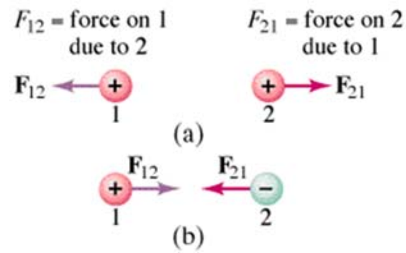
Coulomb's Law

$$F = k\frac{Q_1 Q_2}{r^2}$$

Where $k = 8.988 \times 10^9 \ \frac{\text{N}\cdot\text{m}^2}{\text{C}^2} \approx 9.0 \times 10^9 \ \frac{\text{N}\cdot\text{m}^2}{\text{C}^2}$

The force one tiny charged object exerts on a second one is proportional to the product of the magnitude of the charge on one, Q_1, times the magnitude of the charge on the other, Q_2, and inversely proportional to the square of the distance r between them.

Coulomb's Law calculates the *magnitude* of the electric force that either object exerts on another. The *direction* of the force is along the line between the two objects. Remember like charges repel and opposite charges attract! The charges are considered *point charges*, which means their size is really small compared to the distance between them, *r*. The point charges are also considered to be at rest (electrostatics).



In actual fact, we rarely encounter charges of 1.0 C. Charges produced by rubbing ordinary objects like a comb or plastic ruler, are typically around a microcoulomb ($1 \mu C = 10^{-6} C$ and about $10^{13}\ e^-$) or less. In case you're wondering, the charge on an e^- is about -1.602×10^{-19} C.

Since the electron is the smallest known charge*, and because of its fundamental nature, it is given the symbol *e* and is referred to as the ***elementary charge***, $e = 1.602 \times 10^{-19}$ C, note that it is defined as a positive number! Therefore, the charge on an electron is equal to $-e$ and the charge on a proton is simply *e*. (Confused yet?) So, electric charge is quantized, existing only in discrete amounts such as $1e$, $2e$, etc.

**Quarks have charges smaller than electrons, BUT they have not been detected directly; their charges are equal to* $\frac{1}{3}e$ or $\frac{2}{3}e$.

By now you've probably noticed that Coulomb's Law resembles the law of universal gravitation, $\left(F \propto \frac{1}{r^2}\right)$ in that both are *inverse square laws*.

Also both have proportionality to a product of a property of each body—mass for gravity, electric charge for electricity. However, they differ in that gravity is *always* an attractive force, while the electric force can be *either* attractive or repulsive.

The constant *k* is often written in terms of another constant called the ***permittivity of free space***, symbolized by ε_0. The constants are related as follows:

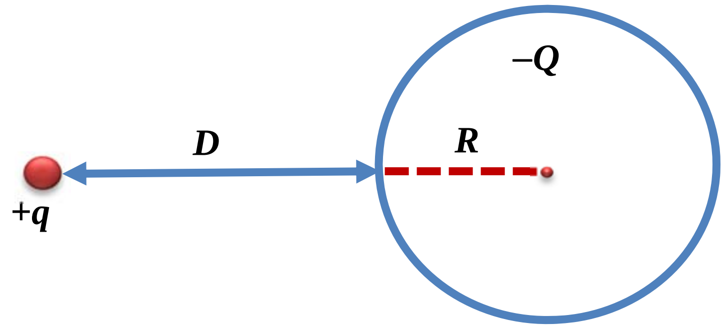
$$k = \frac{1}{4\pi\epsilon_0} \quad \text{and} \quad \varepsilon_0 = \frac{1}{4\pi k} = 8.85 \times 10^{-12}\ \frac{\mathrm{C}^2}{\mathrm{N{\cdot}m}^2}$$

We won't use this too much in this lesson, but we will later!

One last thing…when you plug the charges into Coulomb's Law calculations using the sign and magnitude of the charges, a $+F$ indicates a ***repulsive*** force and a $-F$ indicates an ***attractive*** force.

Example 3

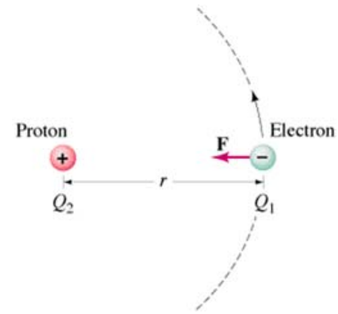
A positive point charge is placed a distance ***D*** away from the closest surface of a metal sphere with a radius ***R*** and charge –***Q***.



Change		Effect of the Force Exerted on the Particle: No Force	Force Increases	Force Decreases	Force Remains the Same
1.	Increase the distance D				
2.	Increase R, keeping the charge a distance D away				
3.	Increase the charge of the particle				
4.	Make the charge of the particle $-q$				
5.	Add negative charge to the sphere				

Example 4

Determine the magnitude of the electric force on the electron of a hydrogen atom exerted by the single proton that is its nucleus. Assume the electron "orbits" the nucleus at its average distance of $r = 0.53 \times 10^{-10}$ m.



Example 5

Which is larger in magnitude, the force that Q_1 exerts on Q_2, or the force that Q_2 exerts on Q_1?

Solving Problems Involving Coulomb's Law & Vectors

So, how do we deal with situations when a charge at rest is in the presence of more than one other charge?

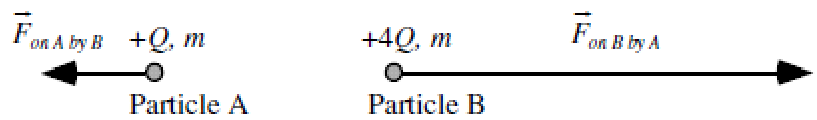
We use vector addition. This is also referred to as the *principle of superposition for forces*.

$$\mathbf{F}_{\text{net}} = \mathbf{F}_1 + \mathbf{F}_2 + \mathbf{F}_3 \ \ldots$$

It is important to draw a free body diagram for *each* body involved. In applying Coulomb's Law, we usually deal with charge magnitudes only (leave out the minus signs) and determine the direction of the force physically and show the force on the diagram. Vector addition is required!

Example 6

Shown below is a student's drawing of the electric forces acting on Particle A (with charge $+Q$ and mass m) and Particle B (with charge $+4Q$ and mass m).

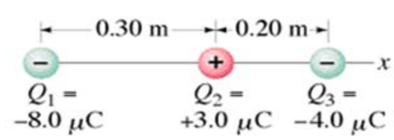


There is something wrong with this diagram. Explain what is wrong and how to correct it.

The forces should be the same magnitude: to correct the diagram, make the arrow on the $+q$ charge the same length as the one on the $+4q$ charge.

Example 7

Three charged particles are arranged in a line. Calculate the net electrostatic force on particle 3 due to the other two charges.



Example 8

Three charged particles, ***A***, ***B***, and ***C***, are fixed in place in a line. Charge ***C*** is twice as far from charge ***B*** as charge ***A*** is. All charges are the same magnitude.

In the chart to the *left* below, use arrows (← or →) to indicate the direction of the net force on charge *C* due to charges *A* and *B*. If the force is zero, state that explicitly.

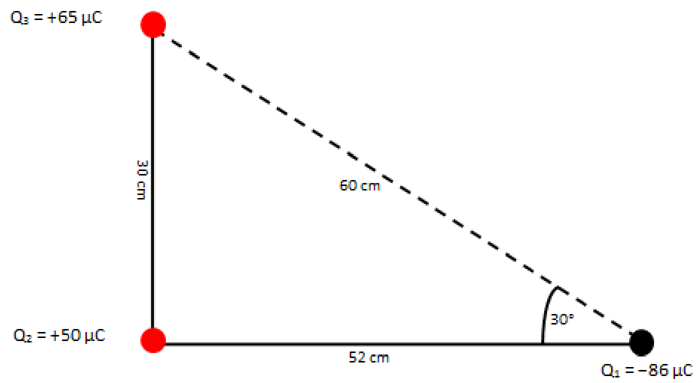
In the chart on the *right* below, use arrows (← or →) to indicate the direction of the net force on charge *B* due to charges *A* and *C*. If the force is zero, state that explicitly.

$\Sigma\vec{F}$ **on charge *C***		$\Sigma\vec{F}$ **on charge *B***	
A *B* *C* + + +	Direction:	*A* *B* *C* + + +	Direction:
A *B* *C* + + −	Direction:	*A* *B* *C* + + −	Direction:
A *B* *C* + − +	Direction:	*A* *B* *C* + − +	Direction:
A *B* *C* + − −	Direction:	*A* *B* *C* + − −	Direction:
A *B* *C* − + +	Direction:	*A* *B* *C* − + +	Direction:
A *B* *C* − + −	Direction:	*A* *B* *C* − + −	Direction:
A *B* *C* − − +	Direction:	*A* *B* *C* − − +	Direction:
A *B* *C* − − −	Direction:	*A* *B* *C* − − −	Direction:

Explain your reasoning.

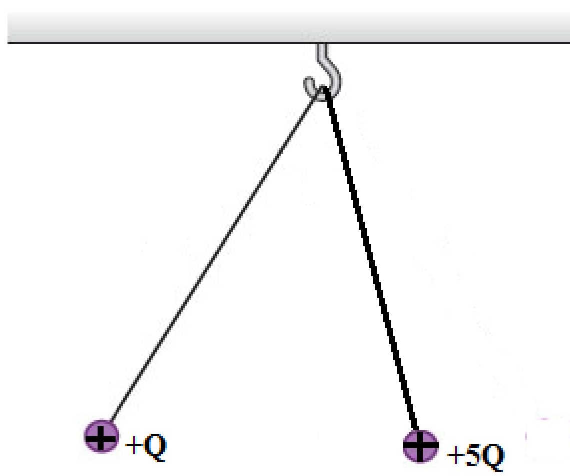
Example 9

Calculate the net electrostatic force on charge Q_3 as shown in the figure due to the charges Q_1 and Q_2.



Example 10

Two equal mass conducting spheres hang stationary at the end of insulating strings as shown. The sphere on the right has a charge of +5Q and the sphere on the left has a charge of +Q. The strings make angles that are less than 45° with the vertical.



Draw a Free Body Diagram for the Left Sphere	Draw a Free Body Diagram for the Right Sphere	Decide which string makes a bigger angle with the vertical plane or if they make the same angle.
Apply Newton's 2^{nd} Law for the Left Sphere	Apply Newton's 2nd Law for the Right Sphere	Based on your analysis, rank the following forces, listing the largest first: $F_{\text{Gravity on }+Q}$, $F_{+5Q\text{ on }+Q}$, $F_{\text{Tension on }+Q}$ Explain your ranking: