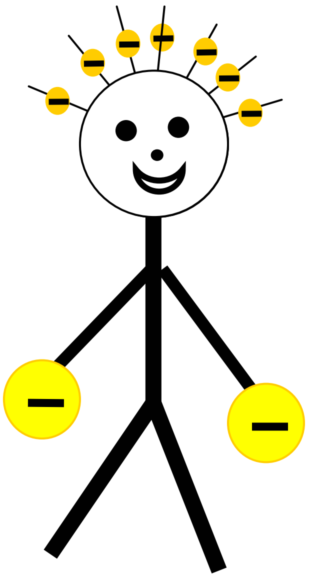
Chapter 1: Electric Charge and Coulomb Law

Electric charge



Electric charge is a fundamental quantity. The unit of electric charge is called the ***coulomb* (C),** name after Charles Coulomb, a French scientist who studied electrical effects. There are two types of charges.

- positive (+)
- negative (-)

As we know all matter is made up of small particles called atoms, each atom consists of electron, proton, and neutron.

Some properties of atomic particles

Particles	Symbol	Mass	charge
Electron	e^-	$9.11\text{x}10^{-31}$ kg	$-1.60\text{x}10^{-19}$ C
Proton	p^+	$1.67\text{x}10^{-27}$ kg	$1.60\text{x}10^{-19}$ C
Neutron	n	$1.67\text{x}10^{-27}$ kg	0 C

Properties of Charge:

Electric charge comes in two types, positive and negative. The nuclei of atoms are positively charged, as are protons. Electrons are negatively charged. There are a few basic rules for charges:

- Like charges repel; unlike charges attract.
- Electric charge is always conserved. Charge cannot be created or destroyed.
- Electric charge is quantized. It is equal to the charge on a single electron or proton.

The SI unit of charge is the coulomb (C). The charge of a single electron is -1.60219×10^{-19}C, or, -1.0C of charge contains 6.24×10^{18} electrons. The same is true for protons if the sign of charge is made positive.

Quantization of charge: What does it mean for charge to be quantized? Charge comes in multiples of an indivisible unit of charge, represented by the letter e. In other words, charge comes in multiples of the charge on the electron or the proton. These things have the same size charge, but the sign is different. A proton has a charge of +e, while an electron has a charge of -e.

Electrons and protons are not the only things that carry charge. Other particles (positrons, for example) also carry charge in multiples of the electronic charge. Those are not going to be discussed, for the most part, in this course, however.

Putting "charge is quantized" in terms of an equation, we say:

$$q = n\,e$$

q is the symbol used to represent charge, while n is a positive or negative integer, and e is the electronic charge, $1.60 \text{ x } 10^{-19}$ Coulombs.

Conservation of Charge: The Law of conservation of charge states that the net charge of an isolated system remains constant.

If a system starts out with an equal number of positive and negative charges, there is nothing we can do to create an excess of one kind of charge in that system unless we bring in charge from outside the system (or remove some charge from the system). Likewise, if something starts out with a certain net charge, say +100 e, it will always have +100 e unless it is allowed to interact with something external to it.

Charge can be created and destroyed, but only in positive-negative pairs.

Electrostatic charging

Forces between two electrically-charged objects can be extremely large. Most things are electrically neutral; they have equal amounts of positive and negative charge. If this wasn't the case, the world we live in would be a much stranger place. We also have a lot of control over how things get charged. This is because we can choose the appropriate material to use in a given situation.

Metals are good conductors of electric charge, while plastics, wood, and rubber are not. They are called insulators. Charge does not flow nearly as easily through insulators as it does through conductors, which is why wires you plug into a wall socket are covered with a protective rubber coating. Charge flows along the wire, but not through the coating to you.

There are three ways that objects can be given a net charge. These are:

1. *Charging by friction* - this is useful for charging insulators. If you rub one material with another (say, a plastic ruler with a piece of paper towel), electrons have a tendency to be transferred from one material to the other. For example, rubbing glass with silk or saran wrap generally leaves the glass with a positive charge; rubbing PVC rod with fur generally gives the rod a negative charge.
2. *Charging by conduction* - useful for charging metals and other conductors. If a charged object touches a conductor, some charge will be transferred between the object and the conductor, charging the conductor with the same sign as the charge on the object.
3. *Charging by induction* - also useful for charging metals and other conductors. Again, a charged object is used, but this time it is only brought close to the conductor, and does not touch it. If the conductor is connected to ground (ground is basically anything neutral that can give up electrons to, or take electrons from, an object), electrons will either flow on to it or away from it. When the ground connection is removed , the conductor will have a charge opposite in sign to that of the charged object.

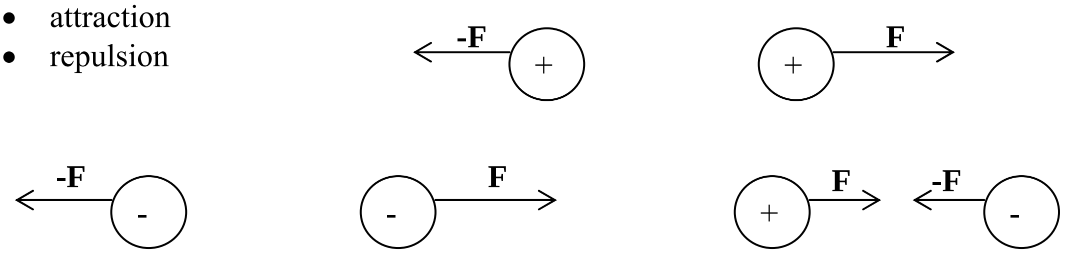
Try this at home

See if you can charge something at home using friction. I got good results by rubbing a Bic pen with a piece of paper towel. To test the charge, you can use a narrow stream of water from a faucet; if the object attracts the stream when it's brought close, you know it's charged. All you need to do is to find something to rub - try anything made out of hard plastic or rubber. You also need to find something to rub the object with - potential candidates are things like paper towel, wool, silk, and saran wrap or other plastic. (Rub your Bic pen to your hair and repeat the same experiment!)

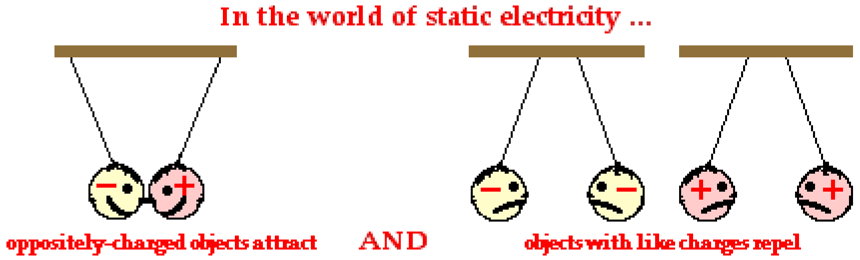
Interaction between charges

There are two different types of electric forces:

- attraction
- repulsion



Law of charges: *Like charges repel and unlike charges attract.*



Coulomb's law

In the experiments studying the properties of electrostatic it was observed that the electric force is:

- inversely proportional to the square of the separation and directed along the line joining them,

- proportional to each of the charges,
- attractive for charges of opposite sign, and repulsive for charges of the same sign.

These properties are summarized in an equation known as Coulomb's law:

$$\vec{F} = \frac{kq_1q_2}{r^2}\hat{r}$$

where

F = force of attraction or repulsion,

q_1 = magnitude of first charge,

q_2 = magnitude of second charge,

r = distance between charges.

The k is a proportionality constant with a value of $k = \frac{1}{4\pi\varepsilon_o}$ = $8.99\text{x}10^9$ $\text{N.m}^2/\text{C}^2$.

The quantity ε_o, called the permittivity constant, is $\varepsilon_o = 8.88\text{x}10^{-12}$ $\text{C}^2/\text{N.m}^2$

Notice that Coulomb's law is the same as Newton's law of universal gravitation.

Gravitational Constant

$$\vec{F} = \frac{Gm_1m_2}{r^2}\hat{r}$$

G ⇔k

m_1 ⇔q_1

m_2 ⇔q_2

Two above laws differ in that gravitational forces are always attractive but electrostatic forces may be either attractive or repulsive. This difference arises from the fact that, although there is only one kind of mass, there are two kinds of charge.

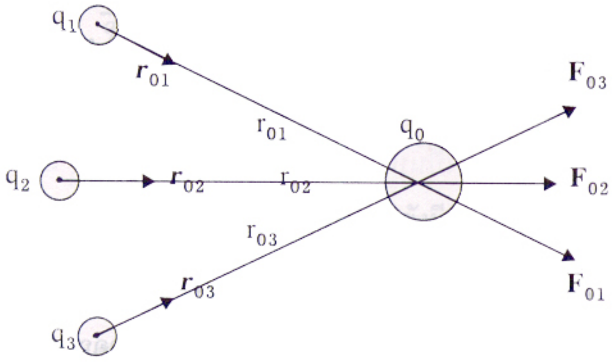
Notice:

1) Electric force is stronger than gravity.

2) Unlike gravity, there is attraction and repulsion.

N charged particles

If we have *n* charged particles, they interact independently in pairs, and the force on any one of them, let us say particle q_0, is given by the vector sum



$$\vec{F}_0 = \vec{F}_{01} + \vec{F}_{02} + \ldots + \vec{F}_{0n} = \sum_{i=1}^{n} \vec{F}_{0i}$$

$$= \frac{1}{4\pi\varepsilon_0}\sum_{i=1}^{n}\frac{q_0q_i\hat{r}_{0i}}{r_{0i}^{\;2}}$$

Where $\vec{F}_{0i}$ is the force acting on particle q_0 by q_1 and $\hat{r}_{0i}$ is a unit vector of r_{0i} with a direction from q_i to q_0

Example 1:

Find the electric force that a proton exerts on an electron in a hydrogen atom. Compare the result with the gravitational force between the two.

Hints:

$$m_1 = 9.1\text{x}10^{-31}\text{kg}\ ;\ m_2 = 1.67\text{x}10^{-27}\text{kg};\ G = 6.67\text{x}10^{-11}\frac{\text{N}\cdot\text{m}^2}{\text{kg}^2}$$

$$q_1 = -1.6\text{x}10^{-19}\text{C};\quad q_2 = +1.6\text{x}10^{-19}\text{C};\quad r = 0.052\text{nm}$$

Solution:

Using Coulomb's Rule, $\vec{F}_e = k\dfrac{q_1q_2}{r^2}\hat{r}$

$$F_e = (9.00\text{x}10^9)\frac{(1.6\text{x}10^{-19}\text{C})^2}{(0.052\text{x}10^{-9}\text{m})^2} = \underline{\underline{8.5\text{x}10^{-8}\text{N}}}$$

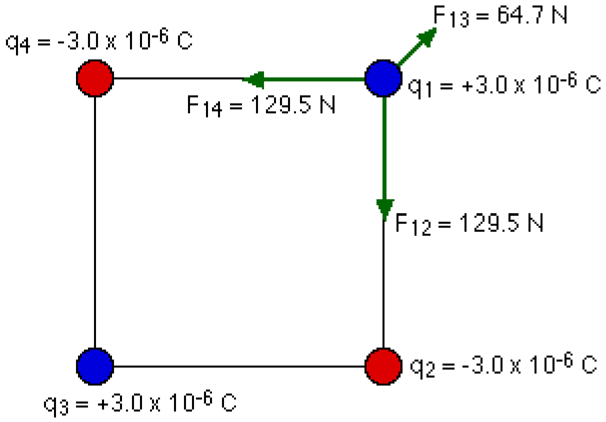
Using the Law of Universal Gravitation, $\vec{F}_g = G\dfrac{m_1m_2}{r^2}\hat{r}$

$$F_g = (6.67\text{x}10^{-11})\frac{(9.1\text{x}10^{-31})(1.67\text{x}10^{-27})}{(0.052\text{x}10^{-9})^2} = \underline{\underline{3.7\text{x}10^{-47}\text{N}}}$$

The ratio is a staggering $\dfrac{F_e}{F_g} = 2.3\text{x}10^{39}$ which is why electric wires work when they run uphill!

Example 2

Four charges are arranged in a square with sides of length 2.5 cm. The two charges in the top right and bottom left corners are +3.0 x 10^{-6} C. The charges in the other two corners are -3.0 x 10^{-6} C. What is the net force exerted on the charge in the top right corner by the other three charges?



To solve any problem like this, the simplest thing to do is to draw a good diagram showing the forces acting on the charge. You should also let your diagram handle your signs for you. Force is a vector, and any time you have a minus sign associated with a vector all it does is tell you about the direction of the vector. If you have the arrows giving you the direction on your diagram, you can just drop any signs that come out of the equation for Coulomb's law.

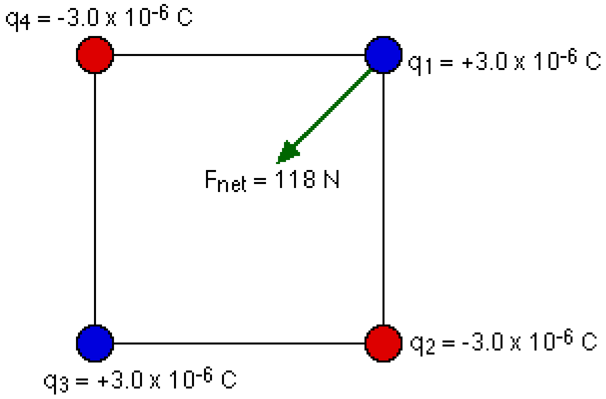
Consider the forces exerted on the charge in the top right by the other three:

from charge 2 : $F_{12} = k\, q_1\, q_2 / r^2 = (8.99 \times 10^9)(+3.0 \times 10^{-6})(-3.0 \times 10^{-6}) / (0.025)^2$
$= -129.5$ N $= +129.5$ N in the direction shown on the diagram

from charge 3 : (note that $r = 0.03536$ m)
$F_{13} = k\, q_1\, q_3 / r^2 = (8.99 \times 10^9)(+3.0 \times 10^{-6})(+3.0 \times 10^{-6}) / (0.03536)^2$
$= +64.7$ N $= +64.7$ N in the direction shown on the diagram

from charge 4 : $F_{14} = F_{12} = +129.5$ N in the direction shown on the diagram

You have to be very careful to add these forces as vectors to get the net force. In this problem we can take advantage of the symmetry, and combine the forces from charges 2 and 4 into a force along the diagonal (opposite to the force from charge 3) of magnitude 183.1 N. When this is combined with the 64.7 N force in the opposite direction, the result is a net force of 118 N pointing along the diagonal of the square.



The symmetry here makes things a little easier. If it wasn't so symmetric, all you'd have to do is split the vectors up in to x and y components, add them to find the x and y components of the net force, and then calculate the magnitude and direction of the net force from the components.