

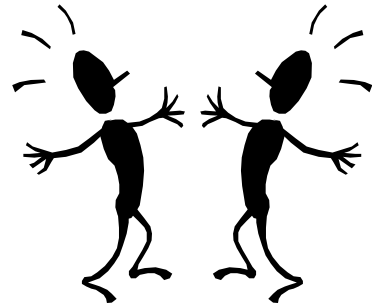
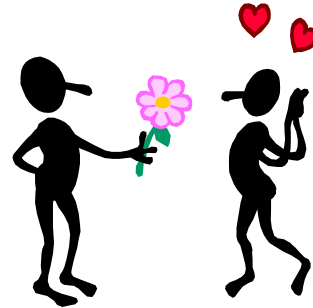
Advanced Higher Physics Electrical Phenomena Unit

Electric Fields

The idea of a field should be familiar to you. A gravitational field and an electric field are two examples of the same type of phenomena. In an electric field a charged particle will experience a force in the same way as a mass experiences a force in a gravitational field.



There is one major difference however. There is only one type of mass but two types of charge. Gravitational force is always attractive whereas, depending on the charges involved, electrostatic forces can be attractive or repulsive.



The relationship to determine the magnitude of the electrostatic force is similar to that for gravity.

Coulomb's inverse square law

$$F = \frac{q_1 q_2}{4\pi\epsilon_0 r^2}$$

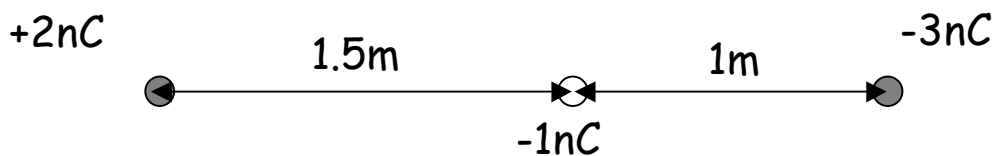
q_1 and q_2 are the magnitudes of the charges (coulombs)
 ϵ_0 is the permittivity of free space = 8.85×10^{-12} F/m

If you put the signs of the charges into the equation any positive answer represents a repulsive force and any negative an attractive force.

You will be expected to be able to determine the force acting on a charge due to the influence of one or more other charges.

The electric field produced by one charge will exert a force on any other charged particles within the field.

Example find the resultant force acting on the -1nC charge



Force due to $+2\text{nC}$:

$$F = \frac{+2 \times 10^{-9} \times -1 \times 10^{-9}}{4\pi\epsilon_0 1.5^2} \quad 4\pi\epsilon_0 \approx 9 \times 10^9$$

$$F = -9 \times 10^{-9} \text{ N} \quad \text{force acts to the left}$$

Force due to -3nC :

$$F = \frac{-3 \times 10^{-9} \times -1 \times 10^{-9}}{4\pi\epsilon_0 1^2} \quad 4\pi\epsilon_0 \approx 9 \times 10^9$$

$$F = +27 \times 10^{-9} \text{ N}$$

force acts to the left

Resultant force = $9 + 27 = 36 \times 10^{-9} \text{ N}$ to the left.

Electric field strength E

The electric field strength at any point is the force acting per unit charge on any charge at that point. Electric field strength has the unit N/C.

The electric field strength due to a point charge can be calculated using the expression

$$E = \frac{q}{4\pi\epsilon_0 r^2}$$

Where q is the magnitude of the point charge
 r is the distance from the point charge.

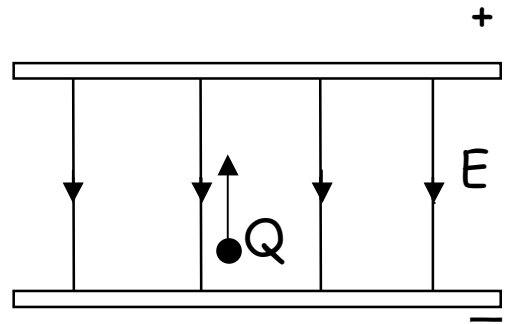
The direction of the electric field is taken as the direction in which a positive test charge would move.

Derivation of potential difference V

Potential difference and a uniform electric field

The potential difference between two points is the work done in moving one coulomb of charge from one point to the other against the electric field, i.e. from the lower plate to the upper plate.

The minimum force needed to move Q coulombs from the lower plate to the upper plate is QE .



$$\text{Work done} = F \times d = QE \times d$$

From Higher work done and potential difference is defined as

$$\text{Work done} = Q \times V$$

Equating gives

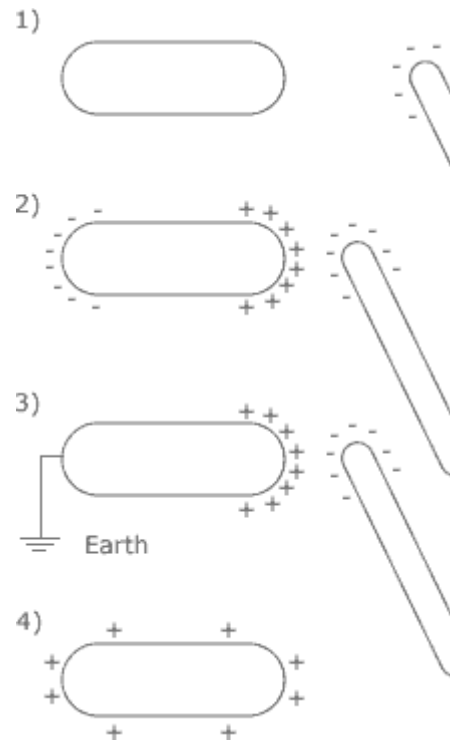
$$QV = QEd$$

$$V = Ed$$

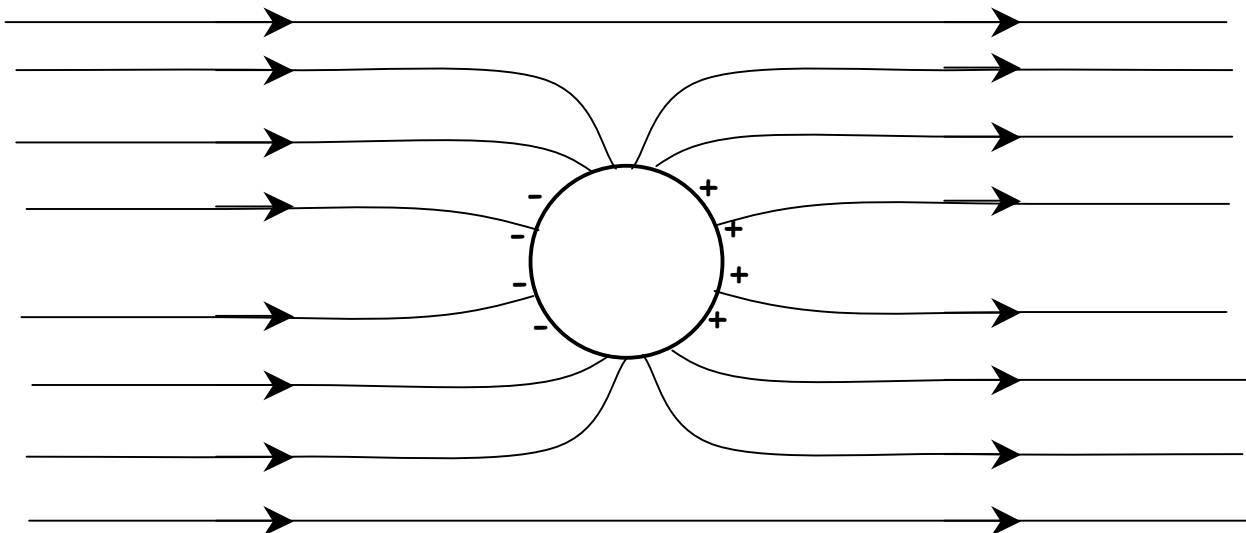
Charging by Induction

1. Bring charged rod towards uncharged conductor.
2. Charged rod causes charges within conductor to redistribute.
3. Earthing conductor allows electrons to leave (as in this case) or enter conductor.
4. Earth connection then charged rod is removed leaving conductor charged.

The conductor always takes the opposite charge to that on the charged rod.



Conductor in an electric field.



The field causes the charges within the conductor to redistribute. However the charges only reside on the surface of the conductor. The electric field strength inside the conductor is zero. This is true of any conductor, the electric field inside any conductor is always zero.

Radio wrapped in foil, no signal, since no electric field can exist inside foil.

A car is the safest place to be in a thunderstorm. If the car is struck by lightning all the charge resides on the outside of the car body.



Electrostatic Potential

The electrostatic potential at a point is similar to gravitational potential in that the electrostatic potential is the work done in bringing unit positive charge from infinity to that point.

$$V = \frac{q}{4\pi\epsilon_0 r}$$

Electric field and potential for charged spheres

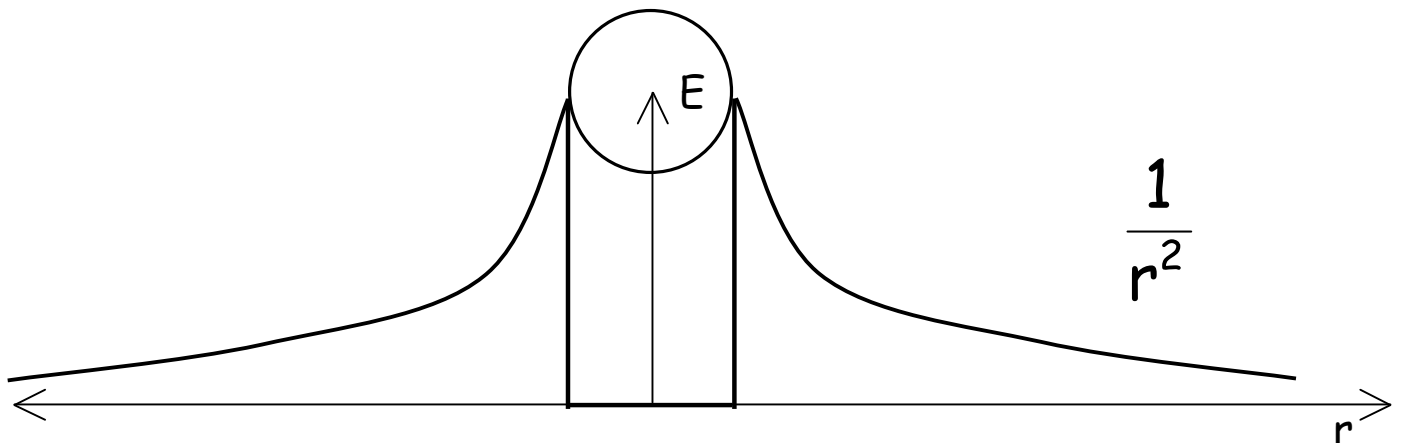
Consider a sphere of radius r with charge q .

The electric field strength at the surface of the sphere will be

$$E = \frac{q}{4\pi\epsilon_0 r^2}$$

this is because the field strength is calculated as if the charge were a point charge of q at the centre of the sphere.

Inside the sphere (solid or hollow) the field strength is zero. Outside the sphere the field strength reduces [inversely proportional to r^2]



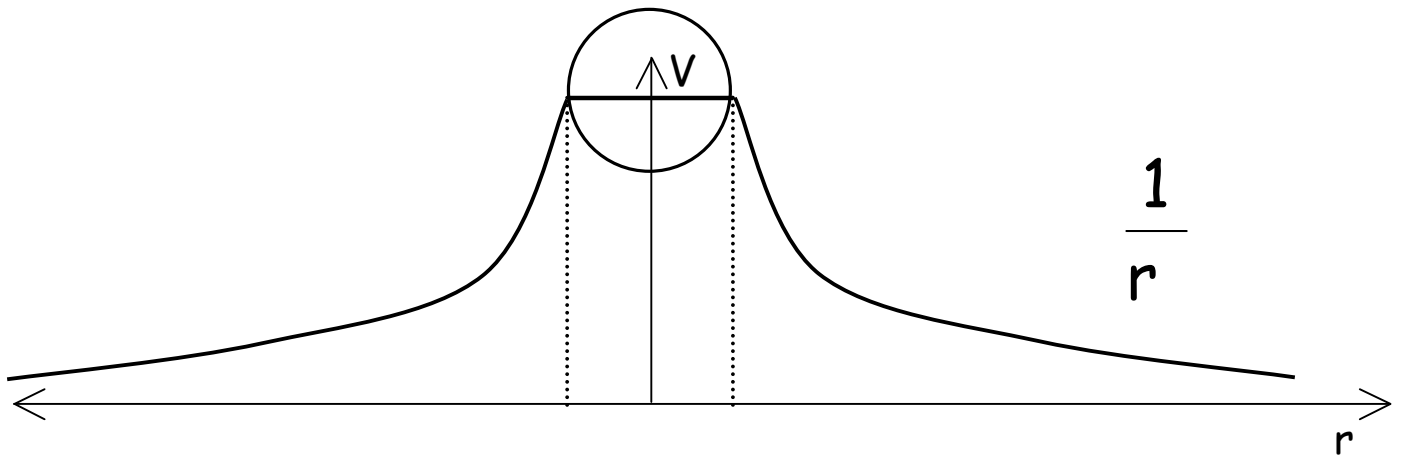
The electrostatic potential at the surface of the sphere will be

$$V = \frac{q}{4\pi\epsilon_0 r}$$

this is because the electrostatic potential is again calculated as if the charge were a point charge of q at the centre of the sphere.

Inside the sphere (solid or hollow) the electrostatic potential is constant at the same value as the surface. Since the field strength is zero inside the sphere no

work has to be done against the field to move the charge anywhere. Outside the sphere the field strength reduces [inversely proportional to r]



Charges in a uniform field

When a charged particle moves in a uniform electric field one of two scenarios will arise.

1. Movement along the field lines.

The particle will accelerate due to an unbalanced force

$$F = qE$$

The particle will gain E_k equal to the work done by the field.

$$\frac{mv^2}{2} = qEd$$
$$v = \sqrt{\frac{2qEd}{m}}$$

There is a limit, however to the magnitude of velocity possible. When $v \approx 10\%$ of speed of light relativistic effects must be taken into account.

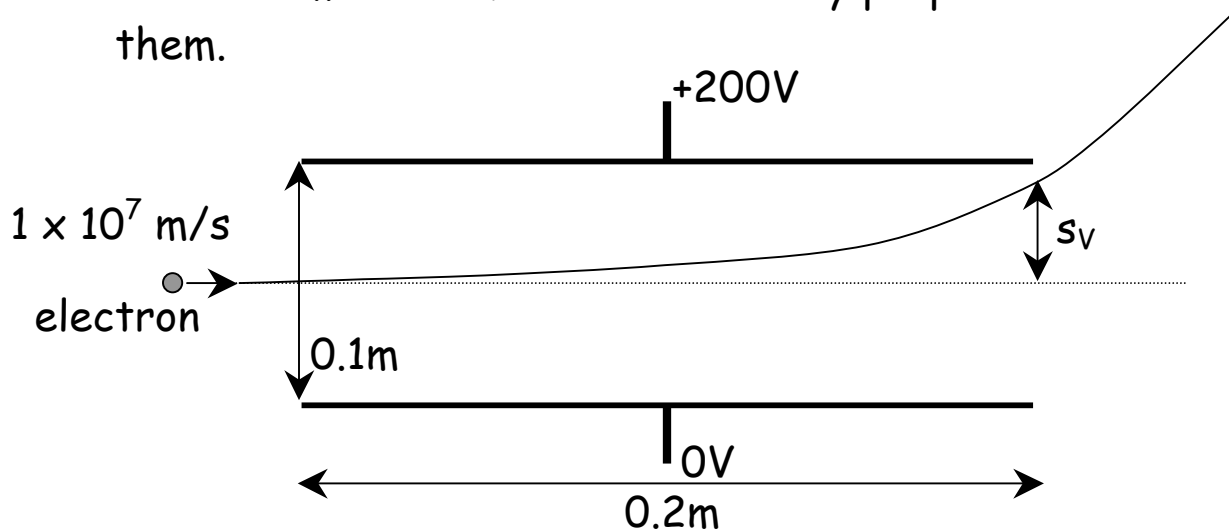
This type of situation is what happens to electrons as they are accelerated through a potential difference such as in a cathode ray tube.

2. Movement perpendicular to field lines.

In this situation we can treat the movement of the charged particle as a projectile where the acceleration is due to the electric rather than gravitational field.

$$a = \frac{F}{m} = \frac{Eq}{m}$$

The particle will accelerate in the direction of the field lines and move with constant velocity perpendicular to them.



Example:

An electron with initial horizontal velocity of $1 \times 10^7 \text{ m/s}$ is fired into a set of parallel plates as shown.

Calculate the vertical displacement of the electron just as it leaves the plates.

$$E = \frac{V}{d} = \frac{200}{0.2} = 1 \times 10^3 \text{ N/C}$$

$$a = \frac{Eq}{m} = \frac{1 \times 10^3 \times 1.6 \times 10^{-19}}{9.11 \times 10^{-31}} = 1.8 \times 10^{14} \text{ m/s}^2$$

time in field

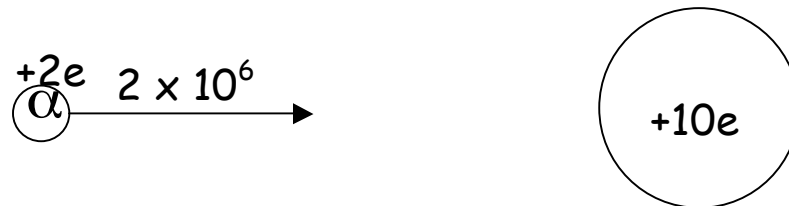
$$t = \frac{d}{v_H} = \frac{0.2}{1 \times 10^7} = 2 \times 10^{-8} \text{ s}$$

$$s_v = \frac{1}{2}at^2 = \frac{1}{2} \times 1.8 \times 10^{14} \times (2 \times 10^{-8})^2$$

$$= 36 \times 10^{-3} \text{ m} = 0.036 \text{ m}$$

Head on collisions between charged particles and nucleus.
[Rutherford's Experiment.]

To find distance of closest approach.



Have to consider energy.

The energy of the alpha will change from initial E_k to zero when velocity is zero at closest approach.

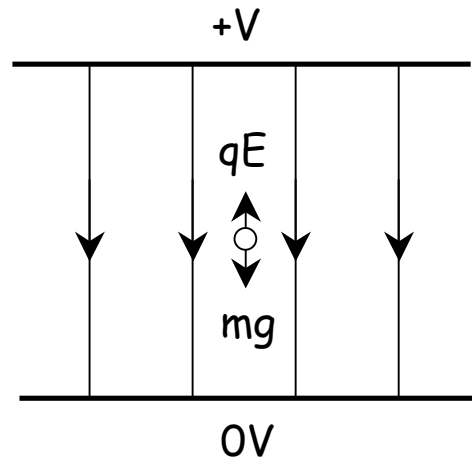
The energy will be converted to electrostatic potential V .

$$\begin{aligned}
 \text{Loss of } E_k &= \text{gain in electrostatic potential} \\
 \frac{mv^2}{2} &= \frac{Qq}{4\pi\epsilon_0 r} \\
 \frac{6.7 \times 10^{-27} \times (2 \times 10^6)^2}{2} &= \frac{(9 \times 10^9) 1.6 \times 10^{-18} \times 3.2 \times 10^{-19}}{r} \\
 1.34 \times 10^{-14} &= \frac{4.608 \times 10^{-27}}{r} \\
 r &= \frac{4.608 \times 10^{-27}}{1.34 \times 10^{-14}} \\
 r &= 3.43 \times 10^{-13} \text{ m}
 \end{aligned}$$

This distance is approx 10 times the nuclear diameter.

Millikan's Experiment.

The charge on the electron was measured by Millikan in an ingenious experiment. The method involved accurate measurements on charged oil drops moving between two parallel metal plates.



When the oil drop was stationary the forces acting on it must be balanced.

$$qE = mg \quad \text{but } E = \frac{V}{d}$$

$$\text{so } q = \frac{mgd}{V}$$

By repeating the experiment many hundreds of times Milliken and his associates discovered that the value obtained for q was 'always' a whole number multiple of a basic quantity of charge.

$$q = n \times 1.6 \times 10^{-19} \text{C} \quad n = \pm 1, \pm 2, \pm 3, \dots$$

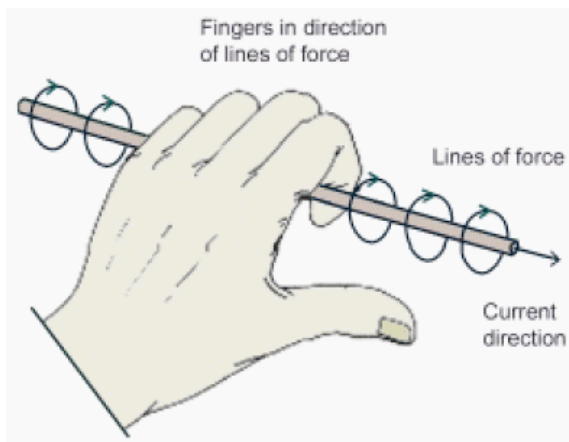
This led to the theory of quantisation of charge where all charges are a whole number multiple of $1.6 \times 10^{-19} \text{C}$.

Electromagnetism

A stationary electric charge generates an electric field around itself. A moving electric charge generates an electric field and a magnetic field around itself.

If a charge moves across a magnetic field it will experience a force.

This is because the magnetic fields interact.



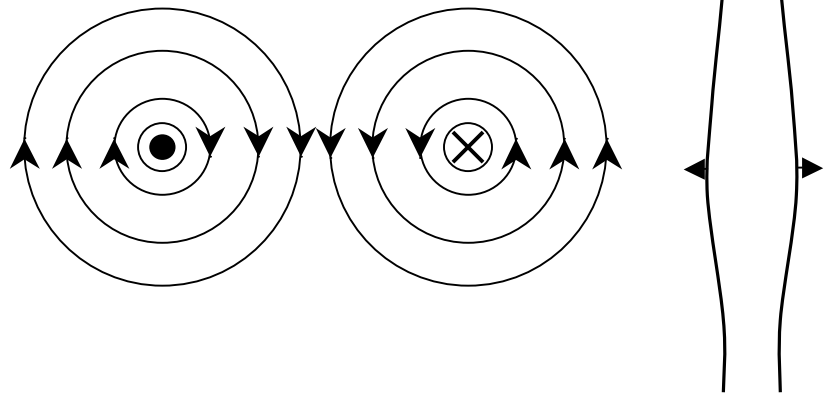
A current carrying wire will generate a magnetic field since the current consists of moving charges. The shape of the field around the wire is a series of concentric circles as shown. [Left hand rule]

If two current carrying conductors are next to each other the magnetic field from one conductor will interact with the field from the other. This will generate a force acting between the conductors.

To determine whether this is an attractive or repulsive force we need to examine the field line pattern produced by the individual conductors.

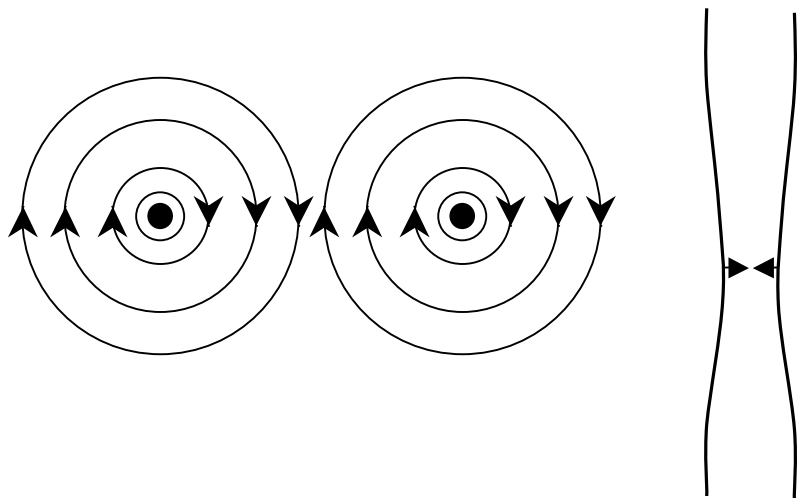
Currents in opposite directions.

The field lines between the conductors are in the same direction. This will cause the conductors to move apart.



Currents in the same direction.

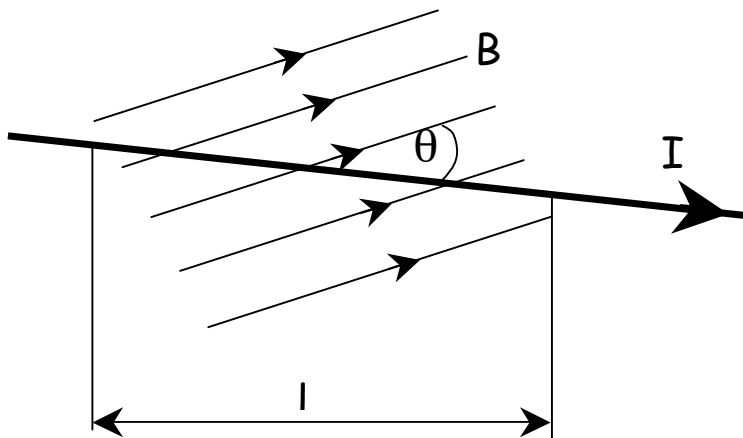
The field lines between the conductors are in opposite directions. This will cause the conductors to move together.



Magnetic Induction

The magnitude of the magnetic field is called the magnetic induction. Magnetic induction is measured in the unit the Tesla (T)

The Tesla is defined as the magnetic induction that will induce a force of 1 newton per metre in a conductor carrying a current of 1 ampere perpendicular to the field.



It is possible to calculate the force acting on a current carrying wire in a magnetic field using the relationship $F = BIl\sin\theta$. θ is the angle between the

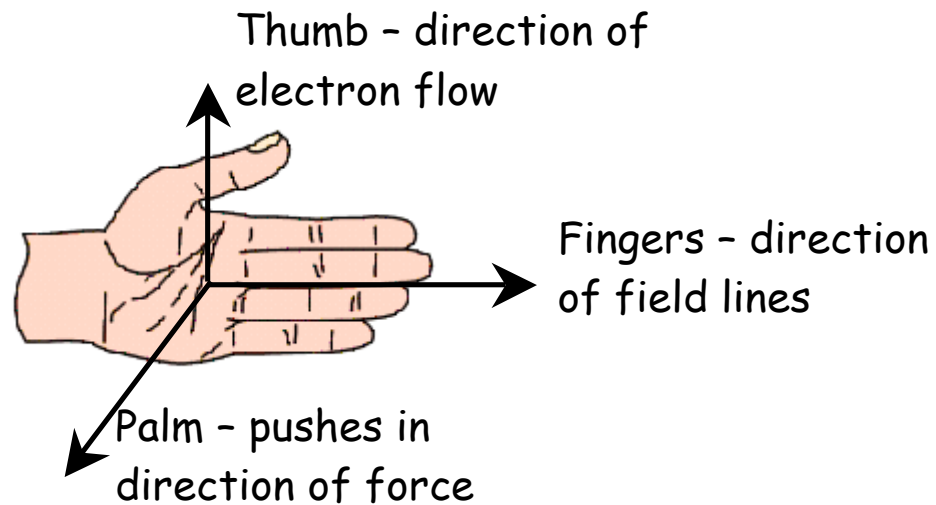
field lines and the direction of the current.

The force is a maximum when $\theta = 90^\circ$, the current perpendicular to the field.

The force is zero when $\theta = 0^\circ$, the current parallel to the field.

How to determine the direction of force on a current carrying conductor in a magnetic field.

This method, known as the Left Hand Rule works for electron current.



Magnetic induction due to an 'infinite' straight conductor

An 'infinite' straight conductor is one greater than 2m in length. The magnetic induction, B , a distance r from the conductor is

$$B = \frac{\mu_0 I}{4\pi r}$$

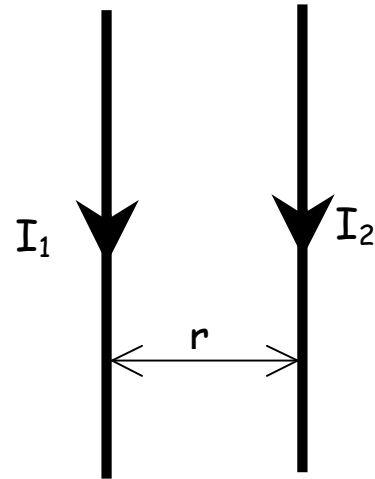
where μ_0 is the permeability of free space

$$\mu_0 = 4\pi \times 10^{-7} \text{ H/m}$$

Force between two parallel current carrying wires

Two wires carrying currents I_1 and I_2 respectively are separated by a distance r .

To calculate the force acting on the wires we consider the effect that the magnetic induction from one wire has on the current carrying other wire.



The magnetic induction due to wire 1 at the position of wire 2 is

$$B = \frac{\mu_0 I_1}{4\pi r}$$

The force acting on wire 2 due to this induction is

$$F = BI_2 l$$

Combining these two expressions we obtain

$$F = \frac{\mu_0 I_1 I_2 l}{4\pi r}$$

$$\frac{F}{l} = \frac{\mu_0 I_1 I_2}{4\pi r}$$

Giving an expression for force per unit length.

Motion in a Magnetic Field

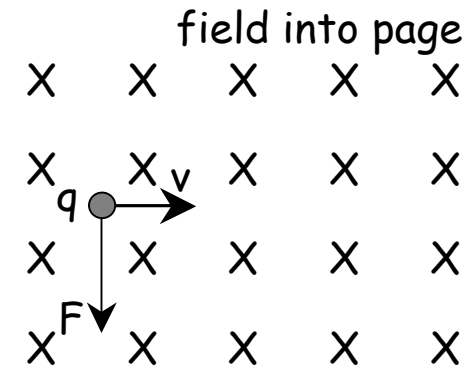
We have seen how to derive an expression to determine the force per unit length acting on a conductor in a magnetic field. Now we need to determine the force acting on a charged particle moving in a magnetic field.

Consider first a particle moving perpendicular to the field.

Any moving charge will constitute a current. The magnitude of the current can be written as

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

So using an expression from previously



$$F = BIl$$

$$F = B \frac{q}{t} l = Bq \frac{l}{t} = Bqv$$

If the particle is not moving perpendicular to the field then, as with the current carrying conductor, the angle between the velocity vector and the field lines must be taken into account.

$$F = Bqv \sin \theta$$

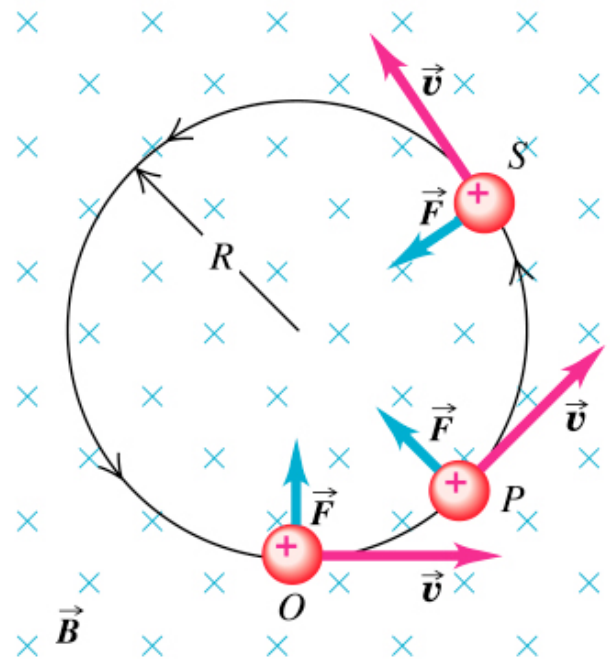
The Left Hand rule can be used to determine the direction of the force acting on a negatively charged particle. If the particle has a positive charge the force acts in the opposite direction.

Because the force is always acting perpendicular to the velocity vector we effectively have a radial force. This will cause the particle to move in a circular orbit.

If the particle is only moving perpendicular to the field lines then the orbit will be a circle of radius r .

$$\frac{mv^2}{r} = Bqv$$

$$r = \frac{mv}{Bq}$$

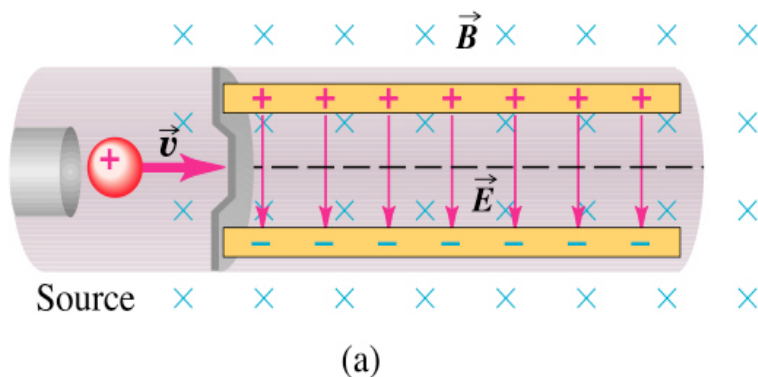
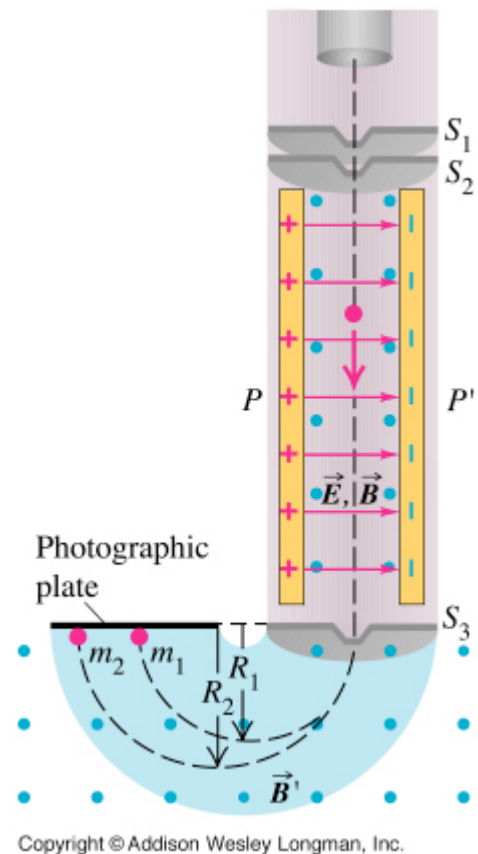


(a)

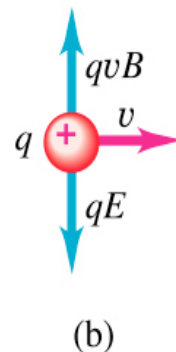
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This relationship is fundamental in the principles of working of the mass spectrometer. If the particles have the same speed then individual masses will have distinct radii of curvature.

The speed of the particles can be selected in the first part of the apparatus. Magnetic and electric fields are set up at the linear part of the spectrometer such that a particle will pass through undeflected. The forces acting on the particle are balanced.



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$$qvB = qE$$

$$v = \frac{E}{B}$$

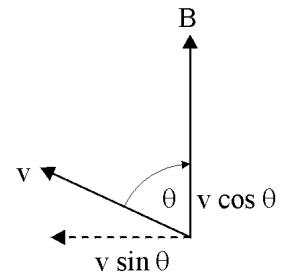
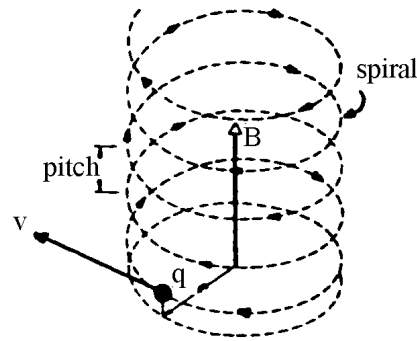
Helical Path.

If the charged particle does not enter the magnetic field at right angles then it will follow a helical path.

We can think of the velocity vector in terms of two components:

Parallel to field lines - no deflection since no force acts on particle.

Perpendicular to field lines - radial force circular path followed.

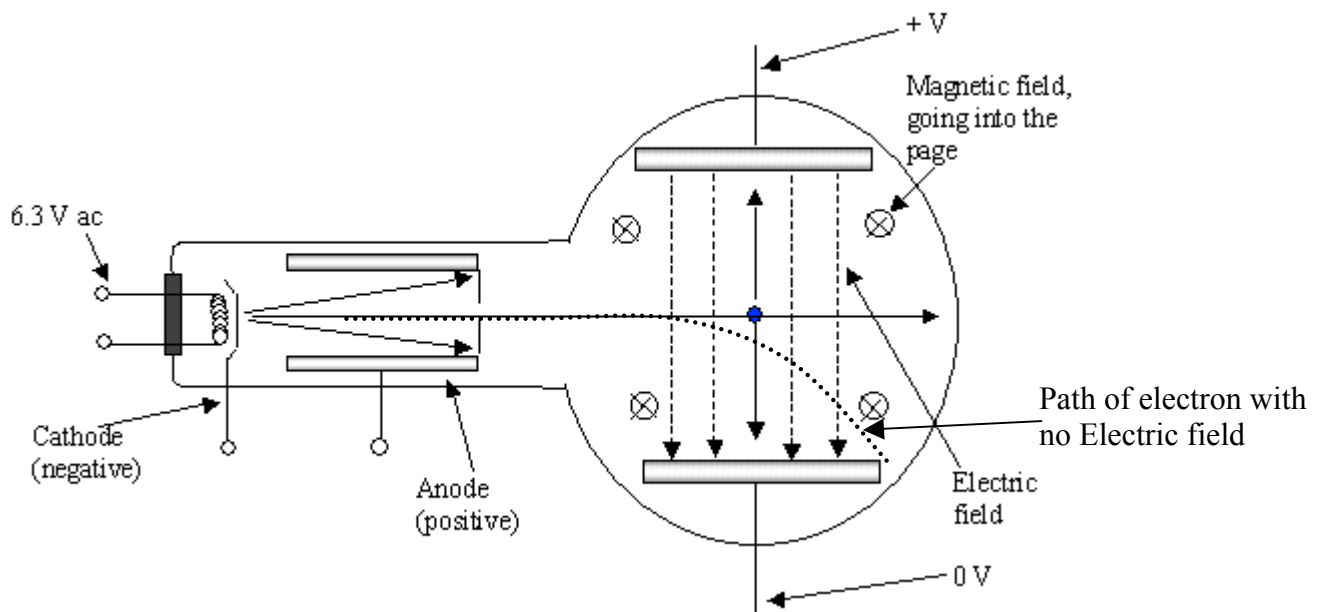


The pitch of the helix can be calculated:

$$\text{pitch} = v_{\parallel} \times T$$

Charge to mass ratio for an electron

This experiment was conducted first by JJ Thomson.



A beam of electrons is passed through a region where there are both magnetic and electric fields. The strength of the fields is adjusted to allow the beam to pass undeflected.

$$v = \frac{E}{B}$$

The electric field is now removed and the radius of curvature of the electron beam is measured.

$$\frac{mv^2}{r} = Bqv$$

$$v = \frac{Bqr}{m}$$

equating these relationships gives

$$\frac{Bqr}{m} = \frac{E}{B}$$

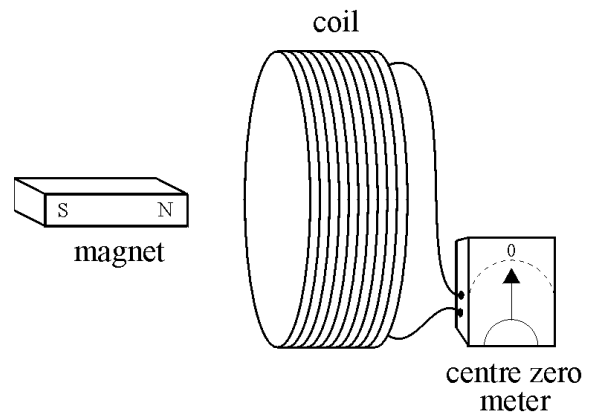
$$\frac{q}{m} = \frac{E}{B^2 r}$$

Now the ratio of charge to mass can be determined.

Self-Inductance

An inductor is a coil of wire which can carry an electrical current.

You may remember from experiments you did at Standard Grade that when a magnet is moved in and out of a coil of wire a reading is observed on the meter. This is known as an induced e.m.f.

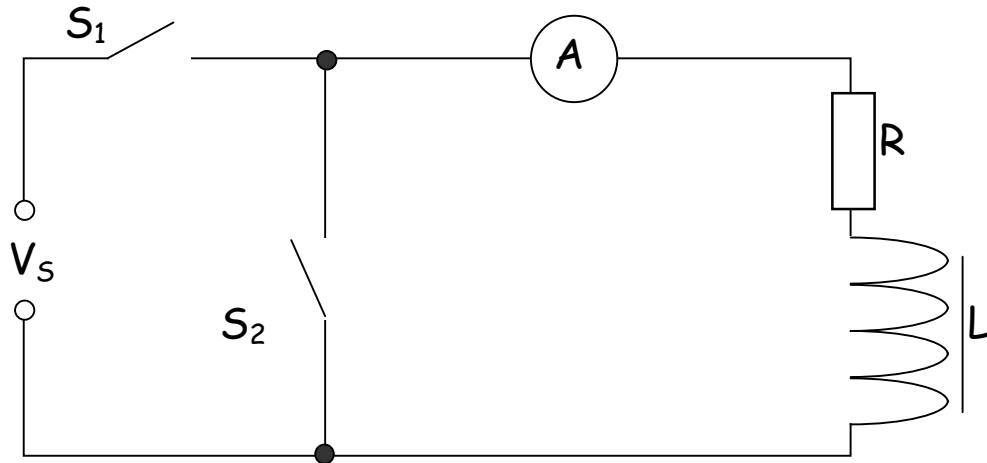


When a current flowing in a coil changes, the coil will generate a varying magnetic field. This varying magnetic field will cause an e.m.f. to be generated in the coil. We will investigate how this leads to the quantity known as the self inductance of a coil.

The direction of the induced e.m.f. is always in the direction so as to oppose the change. If the induced e.m.f. was not opposing the change then the magnetic field would get larger, giving rise to a greater induced e.m.f., making a larger magnetic field

We would be getting energy from nothing, which seems like a good idea but unfortunately contradicts the laws of physics.

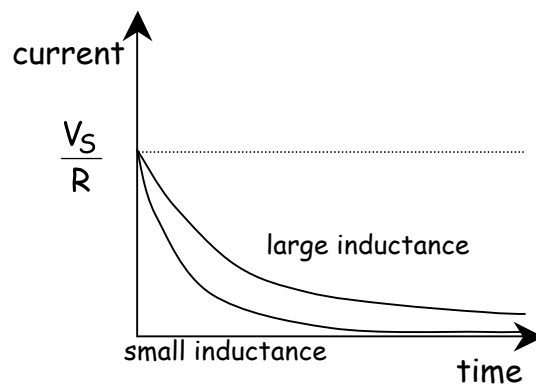
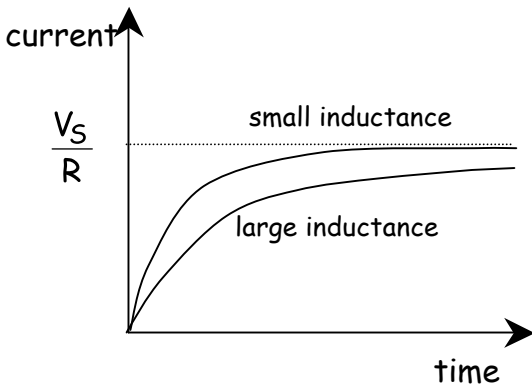
We can investigate the properties of a circuit containing an inductor using the circuit shown below.



Closing S_1 will allow the current growth to be investigated.

Closing S_2 will allow the current decay to be investigated.

Growth and decay graphs are shown below.



The self-inductance of a coil can be determined using the relationship

$$e = -\frac{dI}{dt}L \quad \text{where} \quad e = \text{e.m.f. V}$$

$$\frac{dI}{dt} = \text{rate of change of current A/s}$$

$$L = \text{self inductance. H}$$

The unit of self-inductance is the henry (H). The inductance of an inductor is one henry if an e.m.f. of one volt is induced when the current changes at a rate of one ampere per second.

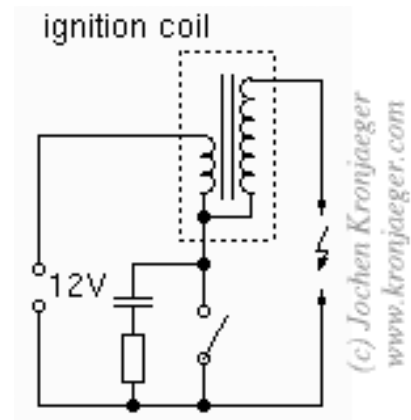
As the current in a coil builds up the energy required to build the current to its steady value is stored in the magnetic field of the coil.

This energy can be released, making the inductor a source of e.m.f.

A practical example of this is a starter coil in a car ignition system. When the switch is opened, the field collapses in a very short time, giving rise to a large e.m.f. which is generated across the spark plug in the cylinder.

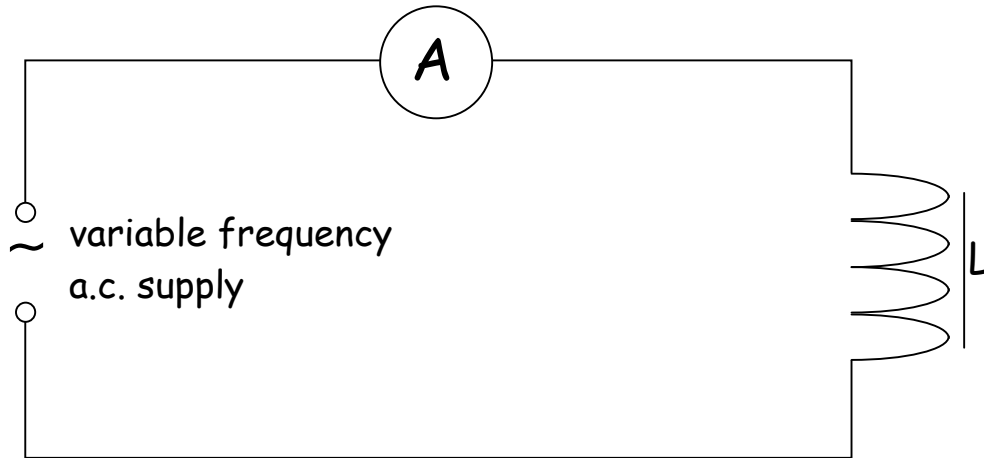
The energy stored in an inductor can be calculated using the relationship

$$E = \frac{1}{2}LI^2$$

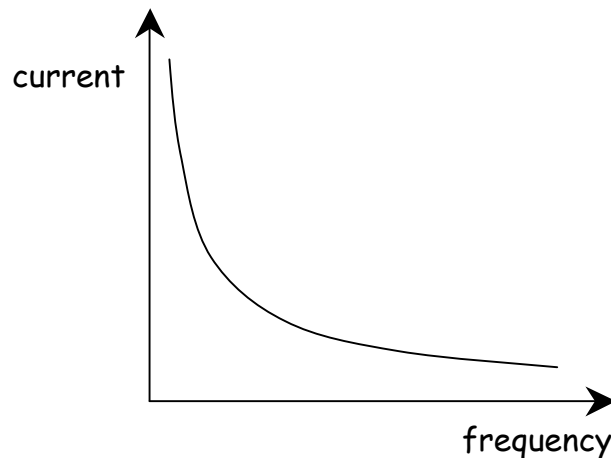


Current and frequency in an inductive circuit.

The circuit below can be used to investigate the relationship between the current flowing in a circuit containing an inductor and the frequency of the supply.



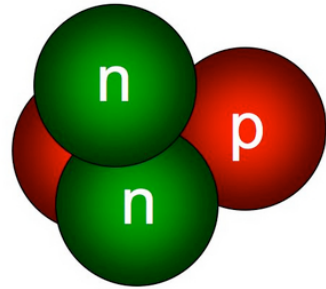
An inductor acts as a block to high frequencies. The greater the frequency the lower the current flowing in an inductive circuit.



This is opposite to capacitive circuits where the current increases with the frequency of the supply.

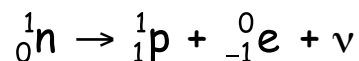
Forces of Nature

Consider a helium nucleus, consisting of two protons and two neutrons. The electrostatic repulsion between the protons should cause the nucleus to fly apart. This obviously does not occur since we are made of atoms and appear to be stable. [most of the time!]



Nuclear particles are held in place by a force known as the Strong Force. This is a very short range force acting only within nuclear dimensions $< 10^{-14}\text{m}$.

There is another nuclear force known as the Weak Force. This force is associated with beta decay.

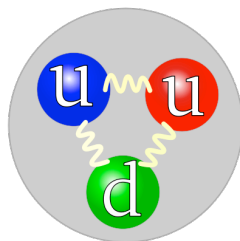


Elementary Particles

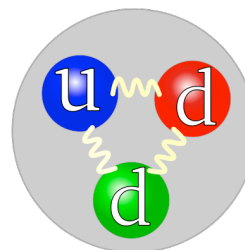
| | | | | |
|---------|---------------------------------|-------------------------------|-------------------------------|--------------------|
| Quarks | u up | c charm | t top | γ photon |
| | d down | s strange | b bottom | g gluon |
| Leptons | ν_e electron neutrino | ν_μ muon neutrino | ν_τ tau neutrino | Z Z boson |
| | e electron | μ muon | τ tau | W W boson |
| | I | II | III | |

Three Families of Matter

There are now hundreds of particles that have been discovered. Protons and neutrons are particles which belong to the group known as hadrons - particles made up of quarks. The proton and neutron are actually baryons, a sub-group of the hadrons. The electron is a lepton which at this time is thought to be structureless.



proton = $u+u+d$



neutron = $u+d+d$