CfE
Advanced Higher

Physics Department

Advanced Higher Physics

Unit 3 Electromagnetism

Topic 1 – Fields

Useful Websites

www.scholar.hw.ac.uk

http://hyperphysics.phy-astr.gsu.edu/hbase/hframe.html

1 Fields	
Content	**Notes**
a) Electric fields and Coulomb's Law	An electric field is the space that surrounds electrically charged particles and in which a force is exerted on other electrically charged particles. Electric field as the force per Unit positive charge. Coulomb's Inverse Square Law for interacting point charges. Electric potential and electric field strength around a point charge and system of charges. Potential difference and electric field strength for a uniform electric field. Investigate the motion of charged particles in uniform electric fields. The electronvolt is the energy acquired when one electron accelerates through a potential difference of one volt. It is a unit commonly used in high energy particle physics.
b) Magnetic Fields and Magnetic Induction	Magnetic effects arise when electric charges are in motion. An electric current consists of moving electric charges and so produces magnetic effects. Also, electrons are in motion around atomic nuclei and individually produce a magnetic effect. Iron, nickel, cobalt and some rare earths exhibit a magnetic effect called ferromagnetism, in which magnetic dipoles can be made to line up, resulting in the material becoming magnetised. Magnetic field patterns around permanent magnets and electromagnets, including a straight wire and a coil. Magnetic induction at a point is the strength of a magnetic field at the point. Investigate the magnitude of the force on a current carrying conductor in a magnetic field. Investigate the magnetic induction at a distance from a long current carrying wire. Comparing gravitational, electrostatic, magnetic and nuclear forces.

Electric Fields – Reminder From Higher Physics Course Work

Electric field lines are (imaginary) lines emanating from point charges. These lines represent the force acting on any charge in the vicinity of the point charge.

Direction:
Direction of the field lines tells which way a **POSITIVE** charge would go (i.e. from positive to negative)

Size:
Size of the force is represented by the density of the lines.
More lines mean a stronger force.

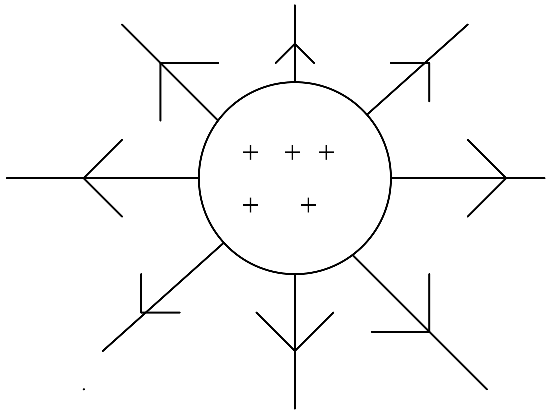
Lines:
Lines never cross
Lines leave the conductors at right angles to the surface.
The closer together the lines, the stronger the electric field.

Please remember

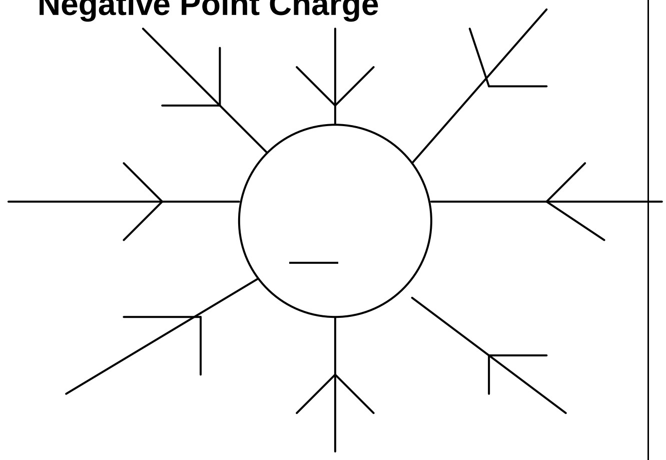
- Every charged body sets up an electric field around itself
- If a second charged body is brought into the field then it experiences a force, whose size depends on the electric field strength
- An electric field is a place where a charge will experience a force

Some Electric Fields

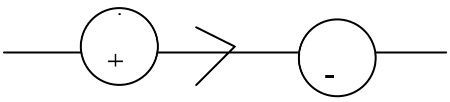
Sphere



Negative Point Charge

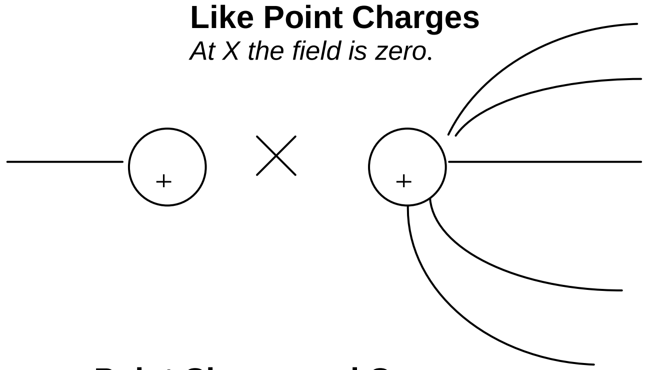


Unlike Point Charges



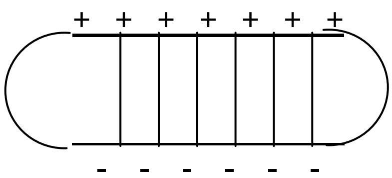
Like Point Charges

At X the field is zero.

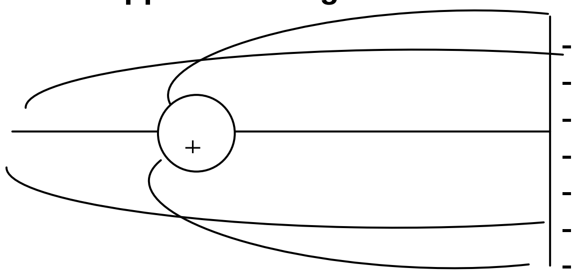


Two Parallel Plates

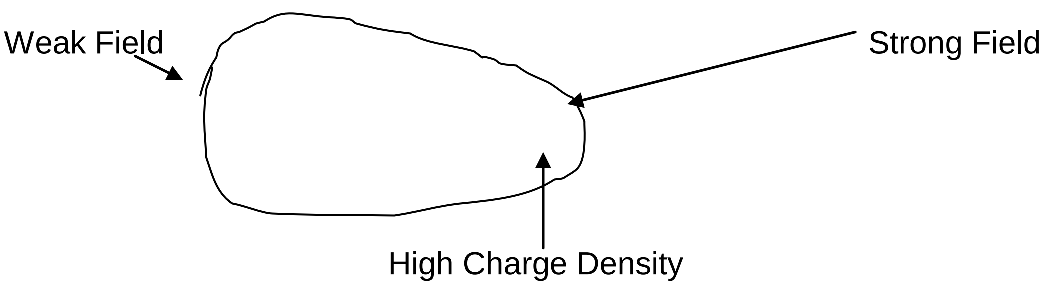
There is a field in the central region between the plates.



Point Charge and One Parallel Plate of the Opposite Charge



Charged Irregular Shaped Object



Electric Field Strength

Electric field strength at a point is defined as the force experienced by a unit **positive** charge in **that** field at **that** point

Coulomb's Law

This law is stated as follows :
The force between two point charges is directly proportional to the product of the charges divided by the square of their distances apart.

Mathematically Coulomb's Law is stated as :

$$\boldsymbol{F \propto \frac{Q_1 Q_2}{r^2}}$$

where
F is the electric or Coulomb force (N)
Q_1 and Q_2 are the charges on two point charges (C)
r is the distance between the two point charges (m) (NB r^2 is m^2)

and......

$$\boldsymbol{F = \frac{Q_1 Q_2}{4\pi\varepsilon_0 r^2}}$$

where
$\boldsymbol{\varepsilon_0}$('Epsilon Nought') is the permittivity of free space
$\boldsymbol{\varepsilon_0}$ equals 8.85 x 10^{-12} Fm^{-1}
1 / $\boldsymbol{4\pi\varepsilon_0}$is the constant of proportionality

Please remember

- This law applies to **point** charges.
- Subatomic particles e.g. electrons and protons can be approximated as point charges.
- **Isolated** uniformly charged conducting spheres behave as if all the charge was concentrated at the centre.
  In practice two small spheres will only approximate to point charges when they are far apart.
- The magnitude of the forces between charged spheres was first investigated quantitatively by the French scientist Coulomb in 1785

What Is Permittivity? (an aside for information)
The force between two charges depends on the distance between them and the medium between the two charges.
e.g. if the medium is an insulator then the force will be less than if the medium were a vacuum.
To take this into account a medium is said to have **PERMITTIVITY.**

General symbol of permittivity is ε

$\boldsymbol{\varepsilon_0}$ is the **permittivity of free space (vacuum).**

ε_{air} = 1.00005 $\boldsymbol{\varepsilon_0}$ therefore for most practical purposes□

ε_{air} = $\boldsymbol{\varepsilon_0}$ (except when it is humid).

Please remember:

- $1 / \boldsymbol{4\pi\varepsilon_0}$ = 8991804694 = 9×10^9 Nm^{2}C^2

- $\boldsymbol{4\pi}$ indicates spherical symmetry
- $\boldsymbol{2\pi}$ indicates cylindrical symmetry
- no $\boldsymbol{\pi}$ term indicates plane symmetry

- $\varepsilon_{\text{water}}$ = 80 ε
  values of electrostatic forces are much weaker (less) in water.
  e.g. W*ater makes the electrostatic forces between the ions of salt crystal much weaker so the ions break away from one and other to form the solution. This is why salt dissolves in water.*

End of Information

- Force is a vector quantity. Therefore if more than two charges are present then the force on any given charge is the vector sum of all the forces acting on that charge.

- The following table contains information which will be required when answering questions in this section of work.

Particle	**Symbol**	**Charge (C)**	**Mass (kg)**	**Typical Diameter of Atoms (m)**	**Typical Diameter of Nuclei (m)**
Proton	p	(e^+)1.60×10^{-19}	1.673×10^{-27}	1×10^{-10}	1×10^{-15}
Neutron	n	0	1.675×10^{-27}	to	to
Electron	e	(e^-)-1.60×10^{-19}	9.11×10^{-31}	3×10^{-10}	7×10^{-15}

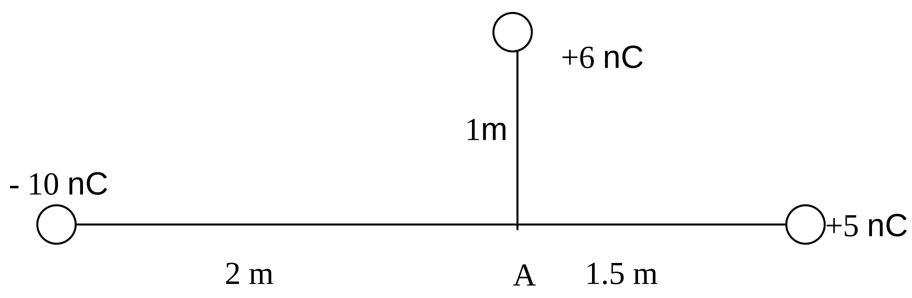
For very small distances, e.g. between nucleons, there is a strong **attractive** nuclear force.
At distances above 1×10^{-15}m the **electrostatic force** comes into play.
The electrostatic force binds atoms together.
At very large distances the **gravitational force** is dominant.

Examples

1. Calculate and compare
   (i) the gravitational attraction and
   (ii) the electrostatic attraction between a proton and an electron at a distance of 10^{-10}m.

$m_p = 1.66 \times 10^{-27}$ kg
$m_e = 9.11 \times 10^{-31}$ kg
$G = 6.67 \times 10^{-11}$ Nm^2kg^{-2}
1 unit of charge = 1.6×10^{-19}C

2. (a) State Coulomb's Inverse Square Law for the electrostatic force between two point charges.
   (b) Three fixed isolated point charges are located as shown in the diagram below.
   Determine the size and direction of the force experienced by a point charge of + 4.0 nC which is placed at position *A*



Electric Field Strength

$$\underline{E} = \frac{\underline{F}}{q}$$

$\underline{E}$ and $\underline{F}$ are vector quantities and the direction of both is the direction a positive charge would move if placed in that field.

where:
E is the electric field strength (NC^{-1})
F is the force (N)
q is the positive charge (C)

From Coulombs Law:

$$F = \frac{1}{4\pi\varepsilon_0}\frac{Q_1 Q_2}{r^2}$$

then using:
$q = Q_1$ = charge on the test charge
$Q = Q_2$ = charge on the body setting up the electric field
r = distance of test charge (q) from the fixed point charge (Q)

gives:

$$F = \frac{1}{4\pi\varepsilon_0}\frac{qQ}{r^2}$$

and so $E = \frac{F}{q}$ becomes

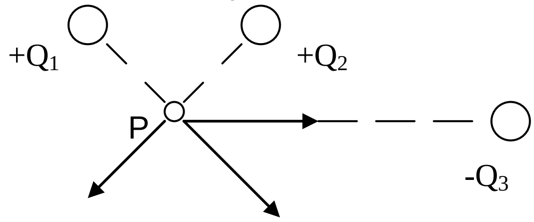
$$\mathbf{E = \frac{1}{4\pi\varepsilon_0}\frac{Q}{r^2}}$$

Please remember

- $F = \frac{1}{4\pi\varepsilon_0}\frac{qQ}{r^2}$
  gives the magnitude of the electric field around an isolated point charge. Its direction is radial.
- $E \propto 1/r^2$ means that the electric field strength decreases rapidly as r increases.

Field Due To A Number Of Point Charges

If a positive point charge was placed at point P, then it would experience **three** electric fields

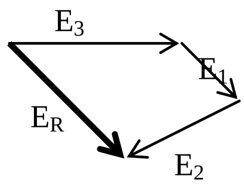


1. $\underline{E}_1$ due to Q_1

2. $\underline{E}_2$ due to Q_2

3. $\underline{E}_3$ due to Q_3

These electric fields are vectors and must be added as such.



Here is an example of this, not drawn to scale.
$\underline{E}_R$ is the resultant electric field.

Example 1
Equal and opposite 10 nC charges are situated at vertices A and B on an equilateral triangle ABC, where AB = 20 mm.
Calculate the resulting electric field strength on a positive charge placed at the third vertex (C).

Answer

$$E = \frac{1}{4\pi\varepsilon_0}\frac{Q}{r^2}$$

$$= \frac{1}{4\pi \times 8.85\times10^{-12}} \quad \frac{10 \times 10^{-9}}{(20 \times10^{-3})^2}$$

$$= 225000 \text{ NC}^{-1}$$

= the electric field strength from one charge

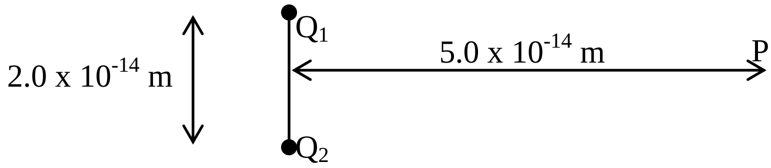
N. B. Vectors must be added 'tip to tail'

Resultant = 2ECos 60^0
= 2 x 225000 x Cos 60^0
= 2 x 225000 x 0.5
= 225000 NC^{-1} parallel to AB

Example 2
The Electric Dipole
An electric dipole consists of two separated point charges of the opposite charge. (see diagram below)
Electric dipoles are used when studying the behaviour of dielectric materials used in the construction of capacitors.

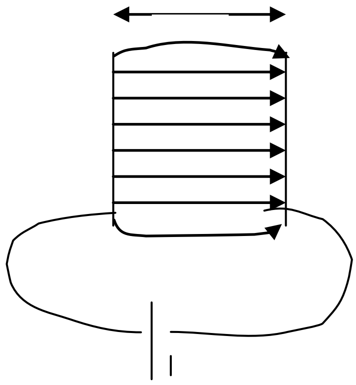
A pair of charges Q_1(+4.0 x 10^{-9} C) and Q_2(-4.0 x 10^{-9} C), separated by 2.0 x 10^{-14} m, makes up an electric dipole.

Calculate the electric field strength at a point P, a distance of 5.0 x 10^{-14} m from the dipole along the axis shown in the diagram below.



See further examples in Scholar notes.

Potential and Electric Field



The field between two charged parallel plates is **uniform** everywhere between the plates except near the edges.

This means that the force a unit charge experiences as it moves in this uniform electric field will be **constant**.

Potential Difference is **defined** as:
the work done in moving a charge *Q* across the field through a distance *d*
Potential Difference is **calculated** as follows :

$W = Fd$ and because $F = QE$
$W = QEd$

Definition of work is $W = QV$ Together these two equations give:

$QV = QEd$ leading to:

$V = Ed$
where
V is the potential difference (Volts)
E is the electric field strength (NC^{-1})
d is the distance the charge is moved through the uniform electric field (m)

Please remember

- This form of the equation is only **true** for a parallel plate capacitor or where the **electric field is uniform**
- Energy stored on a parallel plate capacitor is ½ QV because the average voltage during the charging is ½ the final voltage
- $E = V/d$ means that the units of Electric Field Strength can also be Vm^{-1}. Hence the unit NC^{-1} is equivalent to the unit Vm^{-1}.
- To move a charge from point A to point B in an electric field, where the potential difference between these points is *V* Volts, will require an amount of work to be done.
  This amount of work is independent of the route taken between the points A and B.
  Such a field is known as a **Conservative Field.**

Example
Two parallel plates are spaced 50 mm apart and are connected across a 1200V d.c. supply
Calculate:

i. The electric field strength between the plates.
ii. The work done in moving one electron of charge -1.6×10^{-19} C across the plates.

Electrostatic Potential
Consider a point charge *Q* and the electric field associated with it.
The electric field a distance *r* from the point charge is given by the equations:

$E = -(dV / dx)$ and

$$E = \frac{1}{4\pi\varepsilon_0} \frac{Q}{x^2}$$

Together these equations give:

$$-\frac{dV}{dx} = \frac{1}{4\pi\varepsilon_0} \frac{Q}{x^2}$$

The expression above can be integrated to give the potential *V* at a distance *r* from a point charge.

Potential due to a point charge is **zero at infinity**

$$\int_0^V dV = \int_\infty^r \left(\frac{Q}{4\pi\varepsilon_0 x^2}\right) dx$$

$$-[V]_0^V = \left(\frac{Q}{4\pi\varepsilon_0 x^2}\right)[-1/x]_\infty^r$$

$$-V = (Q / 4\pi\varepsilon_0)\ (-1/r + 0)$$

$$\mathbf{V = \frac{1}{4\pi\varepsilon_o} \frac{Q}{r}}$$

Please remember

- *When a positive charge is moved from infinity to a distance* r *away from the point charge, work is done against the electric field.*

- *This work comes from an external source e.g. the moving belt on a Van de Graaff generator.*

- *The positive charge moving from infinity will gain electric potential energy.*

- *If an external source does work W to bring a positive test charge Q_t from infinity to a point in the electric field then the electric potential* V *is defined as the work done by external forces in bringing unit positive charge from infinity to that point.*

- *A potential exists at a point a distance* r *from a point charge, **BUT** for the system to have energy, a charge must reside at that point. This means that one isolated charge has no electric potential energy.*

- *The electric potential around a point charge $\propto 1 / r$*

- The electric potential is a **scalar** quantity
  If a number of charges lie close to one another the potential at a given point is the **scalar sum** of all the potentials at that point.
  This is unlike the situation with electric field strength.

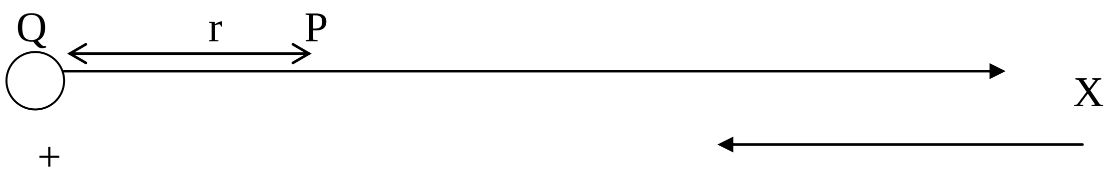
- Negative charges have a negative electric potential.
  Sign of electric potential is determined by the sign of the charge Q

- At positions where E = 0, V must be a constant.

Summary of Electric Potential Due To A Point Charge

- Electrostatic potential (V) at a point P a distance r from a charge Q is defined as:

  The work done by external forces in bringing a positive test charge Q_t from infinity to a point P.



A positive test charge moving from infinity to a point P

- The force acting against Q_t increases as Q_t gets closer to Q.
- Force (F_E) on the unit charge is given by the equation:

$$F_E = \frac{1}{4\pi\varepsilon_0}\frac{Q_tQ}{r^2}$$

- $V = \dfrac{1}{4\pi\varepsilon_o}\dfrac{Q}{r}$

- $V \propto 1/r$

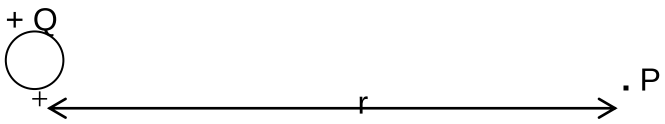
Please note the following similarities.

- In both gravitational and electric fields zero potential is defined as being at a point where $r = \infty$
- In a gravitational field when a mass is moved from infinity, the gravitational field does work on the mass.
  As a result the potential is less than at infinity i.e. a negative number
- In an electric field when a unit **positive** charge is moved, work is done **against** the electric field.
  As a result the potential is increased i.e. a positive number.

Electric Potential Energy

Electric potential at P is given by:

$$V = \frac{1}{4\pi\varepsilon_o}\,\frac{Q}{r}$$



If a test charge Q_t is placed at P, then the electric potential energy of charge Q_t is:

$$\mathbf{E = Q_t V} \qquad \textbf{giving}$$

$$\mathbf{E = Q_t \times \frac{Q}{4\pi\varepsilon_0 r}}$$

A positively charged particle, if free to move in an electric field, will accelerate in the direction of the field.

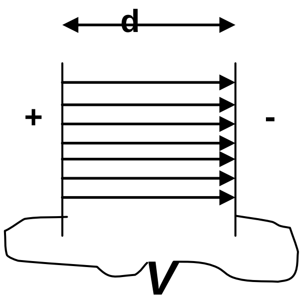
This means that the positive charge is moving from a position of high electric potential energy to a position of lower electric potential energy.

As a result the positive charge loses electric potential energy as it gains kinetic energy.

Motion Of A Charged Particle In Electric Field

Reminder From Higher Physics Course

If an electric field is produced by two charged parallel metal plates, then the field will be uniform.
$E = V/d$



If a positive charge is placed in this field E, then the positive charge will accelerate towards the negative plate.

The acceleration is produced by the force ($F = QE$)
The direction of motion will be parallel to the electric field lines.

Conservation of energy means that:
Gain in kinetic energy of the charged particle = Electrical Work Done

Non Relativistic Treatment
This is for speeds less than 10% of 3×10^{8} ms^{-1} i.e. 3×10^{7} ms^{-1}

$$\tfrac{1}{2} m v^2 = QV$$

$$\Rightarrow \quad v^2 = \frac{2QV}{m}$$

$$\Rightarrow \quad \mathbf{v = \sqrt{(2QV / m)}}$$

where
v is the speed of the particle
m is the mass of the particle
Q is the charge on the particle
V is the p.d between the plates

Uses
There are several uses of electric fields one of which is car paint spray.
This where paint particles are charged and sprayed onto the body of the car.
The paint particles follow the field lines round the car and give it a very even coating of paint.

A Reminder From The Higher Course Work

An electric field applied to a conductor causes electric charges to move.
This is best seen in an electron gun
One example of this is the Cathode Ray Tube.

This illustrates how the movement of charged particles is affected by electric fields when:

1. the electric field direction is parallel to the direction of motion of the particles

2. the electric field direction is at right angles to the direction of motion of the particles.

In a Cathode Ray Tube:
the Cathode - Anode electric field illustrates (1)
the y-plates electric field illustrates (2)

How Does This Work?

- Electrons are released from the cathode and are accelerated by the uniform electric field between the cathode and the anode.
- On reaching the anode the electrons travel at a constant velocity (v_x) until they reach the region between the y-plates.
- At the y-plates the passage of the electrons resembles the trajectory of a projectile and they accelerate towards the positive plate.
- As a result the electrons now have a vertical component of velocity. *(as well as their original horizontal component)*
- As a result the perpendicular field has deflected the beam towards the positive plate.
- The size of the electric field between the y-plates depends on the p.d. (potential difference) applied to the plates.
  This means that the greater the deflection the greater the p.d. between the y-plates.

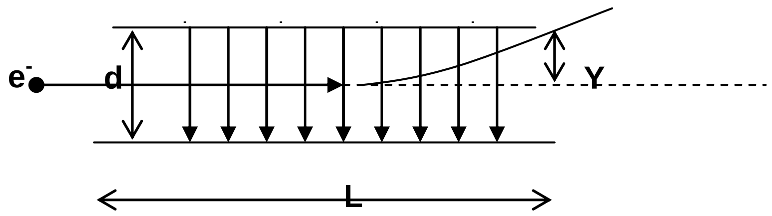
As the electron accelerates from the cathode to the anode it loses E_P (electric potential energy) and gains E_K (kinetic energy).

Therefore by **conservation of energy**, we can calculate the final speed of the electron at the anode:

$$\mathbf{E_P = QV = E_K = \tfrac{1}{2} mv^2}$$

Motion Of Charged Particles In Uniform Electric Fields

If a charged particle (e.g. an electron) was moving perpendicular to a uniform electric field then the result could be something like:



The factors which effect the size of the deflection (Y) in the field are:
- ♦ Speed of the particle (e.g. electron) as it enters the field
- ♦ Strength of the field
- ♦ Charge on the particle

The path of the electron (or whatever particle) in the field is PARABOLIC, just like the path of a short range projectile.

The horizontal and vertical motions can be considered *<u>separately.</u>*


horizontal

vertical

- Horizontal motion is one of constant velocity and $v = s/t$

- Vertical motion is one of uniform acceleration from rest and uses
  $v = u + at$; $s = ut + \frac{1}{2}at^2$; $v^2 = u^2 + 2as$

- $E = F/Q$ where E and Q are constants

- As F is constant, the acceleration is uniform

- Time in the field

  $$t = \frac{\text{distance (length of plates)}}{\textit{horizontal velocity}} = \frac{L}{v}$$

- Acceleration Upwards
  Only upwards if the particle is an electron and the plates were set up as in the diagram on the previous page

  $a = F/m$ and because $F = QE$

  $a = \frac{QE}{m}$ where Q is the charge on an electron

  Remembering that $E = V/d$ where d is the plate separation gives

  $a = \frac{QV}{md}$ **

  Using the equation:

  $s = ut + \frac{1}{2}at^2$ where s is the **deflection of the electron** in the diagram overleaf and has the symbol **Y**

  $Y = ut + \frac{1}{2}at^2$
  and as $u = 0\ ms^{-1}$ this gives us the equation:

  $Y = \frac{1}{2}at^2$
  *Replacing 'a' with the equation ****** above gives:*

  $$\mathbf{Y = \frac{1}{2}\frac{QVL^2}{mdv^2}}$$

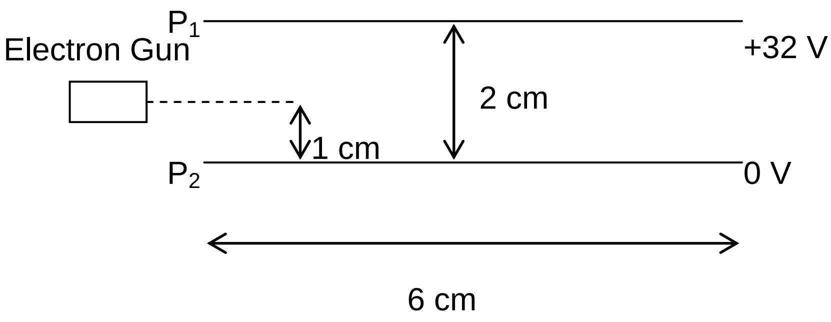
This means that the deflection of the beam can be found if the following are known:

- charge to mass ratio (Q/m)
- physical dimensions of the plates (L and d)
- p.d. across the plates (V)
- speed of the electron (v).
  This can be found from the charge on the electron and the p.d. generating the field that accelerates the electrons in the gun. (See Higher notes.)

The illustration above uses electrons which is the most common example. However the theory is true for any charged particle.

Example 1

The diagram below shows a beam of electrons entering the deflecting device in a cathode ray tube at a speed of 8.0×10^{6} ms^{-1}



i. Calculate the strength of the electric field between the plates.

ii. Calculate the time spent between the plates by an electron in the beam

iii. Find the vertical deflection of the electron beam as it emerges from the space between the plates.

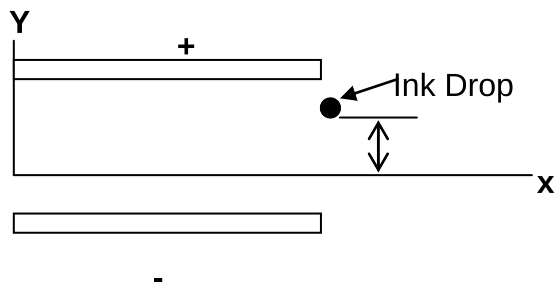
Example 2

The figure below shows the deflecting plates of an inkjet printer.

If an ink drop of mass of 1.3×10^{-10}kg, carrying a charge of 1.5×10^{-13}C enters the deflecting plate system with a speed of 18 ms^{-1}, calculate the vertical deflection of the drop at the far edge of the plates.

The length of the plates is 1.6×10^{-2}m
The electric field between the plates is $1.4 \times 10^{6}NC^{-1}$.

Assume that the ink drops are very small so that gravitational forces can be neglected.



The Electronvolt (eV)

- The electronvolt is an important unit of **energy** in high-energy particle Physics.

- The electronvolt is was mentioned in Unit 1 and is included in these notes because of its widespread use.

- The electronvolt is the energy acquired when one electron accelerates through a potential difference of one volt.

- This energy (=QV) is changed from electrical energy to kinetic energy.

- One electronvolt of energy = QV = $1.6 \times 10^{-19} \times 1 = 1.6 \times 10^{-19}$ J

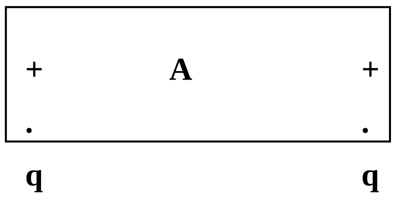
- Often the unit MeV is used
  1 MeV is equivalent to 1.6×10^{-13} J

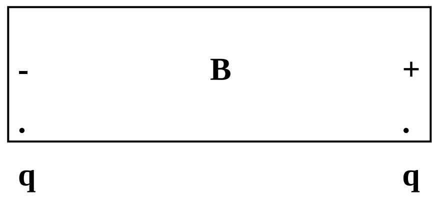
Particle Accelerator – see Higher notes
At CERN, on the banks of Lake Geneva in Switzerland, a particle accelerator has been built below ground.
This type of accelerator know as a LEP (Large Electron Positron Collider) was designed to produce electrons.
These electrons have a kinetic energy of 100GeV (10^{11} eV).
The speed of electrons at this energy will be about one part in 10^{11} less than the speed of light.

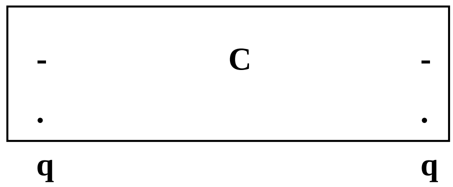
Cosmic Rays – see Higher notes
Energetic charged particles, which originate from the sun, stars and other heavenly bodies, are known as cosmic rays.
Ultra high-energy cosmic rays which probably originate outside our galaxy can have energies up to 1.5×10^{20}eV.
When one of these cosmic rays enters the earth's atmosphere a shower of secondary rays is produced.
Most of the new subatomic particles produced are absorbed in the atmosphere.
Studies of these 'air showers' have provided the evidence that the ultra high-energy rays come from a cluster of galaxies in the constellation Virgo.
One of the galaxies in this constellation is also thought to have a black hole at its centre.

Example

The diagrams below show three separate arrangements of two point charges of equal magnitude. The positions A, B and C are midway between the charges.



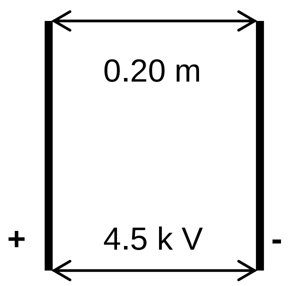




1. Which of the points *A*, *B* or *C* indicates a position in space where:
   (i) the electric potential is non zero and the electric field strength is zero?
   (ii) the electric potential is zero and the electric field strength is non zero?

2. Two large parallel plates separated by a distance *d* have a potential difference *V* between them.
   Show that the electric field strength E is given by:
   $$E = \frac{V}{d}$$

3. Two large parallel metal plates 0.20 m apart have a potential difference of 4.5kV between them. (see diagram below)
   A soap bubble of mass 3.0×10^{-4} kg holding a charge of -3.3×10^{-9} C is released from rest midway between the plates.
   Calculate the size of the electric force acting on the bubble and, ignoring the effects of gravity describe the motion of the bubble immediately after its release.



Comparison Of Gravitational And Electric Fields
Use this table when reviewing the full course notes.

Concept	Electric Field	Gravitational Field
Force	$F = \frac{1}{4\pi\varepsilon_0}\frac{Qq}{r^2}$ Repulsion or attraction	$F = \frac{GMm}{r^2}$ Only attraction
Field Strength	$E = \frac{1}{4\pi\varepsilon_0}\frac{Q}{r^2}$ Force per unit charge. NC^{-1}	$g = \frac{GM}{r^2}$ Force per unit mass. Nkg^{-1}
Force / Weight	$F = QE$	$W = mg$
Potential	$V_E = \frac{Q}{4\pi\varepsilon_0 r}$ *Joules per Coulomb* Zero of potential is at infinity from a charged object. This leads to the definition of potential difference and the volt.	$V_G = -\frac{GM}{r}$ *Joules per kg* Zero of potential is at infinity from the planet.
Work Done	$W = QV_E$ Work Done is the product of charge and the distance the charge is moved through.	$E_p = m V_G$ Gravitational Potential Energy is a product of mass times the change in potential.
Field Lines	Go from positive charge to negative charge	Go towards the mass
Equipotentials	Surfaces of equal electric potential	Surfaces of equal gravitational potential

Magnetic Fields and Magnetic Induction

Background Information

- ***All magnetic phenomena arise from forces between electric charges in motion.***
- ***As electrons are in motion around atomic nuclei then all individual atoms exhibit magnetic effects.***
- ***Modern electromagnetism started in1819 when it was discovered that a current carrying wire can deflect a compass needle.***
- ***An e.m.f. can be produced by moving magnets***

Magnetic Fields

In Unit 1 gravitational fields were investigated and in previously in these notes electric field patterns were described by using field lines.
Field lines are a way to show the effect of “action at a distance” forces.

Similarly magnetic fields can be described using field lines.

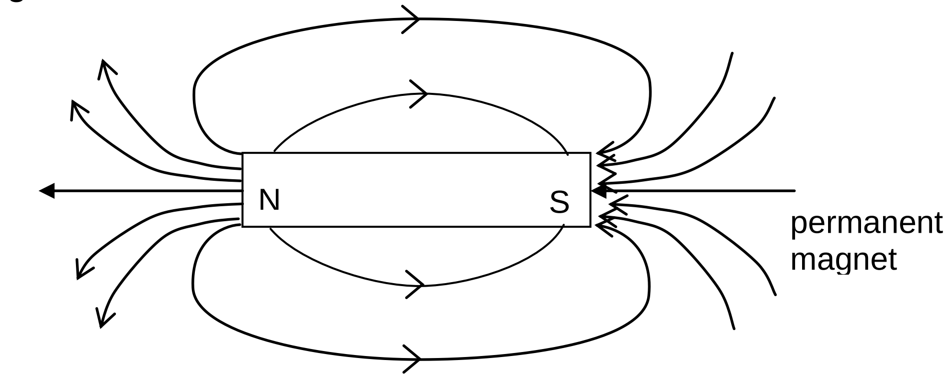
Definition
The direction of the magnetic field lines is defined as the direction the north pole of a compass would point if placed in the same field at the same point.

Permanent magnets or **electromagnets** produce magnetic fields**.**

Definition
A moving charge (a current) will set up a magnetic field as well as an electric field.

Magnetic Field Patterns

1.



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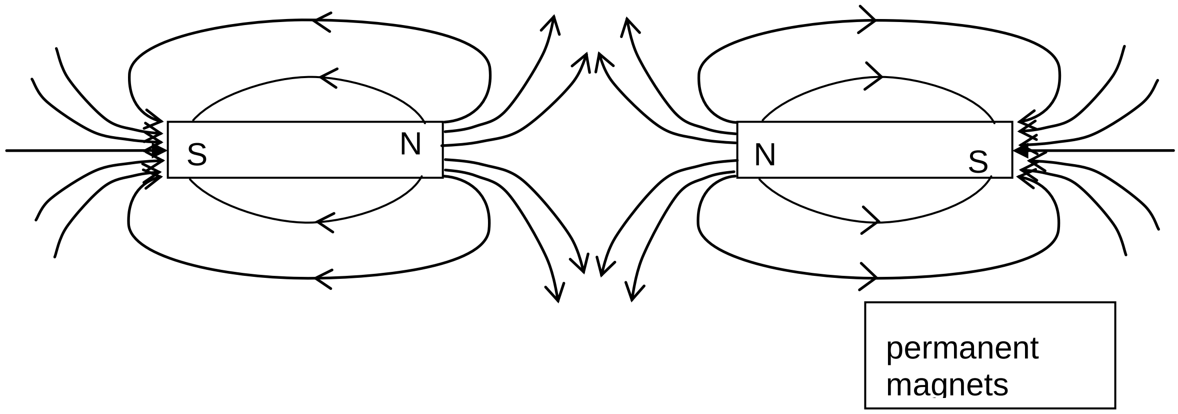

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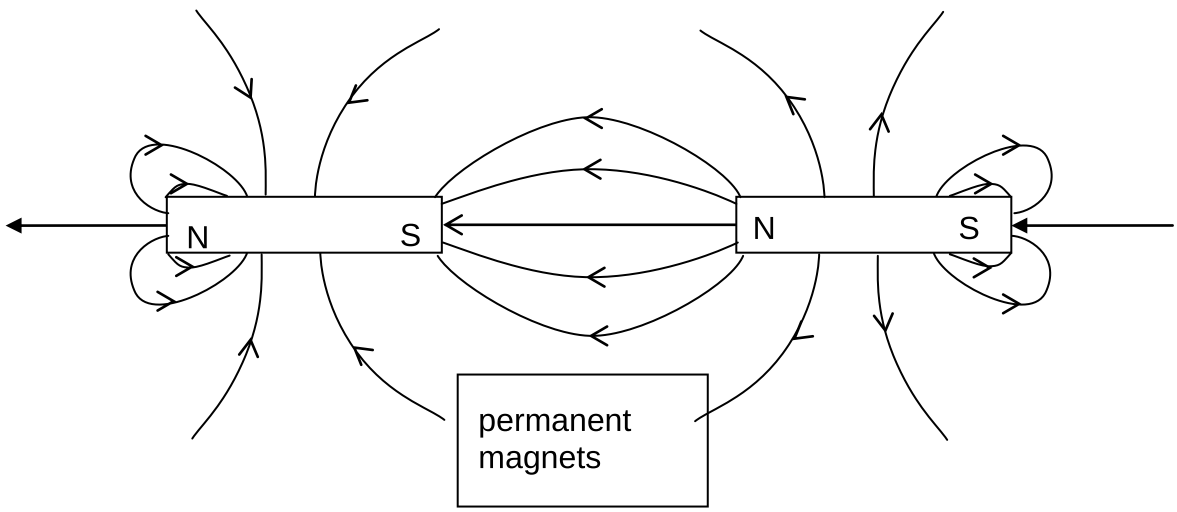
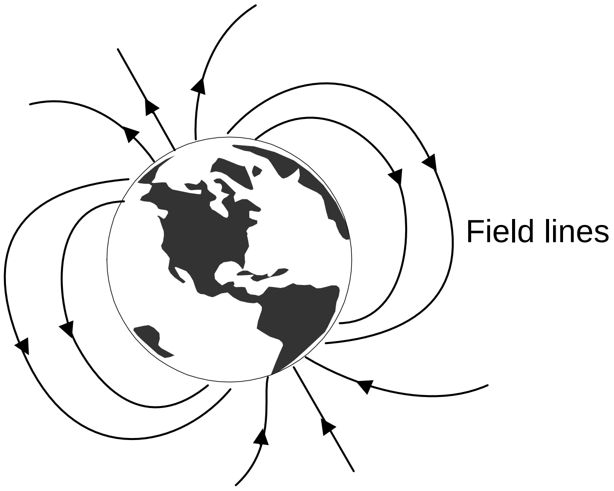


4.



Magnetic field lines round the earth will also point from North to South.
Field lines strike the surface of the Earth at angle.

Terrestrial compass needles (the type we use when hillwalking) point in the direction of the horizontal component of the magnetic field line.

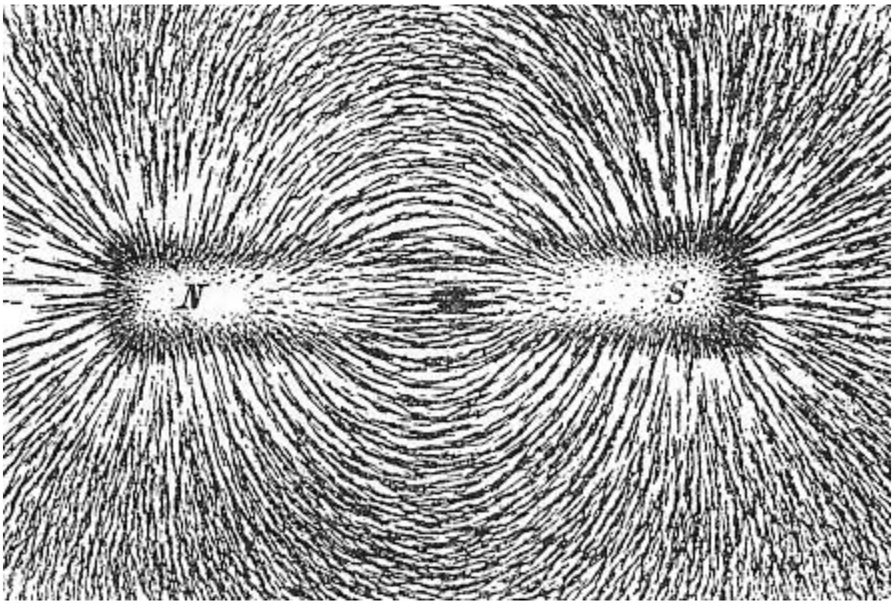
Please remember

- A magnetic field exists around a moving charge.
- An electric field also exists around a moving charge.
- A charged particle moving across a magnetic field will experience a force.
- Each magnet has two poles.
- No monopoles exist in magnetic fields.
  This means that you cannot get a North or a South pole on its own.
  This is different from electric fields where it is possible for one type of charge to set up an electric field.
- North pole is the short for **north seeking pole**.
  This means that the north pole of a magnet will point approximately to the geographic north pole of the Earth
  This happens because the Earth is a self sustaining electromagnet due to convection currents within its molten core.
- Magnetic field lines never cross over each other.
  This is because the direction of the field line is unique at any point.
- Magnetic field lines are three dimensional
- The closer together the field lines the stronger the field.
- Magnetic field lines are only used to visualise the magnitude and direction of the field. They do not exist. (This is the same as electric field lines)

But why are there magnetic fields?
An atom consists of a nucleus surrounded by electrons. As the electrons are moving and charged, they will create a magnetic field in the space around them.

Iron, cobalt, nickel and some rare earth metals are known as **ferromagnets.** Ferromagnetism is the strongest type of magnetism and it is the only type that creates forces strong enough to be felt. An everyday example of ferromagnetism is a fridge magnet used to hold notes on a refrigerator door. The attraction between a magnet and ferromagnetic material was apparent to scientists in the ancient world.

A very common source of magnetic field shown in nature is a **dipole**, with a **'South Pole** and a "**North Pole'.** These are terms dating back to the use of magnets as compasses, interacting with the Earth's magnetic field to indicate North and South on the globe.
Since opposite ends of magnets are attracted, the north pole of a magnet is attracted to the south pole of another magnet.



Newton Henry Black, Harvey N. Davis (1913) *Practical Physics*, The MacMillan Co., USA, p. 242, fig. 200

Summary

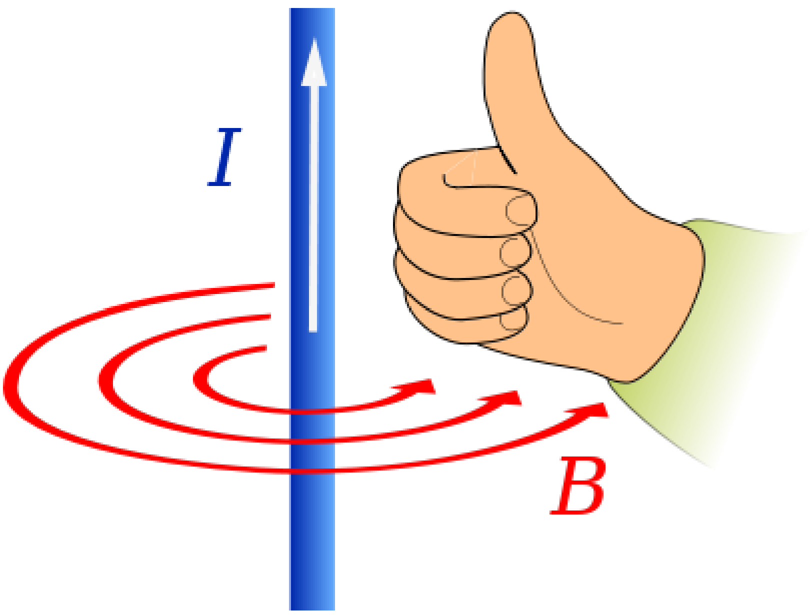
Field Type	Cause of Field
gravitational	mass
electric	charge
Magnetic	movement of charge

Current Carrying Conductors – Reminder From Higher Physics

There must be a magnetic field round a wire carrying a current.
A moving charged particle with generate a magnetic field around it. Therefore because a current is a movement of charge then a current carrying conductor will have a magnetic field around it.
This was first investigated by Oersted (1777 – 1851).

In Int 2, the 'right hand rule' for conventional current flow(opposite to electron flow) was investigated….

Right Hand Rule



Jfmelero

The magnetic field round a current carrying piece of wire is a series of concentric rings.

The right hand rule is applied as follows:

- use your right hand, clench your fist
- the thumb of your right hand points in the direction of the electron flow
- the direction of the magnetic field is the direction in which the fingers on your right hand will point.
- the magnetic field produced by a current carrying wire is circular

Definition

The force due to the magnetic field will cause a current carrying piece of wire to move.
In IIIS /IVS we saw how the magnetic field from a horse shoe magnet and the magnet field round a current carrying wire resulted in the movement of the wire.

Symbols
Imagine an arrow with a pointed tip and crossed feathers at the rear.

If the direction of the field is out of the paper i.e. towards you then the symbol used is

●

which is sometimes shown as a "dot"…the tip of the arrow

If the direction of the field is into the paper i.e. away from you then the symbol used is

X

Please remember

- Magnetic induction is a vector quantity.
  In some texts this may be referred to as the magnetic field strength.

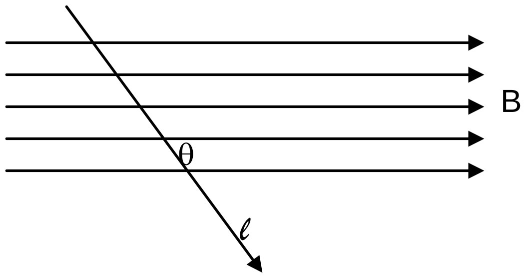
- *The symbol for the magnetic induction is B*

- *Other names for magnetic induction are:*
  magnetic flux density
  magnetic B-field

- Units of magnetic induction is Tesla (T) and 1 T = 1 $NA^{-1}m^{-1}$
  Magnetic Induction is the force on a conductor placed in a magnetic field

Factors Affecting The Size Of The Force

- Current (I)
- Length of The Conductor (ℓ)
- Magnetic Induction (B)
- Angle Between the Conductor and the Magnetic Field (θ)



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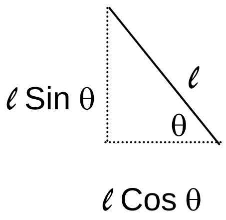
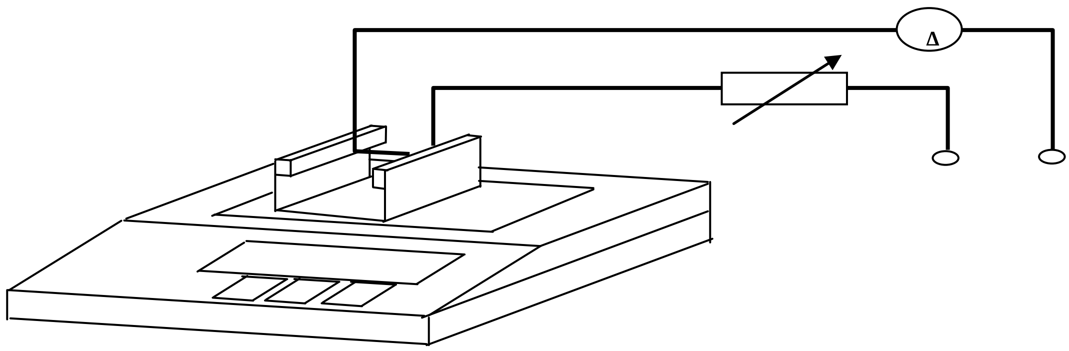


Experiment



1. Place a magnet on a sensitive scale balance
2. Zero the balance
3. Place a fixed number of coils of copper wire in the magnetic field
4. Switch on and measure the current.
5. Read and record the mass (m)
   The size of the force is equal to mg.
6. Adjust the size of the variable resistor to give different values of the current
7. Repeat steps 4 to 6 for a range of values.

Results

Current (A)	**Reading (g)**	**Force due to magnetic field (N)** (Reading x 10^{-3} x 9.8)	**F / I**

Plot a graph of force against current.

*If the reading on the scales is **zero** this means that the magnitude of the force acting downwards is equal in size to the magnitude to the force acting upwards.*
*If the reading on the scales is **positive** this means that the magnetic force is acting downwards.*
*If the reading on the scales is **negative** this means that the magnetic force is acting upwards.*

Repeat the experiment, but this time keep current constant and vary the number of coils i.e. vary ℓ.

Results

No. of coils	**Reading (g)**	**Force due to magnetic field (N)** (Reading x 10^{-3} x 9.8)	**F / ℓ**
5			
10			
15			

Plot a graph of force against number of coils

Repeat the experiment with current and length of wire constant, but vary:

- Direction of flow of current
  Observe what happens

- Direction of magnetic field
  Observe what happens

Use a compass to find the direction of the magnetic field.
Remember north pointer of compass points to south face of magnet.

Magnetic field lines are from north to south.

Do not change anything !

For an increase reading, note which terminal is positive and which is negative.
For a decrease reading, note which terminal is positive and which is negative.

From this experiment the following results were obtained:

- $F \propto I$
- $F \propto \ell$
- $F \propto \sin\theta$

Therefore $F \propto I \ell \sin\theta$

$F = B I \ell \sin\theta$

where the constant of proportionality is the magnetic induction B.

$$\boldsymbol{F = B I \ell \sin\theta}$$

If the conductor (and therefore the current) is perpendicular to the magnetic field then $\theta = 90^0$ and so $\sin\theta = 1$, giving

$$\mathbf{F = B I \ell}$$

If the conductor (and therefore the current) is parallel to the magnetic field then $\theta = 0^0$ and so $\sin\theta = 0$, giving

$$\boldsymbol{F = 0\ N}$$

where
F is the force measured in Newtons (N)
B is the Magnetic Induction measured in Tesla (T)
I is the current measured in Amps (A)
ℓ is the length of the conductor measured in metres (m)
θ is the angle between ℓ and B

It is therefore possible to **define the magnetic induction** in terms of **force per unit current per unit length of wire**. The direction will always be at right angles to the field.

Units are $N\ A^{-1}\ m^{-1}$ equivalent to the tesla

Compare this to the units of g ($N\ kg^{-1}$) in Unit 1 and E ($N\ C^{-1}$) in this unit.

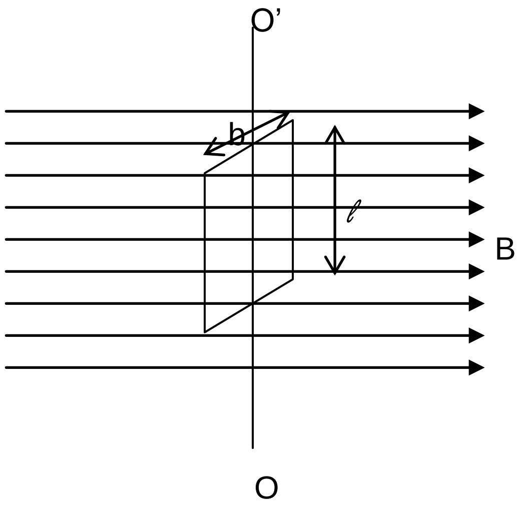
Motors and Meters

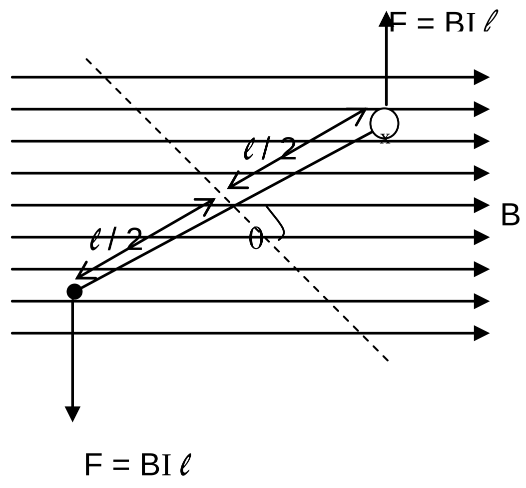
If there is a coil with:

- **N** turns on it
- which has a width of **b**
- and a length of ℓ
- and carries a current of **I**
- in a magnetic field where magnetic induction is **B**

Side View **Top View**

Coil rotates about the axis OO'





With One Coil

The forces acting on each of the sides of width ***b*** are equal in size and opposite in direction. Hence the overall effect is zero.

The two forces acting on the length $\boldsymbol{\ell}$ are equal in size and opposite in direction. They do **not** act along the same line, so the overall effect is a magnetic torque (see Unit 1 notes for more information).
A torque is a turning force.

θ is the angle between the magnetic field and the perpendicular to the plane of the coil (dotted line in right hand diagram above)

Torque, T = Fd
where d is the perpendicular distance between the lines of action of the two forces.

Torque about OO' $= Fd$
$= BI\ell \times b\sin\theta$
$= BIA\sin\theta$ where A is the area of the coil

If there are N coils then the equation becomes:

$$\mathbf{T = BINA\sin\theta}$$

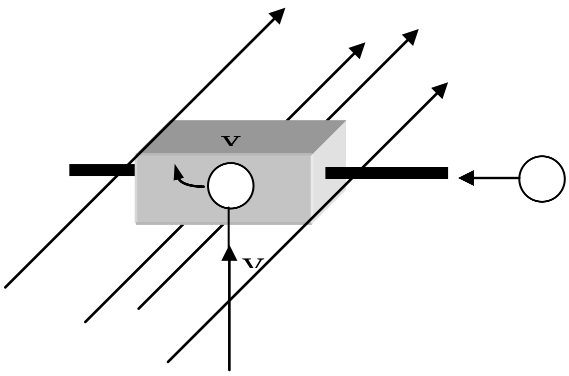
The torque will be greatest when $\sin\theta = 1$ ($\theta = 90^0$) and therefore
$$\mathbf{T = BINA}$$

Hall Effect
Magnetic effect at a distance from a long current carrying wire

A current carrying conductor in a magnetic field has small p.d. across its sides, in a direction at right angles to the magnetic field. This p.d. is known as the **Hall p.d.**

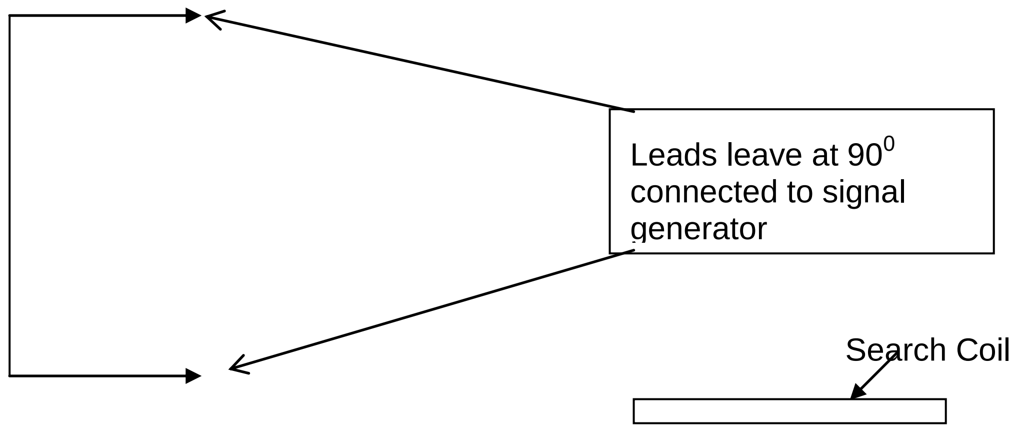
Explanation
- Discovered first by Hall in 1879.
- Attributed to the forces experienced by charge carriers in the conductor.
- These forces act at right angles to the directions of the magnetic field and current.
- These forces cause the charge carriers to be pushed sideways.
- This results in an increase in concentration of charges towards one side of the conductor.
- As a result a p.d. (and an electric field) is produced across the conductor.

Diagram 1



Force on **negative** charge carrier

Experiment To Show The Magnetic Induction In A Long Piece of Wire



- Attach the search coil to voltmeter set to measure mV a.c.
- Place meter stick on the bench
- Place search coil 5 cm from wire
- Orientate search coil until you get maximum reading on the voltmeter.
- **Do not change the orientation of the search coil.**
- Move search coil to a range of distances and measure the voltage at each distance.

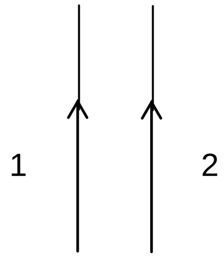
Results

Voltage (mV)				
Distance (m)				

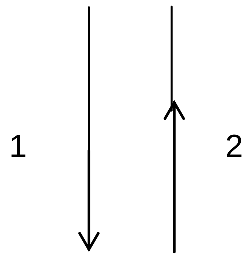
Plot a graph of voltage against distance.

Definition

As was shown in National 5 there is a magnetic field round a current carrying wire.
If two pieces of current carrying wire are placed parallel to each other, then they will exert a force on each other.



The two wires will be attracted to each other if the current is flowing in the same direction in both the wires.



The two wires will repel each other if the current is flowing in the opposite direction in both the wires.

To find the size of this force:

- Use the equation… $F_1 = B_1 I_1 \ell$

- Use the formula… $B_1 = \dfrac{\mu_0 I_1}{2\pi r}$

  where μ_0 is the permeability of free space (see later notes)

  B is the **magnetic induction** at a perpendicular distance (r) from an infinitely long wire that is carrying a current (I).

If the two wires in the above experiment carry currents I_1 and I_2 then the force experienced by wire 2 will be

$$F = B_1 I_2 = \frac{\mu_0 I_1 I_2}{2\pi r} \text{ x length}$$

Thus

$$\frac{F}{l} = B_1 I_2 = \frac{\mu_0 I_1 I_2}{2\pi r}$$

where

- **F / ℓ** is the **force per unit length** between two infinitely long current carrying wires.
  Units are Nm^{-1}

- r is the distance between the wires (r is perpendicular to the wires).
  Units are m

- $I_1 I_2$ are currents.
  Units are A