Module 6 Particles & Medical Physics

Module 6: Particles and medical physics

In this module, learners will learn about capacitors, electric field, electromagnetism, nuclear physics, particle physics and medical imaging.

Module 6 Particles & Medical Physics

Unit 3 Electromagnetism

6.3 Electromagnetism

This section provides knowledge and understanding of magnetic fields, motion of charged particles in magnetic fields, Lenz's law and Faraday's law. The application of Faraday's law may be used to demonstrate how science has benefited society with important devices such as generators and transformers. Transformers are used in the transmission of electrical energy using the national grid and are an integral part of many electrical devices in our homes. The application of Lenz's law allows discussion of the use of scientific knowledge to present a scientific argument (HSW1, 2, 3, 5, 6, 7, 8, 9, 11, 12).

Module 5 – Newtonian world and astrophysics

5.1 Thermal physics
5.2 Circular motion
5.3 Oscillations
5.4 Gravitational fields
5.5 Astrophysics and cosmology

Module 6 – Particles and medical physics

6.1 Capacitors
6.2 Electric fields
You are here! → 6.3 Electromagnetism
6.4 Nuclear and particle physics
6.5 Medical imaging

6.3 Electromagnetism

- 6.3.1 Magnetic Fields
- 6.3.2 Motion of Charged Particles
- 6.3.3 Electromagnetism

6.3.1 Magnetic Fields

6.3.1 Magnetic fields

Learning outcomes

Learners should be able to demonstrate and apply their knowledge and understanding of:

(a) magnetic fields are due to moving charges or permanent magnets

(b) magnetic field lines to map magnetic fields

(c) magnetic field patterns for a long straight current-carrying conductor, a flat coil and a long solenoid

(d) Fleming's left-hand rule

(e) **(i)** force on a current-carrying conductor; $F = BIL \sin \theta$

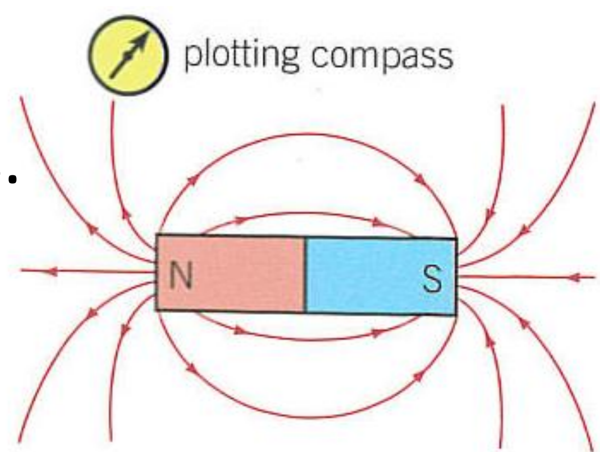
(ii) techniques and procedures used to determine the uniform magnetic flux density between the poles of a magnet using a current-carrying wire and digital balance

(f) magnetic flux density; the unit tesla.

What are magnetic fields?

Magnetic Fields

- A region surrounding a permanent magnet or a current-carrying wire in which magnetic materials experience a force.
- Magnetic field lines are used to map magnetic field patterns.
  - Shown using a plotting compass.



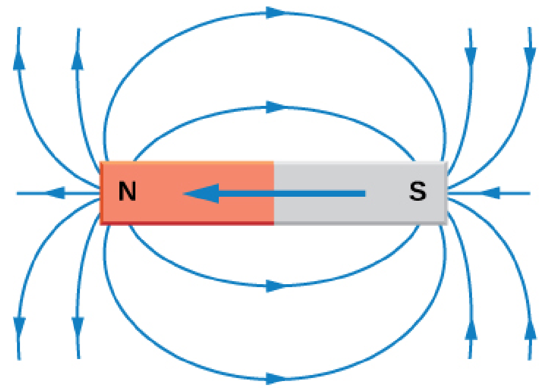
Magnetic Field Patterns

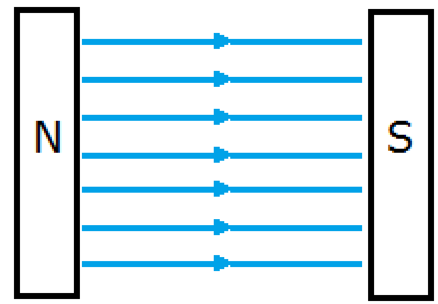
- Arrows on field lines point from North to South.

- Stronger magnetic fields are shown with lines closer together.

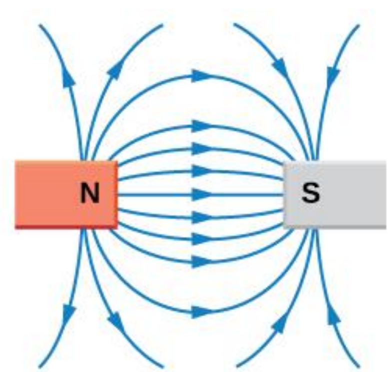
- Equally spaced, parallel lines show uniform magnetic fields, where the field strength stays constant.

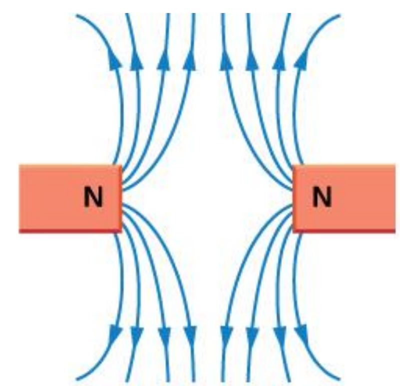
- Like poles repel (N-N, S-S) and unlike poles attract (N-S)





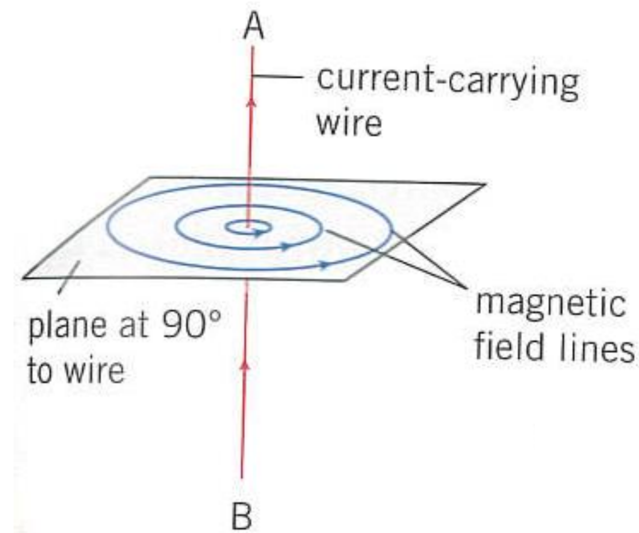
Uniform Magnetic Field

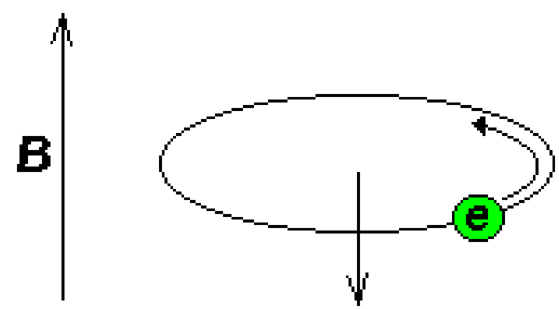




Electromagnetism

- Any moving charged particle creates a magnetic field around it.
  - So a magnetic field appears around a current-carrying wire.
  - Bar magnets contain atoms which are aligned with each other – their charged electrons orbit the nuclei in the same directions.
  - Non magnetic materials have atoms aligned more randomly – fields cancel each other.





Magnetic field produced by circulating electron

Right-Hand Grip Rule

- Shows direction of current and field around a wire

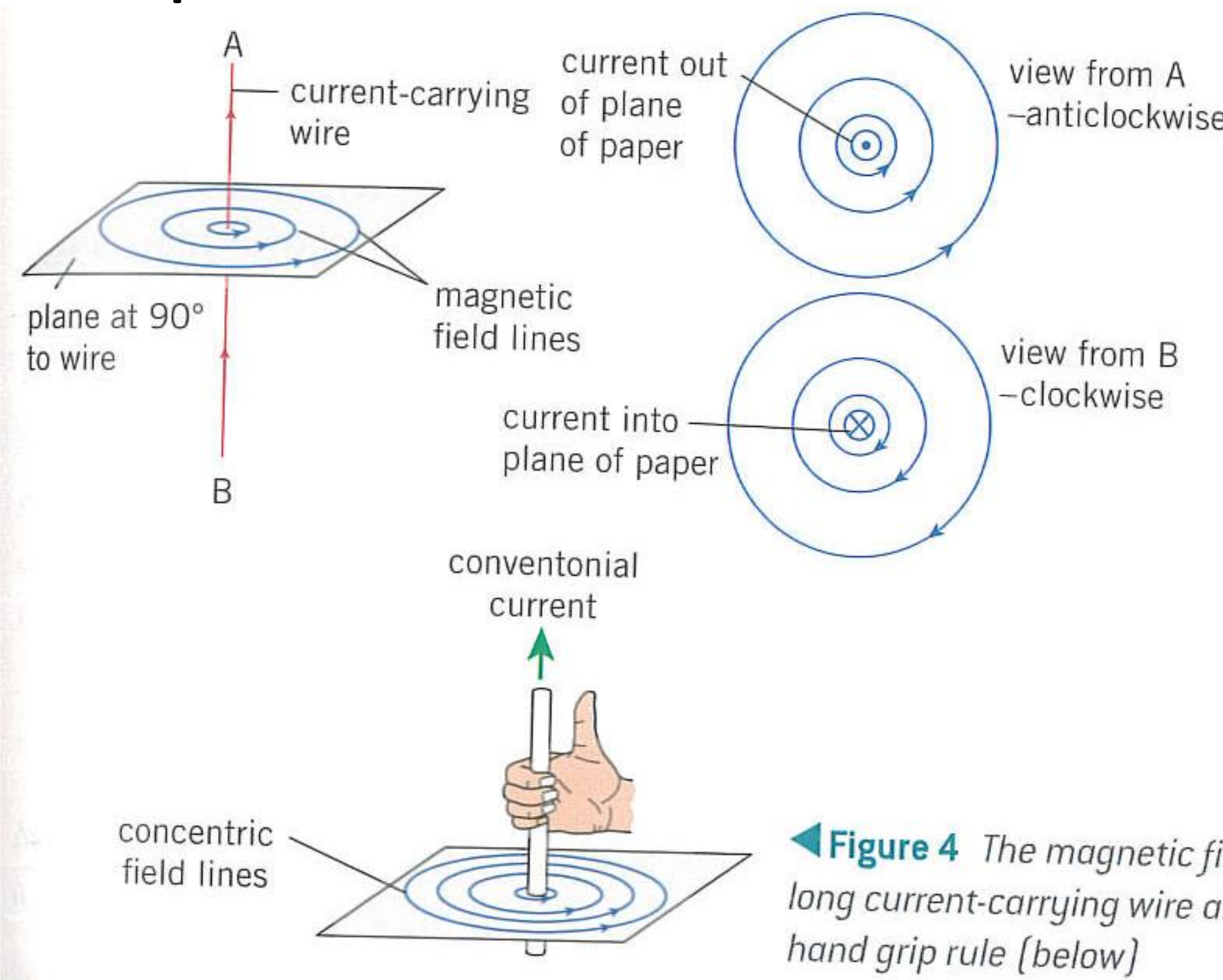
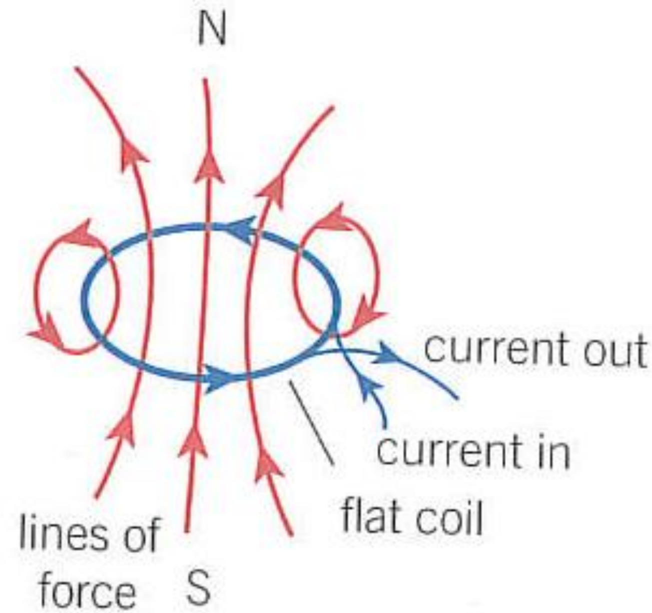


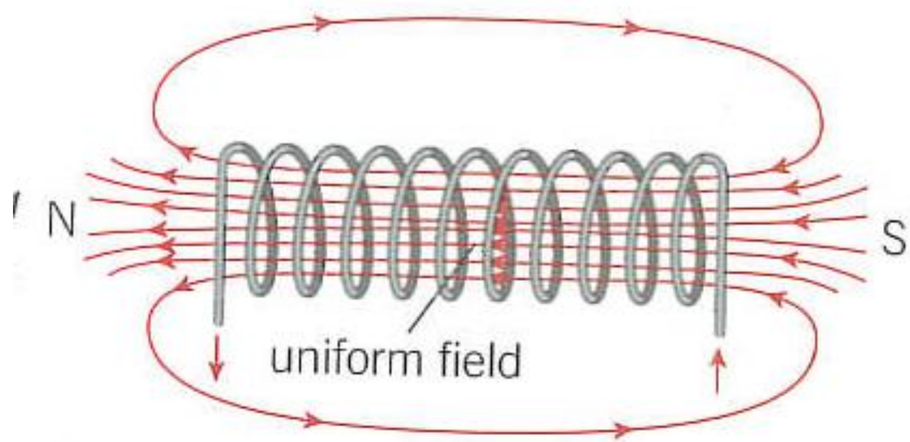
Figure 4 *The magnetic field around a long current-carrying wire and the right-hand grip rule (below)*

Fields around a coil & a solenoid

- Can still use the right hand
  - Curling fingers represent conventional current in the coil/solenoid
  - Thumb represents magnetic field direction.



- Field lines around a solenoid appear like those around a bar magnet.



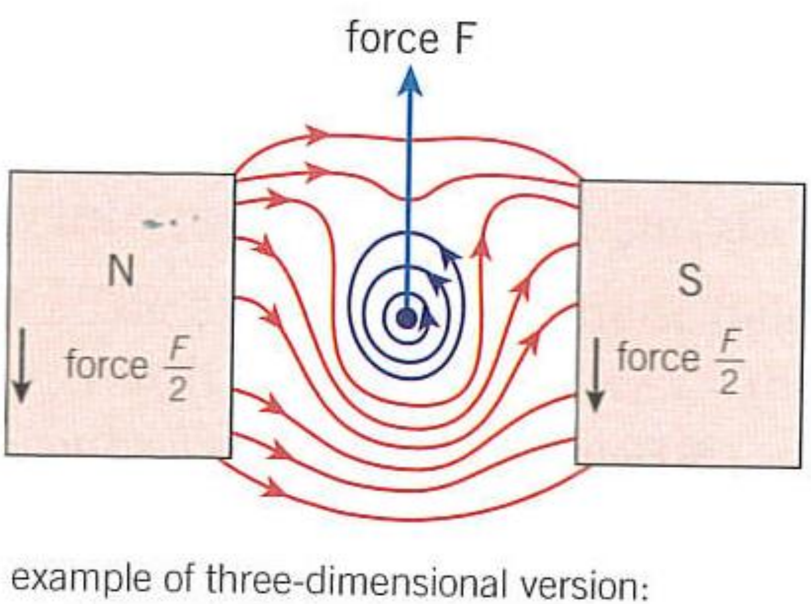
Magnetic Field Strength

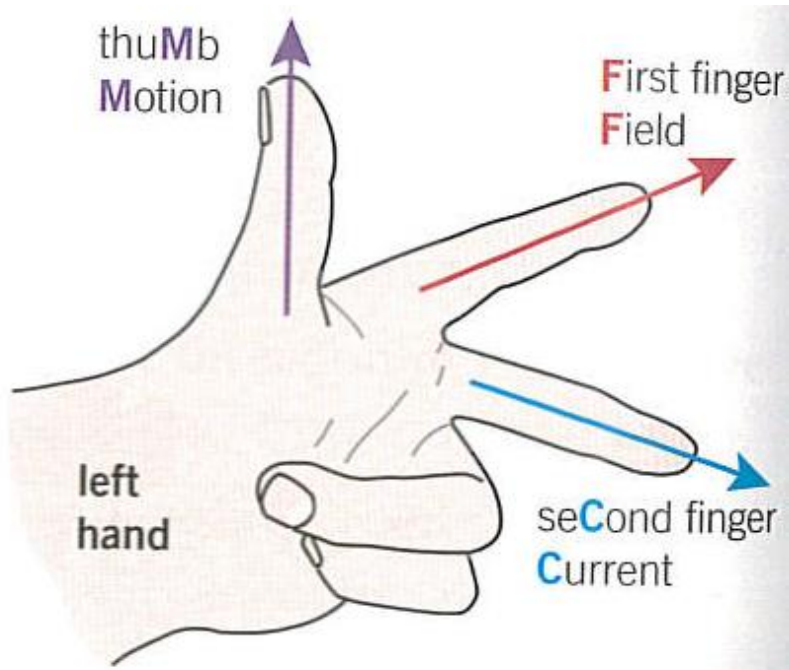
- Measured in tesla (T)

Object	Typical field strength /T
Interstellar space	1.0×10^{-9}
Earth at equator	3.0×10^{-5}
Small bar magnet	1.0×10^{-2}
Large electromagnet	1.5×10^{0}
Neutron star	1.0×10^{8}

Magnetic Fields & Forces

- Flemming's Left-Hand rule
  - Shows the direction of force experienced by a current carrying wire inside a magnetic field





Factors affecting this force

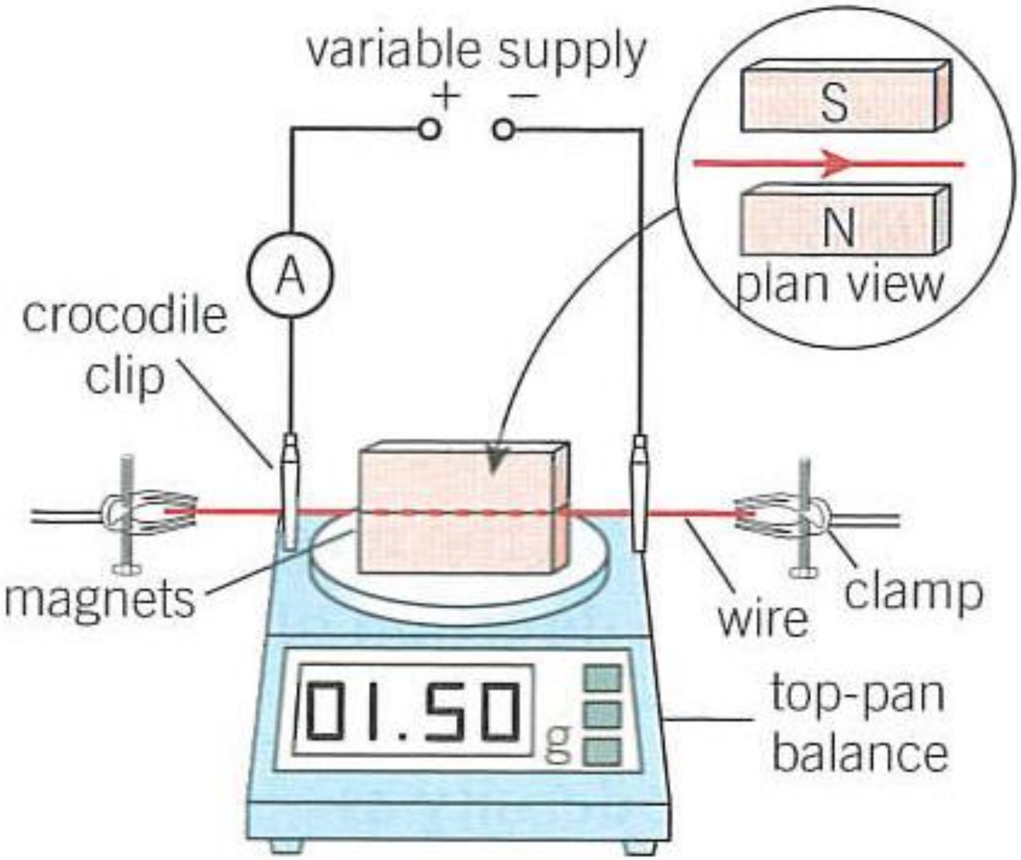
- Current, I
- Length of wire in the magnetic field, L
- Sin θ, where θ is the angle between the field and the current direction
  - Max when angle is 90^o, min when angle is zero.
- Magnetic field strength, B

$$F = BIL\sin\theta$$

Magnetic Field Strength, B

- Called Magnetic Flux Density
  - A vector quantity
  - Unit is tesla (T)
  - Equivalent to $Nm^{-1}A^{-1}$
- Analogous to Electric Field Strength, E
- Analogous to Gravitational Field Strength, g

Determining B



Current I/A	Change in mass m/g	Force F/N
0.00	0	
1.00	0.31	
2.00	0.64	
3.00	0.89	
4.00	1.24	
5.00	1.50	
6.00	1.83	
7.00	2.14	

L = 5.0cm, θ = 90°

Complete the table, plot F against I, use the gradient to calculate B.

6.3.1 Magnetic Fields (review)

6.3.1 Magnetic fields

Learning outcomes

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(d) Fleming's left-hand rule

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(ii) techniques and procedures used to determine the uniform magnetic flux density between the poles of a magnet using a current-carrying wire and digital balance

(f) magnetic flux density; the unit tesla.

6.3.2 Motion of Charged Particles

6.3.2 Motion of charged particles

Learning outcomes

Learners should be able to demonstrate and apply their knowledge and understanding of:

(a) force on a charged particle travelling at right angles to a uniform magnetic field; $F = BQv$

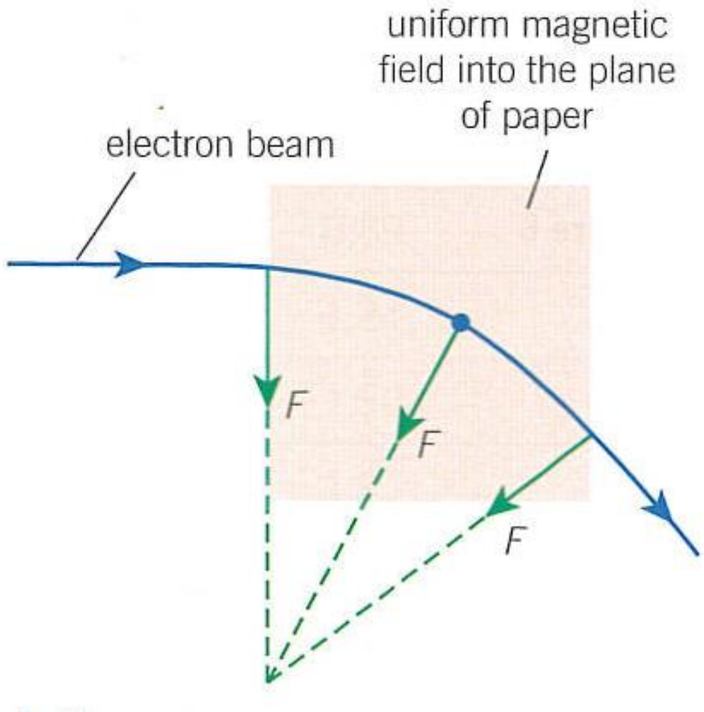
(b) charged particles moving in a uniform magnetic field; circular orbits of charged particles in a uniform magnetic field

(c) charged particles moving in a region occupied by both electric and magnetic fields; velocity selector.

How do moving charges behave in magnetic fields?

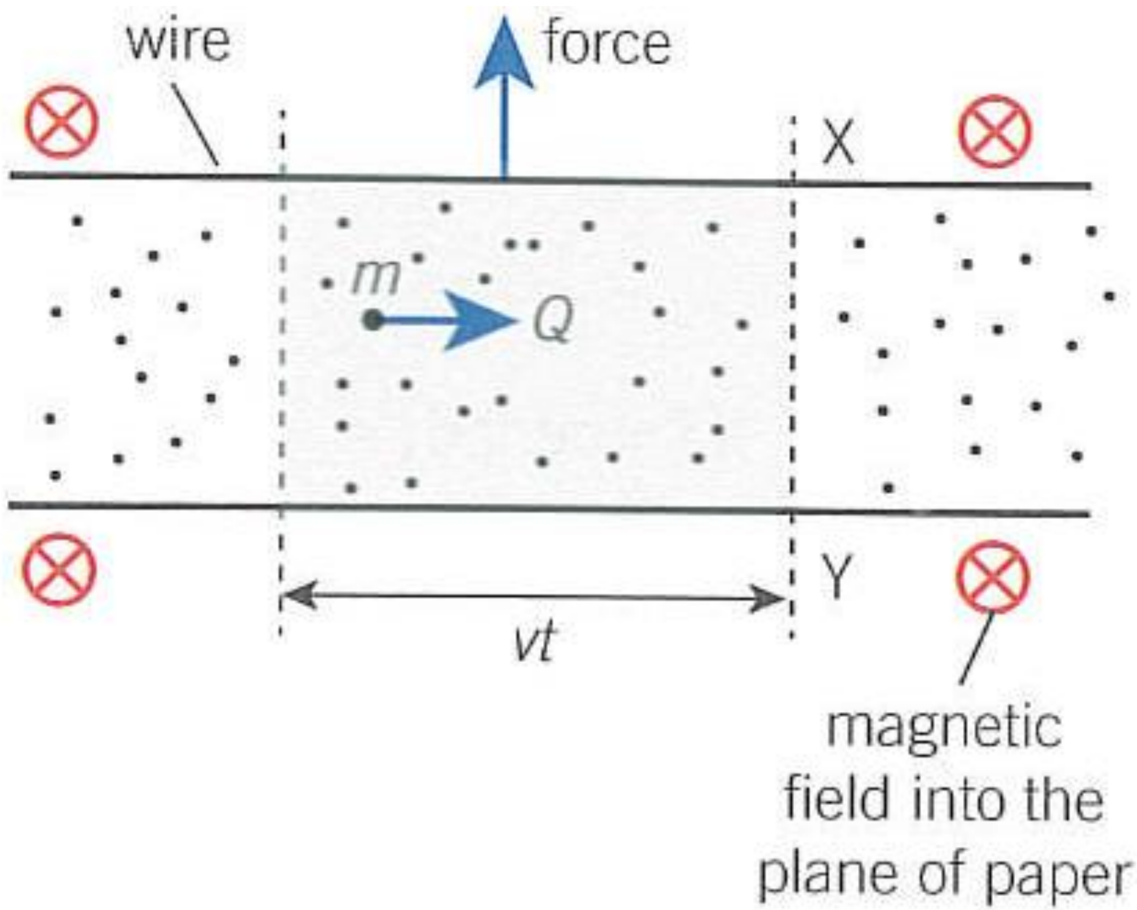
They move in circles

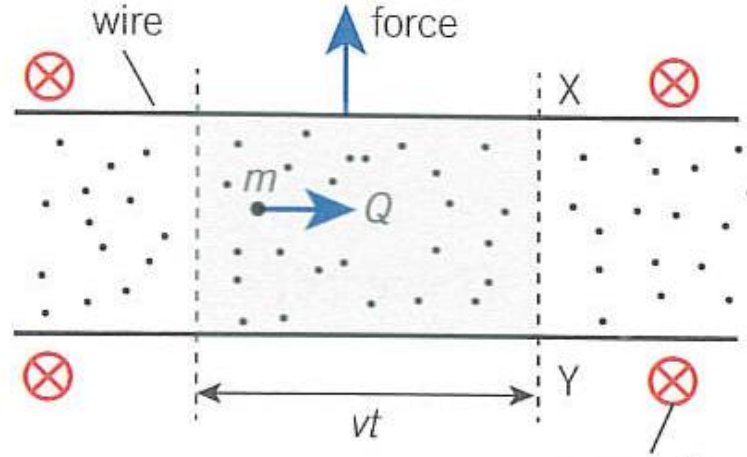
- A charged particle moving through a uniform magnetic field will experience a constant force.
  - The moving charge has its own magnetic field.
- Flemming's Left-hand rule describes the direction of the force.
  - This uses conventional flow though.
- The force is perpendicular to the motion of the particle
  - Acceleration is centripetal.



Example

- An electron with charge Q moving through a wire with length L at speed v over time t through a perpendicular magnetic field with flux density B





The force on the electron is

$$F = BIL$$

In other words:

$$F = BIvt$$

Current is a rate of flow of charge. If there are N particles of charge Q:

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

So the force acting on the wire is:

$$F = B \times \frac{NQ}{t} \times vt = NBvQ$$

So the force acting on each electron is:

$$F = \frac{NBQv}{N} = BvQ$$

For an electron or proton the equation can be rewritten as:

$$F = Bev$$

So how big is the circular path?

If the force on the charged particle is:

$$F = BvQ$$

And this force is a centripetal force:

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

Then:

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

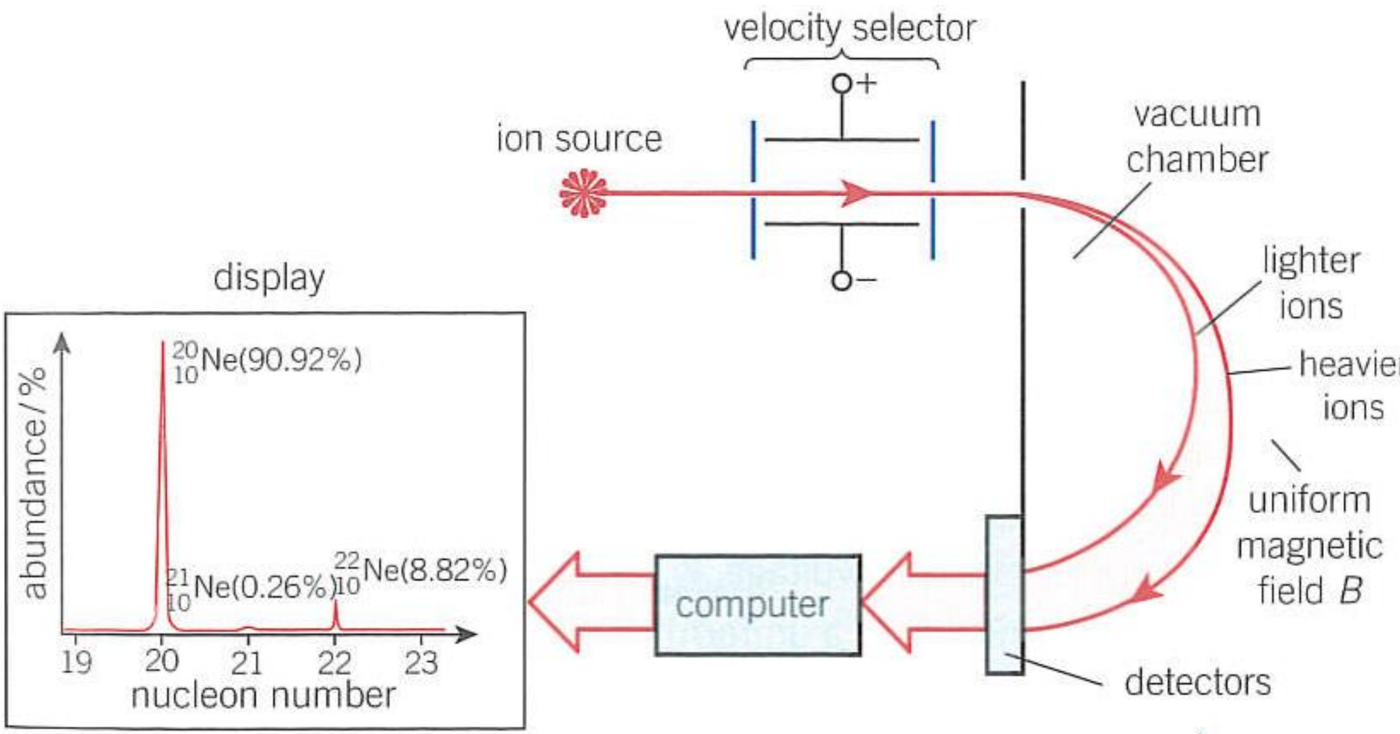
So the radius of the circular path will be:

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

- The faster the particle the larger the radius.
- The higher the mass the larger the radius.
- The stronger the magnetic field the smaller the radius.
- The greater the charge the smaller the radius.

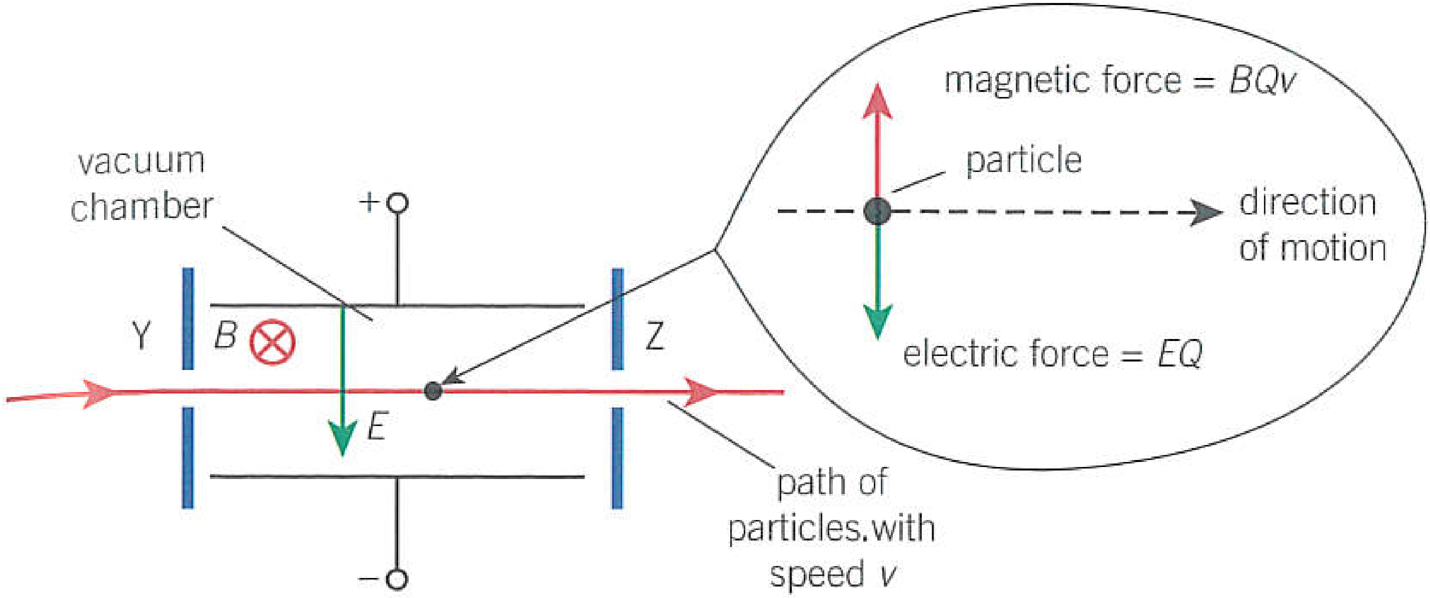
Velocity Selector

- A device which uses electric & magnetic fields to select charged particles of a specific velocity.
- This ensures that particles of the same charge entering a mass spectrometer do so at the same velocity and so are separated according to their mass.

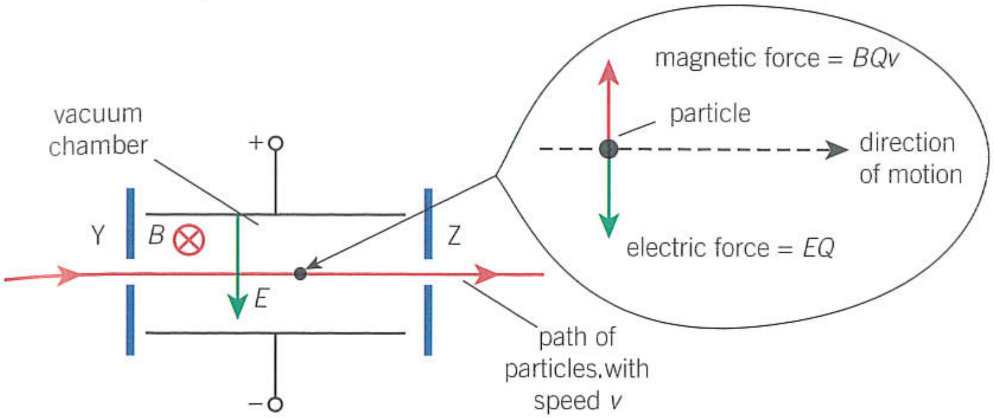


So how does it work?

- Two parallel plates produce a uniform electric field, E.
- A perpendicular magnetic field B is applied.
- Charged particles with various speeds enter slit Y.
- The two fields deflect particles in opposite directions.
- Only those with a specific speed pass through slit Z.



For an undeflected particle:



The opposing forces (electric/magnetic) are balanced:

$$EQ = BQv$$

Charge Q can be cancelled:

$$E = Bv$$

Speed will only depend on the ratio of E to B:

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

- Questions

6.3.2 Motion of Charged Particles (review)

6.3.2 Motion of charged particles

Learning outcomes

Learners should be able to demonstrate and apply their knowledge and understanding of:

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6.3.3 Electromagnetism

6.3.3 Electromagnetism

Learning outcomes

Learners should be able to demonstrate and apply their knowledge and understanding of:

(a) magnetic flux ϕ; the unit weber; $\phi = BA\cos\theta$

(b) magnetic flux linkage

(c) Faraday's law of electromagnetic induction and Lenz's law

(d) **(i)** e.m.f. = − rate of change of magnetic flux linkage; $\mathcal{E} = -\frac{\Delta(N\phi)}{\Delta t}$

(ii) techniques and procedures used to investigate magnetic flux using search coils

(e) simple a.c. generator

(f) **(i)** simple laminated iron-cored transformer; $\frac{n_s}{n_p} = \frac{V_s}{V_p} = \frac{I_p}{I_s}$ for an ideal transformer

(ii) techniques and procedures used to investigate transformers.

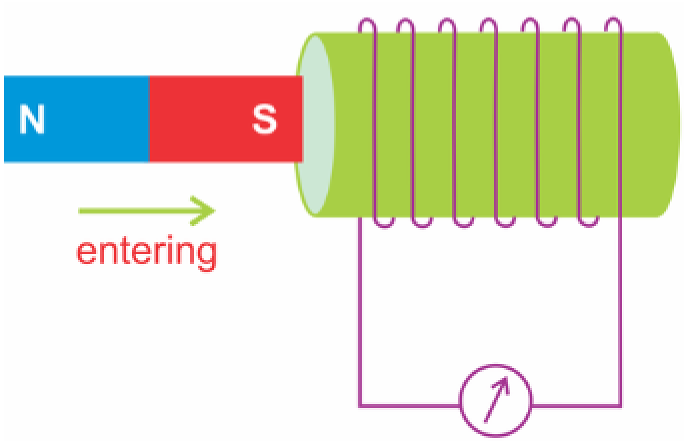
How can we generate electrical currents?

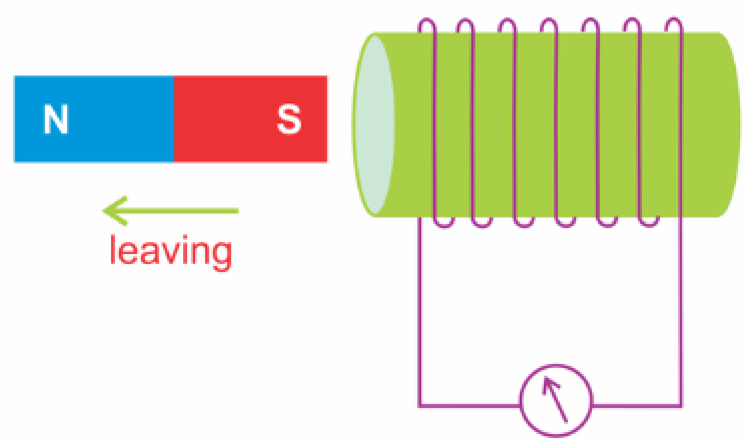
Electromagnetic Induction

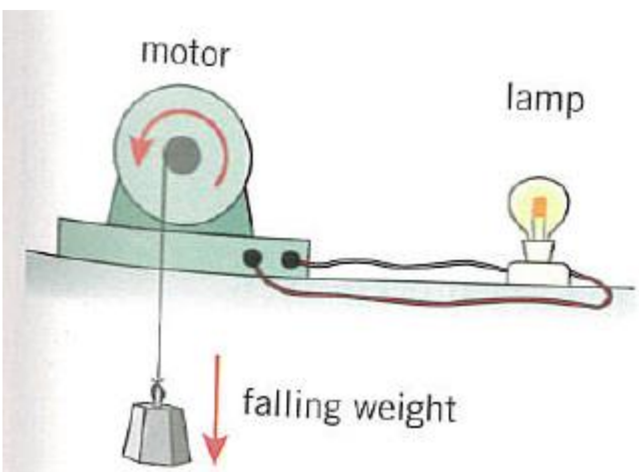
- We’ve seen how current-carrying wires produce magnetic fields.
- But magnetic fields can be used to produce electrical currents.

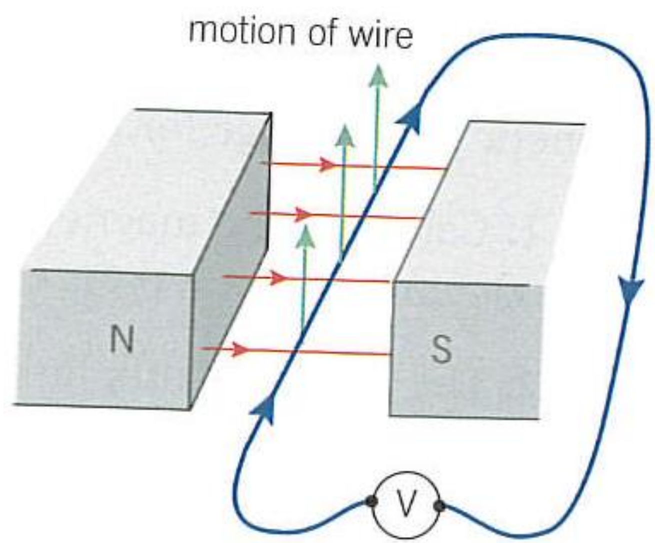
- We just need a coil of wire & a magnet

Show:


N
S
entering


N
S
leaving


motor
lamp
falling weight

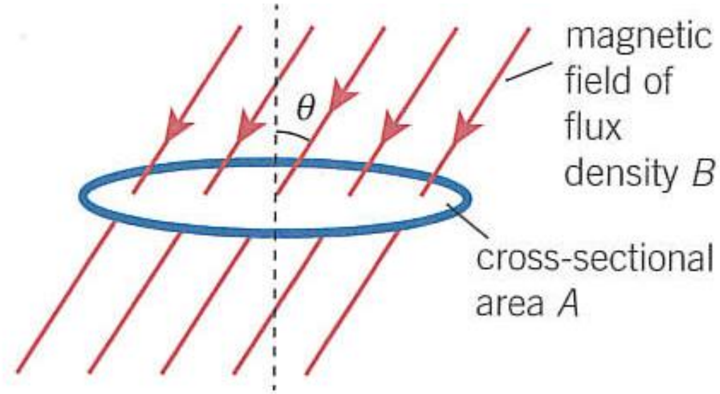

motion of wire
N
S
V

Magnetic Flux, ϕ (Greek letter, Phi)

- We've seen how Magnetic Flux Density is a way we can measure the intensity of a magnetic field.
  - Measured in Tesla (NmA^{-1})
- Magnetic Flux is the product of the Normal Magnetic Flux Density multiplied by the Area over which the magnetic field is being applied.

Magnetic Flux , ϕ

The unit of Magnetic Flux is Tm^2 which has the name of the Weber, Wb.

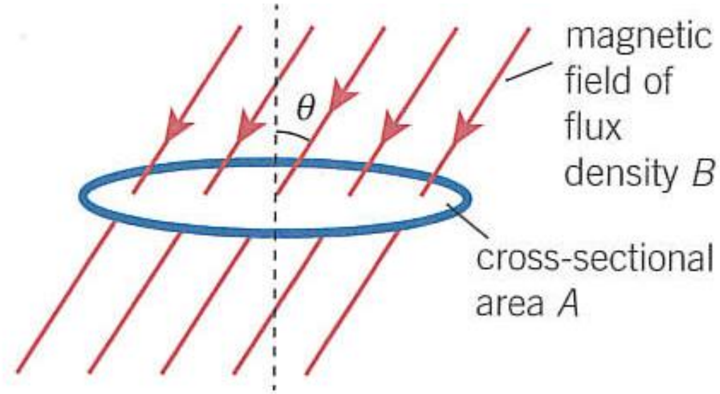


▲ **Figure 5** *Magnetic flux ϕ is the product of the component of the magnetic flux density perpendicular to the area and the cross-sectional area*

- The angle at which the magnetic field passes through the area is crucial, since only the Normal component contributes to Magnetic Flux.
  - Hence:

$$\phi = (B\cos\theta) \times A \quad \text{Or} \quad \phi = BA\cos\theta$$

Magnetic Flux , ϕ



▲ **Figure 5** *Magnetic flux ϕ is the product of the component of the magnetic flux density perpendicular to the area and the cross-sectional area*

- When the magnetic field passes through at right angles:
  - Cos θ will be 1 so:

$$\phi = BA$$

Magnetic Flux Linkage

- The product of the Magnetic Flux, ϕ, and the number of turns in a coil, N.

Magnetic Flux Linkage = $N\phi$

The unit of Magnetic Flux Linkage is also the Weber, Wb, but is sometimes referred to as Weber-Turns

Explaining Electromagnetic induction

- An EMF will be produced when:
  - There is a change to the Magnetic Flux linked to a circuit.
  - Since: $\phi = BA\cos\theta$
  - And EMF will be produced whenever there is a change to B, A or θ

What is Faraday's Law?

Faraday's Law

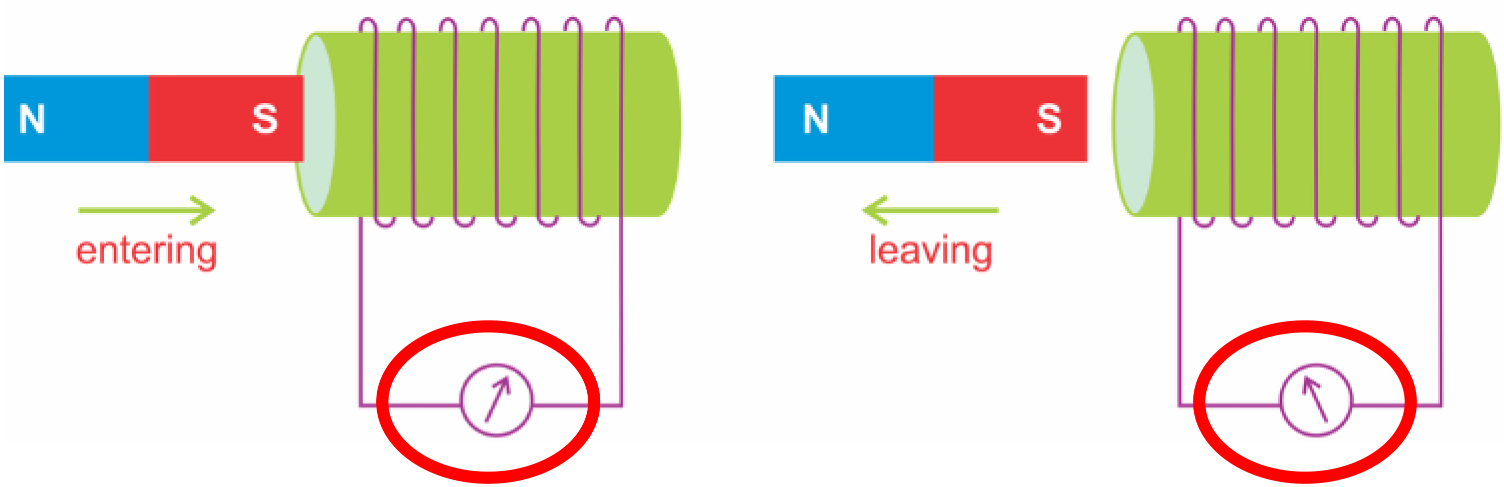
- The magnitude of the induced EMF is directly proportional to the rate of change of the magnetic flux linkage:

$$\varepsilon \propto \frac{\Delta(N\phi)}{\Delta t}$$

The constant of proportionality is -1 as we shall see explained later.

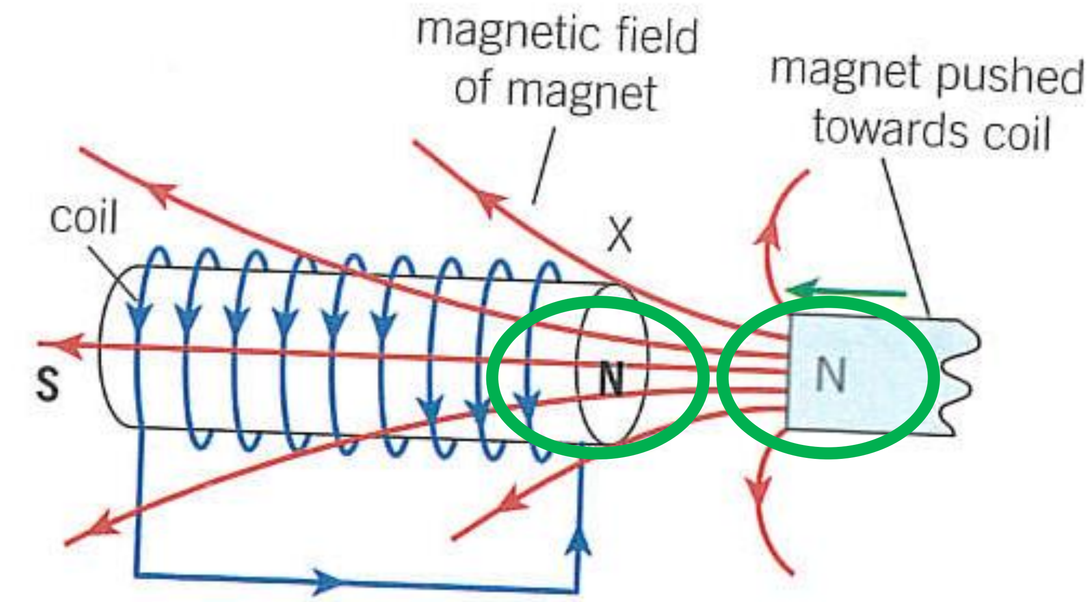
$$\varepsilon = -\frac{\Delta(N\phi)}{\Delta t}$$

What is Lenz’s Law?

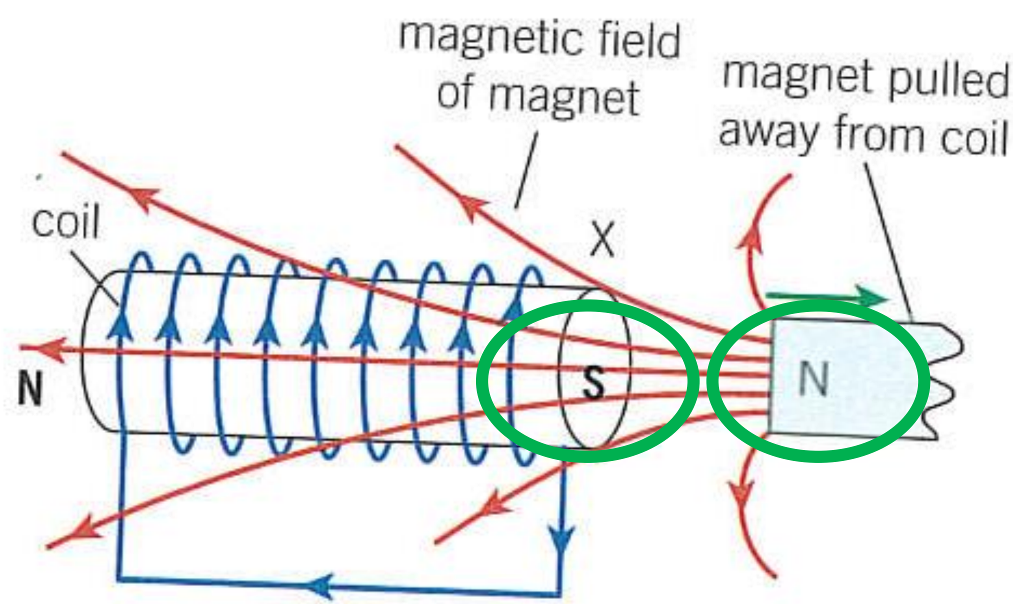


- After pushing a magnet into a coil, the direction of the induced emf is reversed when pulling the magnet back out again.
- The induced current in the coil produces a magnetic field of its own in the shape of that of a bar magnet.
- The induced electrical energy equals the work done pushing the magnet against the induced magnetic field.

- When the magnet is pushed into the coil:
  - The magnetic field induced must be such that it repels the approaching magnet.



- The opposite is true when pulling the magnet back out.
  - Now the induced field attracts the magnet being withdrawn.



Lenz’s Law

- Lenz’s Law describes how energy is being conserved:

- The direction of the induced emf or current is always such as to oppose the change producing it.

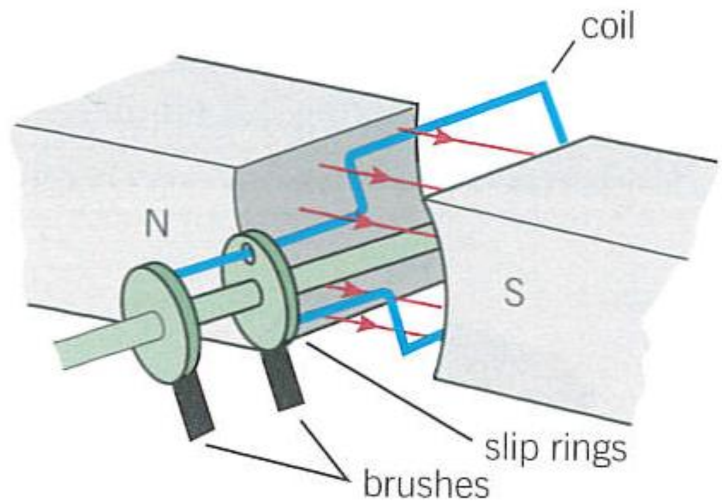
- This has to be the case, otherwise electrical energy would be created out of nowhere.

What is
Cole’s Law?

- Thinly sliced cabbage, onion & carrot mixed with mayonnaise.

Can we explain an ac generator with Faraday’s Law?

An AC Generator



- A rectangular coil of cross sectional area, A, containing N turns rotating in a uniform magnetic field of flux density, B.

- Recall:
  - Magnetic Flux is the product of the Normal Magnetic Flux Density multiplied by the Area over which the magnetic field is being applied.

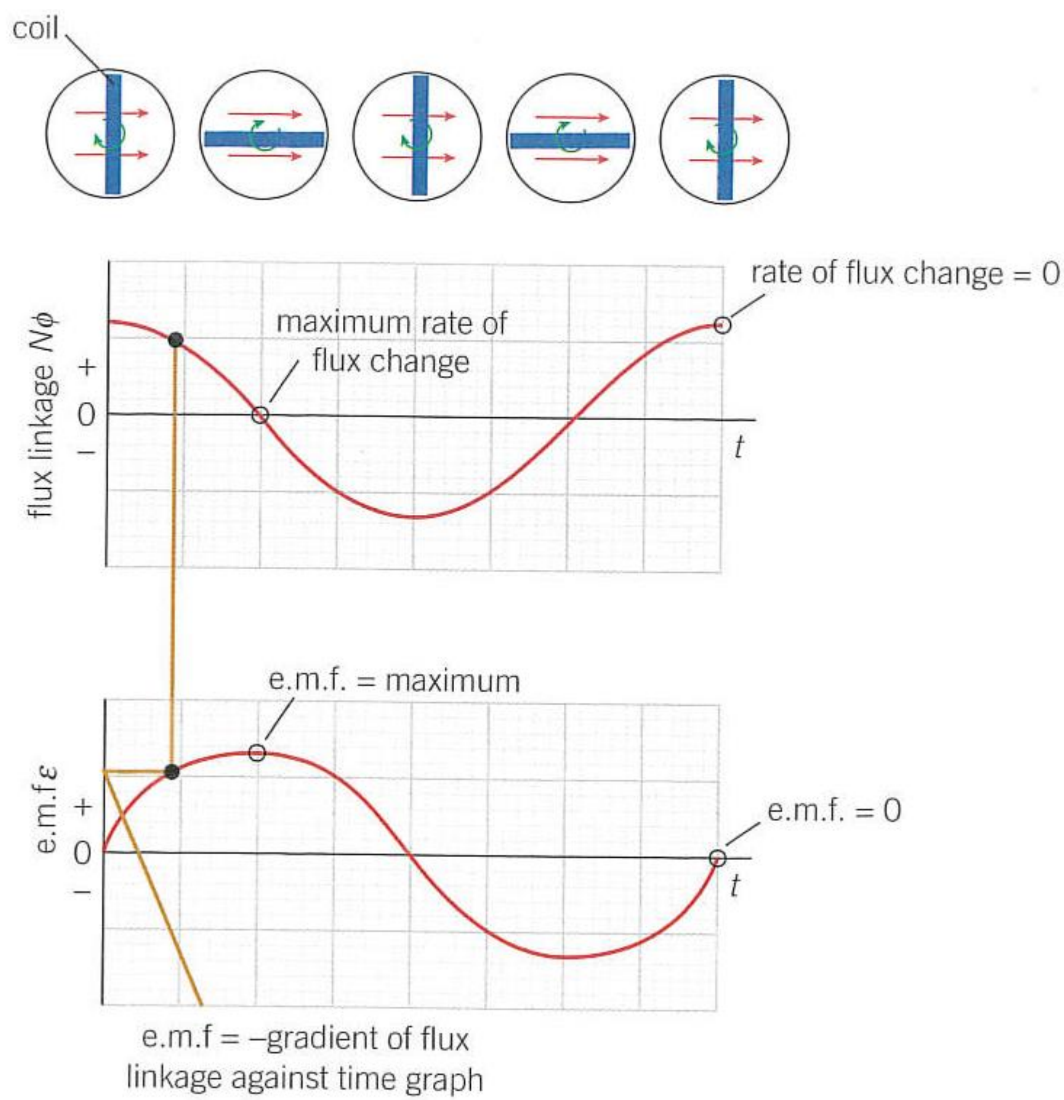
$\phi = BA\cos\theta$ Magnetic Flux Linkage = Nϕ

Since: Magnetic Flux Linkage = N(BAcosθ)

- As θ changes:
  - The induced emf varies according to the rate of change of magnetic flux linkage

$$\varepsilon = -\frac{\Delta(BAN\cos\theta)}{\Delta t}$$

$$\varepsilon \propto -\frac{\Delta(\cos\theta)}{\Delta t}$$



Transformers

(not robots in disguise).

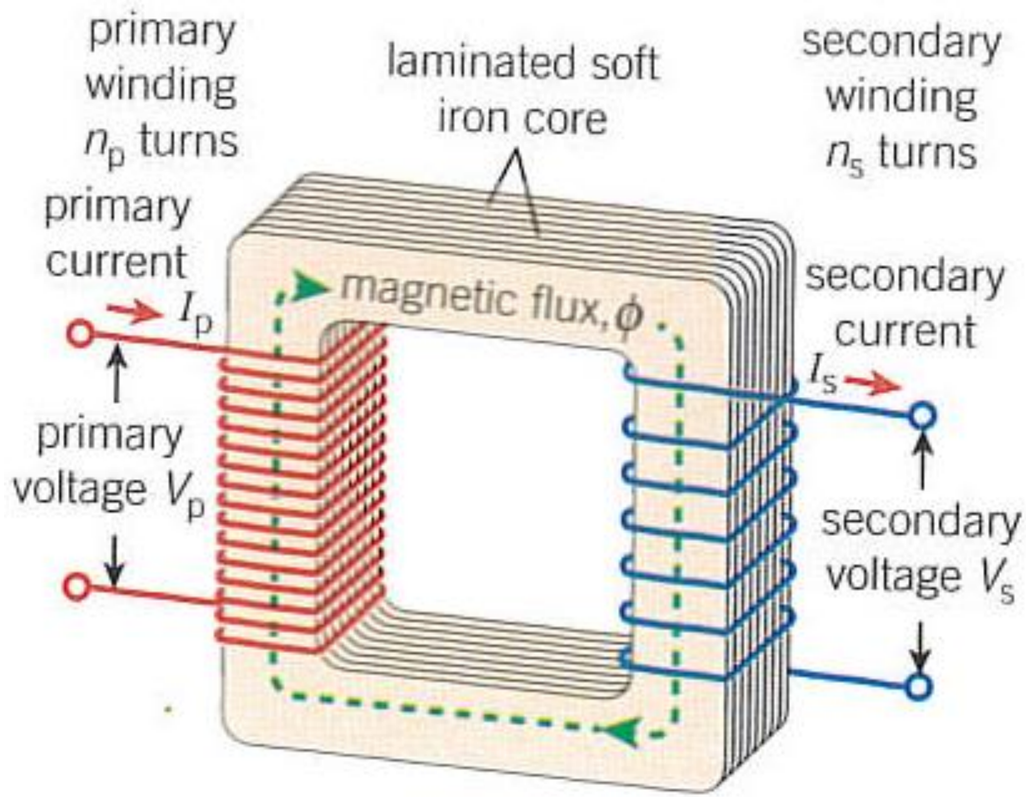
Transformers change voltages

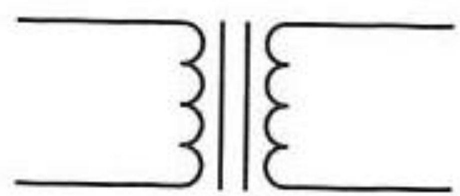
- Step-up and step-down transformers are used to change the voltages of AC supplies.
  - Phone chargers step down from 230v to about 5v
  - Power stations step up from about 25000v to about 400000v for supplying to the National Grid.

How do they work?

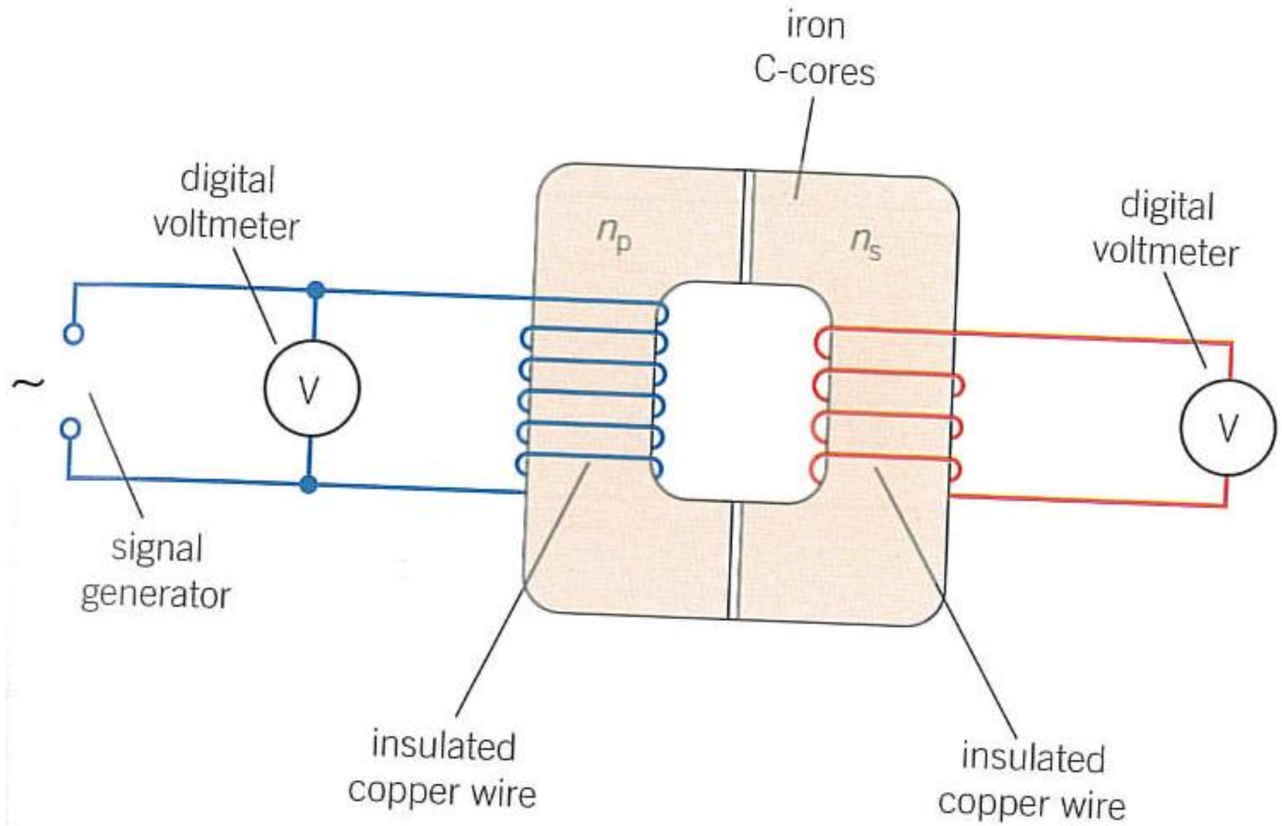
- AC input to a primary coil wrapped around an iron core.
- Produces a varying magnetic flux in the core.
- Produces a varying emf in the secondary coil.
- Input voltage & output voltage are related by the turn ratio.

$$\frac{n_s}{n_p} = \frac{V_s}{V_p}$$





Investigations



Efficiencies of Transformers

- Transformer efficiencies can be made to be almost 100%:
  - Use of low resistance coil wires to reduce heating.
  - Use of laminated iron core to reduce the currents induced in the core itself (eddy currents).
  - Use of soft iron for the core which magnetises/demagnetises easily.

If efficiency is 100%

$P_s = P_p$ So $V_s I_s = V_p I_p$

$$\frac{I_p}{I_s} = \frac{V_s}{V_p}$$

- Questions
- Practice questions

6.3.3 Electromagnetism (review)

6.3.3 Electromagnetism

Learning outcomes

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