9749 H2 Physics

Topic 16 : Electromagnetism

DUNMAN HIGH SCHOOL

Year 6 (2025)

Guiding Questions

- What is a magnet? Are there "magnetic" charges?
- Do magnetic fields have effects on electric charges?
- What do field lines represent? Do field lines represent similar things for electric fields and magnetic fields?
- Why is the word "flux" used when talking about a magnetic field?

Content

- Concept of a magnetic field
- Magnetic fields due to currents
- Force on a current-carrying conductor
- Force between current-carrying conductors
- Force on a charge

Learning Outcomes

Candidates should be able to:

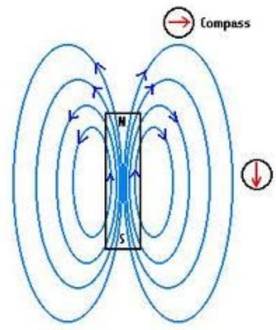
Magnetic Field	(a)	show an understanding that a magnetic field is an example of a field of force produced either by current-carrying conductors or by permanent magnets
	(b)	sketch flux patterns due to currents in a long straight wire, a flat circular coil and a long solenoid
	(g)	define magnetic flux density
	(c)	use $B = \dfrac{\mu_o I}{2\pi d}$, $B = \dfrac{\mu_o N I}{2r}$ and $B = \mu_o n I$ for the flux densities of the fields due to currents in a long straight wire, a flat circular coil and a long solenoid respectively
	(d)	show an understanding that the magnetic field due to a solenoid may be influenced by the presence of a ferrous core
Magnetic force on current-carrying conductors	(e)	show an understanding that a current-carrying conductor placed in a magnetic field might experience a force
	(f)	recall and solve problems using the equation $F = BIL \sin\theta$, with directions as interpreted by Fleming's left-hand rule
	(h)	show an understanding of how the force on a current-carrying conductor can be used to measure the flux density of a magnetic field using a current balance
	(i)	explain the forces between current-carrying conductors and predict the direction of the forces
Magnetic force on moving charges	(j)	predict the direction of a force on a charge moving in a magnetic field
	(k)	recall and solve problems using $F = BQv \sin\theta$
	(l)	describe and analyse deflections of beams of charged particles by uniform electric and uniform magnetic fields
	(m)	explain how electric and magnetic fields can be used in velocity selection for charged particles.

1. Magnetic Fields due to Current

(a) **show an understanding that a magnetic field is an example of a field of force produced either by current-carrying conductors or by permanent magnets**
(b) **sketch flux patterns due to currents in a long straight wire, a flat circular coil and a long solenoid**

1.1 Magnetic Effect of a Current

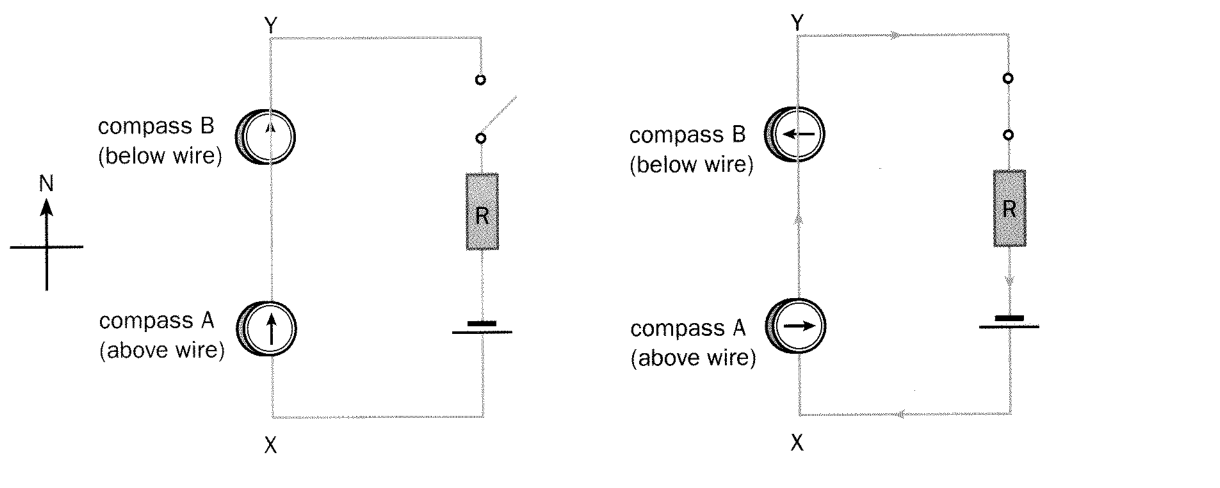
A magnetic field can be produced by:

(i) *Permanent magnets*	(ii) *Current-carrying conductors*
 The magnetic field around a permanent magnet [1] can be seen by sprinkling some iron filings around it.	In 1820, Hans Christian Oersted, a Danish professor, discovered the magnetic effect of an electric current by chance. During a class demonstration, he noticed that when a current was flowing through a wire, it caused the needle of a compass nearby to be deflected. This indicated the presence of a magnetic field. Oersted's observation eventually led to the discovery of **electromagnetism** – the relationship between electricity and magnetism.

1.2 Oersted's experiment

Fig. 1 shows the result of Oersted's experiment. It showed that a magnetic field was present when a current flowed through wire XY. The wire XY was placed in the north-south direction.

Note:
The assumption in the experiment in Fig. 1 is that the Earth's magnetic field is negligible compared to the ones generated by the wire in the vicinity of the compass.



No current flowed through XY. The needles of both compasses pointed to the north	Current flowed through XY. The needle of compass A (placed above the wire) pointed to the east. The needle of compass B (placed below the wire) pointed to the west.
(a) Open Circuit	(b) Closed Circuit

Fig. 1: The positions of the needles of compasses A and B in Oersted's experiment

[1] By convention, magnetic field lines leave the north pole and enter the south pole of a magnet; the field lines do not start or end at the north or south poles of a magnet, they continue to go from south pole to the north pole in the magnet.

1.3 Properties of Fields [2]

The following are characteristics of field lines:

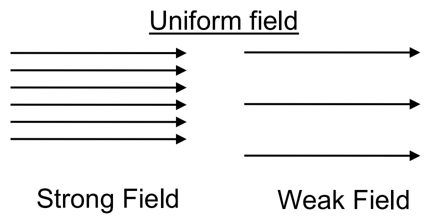
1. They are imaginary.

2. A strong field is represented by lines that are closer to one another; a weak field is represented by lines that are further apart.

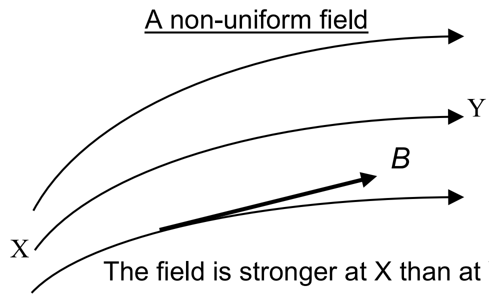
3. Field lines cannot cross one another (since this would imply that at the cross-over point, the field would have two directions).

4. The **direction of a field at a point** in space is along a ***tangent*** to the field line at that point.

5. Field lines can be directed **out of the paper (represented by dots)** or **into the paper (represented by crosses)**. The field lines will be perpendicular to the paper.

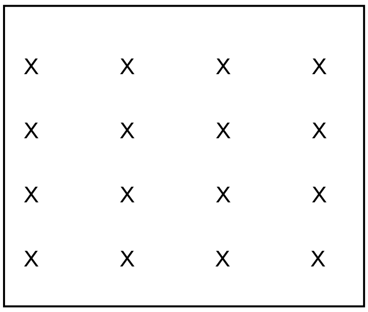


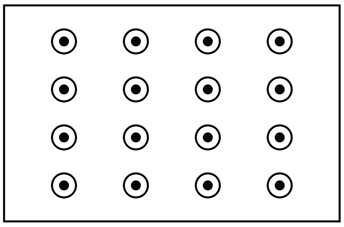
A uniform field has the **same field strength** within it.



The field is stronger at X than at Y

Field lines pointing into the paper.





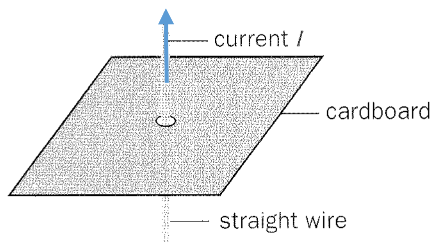
Field lines pointing out of the paper.

1.4 Magnetic flux pattern around a long straight current-carrying wire

An experiment can be conducted to plot the magnetic flux pattern around a long straight current-carrying wire (Fig. 2a➔b➔c).

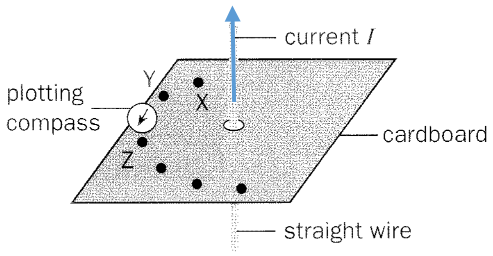
The magnetic flux pattern obtained consisted of concentric circles (Fig 2c)

The circles nearer the wire were closer to one another. This implies that the magnetic flux density [3] was greater at regions nearer the wire.

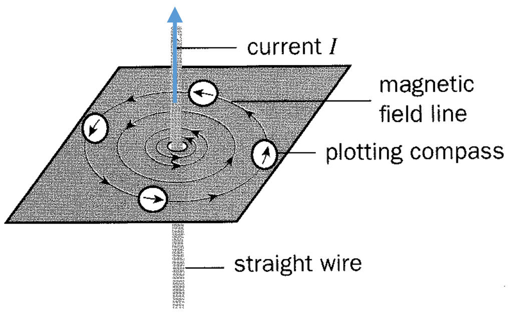


(a) A wire threaded through a cardboard sheet

[2] Michael Faraday (1791–1867) introduced field lines as a way to represent fields. This creative conceptual model provides us with a powerful tool for thinking and communication about interaction at a distance.
[3] The term 'magnetic field strength' is not used nowadays. The term used to *represent* field strength in a magnetic field is called '***magnetic flux density***'.



(b) The positions of the S and N ends of the compass needle are marked with pencil dots.



(c) The magnetic flux pattern of a long straight current-carrying wire

Fig. 2: Experiment to determine the magnetic flux pattern of a long straight current-carrying wire

1.5 Right-Hand Grip Rule (RHGR)

The RHGR is a common mnemonic for understanding notation conventions for physical quantities in 3 dimensions; it states that

Version 1: when the thumb of the right-hand points in the direction of the conventional current, the curled fingers point in the direction of the magnetic field lines (Fig. 3a).

Version 2: when the thumb of the right-hand points in the direction of the magnetic field lines, the curled fingers point in the direction of the conventional current (Fig. 3b).

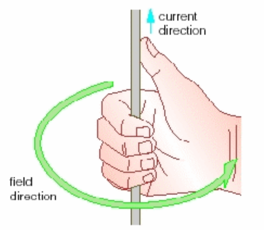


Fig. 3a: Version 1 of RHGR

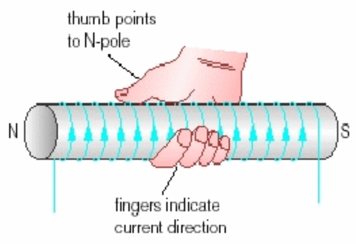


Fig. 3b: Version 2 of RHGR

Both versions of RHGR are correct and which version to use is a matter of convenience in different circumstances.

It can be applied to

(a) **a long straight current-carrying wire** (Fig. 4),
easier to use "Version 1 of RHGR"

(b) **a flat circular current-carrying coil** (Fig. 5), and
easier to use "Version 2 of RHGR".

(c) **a long current-carrying solenoid (coils of wire)** (Fig. 6).
easier to use "Version 2 of RHGR".

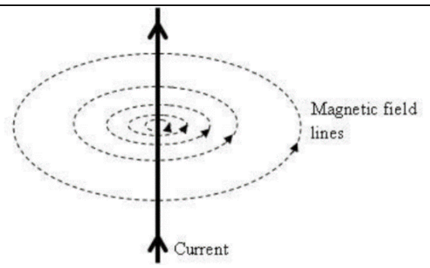


Fig. 4: RHGR for a long straight current-carrying wire

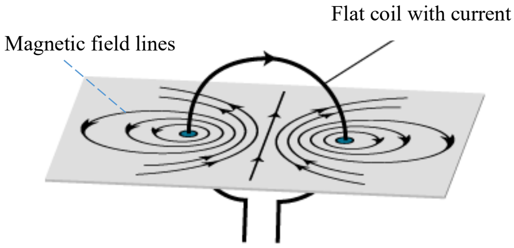


Fig. 5: RHGR for a flat circular current-carrying coil

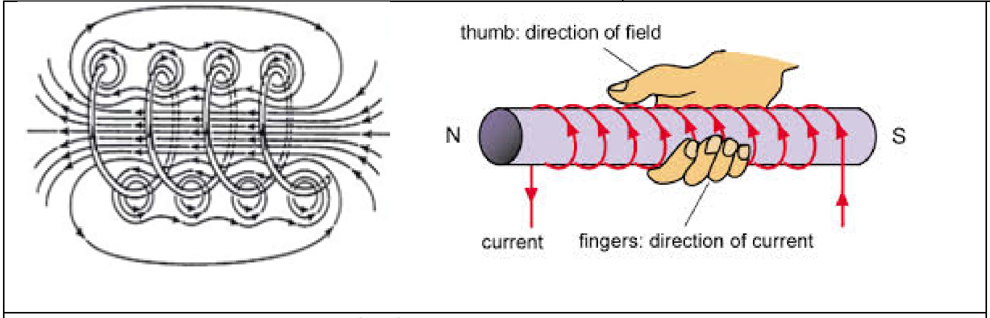


Fig. 6: RHGR for a long current-carrying solenoid

Note:
Many of the magnetic flux pattern shown in the figures are in 3D for illustrative purposes only (e.g., Figs. 2c, 3a, 3b, 4, 5 & 6). In exams, Cambridge has so far required 2D answers from students for sketches of magnetic flux patterns (e.g., Figs. 7, 8, 12a, 12b, 12d & 12e).

From Fig. 6, the following observations are made:-

- The magnetic flux pattern of a long current-carrying solenoid resembles that of a bar magnet. Thus, the long solenoid acts like a bar magnet. It has two poles and can be used as an **electromagnet**.

- The magnetic flux density inside the long current-carrying solenoid is closer than the magnetic flux density outside. This means that the magnetic flux density inside the long current-carrying solenoid is greater. The magnetic flux density inside the long current-carrying solenoid can be taken to be **uniform**.

1.6 Factors that affect the direction and strength of a magnetic field around a long straight current-carrying wire [4]

The factors that affect the direction and strength of a magnetic field around a long straight current-carrying wire (Fig. 4) viewed from the top are illustrated in Fig. 7 and Fig. 8.

(a) Direction of current reversed

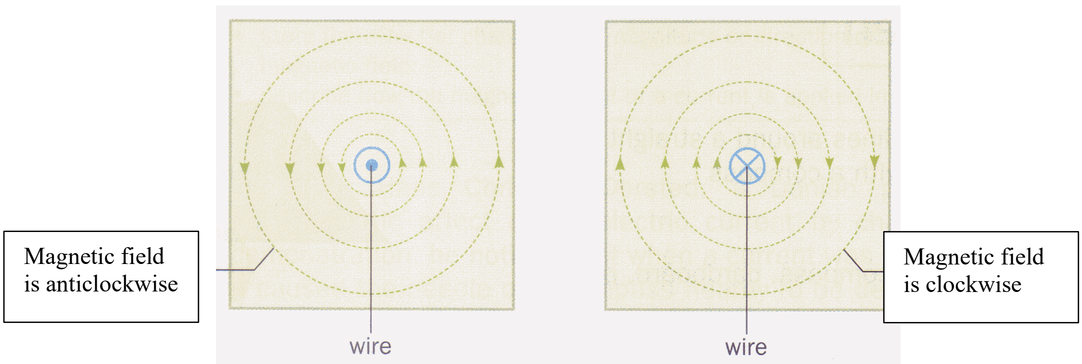


Fig. 7: When the direction of the current is reversed, the direction of the magnetic field is reversed.

[4] Cambridge had set a couple of questions on this learning outcome, especially for the case of a long straight current-carrying wire (Fig. 4) viewed from the top. Ensure that you sketch your diagrams properly and pay attention to details:
1. Spacing between field lines indicate field strength; &
2. Field lines should not cross each other.
Get a compass (drafting), if necessary, to draw perfect circles.

(b) Magnitude of current increased

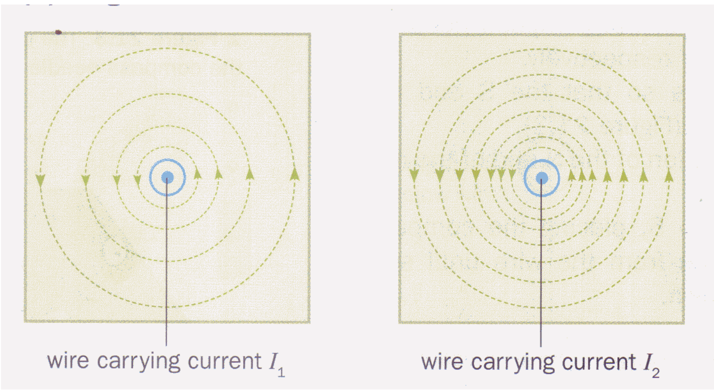


Fig. 8: When the current is increased from I_1 to I_2, the magnetic flux density increases.

(d) show an understanding that the magnetic field due to a solenoid may be influenced by the presence of a ferrous core

1.7 Factors that affect the strength of a magnetic field inside a long current-carrying solenoid

A ferrous ("soft" iron) core has the effect of increasing the magnetic flux density inside a long solenoid compared to the air core solenoid on the left in Fig. 9.

This is because the magnetic permeability of the ferrous core ($k\mu_o$) is greater than the magnetic permeability of air (μ_o).

Other methods to increase the magnetic flux density of the long solenoid include:-

- Increasing the current I flowing through the long solenoid;
- Increasing the number of turns per unit length n of the solenoid.

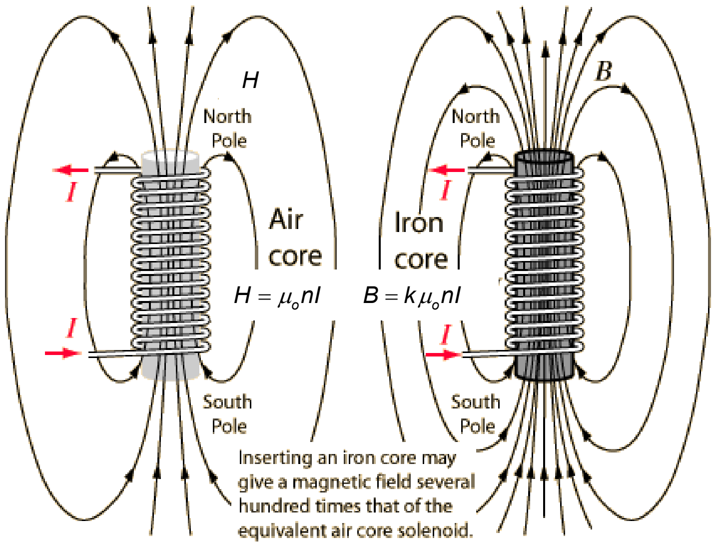
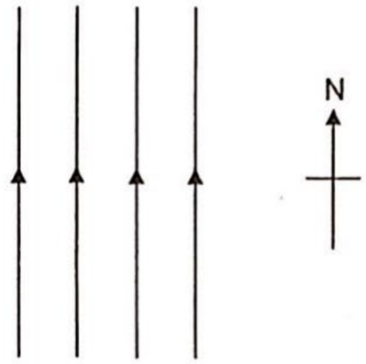


Fig. 9 (Left) Solenoid with air core
(Right) Solenoid with ferrous core

Quiz 1

Fig. (a) below shows the Earth's local field in a horizontal plane. Sketch in Fig. (b) the combined field due to the Earth and a bar magnet with its N pole pointing N. Indicate with a cross "X" the positions of neutral points where the resultant field is zero.

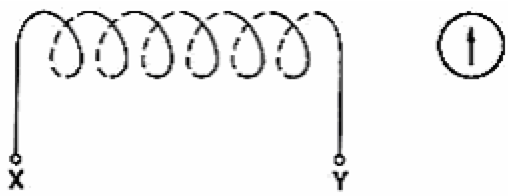


(a) Earth's local field in a horizontal plane

(b) Effect of Earth's field on that of a bar magnet.
X = neutral point

<u>Example 1 (J94/I/17)</u>:

A plotting compass is placed near a solenoid. When there is no current in the solenoid, the compass needle points due north as shown.

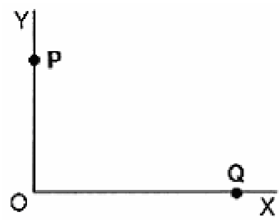


When there is a current from X to Y, the magnetic flux density of the solenoid at the compass is equal in magnitude to the Earth's magnetic flux density at that point.

In which direction does the plotting compass point?

A **B** **C** **D**

<u>Example 2 (J00/I/19)</u>:



The diagram shows a flat surface with lines OX and OY at right angles to each other.

Which current in a straight conductor will produce a magnetic field at O in the direction OX?

A At P into the plane of the diagram
B At P out of the plane of the diagram
C At Q into the plane of the diagram
D At Q out of the plane of the diagram

(e) show an understanding that a current-carrying conductor placed in a magnetic field might experience a force

2. The Motor Effect – Force due to Magnetic Fields

2.1 Possible Forces due to Magnetic Fields

A **magnetic field** (of force) is a region of space within which a *non-contact* (magnetic) force

- MUST act on a permanent magnet or ferromagnetic material, and
- MIGHT act on a current-carrying conductor or a moving charge.

Why ***might*** and not **MUST** act like in gravitational and electric fields?

In the cases of a **current-carrying conductor** and a **moving charge**, the presence of a force is dependent on the **direction of motion of the charge(s)** with respect to the **direction of the magnetic field** concerned, there is **no force** if these directions are **parallel**. (Fig. 10)

The similarity in interaction of a **current-carrying conductor** and a **moving charge** with a **magnetic field** is not surprising once the definition of current is considered:

Current is the rate of flow of charge.

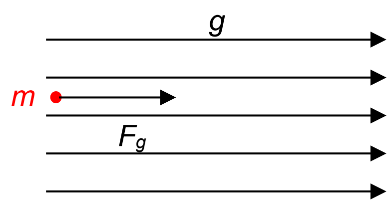
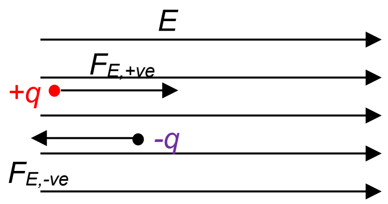
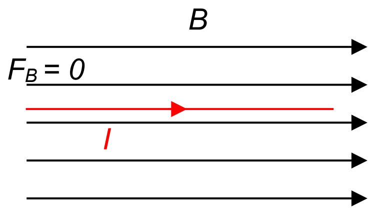
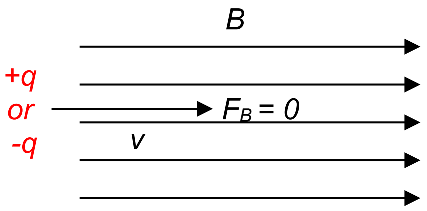
	
(a) Non-zero gravitational force F_g acting on a point mass *m* placed in a uniform gravitational field of field strength *g*	(b) Non-zero electric force $F_{E,+ve}$ and $F_{E,-ve}$ acting on a originally stationary positive point charge $+q$ and a originally stationary negative point charge $-q$ respectively in a uniform electric field of field strength *E*
	
(c) The magnetic force F_B, acting on a conductor carrying a current *I* placed parallel to a uniform magnetic field of flux density *B*, is zero.	(d) The magnetic force F_B, acting on a moving charge (whether positive $+q$ or negative $-q$) whose velocity *v* is parallel to a uniform magnetic field of flux density *B*, is zero.

Fig. 10: Illustration of field interaction with objects of different properties

(g) define magnetic flux density

2.2 Definitions for magnetic flux density and the tesla

The **magnetic flux density of a magnetic field** is defined as the **magnetic force per unit current per unit length** acting on a **straight** current-carrying conductor placed **perpendicular** to a **uniform magnetic field**.

Note:
The definition of *magnetic flux density* is frequently tested by Cambridge.

Mathematically,

$$B = \frac{F}{IL \sin\theta}$$

where, B = magnetic flux density,
F = magnetic force acting on the conductor
I = current, L = length of conductor, θ = angle between B and I

The unit of B is tesla (symbol: T, named after Nikola Tesla).

The tesla is the magnetic flux density of a magnetic field when the **magnetic force per unit current per unit length** acting on a **straight** current-carrying conductor placed **perpendicular** to a **uniform magnetic field** is **one newton per ampere per metre.**

i.e.

$$1\text{ T} = \frac{1\text{ N}}{(1\text{A})(1\text{m})\sin 90^\circ}$$

Note:
The definition of *tesla* is no longer necessary in the syllabus, but it is useful for questions involving dimensional analysis.

(f) recall and solve problems using the equation *F = BIL* sin θ, with directions as interpreted by Fleming's left-hand rule.

2.3 Magnitude and direction of Magnetic Force – Current-carrying Conductor

From the definition of B, the **magnitude** of the magnetic force acting on a current-carrying conductor placed at an angle θ to the magnetic field can be expressed as

$$F = BIL \sin\theta$$

Hence, $F_{max} = BIL$ when $\theta = 90^\circ$ (**I is perpendicular to B**)
$F_{min} = 0$ when $\theta = 0^\circ$ or $\theta = 180^\circ$ (**I is parallel to B**)

Fleming's Left-Hand Rule (FLHR)(for electric motors) shows the direction of the *magnetic force (F)* acting on a conductor carrying a *current (I)* in a *magnetic field (B).*

The left hand is held with the *thumb*, *index finger* and *middle finger* mutually at right angles:

- The *thumb* represents, and points in the direction of, the magnetic force *F.*
- The *index finger* represents, and points in the direction of, the magnetic flux density *B.*
- The *middle finger* represents, and points in the direction of, *conventional* current *I.*

What if the current and the magnetic flux density are not perpendicular to each other i.e., the angle between them θ is not 90°?

If so, the magnetic flux density can be resolved such that it has components parallel and perpendicular to the current as shown in Fig. 11 (middle diagram).

Note:
When applying FLHR (for electric motors), think about the 'cause and effect':
- Cause: a conductor that carries a current;
- Effect: magnetic force acting on the current-carrying conductor.

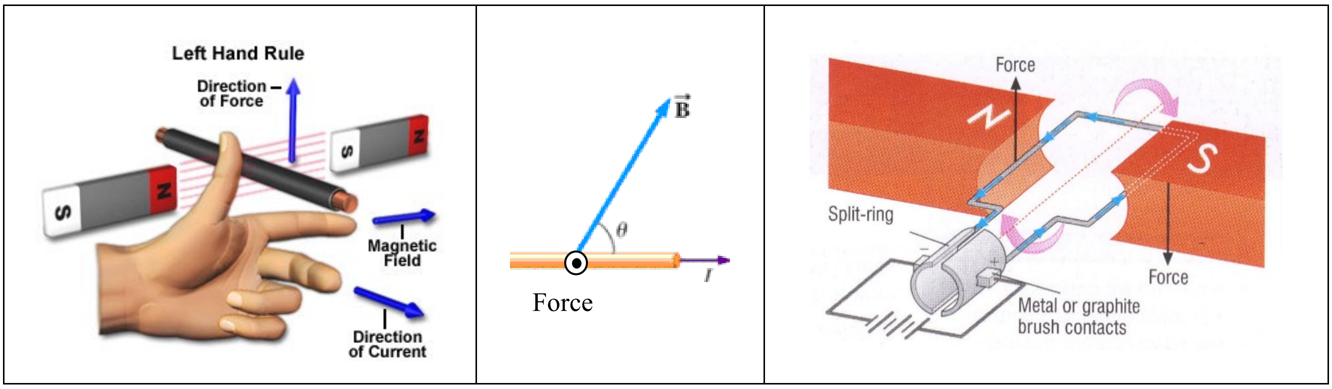
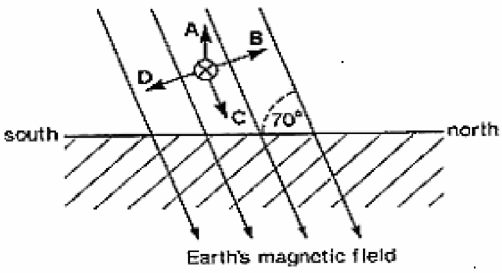


Fig. 11: Illustrations of applications of FLHR;

<u>Example 3 (J95/I/18)</u>:

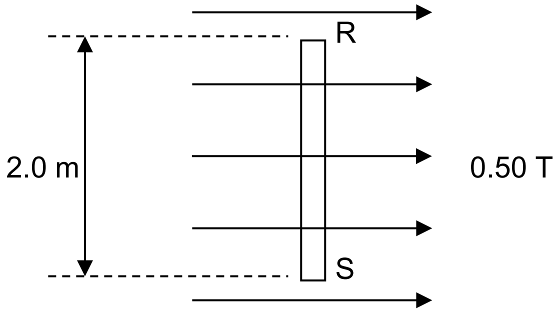
A horizontal power cable carries a steady current in an East-to-West direction i.e., into the plane of the diagram.

Which arrow shows the direction of the force on the cable caused by the Earth's magnetic field, in a region where this field is at 70° to the horizontal?



<u>Example 4 (N98/I/19)</u>:

The diagram shows a current-carrying conductor RS of length 2.0 m placed perpendicularly to a magnetic field of flux density 0.50 T. The resulting force on the conductor is 1.0 N acting into the plane of the paper.



What is the magnitude and direction of the current?

A 1.0 A from R to S
B 1.0 A from S to R
C 2.0 A from R to S
D 2.0 A from S to R

(i) explain the forces between current-carrying conductors and predict the direction of the forces.

In a *gravitational* field, forces between 2 point masses are always *attractive*.

In an *electric* field, forces between 2 point charges are as follows:
like charges *repel*, unlike charges *attract*.

In a *magnetic* field, when we consider forces between 2 current-carrying conductors which are parallel and very thin:

Case I: If the currents are in the <u>*same* direction</u>, they *attract*,
Case II: If the currents are in <u>*opposite* directions</u>, they *repel*.

Explanation for **Case I**:

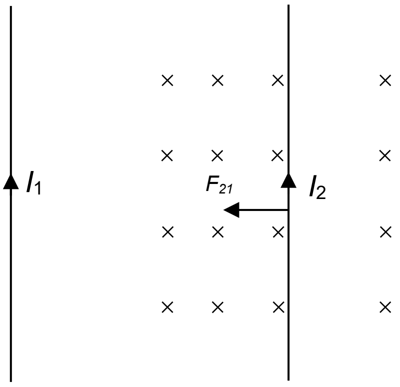


Fig. 12a: Illustration of force on wire 2

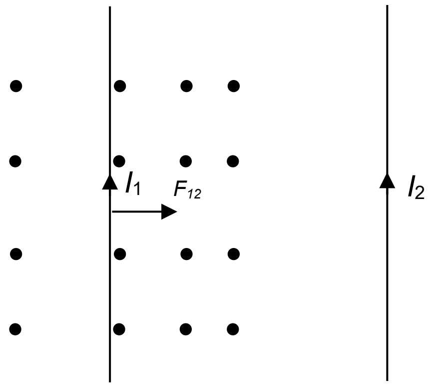
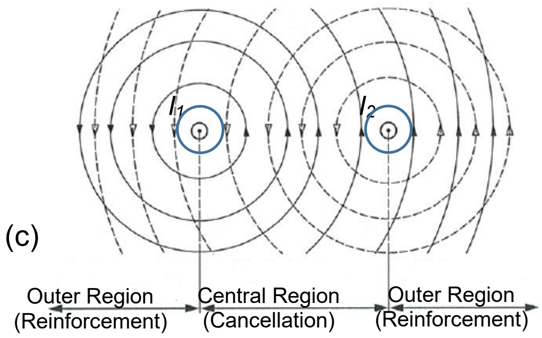


Fig. 12b: Illustration of force on wire 1

Consider Fig. 12a, in the region on the right of I_1, the direction of B due to I_1 is into the paper (represented by x x). In this region, the direction of the force F_{21} acting on I_2, by FLHR, is to the left, i.e. towards I_1.

Consider Fig. 12b, in the region on the left of I_2, the direction of B due to I_2 is out of the paper (represented by • •). In this region, the direction of the force F_{12} acting on I_1, by FLHR, is to the right, i.e. towards I_2.

The resultant magnetic field lines in the *central* region will be *further apart* because of the <u>cancellation</u> of magnetic field due to I_1 and I_2. In the *outer* regions, the resultant magnetic field lines will be *closer* as the field lines due to I_1 and I_2 <u>reinforce</u> each other. (Fig. 12c & 12d)



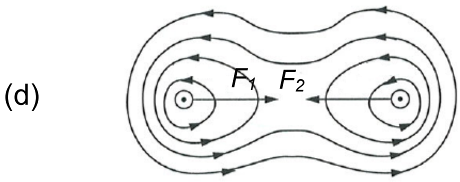


Fig. 12c: Top view of cancellation and reinforcement of magnetic field lines
Fig. 12d: Resultant magnetic field for Case I

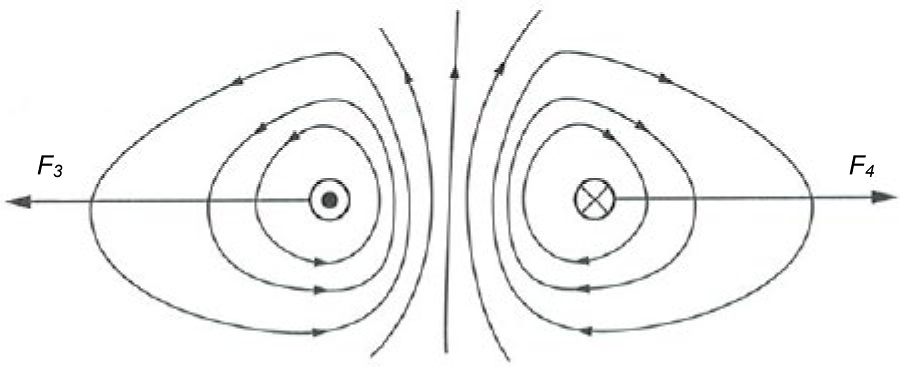
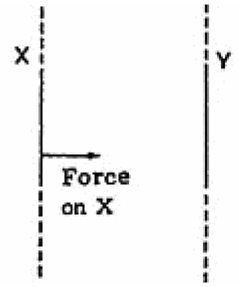


Fig. 12e: Resultant magnetic field for Case II

Example 5 (J79/II/20):



Two long, parallel wires X and Y carry currents of 3.0 A and 5.0 A respectively. The force per unit length experienced by X is 5.0×10^{-5} N to the right as shown in the diagram.

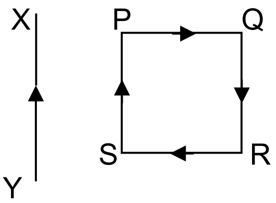
The force per unit length experienced by wire Y is

A 2.0×10^{-5} N to the left
B 3.0×10^{-5} N to the right
C 5.0×10^{-5} N to the left
D 5.0×10^{-5} N to the right

Example 6 (N89/I/19):

A long straight wire XY lies in the same plane as a square loop of wire PQRS which is free to move. The sides of PS and QR are initially parallel to XY.

The wire and loop carry steady currents as shown in the diagram.



What will be the effect on the loop?

A It will move towards the long wire.
B It will move away from the long wire.
C It will rotate about an axis parallel to XY.
D It will be unaffected.

(j) predict the direction of the force acting on a charge moving in a magnetic field.

2.4.1 Magnitude and direction of Magnetic Force – Moving Charges

The direction of the force acting on a moving charge also follows **FLHR**.

By convention, the direction of *I* is given by the direction of flow of positive charges.

Hence the direction of *I* is replaced by the direction of *v*, which represents the velocity of the moving **positive** charge (Fig. 13a).

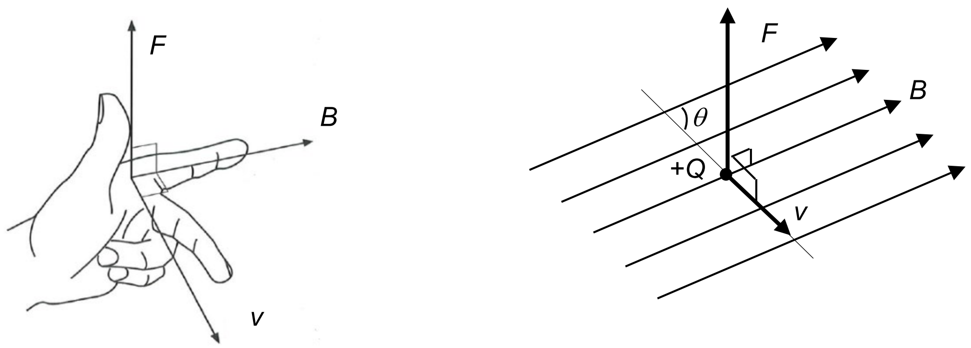


Fig. 13a: Illustrations of applications of FLHR (for positive charges)

For a **negative** charge, the direction of *I* is in the *opposite direction* to the *direction of flow* of *negative charge*. The **direction of the force is reversed.** (Fig. 13b)

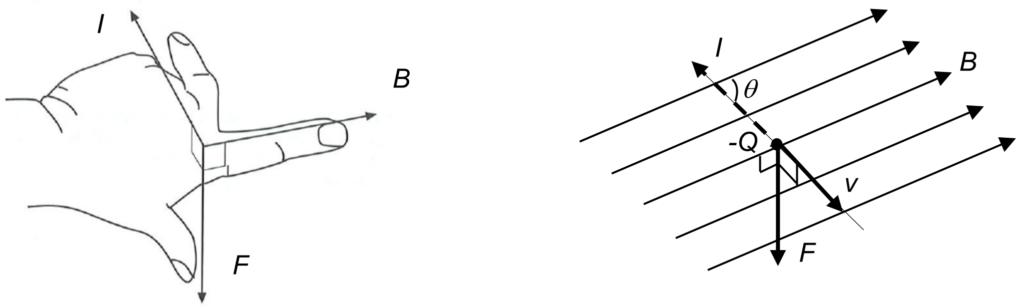
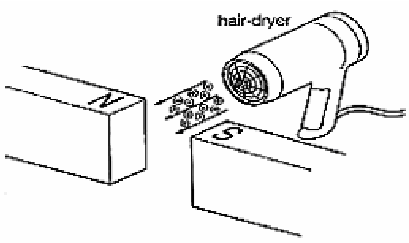


Fig. 13b: Illustrations of applications of FLHR (for negative charges)

<u>Example 7 (J97/I/19)</u>:

Hot air from a hair-dryer contains many positively charged ions. The motion of these ions constitutes an electric current. The hot air is directed between the poles of a strong magnet, as shown. What happens to the ions?



They are deflected

A	towards the north pole N	**B**	towards the south pole S
C	downwards	**D**	upwards

(k) recall and solve problems using the equation $F = BQv \sin\theta$

The **magnitude** of the magnetic force F acting on a charge Q moving with a velocity v at an angle θ to the magnetic field of flux density B is given by the equation

$$\boxed{F = BQv \sin\theta}$$

Example 8 (N06/I/27):

The acceleration of an electron of mass m and charge e, moving with uniform speed v at right angles to a magnetic field of flux density B, is given by

A $\dfrac{Bev}{m}$ **B** $\dfrac{Be}{m}$ **C** $\dfrac{Bv}{m}$ **D** $Bevm$

Note:
The motion of a charged particle in an uniform magnetic field is connected to the topic of "Motion in a Circle"

(h) show an understanding of how the force on a current-carrying conductor can be used to measure the flux density of a magnetic field using a current balance.

2.5 Application: Current Balance [5]

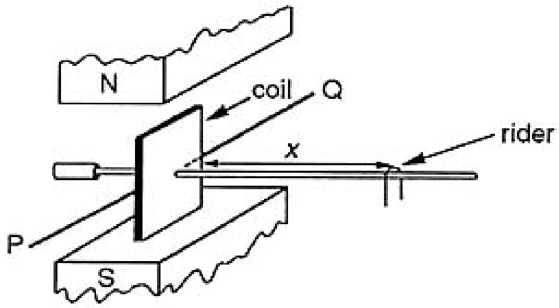
A current balance is like a beam balance. They both use some 'weights' for measurement.

In a beam balance, 'weights' on one side is balanced by some other 'weights' on the other side.

In a current balance as shown in Example 9, it is balanced by a force on a current-carrying conductor.

[5] The current balance is invented by Lord Kelvin, who is famous for his work in accurately determining the value of absolute zero in degree Celsius.

Example 9 (J87/III/12):



A small square coil of N turns has sides of length L and is mounted so that it can pivot freely about a horizontal axis PQ, parallel to one pair of sides of the coil, through its centre as shown. The coil is situated between the poles of a magnet which produces a uniform magnetic field of flux density B. The coil is maintained in a vertical plane by moving a rider of mass M along a horizontal beam attached to the coil.

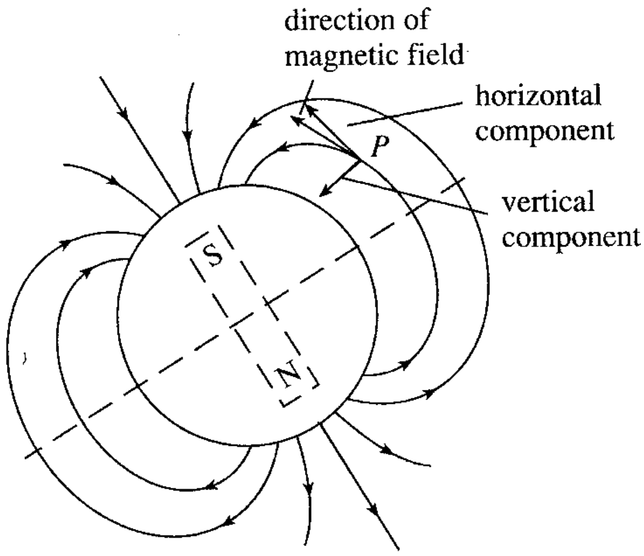
When a current I flows through the coil, equilibrium is restored by placing the rider a distance x along the beam from the coil. Starting from the definition of magnetic flux density, show that B is given by the expression

$$B = \frac{Mgx}{IL^2N}$$

ANNEX

A Magnetic Field of the Earth

Earth is a large magnet. The magnetic north pole of the magnet lies beneath the geographic south pole of the Earth. The axis of rotation (along the geographic North-South line) and the magnetic axis (along the magnetic North-South line) are off by 11^0. The Earth's magnetic field lines are *almost parallel* to the surface near the equator and are *almost perpendicular* near the magnetic poles; at the *geographic south* pole (magnetic north pole) of the Earth, the direction of the field is *vertically upwards* whereas at the *geographic north* pole (magnetic south pole), it is *vertically downwards*.



The Earth's magnetic field at a point such as *P* can be resolved into two mutually perpendicular components: the horizontal component and the vertical component. The angle that the magnetic field lines make to the surface is called the angle of dip or inclination.

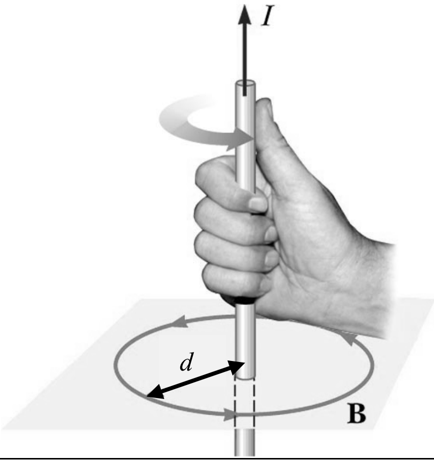
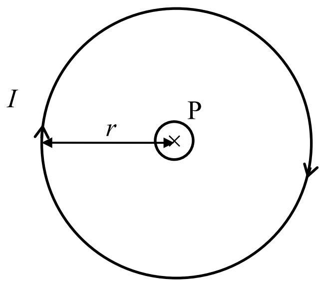
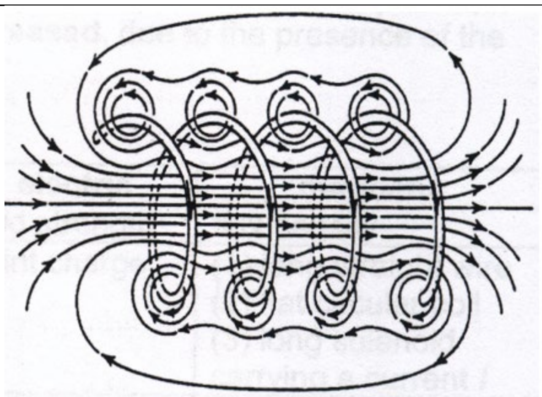
INQUIRY :

Other than being part of your everyday life, this topic has wide-ranging applications, which you can research on:

- Large Hadron Collider
- Maglev – Train Transportation
- Magnetic Suspension
- Railgun
- Velocity Selector

(c) use $B = \frac{\mu_o I}{2\pi d}$, $B = \frac{\mu_o N I}{2r}$ and $B = \mu_o n I$ for the flux densities of the fields due to currents in a long straight wire, a flat circular coil and a long solenoid respectively

Ampere's Law, proposed by French scientist Andre-Marie Ampere, provides the relation between the current in an arbitrarily shaped wire and the magnetic field produced by the current in the wire. Using Ampere's law, the different formulae for calculating the magnetic flux density, *B,* due to the various types of conductors may be derived.

Shape of conductor	Magnetic Flux Pattern	Calculation of Magnitude of Magnetic Flux Density
Long straight wire		$B = \frac{\mu_o I}{2\pi d}$ where μ_o is the permeability of free space and is equal to $4\pi \times 10^{-7}$ H m^{-1} (given in Data List). I = current through wire d = perpendicular distance from wire
Flat circular coil		$B = \frac{\mu_o N I}{2r}$ where μ_o is the permeability of free space and is equal to $4\pi \times 10^{-7}$ H m^{-1} (given in Data List). I = current through coil N = number of loops of coil r = radius of coil
Long solenoid **(Infinitely long)**		$B = \mu_o n I$ where μ_o is the permeability of free space and is equal to $4\pi \times 10^{-7}$ H m^{-1} (given in Data List). I = current through wire $n = N/l$ = number of turns per unit length of solenoid

Note:
The three equations for calculating B need not be recalled or derived, just used.

Example 10 (modified from N94/II/4):

A 2.0 m long solenoid has 1400 turns and carries a current of 3.5 A. Calculate the magnetic flux density on the axis of the solenoid.

(I) describe and analyse deflections of beams of charged particles by uniform electric and uniform magnetic fields

Recall:

From Newton's 1st Law, an object will remain at rest or move at constant velocity in a straight line unless it is acted on by a non-zero net force.

If the object is charged, this non-zero net force could be provided by a uniform electric field or uniform magnetic field.

For our discussion, we will focus on how the **path of *moving* charged particles** are deflected by **uniform electric** and **uniform magnetic fields** (Fig 14).

	State	Effect of applied electric field only	Effect of applied magnetic field only
Charged particle	Moving *perpendicular* to the field such that the velocity of the charge and applied field strength are *planar*.	Accelerate parallel to electric field due to an **electric** force; Subsequent path is **parabolic** (Fig. 15); The electric force *does work* on the charged particle and its speed **changes**.	Accelerate in the plane containing the velocity vector and perpendicular to it due to a **magnetic** force; Subsequent path is **circular** (Fig. 16); The magnetic force does *no work* on the charged particle and its speed remains **constant**.

Fig. 14: Summary of trajectories of moving charges in uniform electric and uniform magnetic fields

2.6.1 Deflection of charged particle by uniform electric field

- Refer to lecture resources on "Electric Fields" for details

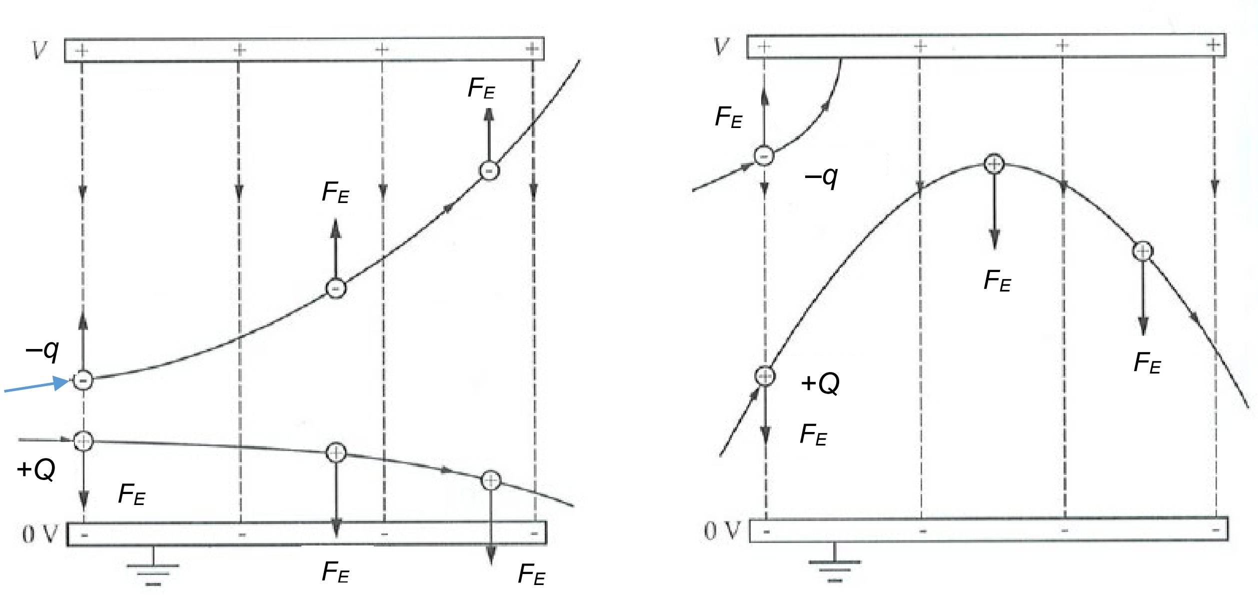


Fig. 15: Deflection by uniform electric field

2.6.2 Deflection of charged particle by uniform magnetic field:

Consider a positively charged particle (mass *m*) of charge +*q*, moving at an initial velocity *v* in a uniform magnetic field (*B*) at **right angles** to the field lines. The *plane of the circular path* is **perpendicular** to the magnetic field lines.

The **magnetic force F_B** is the resultant force that provides **the centripetal force** for the particle to move in a circle.

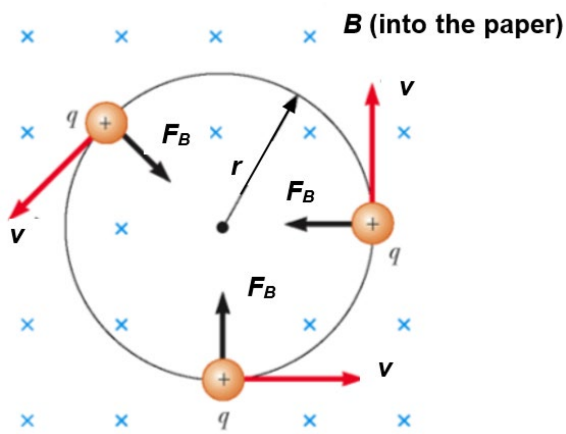


Fig. 16: Deflection by uniform magnetic field

> **Note:**
> F_B is always directed toward the *centre of the circle* (according to Fleming's left-hand rule).

By Newton's 2nd law,

$$F_B = ma = m\left(\frac{v^2}{r}\right) \rightarrow Bqv\sin 90° = ma = \frac{mv^2}{r}$$

Its centripetal acceleration is given by $a = \frac{F_B}{m} = \frac{Bqv}{m} = \frac{v^2}{r}$

The radius of the circle is given by $r = \frac{mv}{Bq}$

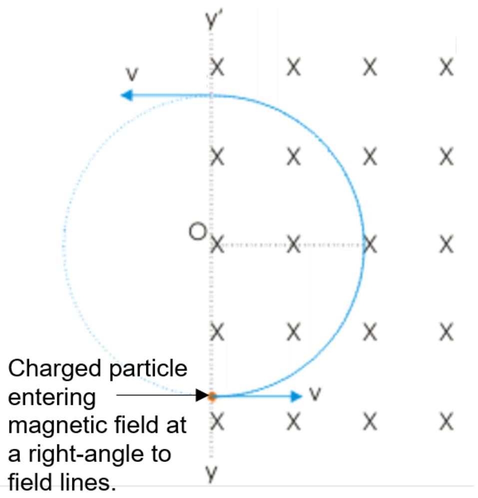
Note:
Do not memorise the final expression. Learn and understand the steps in the derivation!

Since its speed is constant in a circular path, its kinetic energy is **constant**. Work done by the magnetic force F_B on the particle is always zero because F_B is always *perpendicular* to its motion.

The period of revolution,

$$T = \frac{2\pi r}{v} = \frac{2\pi\left(\frac{mv}{Bq}\right)}{v} = \frac{2\pi m}{Bq},$$

which is independent of v.



If a charged particle enters a uniform magnetic field at **right angles** to the field lines (i.e. angle between B & v, $\theta = 90^o$), it will move in a **circular** path.

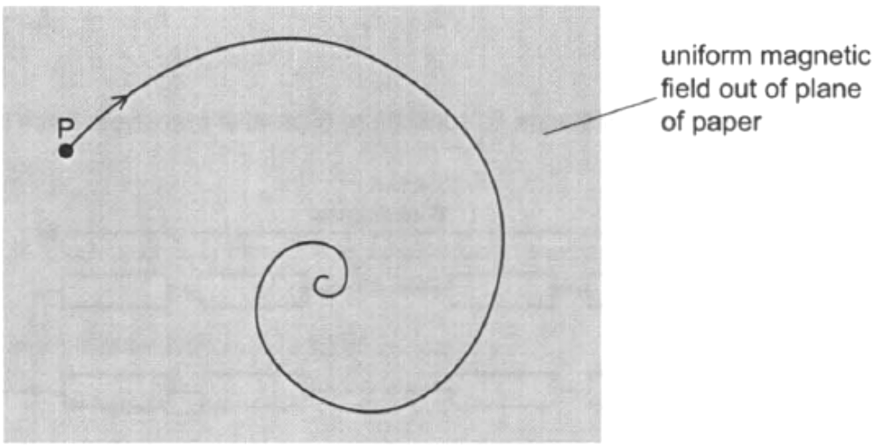
Note:

Since the orbital period does not depend on the speed of the charge, fast- and slow-moving charges take the *same time* to complete one cycle.

Fast moving charges move in a *large circle* and *slow-moving* charges move in a *small circle*.

<u>Example 11 (N09/I/30)</u>:

A charged particle is moving in a region where there is a uniform magnetic field acting out of the plane of the paper. The path of the particle begins at P and is as shown.



What can be deduced about the charge on the particle and its speed?

	charge	speed
A	negative	decreasing
B	negative	increasing
C	positive	decreasing
D	positive	increasing

2.6.3 Charged particle entering magnetic field at an angle

Note:
- 2014/H2/P3/Q7

A charged particle having a velocity directed at an angle θ (neither completely parallel nor perpendicular) to a uniform magnetic field moves in a **helical path** [1] (Fig. 17).

The component of velocity *perpendicular* to *B* field moves it in a *circle*, while the component of velocity *parallel* to *B* field moves it *along* the *B* field. So, as the particle moves in a circle, it advances along the *B* field, resulting in a *helical* path.

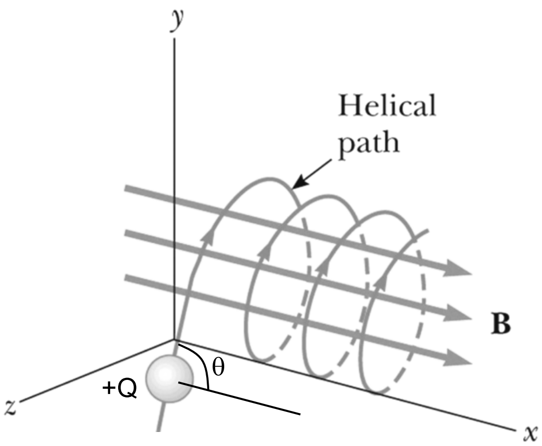


Fig. 17: Helical path of a charged particle in uniform magnetic field. If **0° <** θ **< 90°**, the charged particle will move in a **helical** path. (i.e. it spirals forward).

(m) explain how electric and magnetic fields can be used in velocity selection for charged particles.

Crossed uniform magnetic and electric fields:

2.7 Application TWO: Velocity Selector

Uniform magnetic and electric fields that are **perpendicular** to each other (i.e., crossed fields) could be used to *select* charged particles of a *particular speed*. This arrangement produces forces *opposite in directions* acting on a beam of charged particles passing through the *crossed fields*.
Fig. 18 shows one such combination of fields.

Note:
The velocity selector is invented in 1898 by Wilhelm Wien, who is famous for his displacement law for blackbody radiation.

[1] 2014/H2/P3/Q7 & 2009/9745/P3/Q2

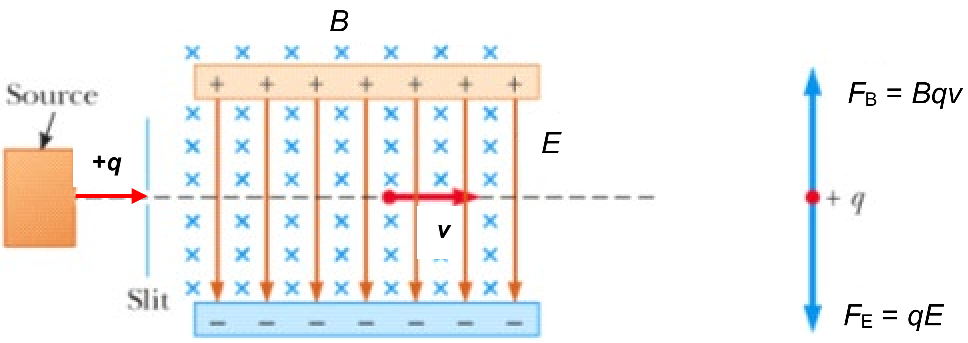


Fig. 18: Velocity Selector

Positively charged particles (+q) moving *perpendicularly* through the crossed fields experience **opposing** magnetic and electric forces, F_B and F_E respectively.

The charged particles will remain on a **straight path** if the **magnitude** of electric force F_E and the magnetic force F_B are *equal*, i.e. $F_B = F_E$ → $qvB = qE$

i.e. $F_B = F_E \rightarrow Bqv = qE$ - - - - - (1)

For faster particles, $F_B > F_E$. They will be deflected upwards.

For slower particles, $F_B < F_E$. They will be deflected downwards.

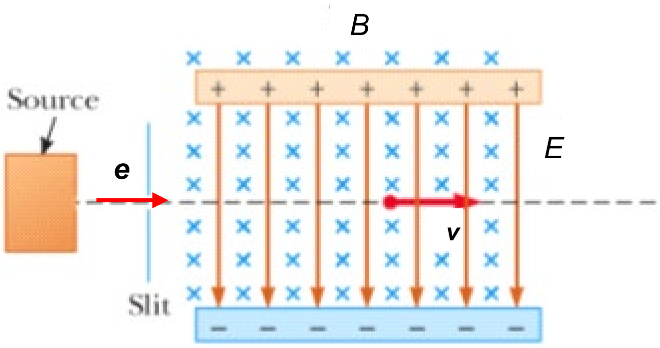
From equation (1) above, $\boxed{v = \frac{E}{B}}$

where
v = speed of charge (unit: m s^{-1})
B = uniform magnetic flux density (unit: T)
E = uniform electric field strength (unit: N C^{-1})
q = charge of the particle (unit: C)

By changing the ratio of E to B, charged particles of a **certain** selected speed may be collected from their undeflected path, i.e. **velocity selection** takes place.

Example 12 (N03/I/27):

A beam of electrons enters a region in which there are magnetic and electric fields directed at right angles. It passes straight through without deviation.



A second beam of electrons travelling twice as fast as the first is then directed along the same line.

How is this second beam deviated?

A downwards in the plane of the paper
B upwards in the plane of the paper
C out of the plane of the paper
D into the plane of the paper

Example 13 (N13/I/29):

A velocity selector for protons has an electric field of strength 3.0×10^{5} V m^{-1} at right-angles to a magnetic field of flux density 1.5×10^{-2} T.

What is the speed of the protons that pass undeflected through the selector?

A 2.0×10^{7} m s^{-1}
B 3.0×10^{5} m s^{-1}
C 4.5×10^{3} m s^{-1}
D 5.0×10^{-3} m s^{-1}

ANNEX

B. Comparisons between the three different fields:

	gravitational	**electric**	**magnetic**
The	field strength	field strength	flux density
due to a	point mass *M*	point charge *Q*	(1) long straight wire (2) flat circular coil (3) long solenoid carrying a current *I*
at a point	distant *r* from *M*	distant *r* from *Q*	(1) distance *d* from *I* (2) distance *r* from *I*, i.e. at centre of coil (3) within solenoid
is expressed as	$g = \frac{GM}{r^2}$	$E = \frac{Q}{4\pi\varepsilon_o r^2}$	(1) $B = \frac{\mu_o I}{2\pi d}$ (2) $B = \frac{\mu_o NI}{2r}$ (3) $B = \frac{\mu_o NI}{L} = \mu_o nI$
force on a	point mass *m*	point charge *q*	conductor with current *I*, of length *L* at angle θ to direction of field
is expressed as *F*	$= mg$	$= qE$	$= BIL \sin \theta$
force between two	masses m_1, m_2	charges Q_1, Q_2	parallel conductors of currents I_1, I_2
separated by distance	*r*	*r*	*d*
is expressed as *F*	$= \frac{Gm_1m_2}{r^2}$	$= \frac{Q_1Q_2}{4\pi\varepsilon_o r^2}$	$= \left(\frac{\mu_o I_1 I_2}{2\pi d}\right)L$

Tutorial: Electromagnetism

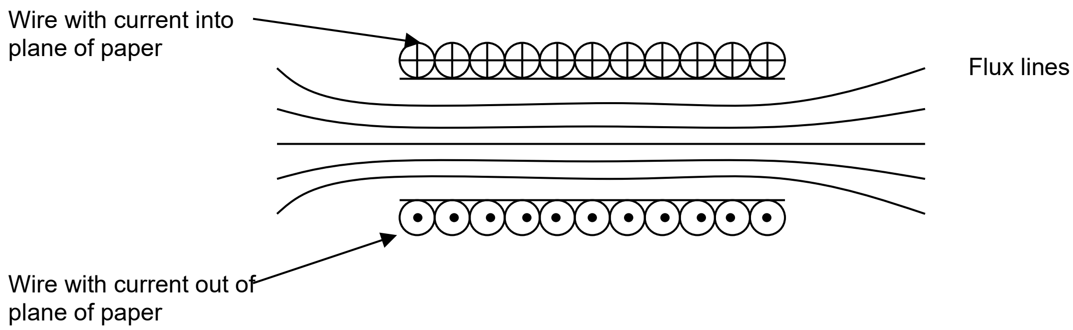
Magnetic Fields

1. Sketch magnetic flux patterns due to a long straight wire, a flat circular coil and a long solenoid.

2. Sketch the resultant fields around two long wires carrying currents of the same magnitudes. The directions of the currents are as shown in the figures:

(a) Currents in the same direction (b) Currents in opposite directions

3. **[J97/II/3]**
The diagram below illustrates the pattern of the magnetic flux due to a current in a solenoid.



On the diagram above,

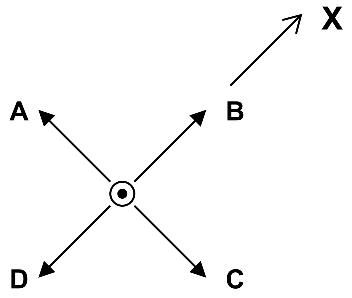
(i) Draw arrows to show the direction of the magnetic field in the solenoid.
(ii) Draw a line to represent a current-carrying conductor in the magnetic field which does not experience a force due to the magnetic field. Label the conductor C.

Magnetic force on current-carrying conductors

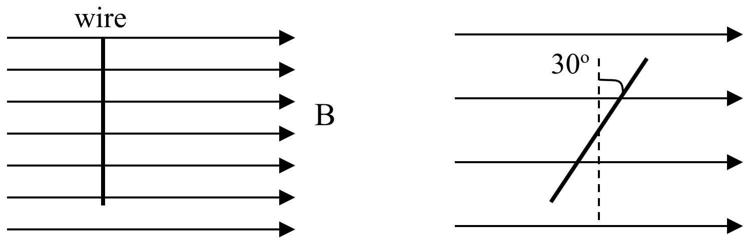
4. **[N98/I/27]**
An electron is moving along the axis of a solenoid carrying a current. Which of the following is a correct statement about the electromagnetic force acting on the electron?

A The force acts radially inwards
B The force acts radially outwards
C The force acts in the direction of motion
D No force acts

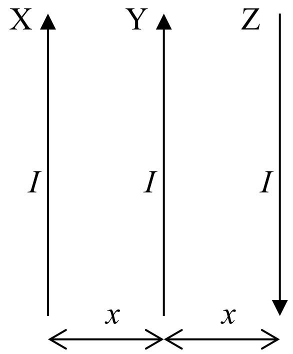
5. [J01/I/18]
The diagram shows cross-section of a straight wire that carries a steady current out of the plane of the paper towards the observer. The arrows represent the directions of four magnetic fields, A, B, C and D. Which field causes the wire to move towards the point X?



6. [N02/I/25]
A straight, horizontal, current-carrying wire lies at right angles to a horizontal magnetic field. The field exerts a vertical force of 8.0 mN on the wire. The wire is rotated, in its horizontal plane, through 30° as shown. The flux density of the magnetic field is halved. What is the vertical force on the wire? [?.? mN]



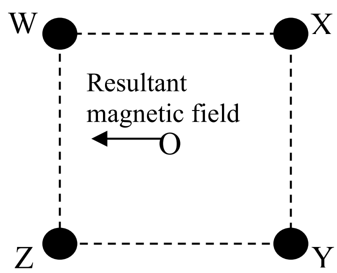
7. [N99/I/18]
The diagram shows 3 parallel wires X, Y, Z that carry currents of equal magnitude in the directions shown. The resultant force experienced by Y due to the currents in X and Z is



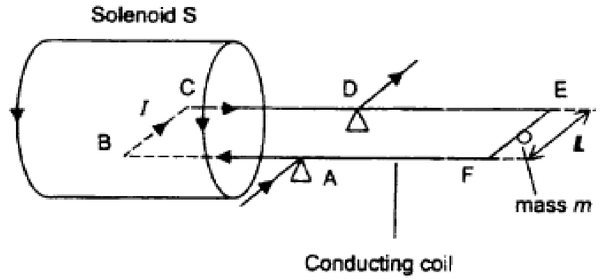
A perpendicular to the plane of the paper
B to the left
C to the right
D zero

8. [J96/I/18]
Four parallel conductors, carrying equal currents, pass vertically through the four corners of a square WXYZ. In two conductors, the current is flowing into the page, and in the other two, out of the page. In what directions must the current flow to produce a resultant magnetic field in the direction shown at O, at the centre of the square?

	Into the page	Out of the page
A	W & X	Y & Z
B	W & Y	X & Z
C	W & Z	X & Y
D	Y & Z	W & X



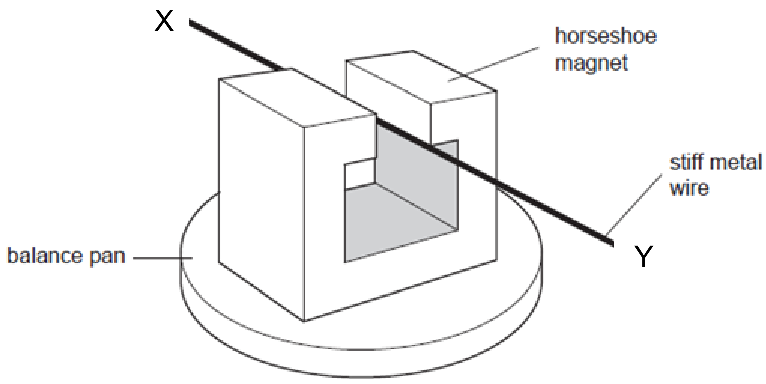
9. A solenoid S which has n turns per unit length is connected in series with a horizontal rectangular conducting coil BCEF as shown below. The coil is pivoted freely at the midpoints of the side BF and CE. The side BC of length *L* is inside a solenoid S and perpendicular to the axis of the solenoid. When the current I flows in ABCD and the solenoid, a mass *m* hanging on the side EF is required to restore equilibrium.



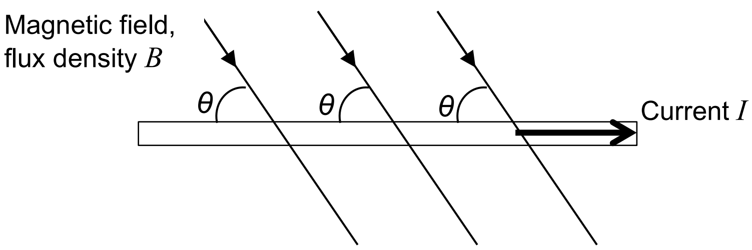
(i) Derive an expression for the magnetic flux density *B* inside the solenoid S in terms of *m*, *g, L and* I, where *g* is the acceleration due to gravity.

(ii) If *m* = 0.10 g, *L* = 2.5 cm, and *n* = 1800 turns m^{-1}, determine the value of I. [?.?? A]

10. [N04/I/24]
A horseshoe magnet rest on a top-pan balance with a wire situated between the poles of the magnet. When no current flows in the wire, the reading on the balance is 142.0 g. When a current of 2.0 A flows in the wire in the direction XY, the reading on the balance changes to 144.6 g. What is the reading on the balance when there is a current of 3.0 A in the wire in the direction YX? [???.? g]



11. (a) A straight conductor carrying a current I is at an angle θ to a uniform magnetic field of flux density *B*, as shown below.

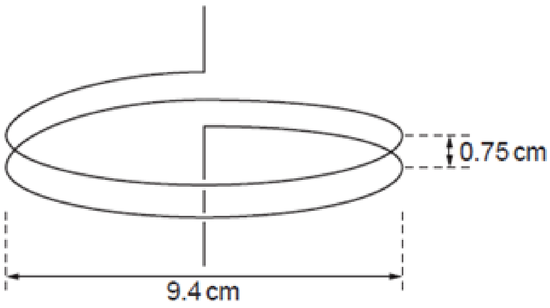


The conductor and the magnetic field are both in the plane of the paper. State

(i) an expression for the force per unit length acting on the conductor due to the magnetic field,

(ii) the direction of the force on the conductor.

(b) A coil of wire consisting of two loops is suspended from a fixed point as shown below.



Each loop of wire has a diameter 9.4 cm and the separation of the loops is 0.75 cm. The coil is connected into a circuit such that the lower end of the coil is free to move.

(i) Explain why, when a current is switched on in the coil, the separation of the loops of the coil decreases.

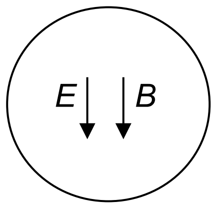
(ii) Each loop of the coil may be considered as being a long straight wire. When the current in the coil is switched on, a mass of 0.26 g is hung from the free end of the coil in order to return the loops of the coil to their original separation. Calculate the current in the coil. [?? A]

Magnetic force on moving charges

12 In a C.R.O. tube, the electron beam passes through a region when there are electric and magnetic fields directed downwards as shown.

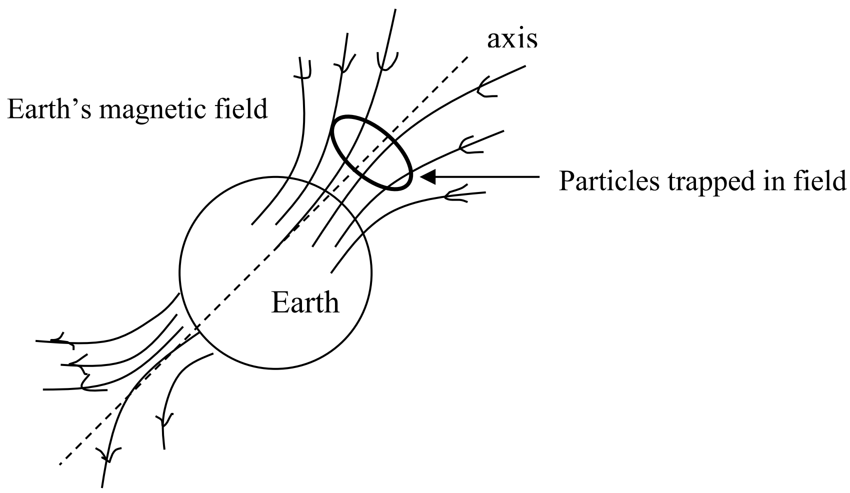
The deflections of the spot from the centre of the screen produced by *E* and *B* acting separately are equal in magnitude. Sketch the position of the spot on the screen when both fields are operating together.

Front view of screen



13 [N04/III/5(d)]

Charged particles from the sun, on approaching the Earth, may become trapped in the Earth's magnetic field near the poles, as shown below. This can cause the sky to glow. The phenomenon is called the aurora borealis.



Some of the charged particles travel in a circle of radius 50 km in a region where the magnetic flux density is 6.0×10^{-5} T.

(i) For a charged particle of charge to mass ratio *e/m*, deduce an expression for its speed *v* when traveling in a circle of radius *r* with a magnetic field of flux density *B*.

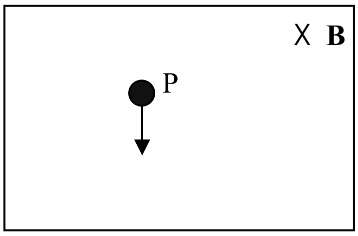
(ii) Use your answer to (i) and the information about the path of the particles to show that the charged particles causing the aurora cannot be electrons.

(iii) Suggest what could cause the aurora and, for your suggested particle, calculate its speed as it travels in a circle.

14 [N03/2/6b mod]

An electron is traveling at right angles to a uniform magnetic field of flux density 1.5 mT, directed into the plane of the paper, as illustrated below. When the electron is at P, its velocity is 2.9 x 10^7 m s^{-1} in the direction shown. This is normal to the magnetic field.

(a) On the figure, sketch the path of the electron, assuming that it does not leave the region of the magnetic field.



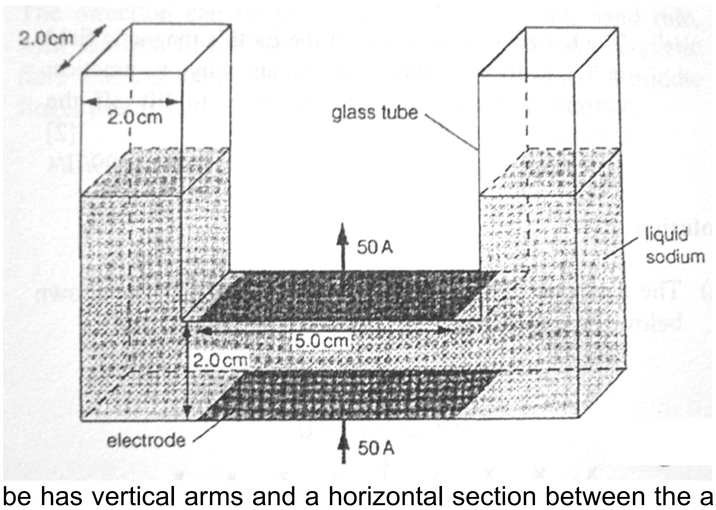
Region of magnetic field into the plane of the paper

(b) Calculate, for the electron,
- (i) the force on it due to the magnetic field [?.?? × 10^{-15} N]
- (ii) the radius of its path [0.?? m]
- (iii) the time taken for it to complete half a revolution [?.?? × 10^{-8} s]
- (iv) its kinetic energy [?.?? × 10^{-16} J]

(c) Determine the minimum potential difference required to accelerate the electron to this speed from rest. [?.?? x 10^3 V]

15 [N97/III/4 part]

A glass U-tube is constructed from hollow tubing having a square cross-section of side 2.0 cm, as shown below.

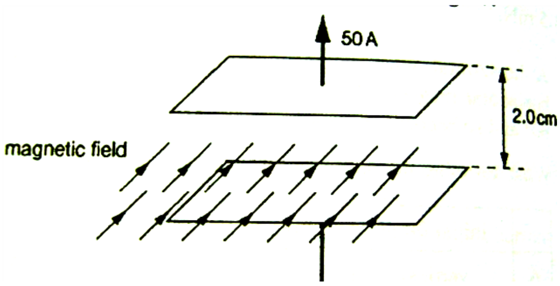


The U-tube has vertical arms and a horizontal section between the arms. Electrodes are set into the upper and lower faces of the horizontal section. Each electrode is of length 5.0 cm and width 2.0 cm. The U-tube contains liquid sodium of density 9.6 x 10^2 kg m^{-3} and of resistivity 4.8 x 10^{-8} Ω m.

(a) Assuming that the liquid sodium outside the electrodes has no effect on the resistance between the electrodes, calculate

(i) the resistance of the liquid sodium between the electrodes [?.? × 10^{-7} Ω]
(ii) the potential difference V between the electrodes required to maintain a current of 50 A in the liquid sodium [?.? × 10^{-5} V]

(b) A uniform horizontal magnetic field of flux density 0.12 T is now applied at right angles to the axis of the horizontal section of the tube in the region between the electrodes as shown below.



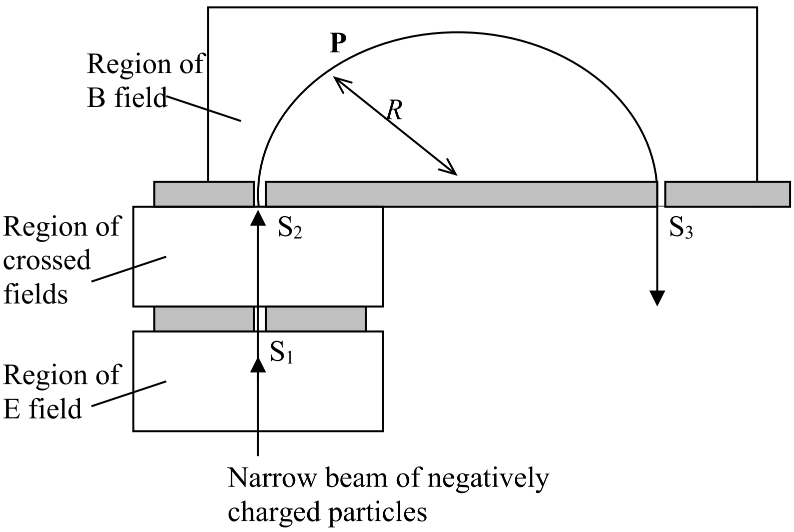
A force is exerted on the liquid due to the magnetic field. For this force,
(i) state and explain its direction,
(ii) calculate its magnitude. [?.?? N]

(c) By considering the pressure difference caused by the force, determine the difference in height of the surfaces of the liquid sodium in the vertical arms of the U-tube. [?.??? m]

(d) The technique outlined above could be used as a means to pump liquid. Suggest one advantage and one disadvantage of such a system.

Crossed Fields

16 **[H2 Only]** A narrow beam of negatively charged particles are accelerated by a potential difference V towards the slit S_1. Subsequently, the beam enters a region where a uniform electric field E and a uniform magnetic field B_1 exist simultaneously through slits S_1, before entering a region of magnetic field B_2 through the slit S_2 to exit through slit S_3.



(a) For a particle with charge Q and mass M, show that its speed just before entering S_1 is given by the expression $\sqrt{\dfrac{2QV}{M}}$.

(b) The uniform magnetic field in the region between S_1 and S_2 is applied in a direction out of the plane of the paper.

(i) State the direction of the electric field in that same region if there are to be some charged particles arriving at slit S_2.
(ii) Explain how this combination of magnetic and electric fields allows particles of only one speed v to pass through S_2.
(iii) Deduce an expression for v in terms of B_1 and E.
(iv) Sketch two possible paths, in the region of the crossed-fields, one of particles with a speed *greater than v* and one of particles with a speed *less than v*. Label them W and X respectively.

(c) When the particles enter the magnetic field B_2, particles with a charge to mass ratio of $\left(\frac{Q}{M}\right)_1$ travel in a circular path with a radius R and exit the field through slit S_3.

(i) Deduce the direction of the magnetic field B_2.
(ii) Indicate on the diagram, the direction of the velocity and resultant force acting on the particle at point P.
(iii) Write an expression for the radius R in terms of $\left(\frac{Q}{M}\right)_1$, B_2 and v.
(iv) Sketch two possible paths, in the region of the field B_2, one of particles with a charge to mass ratio larger than $\left(\frac{Q}{M}\right)_1$ and one of particles with a charge to mass ratio less than $\left(\frac{Q}{M}\right)_1$. Label them Y and Z respectively.

~ END OF TUTORIAL ~