TOPIC 16: ELECTROMAGNETISM

Learning Outcomes: Candidates should be able to:

Magnetic Field, Field Lines, Flux Patterns & 3 Field Formulae	
a.	Show an understanding that a <u>magnetic field</u> is an example of a field of force produced either by current-carrying conductors or by permanent magnets.
b.	Sketch <u>flux patterns</u> due to currents in a <u>long straight wire, a flat circular coil and a long solenoid.</u>
c.	Use $B = \frac{\mu_0 I}{2\pi d}$, $B = \frac{\mu_0 N I}{2r}$ and $B = \mu_0 n I$ for the flux densities of the fields due to currents in a <u>long straight wire</u>, <u>a flat circular coil</u> and a <u>long solenoid</u> 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 a Current-Carrying Conductor	
e.	Show an understanding that a current-carrying conductor placed in a magnetic field might experience a <u>force.</u>
f.	Recall and solve problems by using the equation <u>$F = BIL \sin\theta$</u>, with directions as interpreted by <u>Fleming's left-hand rule</u>.
Magnetic Flux Density	
g.	Define <u>magnetic flux density</u>
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 <u>current balance</u>.
Force betw Current-Carrying Conductors, Force on a Moving Charge & the Velocity Selector	
i.	Explain the forces between current-carrying conductors and predict the directions of the forces (using FLHR & the Right Hand Grip Rule)
j.	Predict the direction of the <u>force on a charge moving</u> in a magnetic field.
k.*	Recall and solve problems using <u>$F = B Q v \sin\theta$</u>.
l.*	Describe and <u>analyse deflections of beams of charged particles</u> by uniform electric and uniform magnetic fields.
m.*	Explain how electric and magnetic fields can be used in <u>velocity selection</u> for charged particles.

* Only applicable to the H2 syllabus.

In A Level, you will learn 3 different types of field:-

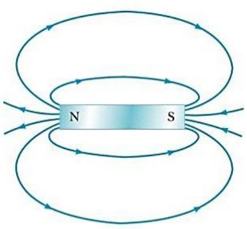
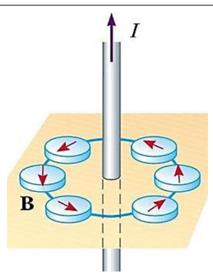
- **Gravitational field**: A region of space where a mass experiences a gravitational force.
- **Electric field**: A region of space where an electric charge experiences an electrical force.
- **Magnetic field**: A region of space where a magnetic north pole (or a current-carrying conductor, or a moving charged particle) experiences a magnetic force.

16.1 Magnetic Fields & Magnetic Field Lines

a.	*Show an understanding that a* ***magnetic field*** *is an example of a <u>field of force</u> produced either by <u>current-carrying conductors or by permanent magnets</u>.*

(a) A **magnetic field:**

- a region of space where a <u>magnetic force</u> is experienced by a <u>magnetic north pole</u> (or a current-carrying conductor, or a *<u>moving</u>* charged particle) [2010P3 Q3(b)]
- can be produced by:

(i) Permanent magnet		**(ii) Current-carrying conductor / moving charged particle**	
 **Fig. 16.1**	The magnetic field around a permanent magnet can be seen by sprinkling some iron filings around it.	 **Fig. 16.2**	The *motion of the electric charge* in the conductor produces the magnetic field. (In 1819, the Danish physicist, Hans Christian Oersted first discovered that <u>magnetic fields are produced by electric currents</u>).

- represented by "magnetic field lines".

  Direction of each magnetic field line is the direction the north pole of a free compass needle would point if it were placed along the line.

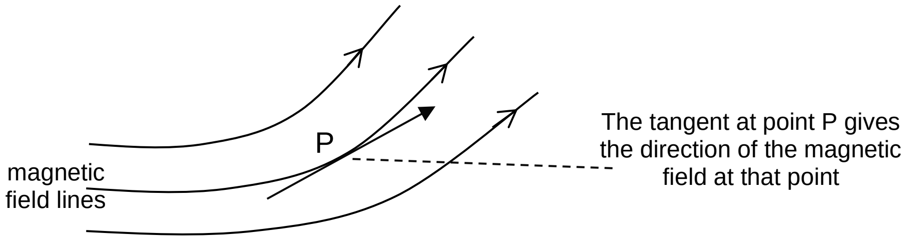


Fig. 16.3: direction of magnetic field **at point P**

(b) **Characteristics of magnetic field lines:**

- lines **leave the north pole** and enter the south pole of a magnet (Fig. 16.1).
- do not cross / intersect one another. (Why?)

When we discuss magnetic field lines in the field, we refer to the resultant field lines. Any individual magnetic field lines (which are vector quantities) intersecting at a point will result in a resultant field line at that point.

- may be straight or curved.

  The tangent to a curved field line at pt P indicates the *direction* of the *magnetic flux density **B*** at that point.

What is **magnetic flux density, B**?

We will formally define magnetic flux density only at section 16.4. However, to aid understanding, we need to introduce the conceptual idea of what B is.

Magnetic flux density is a **measure** of (but not equal to) the **field strength**. The number of magnetic field **line per unit area (i.e. line density)** represents **B**, where the higher the line density (i.e. the value of B), the stronger the magnetic field around that point (akin to E-Field and G-Field).

- represented by crosses or dotted circles

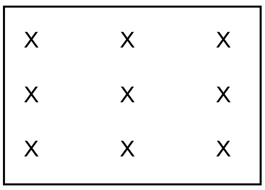


Fig. 16.4: magnetic field pointing **into** the plane of paper (perpendicularly).

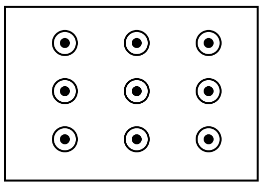


Fig. 16.5: magnetic field pointing **out of** the plane of paper (perpendicularly).

- **Uniform** magnetic field (i.e. a region where the B vector is const in magnitude & direction): lines are parallel and evenly-spaced (Fig. 16.6 & 16.7)

- Number of lines per unit area (line density) is a measure of the magnitude of B (similar to gravitational & electric fields)

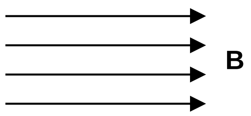


Fig. 16.6:
Uniform strong field

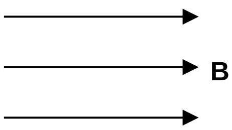


Fig. 16.7:
Uniform weak field

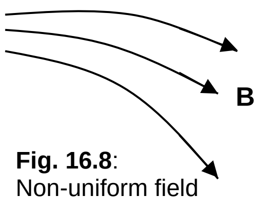


Fig. 16.8:
Non-uniform field

16.2 Flux Patterns & Formulae for 3 Sources of magnetic fields

b.	*Sketch flux patterns due to currents in a long straight wire, a flat circular coil and a long solenoid.*
c.	*Use* $B = \frac{\mu_0 I}{2\pi d}$, $B = \frac{\mu_0 N I}{2r}$ *and* $B = \mu_0 n I$ *for the flux densities of the fields due to currents in a long straight wire, a flat circular coil and a long solenoid respectively.*

- Pattern formed by the field lines is known as the *flux pattern* (i.e. Fig. 16.6 & 16.7 & 16.8)
- flux patterns produced by the 3 different current-carrying conductors are illustrated below:

16.2.1 Magnetic Field due to current in a Long Straight Wire

When a long straight wire carries a current in the direction shown in Fig. 16.9a, a magnetic field is generated around the wire.

3D representation:

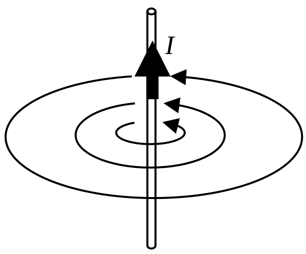
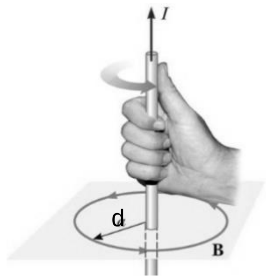


Fig. 16.9a



A representation of how Right Hand Grip Rule is used to determine the magnetic flux density produced by a current

Fig. 16.9b

Top view:

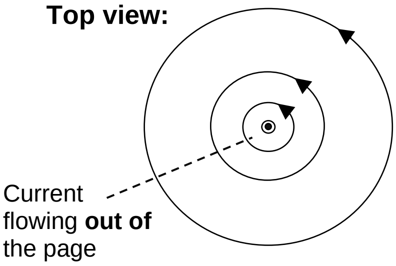


Fig. 16.10a

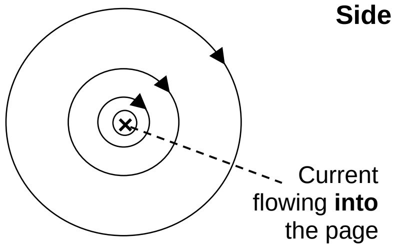


Fig. 16.10b

Side view:

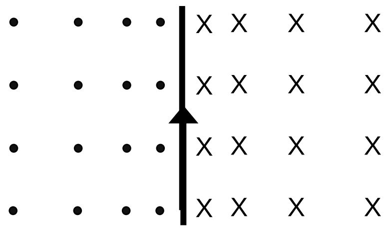


Fig. 16.10c

- **Direction of field lines:** determined by the **right-hand grip rule** (Fig. 16.9b). When the thumb of the right-hand points in the direction of the current, the other fingers indicate the direction of the B field lines produced by the current.

- A "**dot**" (Fig. 16.10a) indicates current is flowing perpendicularly out of the plane of the paper.
- A "**cross**" (Fig. 16.10b) indicates current is flowing perpendicularly into the plane of the paper.

- Although the magnetic flux patterns are formed by *complete* concentric circles, a **gap** is left in each circle to indicate that the wire is *in front* of the field in that gap. (refer Fig. 16.9a)

- Distance between successive circles increases as one moves outwards from the wire; this indicates the field is weaker as one moves away from the wire. (refer eqn 16.2.1)

- Can be shown that the magnetic flux density *B* at any point which is at a perpendicular distance *d* from the wire carrying a current I is given by

$$\boxed{B = \frac{\mu_o I}{2\pi d}}$$ eqn (16.2.1) SI unit: **tesla** (**T**)

where μ_o = permeability of free space (vacuum) = $4\pi \times 10^{-7}$ henry per metre ($H\ m^{-1}$)

d = perpendicular distance of the pt from the wire in metres

The above equation & μ_o are provided in the *List of Data and Formulae* given in the A Level Examinations.

16.2.2 Magnetic Field due to current in a Flat Circular Coil

- When a current flows in a flat circular coil, the flux pattern of the field is as shown below.

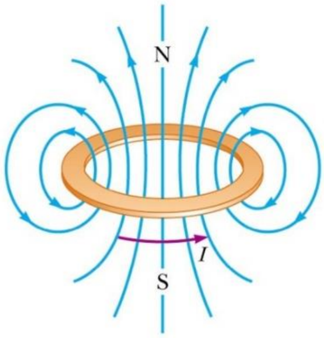


Fig. 16.11a: Magnetic field lines around a circular coil. (3d, side view)

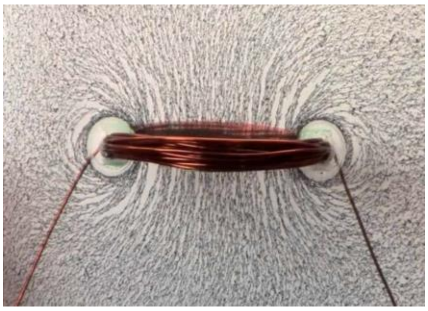


Fig. 16.11b: Iron filings sprinkled around a circular coil. (3d, top view)

- direction of field lines: also determined by the **right-hand grip rule**. (Verify for Fig. 16.11a)

2nd Application of Right-Hand Grip Rule:
Thumb: represents the direction of B-field lines **inside** circular coil
Curled fingers: represent the direction of the current that produces the B-field lines. (Contrast with the 1st Application of RHG Rule in Fig. 16.9b)

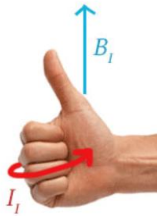


Fig. 16.12a

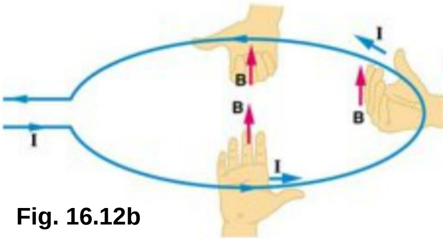


Fig. 16.12b

You can also apply the previous method of RHGR for each small section of the circular coil to get back the same result (Fig. 16.12b). Using this method, you will also be able to see that B-field lines outside the coil will be in opposite direction to the B-field lines inside the coil.

- at **centre** of coil: the field line is straight and perpendicular to the plane of coil.
- can be shown that the magnetic flux density B at the **centre** of a flat circular coil with N turns and radius r is given by,

$$\boxed{B = \frac{\mu_o NI}{2r}} \qquad \text{eqn (16.2.2)}$$

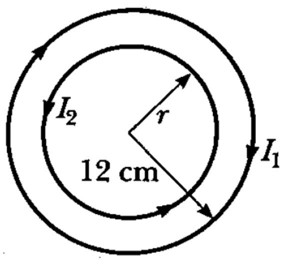
where μ_o = permeability of free space (vacuum), N = number of turns in the coil
r = radius of coil, I = current in coil

Worked Example 1

Two coplanar circular loops of wire carry current of I_1 = 5.0 A and I_2 = 3.0 A in opposite directions as in the figure shown.

(a) If r = 9.0 cm, what is the magnitude and direction of the net magnetic field at the center of the two loops?

(b) Determine the value of r such that the net field at the centre is zero.



Solution:

Note that the current in the two loops are in the opposite directions.

Since this is a circular loop, the relevant equation is $B = \dfrac{\mu_o NI}{2r}$.

Applying RHGR,

- B due to current in the bigger loop points into the page,
- B due to current in the smaller loop points out of the page.

(a) B at the centre due to the larger circular coil carrying 5 A

$= \dfrac{\mu_o NI}{2r}$ where N = 1

$= \dfrac{(4\pi \times 10^{-7})(1)(5.0)}{2(0.12)}$

$= 2.618 \times 10^{-5}$ T, **into the page (deduce from RHG Rule)**

B at the centre due to the smaller circular coil

$= \dfrac{(4\pi \times 10^{-7})(1)(3.0)}{2(0.09)}$

$= 2.094 \times 10^{-5}$ T, **out of the page (deduce from RHG Rule)**

Resultant B at the centre = difference betw them = 5.24×10^{-6} T, into page

(b) For resultant B to be 0 at the centre,

$$\frac{\mu_o(5.0)}{0.24} = \frac{\mu_o(3.0)}{2r}$$

Solving, **r = 7.2 cm**

16.2.3 Magnetic Field due to Current in a Long Solenoid

d.	*Show an understanding that the magnetic field due to a solenoid may be influenced by the presence of a ferrous core.*

- A solenoid is like an extended coil of wire.
- For a current-carrying solenoid (Fig.13), the flux pattern is as shown in Fig. 14.
  (Here the cross & dot are used to indicate the directions of the current: a cross indicates current flowing into plane of paper)

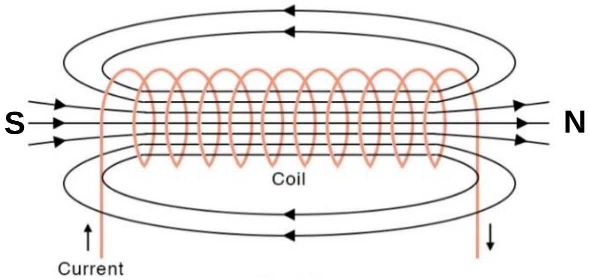


Fig 16.13: Flux pattern for a current-carrying solenoid.

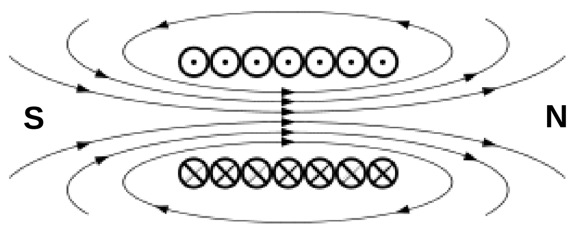


Fig 16.14: Flux pattern for a solenoid (cross-sectional view).

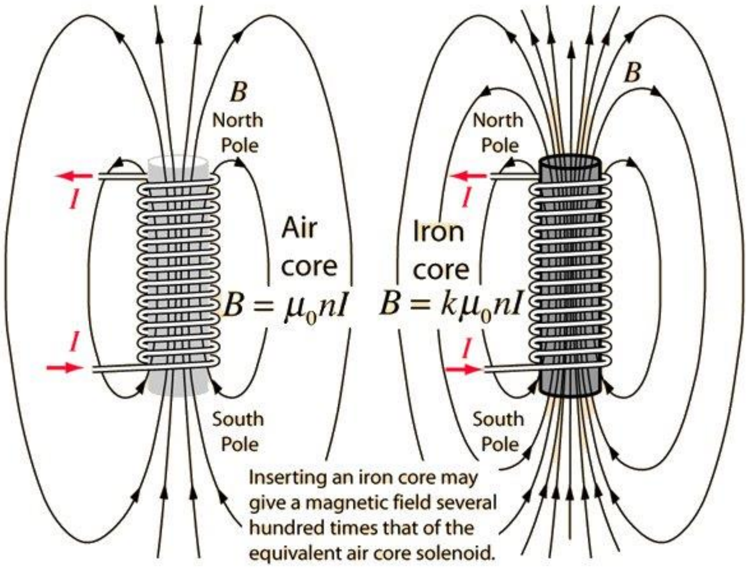
- **Within** the solenoid: Field is uniform; hence, field lines are straight and parallel to the axis of the solenoid.
- **Outside** of solenoid: Flux pattern is similar to that of a bar magnet. (See Fig. 16.1). Magnetic flux density is lower at the ends due to spreading of field lines at the ends of the solenoid compared to the centre.

- **Inside** the solenoid: magnetic flux density *B* (in tesla) is given by

$$\boxed{B = \mu_o nI} \qquad \text{eqn (16.2.3)}$$

where μ_o = permeability of free space (vacuum) = $4\pi \times 10^{-7}$ henry per metre (Hm^{-1})
n = number of turns **per unit length** of the solenoid
I = current in the solenoid expressed in amperes

- Take note that *n* is the number of turns per unit length, ***NOT*** *N (which represent the total number of turns in eqn 16.2.2).*
- Essentially, *n* = $\frac{N}{L}$ *where L* = length of the solenoid
- Direction of B produced by the current in the solenoid can be found using RHGR.
- Value of B can be increased (by about 1000 times) by inserting a ferrous (iron) core inside the solenoid.



Key Learning pts:
(1) In the above 3 scenarios, we are finding the magnetic flux density *B* **PRODUCED** by each of the conductor (i.e., long straight wire, flat circular coil, or solenoid).
(2) In the next section, we will be looking at other formulas which involved magnetic flux density *B*. However, those are B external to the conductors (as opposed to B produced by the conductors)
(3) Pay attention to these nuance differences.
(4) All the 3 equations can be found in the List of Formulae during exams, no need to memorise.

Worked Example 2 [N20/II/6b&c]

(a) A long solenoid of diameter 4.0 cm has 520 turns of insulated copper wire. The diameter of the wire is 0.46 mm. The wire is wrapped in a single layer with no gaps between each of the turns. The copper has resistivity $1.7 \times 10^{-8}\ \Omega$ m.

Calculate the resistance *R* of the wire of the solenoid. [3]

(b) The solenoid in (a) is connected to a 24 V supply.

Use information from (a) to calculate the magnetic flux density B along the axis of the solenoid, at its centre. [3]

Solution:

(a) We use the equation we've learnt in COE,

$$R = \frac{\rho L}{A}$$

where L = total length of the wire (**not** the length of solenoid)
= number of turns × circumference of each turn
= 520 × π × diameter of solenoid
= 520 × π × 0.040
= 65.3 m

and A = cross-sectional area of wire
= π × (radius of wire)^2
= $\pi \times (0.46 \times 10^{-3} / 2)^2$
= 1.66×10^{-7} m^2

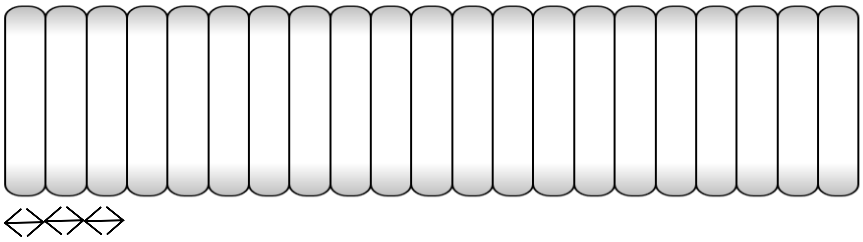
Common Mistake:
Confusion with use of diameter of solenoid & diameter of wire in calculation of L & A.

Hence, R = 6.7 Ω

(b) Given that this is a solenoid, $B = \mu_o n I$ *(from List of Formulae)*

Current in the solenoid, I = V / R = 24 / 6.7 = 3.6 A
Number of turns per unit length, n = total number of turns / length of solenoid

To find the length of solenoid, we can imagine the following solenoid.



Length of the solenoid = total number of turns × diameter of each wire (turn)

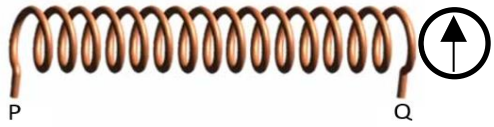
Hence, n = 1 / diameter of each wire = 2.17×10^3 m^{-1}

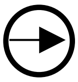
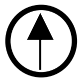
Therefore, $B = (4\pi \times 10^{-7})(2.17 \times 10^3)(3.6)$ = 9.82 Tesla

Worked Example 3

The diagram shows the needle of a compass pointing north when there is no current in the solenoid placed *near* to the compass.
When there is a current from P to Q, the magnetic field of the solenoid at the compass is equal in magnitude to the Earth's magnetic field at that point.

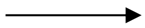
What is the orientation of the needle when there is a current in the solenoid?



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

Solution:

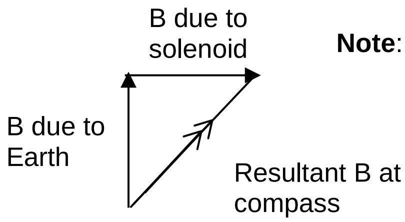
- Since current flows from P to Q, using RHGR, direction of B due to the solenoid at the location of the compass is horizontally to the **right** (since compass is **near** solenoid).

 B at compass due to solenoid

- From the question, we also deduce that magnetic field due to Earth is as shown:

 B at compass due to Earth

- Using vector sum, direction of **resultant** magnetic flux density is



Note: length of both vectors are equal

- Answer: B

Example 4 [N92/1/19 modified]

An overhead power cable carries a current of 2000 A.
At what distance would the magnetic flux density due to the current in the cable be 100 μT?

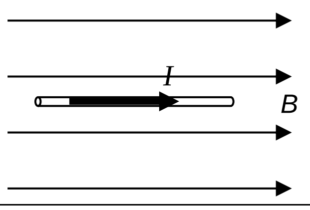
Solution:

Tutorial qn: Q1, Q2, Q3, Q4, Q5, Q6, Q7

16.3 Magnetic Force on a Current-Carrying Conductor

e.	*Show an understanding that a current-carrying conductor placed in a magnetic field* ***might*** *experience a force.*
f.	*Recall and solve problems by using the equation $F = BIL \sin \theta$, with directions as interpreted by Fleming's left-hand rule.*

- When a conductor carrying a current is placed in a magnetic field, it *might* experience a **magnetic force**. (Why '*might*'?)

<table>
<tr>
<td>If current-carrying conductor is placed <u>parallel</u> to the <u>external</u> B-field,
</td>
<td>There will be NO magnetic force F_B acting on the conductor.</td>
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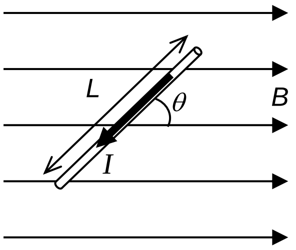
<tr>
<td>If current-carrying conductor is placed <u>at an angle θ</u> to the <u>external</u> B-field,
</td>
<td>For a conductor of length L carrying a current I in a magnetic field of flux density B placed at angle θ to the B-field lines, the magnitude of the magnetic force F_B on the conductor is given by

$$\boxed{F_B = BIL \sin \theta} \quad \text{...(eqn 16.3.1)}$$
F_B : magnetic force exerted on the conductor
B : magnetic flux density <u>external</u> to the conductor
I : current in the conductor
θ : angle between the conductor and the B-vector
L : length of conductor (within the field). Any length outside the field does <u>not</u> contribute to any magnetic force.
$L\sin\theta$: length of conductor (within the field) that is perpendicular to the field

▪ If wire is <u>parallel</u> to field lines: then $\theta = 0°$, and $F_B = 0$, i.e., no magnetic force acts on conductor
▪ If wire is <u>at right angles</u> to B: $\theta = 90°$, force acting on conductor would be maximum ($F = BIL\sin 90^0$)
▪ Magnitude of the force varies from zero to a maximum as θ varies

Note:
The magnetic flux density B in the above equation is NOT PRODUCED by the current in the conductor. It can be produced by any other sources (e.g., magnets, solenoid etc) and is <u>EXTERNAL</u> to the conductor.</td>
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- The direction of the magnetic force can be found using the **Fleming's Left-hand rule (FLHR)**.

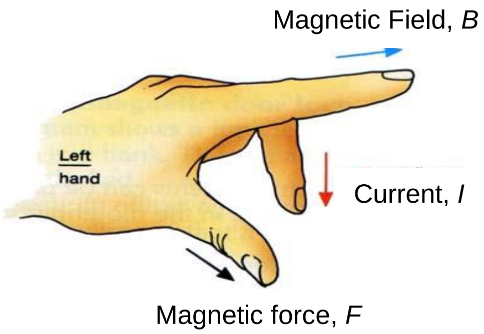


Fig 16.15: Fleming's left-hand rule

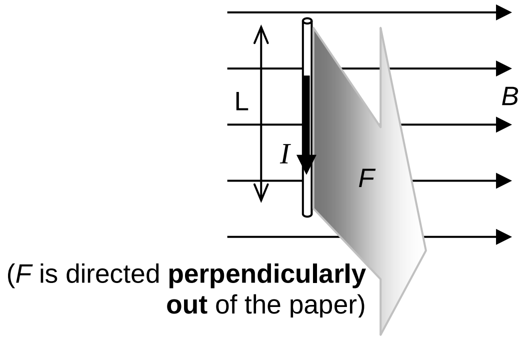
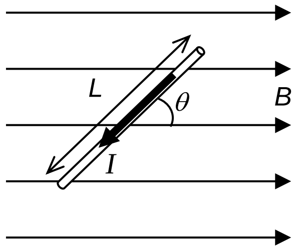


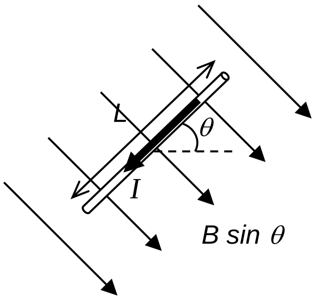
Fig 16.16: A conductor (wire) carrying a current I in a field of flux density B.



- It is straight-forward to apply FLHR if the conductor is placed at 90° to the B-field.

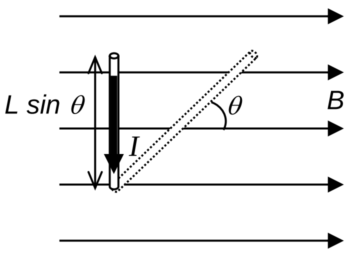
- What if the conductor is placed at an angle to the field?

<u>Method 1: Resolving B into component perpendicular to conductor</u>



(1) Resolve B into component <u>perpendicular</u> to the conductor.
(2) Component of B <u>parallel</u> to the conductor **will not** contribute in any magnetic force acting on the conductor.
(3) The magnetic force acting on the conductor is given by $F_B = (B \sin \theta)(IL)$, which is the same as before.

<u>Method 2: Resolving L into component perpendicular to B</u>



(1) Resolve L into component <u>perpendicular</u> to B field lines.
(2) Component of L <u>parallel</u> to the B field lines **will not** contribute in any magnetic force acting on the conductor.
(3) The magnetic force acting on the conductor is given by $F_B = (BI)(L \sin \theta)$, which is the same as before.

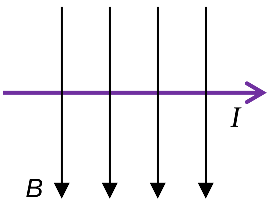
Note: *Regardless of the angle* θ, the force is <u>always perpendicular to the *plane* containing both the current *I* and the magnetic flux density *B*</u> (you can apply FLHR on the two methods and come to conclusion that the F_B is pointing perpendicularly out of the paper.)

Example 5: In (b), How to apply FLH Rule to predict dir of *F*, if *B* is NOT at right-angles to *I*?

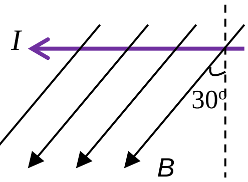
Each of the 3 diagrams below shows a magnetic field of flux density 2 T that lies in the plane of the page. In each case, a current *I* of 10 A is directed as shown.

Use Fleming's left hand rule to predict the directions of the forces and work out the magnitude of the forces on a 0.5 m length of wire that carries the current.

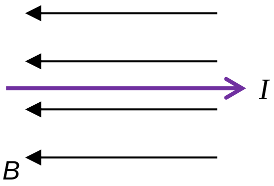
(a)



(b)



(c)

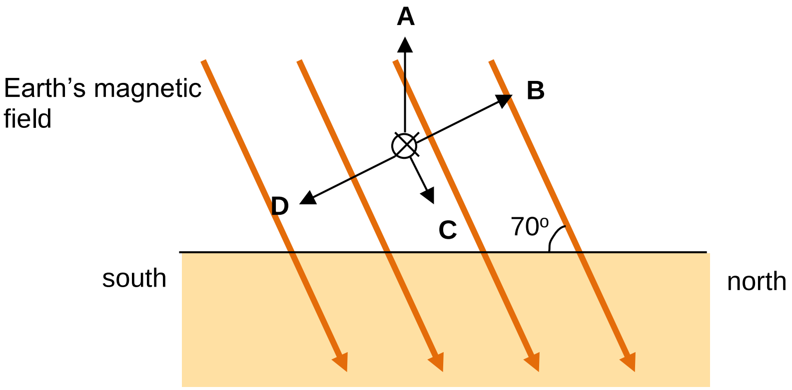


Solution:

$F = BIL \sin \theta$ $\quad$ $F = BIL \sin \theta$ $\quad$ $F = BIL \sin \theta$

Worked Example 6 [N95/I/18]: Can FLH Rule be *directly* applied here?

A horizontal power cable carries a steady current in an east-to-west direction, i.e. perpendicularly 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 70º to the horizontal?



Solution:

Fleming's Left Hand Rule can be applied directly as θ between B & current I is 90º.
Hence, force points along arrow **D.**

16.4 Magnetic Flux Density

g.	*(2021 P3 Q8 (a)) Define magnetic flux density.*	[3]

The **magnetic flux density** (***B***) at any point is defined as the force acting per unit current in a wire of unit length placed *at* right-angles to the field.

- Magnetic flux density $\boxed{B = \dfrac{F}{I\,L\,\sin\theta}}$ ...(eqn 16.4.1)

Nikola Tesla
(1856 – 1943)

B : magnetic flux density **external** to the conductor
F : magnetic force exerted on the conductor
I : current in the conductor
θ : angle between the conductor and the B-vector
L : length of conductor (**within the field**). Any length outside the field does not contribute to any magnetic force.
$L\sin\theta$: length of conductor (**within the field**) that is **perpendicular** to the field

- a vector quantity and its unit is **tesla (T)**

- Typical values for magnetic flux density: remember these to answer "estimate questions". (Refer to Topic 1: Measurement)

Source of field	B/T
Strong laboratory magnet	2
Bar magnet	10^{-2}
Surface of the Earth	5×10^{-5}

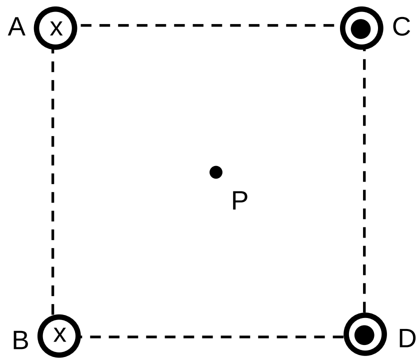
Watch this 9 minute video to learn some concepts and formulae on Electromagnetism **https://tinyurl.com/yckz7w5h**

Note:

Worked Example 7

Four long, parallel conductors carrying <u>equal</u> currents are placed at four corners of a <u>square</u>, as shown in the figure.

Determine the direction of the resultant magnetic flux density at point P, <u>centre</u> of the square.



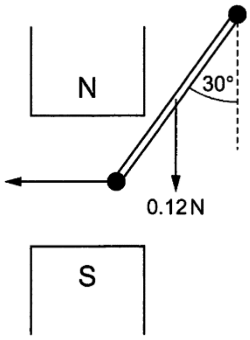
Solution:

Using **Right Hand Grip Rule**,
- direction of flux density at P due to current A is $\overrightarrow{PB}$, ie ↙
- direction of vector B at P due to current B is $\overrightarrow{PD}$, i.e. ↘
- direction of vector at P due to current C is $\overrightarrow{PD}$, i.e. ↘
- direction of flux density at P due to D is $\overrightarrow{PB}$, i.e. ↙

By vector addition of all 4 vectors, direction of the resultant magnetic flux density is <u>**downward**</u> (as leftward & rightward components cancel out each other)

Worked Example 8

A rigid square coil of side 60 mm has 50 turns. It hangs vertically so that it rotate freely about one side.

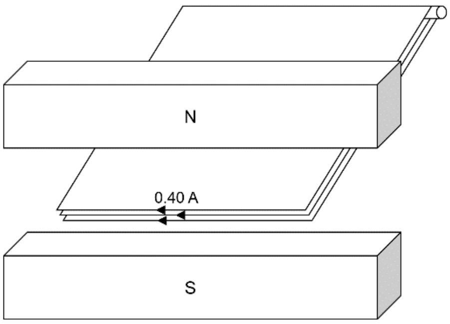


When a current of 0.40 A passes through the coil, it hangs at an angle of 30° to the vertical with its lowest side in the vertical magnetic field of a magnet. The weight of the coil is 0.12 N.

What is the flux density of the field between the magnets?

Solution:

Trigger: *50 turns.*
- *Each turn of the coil <u>within the magnetic field</u> will experience a magnetic force.*
- *We should try to imagine the 3D setup of this question.*
- *Using FLHR, the magnetic force will be pointing out of the page (using the 3D setup), or pointing leftward (using diagram from original question)*



Trigger keywords: *… rotate freely…*
- *Question is hinting to use moments about the pivot.*
- *Weight will provide ACW moment.*
- *Total magnetic force on all 50 turns will provide CW moment.*

Total magnetic force = 50 × BIL
CW moment by total magnetic force = 50BIL × (0.060 cos 30°)
ACW moment by weight = 0.12 × (0.030 sin 30°)

Since the coil is in equilibrium, 50BIL × (0.060 cos 30°) = 0.12 × (0.030 sin 30°)
50 × B × (0.40)(0.060) × (0.060 cos 30°) = 0.12 × (0.030 sin 30°)
B = 0.029 T

Tutorial qn: Q8, Q9, Q10, Q11, Q15

16.4.1 Measuring Flux Density with a Current Balance

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**.*

The current balance uses the magnetic force on a current-carrying conductor to measure magnetic flux density. It employs the **principle of moments**.

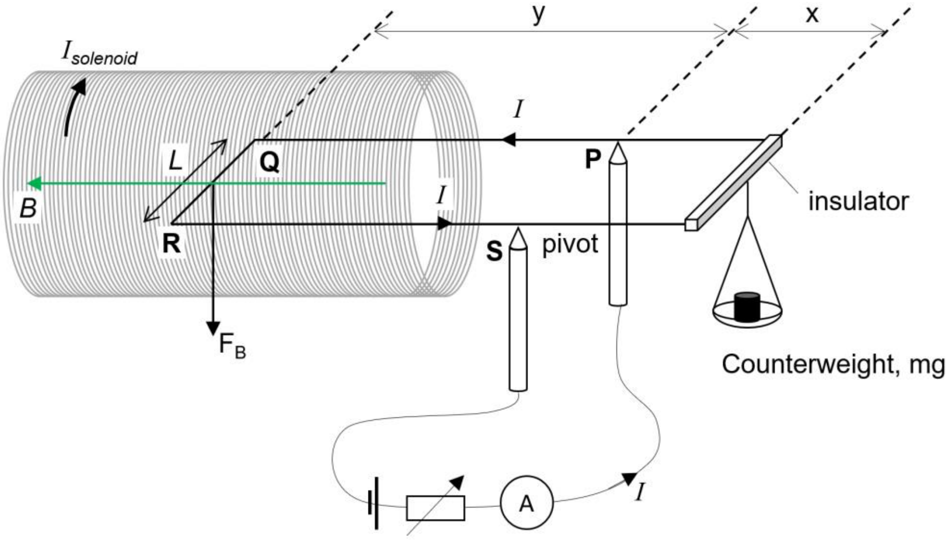


Fig. 16.17: Use of a current balance to determine B within solenoid

- From the circuit, a current I will flow from the positive terminal of the emf through the conducting frame PQRS and then back to the negative terminal of the emf.
- A separate current $I_{solenoid}$ is flowing in the solenoid which produce a magnetic flux density *B*.
- Side QR is within the solenoid.
- Using Fleming's Left Hand Rule, a magnetic force of $F_B = BIL$ acts on the side RQ downward. This results in a anti-clockwise moment about the pivot.
- To maintain equilibrium, a counterweight mg is placed on the right side to exert an clockwise moment about the pivot.

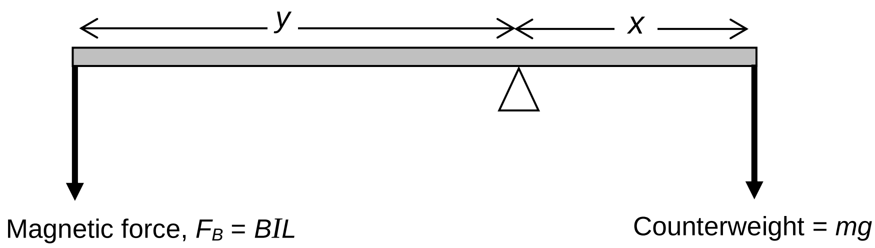


Fig 16.18: Front view of a current balance: equilibrium restored

- By the **principle of moments**:

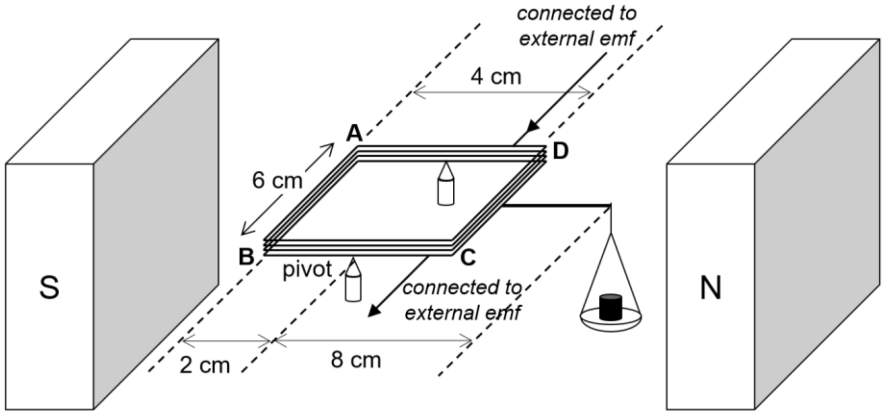
$$\textbf{Clockwise moments} = \textbf{Anticlockwise moments}$$
$$(mg)(x) = (F_B)(y)$$
$$= (BIL)(y)$$
$$\Rightarrow B = \frac{mgx}{ILy}$$

By measuring the current I, the mass *m*, the distances *x* and *y*, the magnetic flux density *B* can be calculated.

Tutorial qn: Q12

Worked Example 9: Current Balance of a different design from Fig 16.17

A 100-turn rectangular coil 6.0 cm by 4.0 cm is pivoted in the middle as shown below. A horizontal uniform magnetic field of direction perpendicular to the axis of the coil passes through the whole coil.



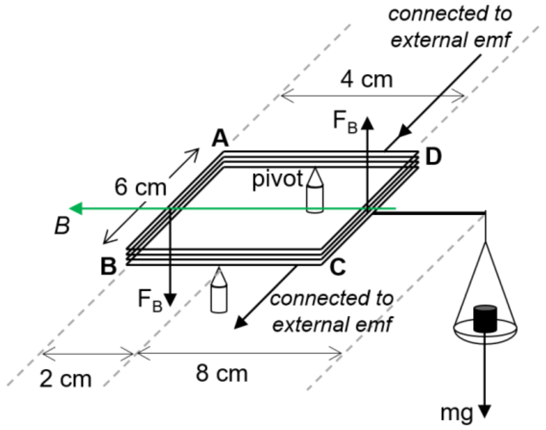
When a current of 0.50 A flows through the coil, the coil is balanced by placing a 50 mg mass on the pan, 8.0 cm from the pivot.

(a) Determine the magnitude of the magnetic flux density.
(b) State the direction of the current in the arm AB.

Solution:

Thought Process:

- *Since the coil is balanced, CW moment by mass must be equal to some ACW moment.*
- *What can provide for ACW moment? Clearly, it should be the magnetic force.*
- *Current will flow in loop in a coil, Hence, current in AB will be opposite in direction to CD.*
- *Since the magnetic field passes through the whole coil, F_B exist in both AB and CD.*
- *F_B on **AB** must act downward since it provides for ACW moment.*
- *By FLHR, we can deduce current is flowing from A to B, and hence, flowing from C to D.*
- *Therefore, F_B on **CD** will be acting upward (which will provide for ACW moment as well)*
- *Similar to example 8, since there are 100 turns, F_B on AB = 100 × BIL*



(a) Taking moments about the pivot,

sum of anti-clockwise moments due to F_B **on AB & CD** = clockwise moment due to mg

$$\underbrace{NBIL \times 0.02}_{\text{ACW due to } F_B \text{ on AB}} + \underbrace{NBIL \times 0.02}_{\text{ACW due to } F_B \text{ on CD}} = mg \times 0.08$$

$$(100)(B)(0.50)(0.06) \times 0.02 + (100)(B)(0.50)(0.06) \times 0.02 = (50 \times 10^{-3} \times 10^{-3}) \times 9.81 \times 0.08$$

$$B = 3.27 \times 10^{-4}\ \text{T}$$

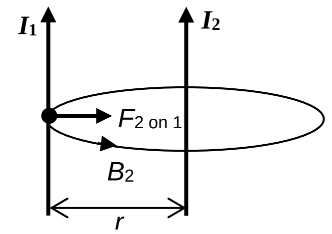
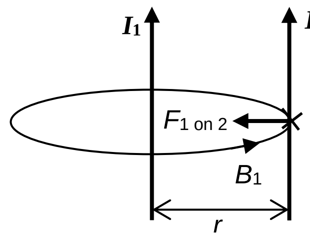
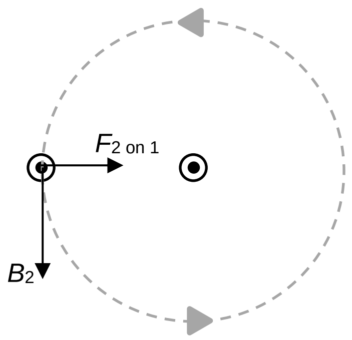
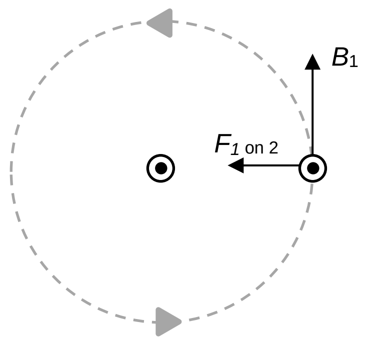
(b) Direction of current is from A to B.

16.5 Forces between 2 Current-carrying Long Straight Conductors

i.	***Explain*** *the forces betw current-carrying conductors and* ***predict*** *directions of the forces.*

If 2 current-carrying long straight wires are close enough, then each wire is in the magnetic field which the *current in the other wire creates*. Each wire should thus experience a force ($F = BIL \sin\theta$). Whether the forces are 'attractive' or 'repulsive' can be explained using the Right Hand Grip Rule and Fleming's Left-Hand Rule.

16.5.1 Current Flowing in the *Same Direction* in 2 Wires → Attractive Forces

direction of force acting **on wire 1:**	direction of force acting **on wire 2:**
 **Fig. 16.19a**	 **Fig. 16.19b**
 **Top view**	 **Top View**
Using RHGR, current in wire I_2 will induce a magnetic flux density $B_2 = \frac{\mu_0 I_2}{2\pi r}$, pointing out of the page. Using FLHR, $F_{2\text{ on }1}$ will be pointing to the right. Using F = BIL, $F_{2\text{ on }1} = (B_{\text{induced by wire 2}})(I_1)(L)$ $= (\frac{\mu_0 I_2}{2\pi r})(I_1)(L)$ $= \frac{\mu_0 I_2 I_1 L}{2\pi r}$	Using RHGR, current in wire I_2 will induce a magnetic flux density $B_2 = \frac{\mu_0 I_1}{2\pi r}$, pointing into the page. Using FLHR, $F_{1\text{ on }2}$ will be pointing to the left. Using F = BIL, $F_{1\text{ on }2} = (B_{\text{induced by wire 1}})(I_2)(L)$ $= (\frac{\mu_0 I_1}{2\pi r})(I_2)(L)$ $= \frac{\mu_0 I_1 I_2 L}{2\pi r}$
Conclusion: ▪ Hence, the 2 wires attract each other. ▪ $F_{2\text{ on }1} = F_{1\text{ on }2} = \frac{\mu_0 I_1 I_2 L}{2\pi r}$. They form an action-reaction pair.	

16.5.2 Current Flowing in the *Opposite Directions* → Repulsive Forces

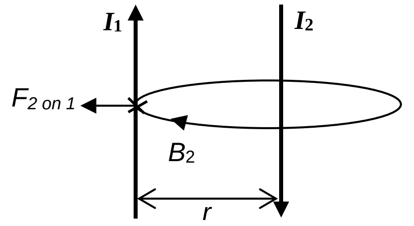
<table>
<tr><td>direction of force acting on wire 1:</td><td>direction of force acting on wire 2:</td></tr>
<tr><td>

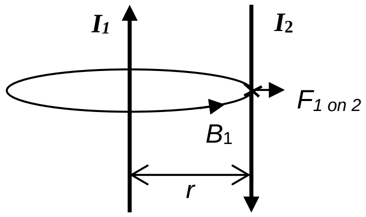
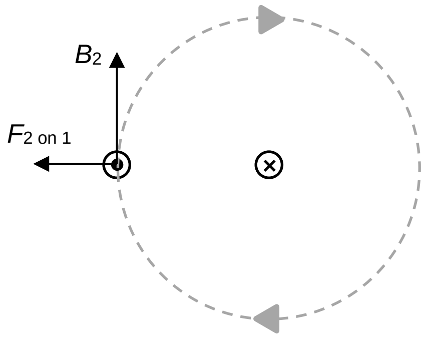
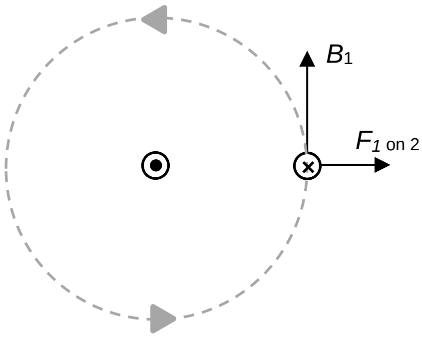
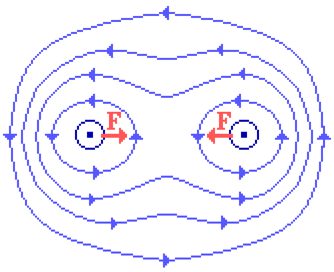
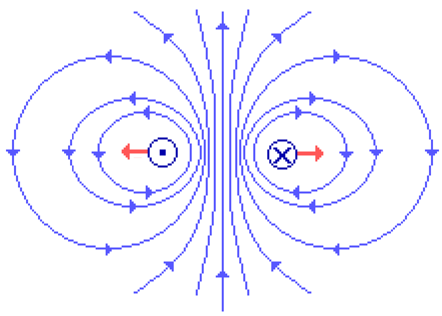
Fig. 16.20a</td><td>

Fig. 16.20b</td></tr>
<tr><td>

Top view</td><td>

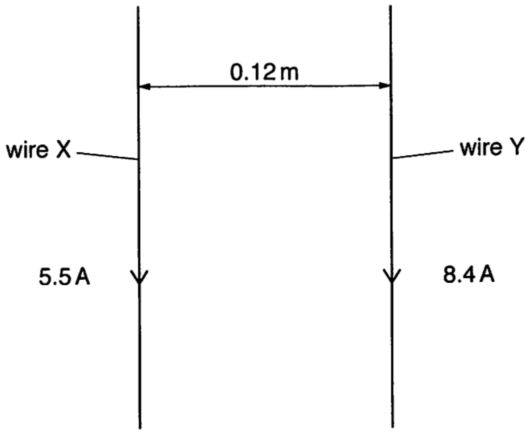
Top View</td></tr>
<tr><td colspan="2">By a similar argument using the RHGR & FLHR:
▪ The 2 wires here will repel each other.
▪ They will form an action-reaction pair as well, where $F_{2\text{ on }1} = F_{1\text{ on }2} = \dfrac{\mu_0 I_1 I_2 L}{2\pi r}$.
▪ Like currents attract, unlike currents repel.</td></tr>
</table>

16.5.3 Resultant magnetic flux pattern due to 2 Current-carrying Long Straight Conductors

<table>
<tr><td>Both current point out of the page</td><td>Left current into the page,
Right current out of the page</td></tr>
<tr><td>
</td><td></td></tr>
</table>

Example 10 [2019/2/4b]

Two long straight wires X and Y are separated by a distance of 0.12 m. The current in wire X is 5.5 A. The current in wire Y is 8.4 A.



Both currents are in the same direction, as shown in the figure above.

Calculate the force per unit length on wire X. State the direction of this force.

Solution:

Tutorial qn: Q13

16.6 Magnetic Force on a Moving Charge in a Magnetic Field

j.	*Predict the direction of the force on a charge moving in a magnetic field.*
k.*	*Recall and solve problems using $F = B Q v \sin\theta$.*

(a) Formula for the Force on a moving charge

- Since current, which consists of moving charges, can experience a force in a magnetic field, a *moving* charge will also experience a force in a magnetic field.
- Consider a charge *q* moving at a constant speed *v* at right angles to a field of flux density *B*. Suppose the charge travels a distance *L* in time *t*, its speed is $v = \frac{L}{t}$.
- Given $F = BIL \sin\theta$ and $I = \frac{q}{t}$, we get:

$$F = (B)\left(\frac{q}{t}\right)(L) \sin\theta$$

$$F = (B)(q)\left(\frac{L}{t}\right) \sin\theta$$

$$F = Bqv \sin\theta$$

- Hence the magnetic force on a moving charge *q* is:

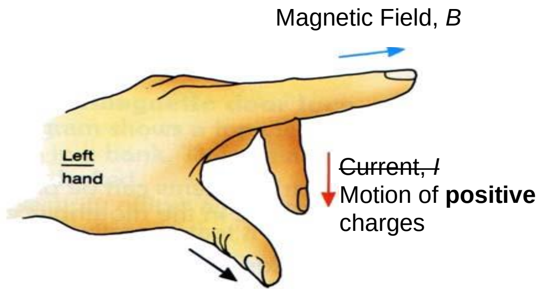
$$\boxed{F = Bqv \sin\theta} \qquad \text{(eqn 16.6.1)} \qquad \theta \text{ : angle between } B \text{ and } v.$$

Magnetic force = 0, if
- charge is stationary or
- $\theta = 0°$, i.e. *v* is parallel to *B*

(b) Direction of magnetic force & its effect on the speed

Direction of magnetic force:

- Direction if the magnetic force is determined using *Fleming's Left Hand Rule*.
- Recall that current is always defined as conventional current, which is the flow of **positive charges**.
- Hence, the *middle* finger must point in the direction of the motion of **positive** charge when using FLHR.

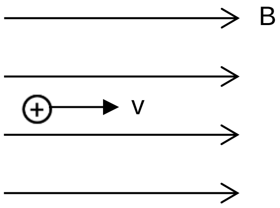


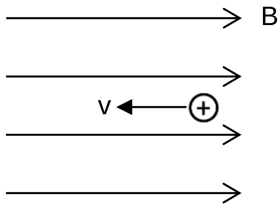
In summary, if:
- **positive charges are moving:** middle finger points in the same direction of positive charge flow
- **negative charges are moving:** middle finger points in the OPPOSITE direction of negative charge flow.

Effect on speed:
- Since magnetic force is always perpendicular to velocity, work done by magnetic force = 0.
- Hence, KE and speed of charge remains **unchanged**.

(c) 3 Possible Path Shapes (trajectories) depending on θ

1. If $\theta = 0°$, the charged particle will take a straight path (i.e. undeflected) since $F = 0$ N.





2. If $\theta = 90°$, the charged particle will take a circular path since by FLHR, the magnetic force will always be perpendicular to the velocity of the charged particle.

   Hence, the magnetic force provides for the centripetal force required for a circular motion.

Case 1: Moving charge is already inside a uniform magnetic field: Path may be a full circle.

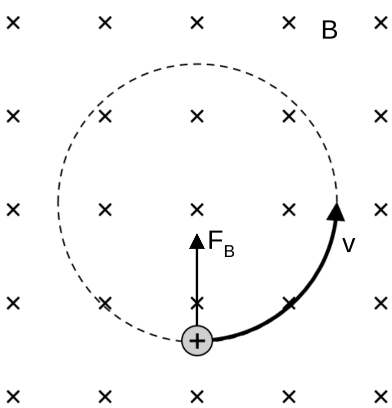


Fig. 16.21a

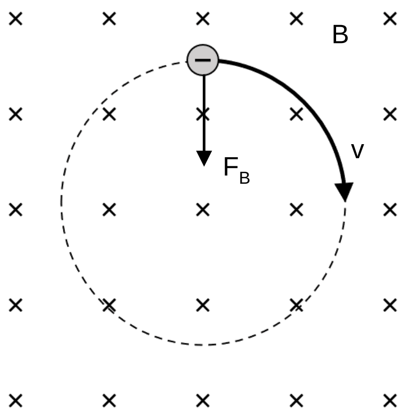
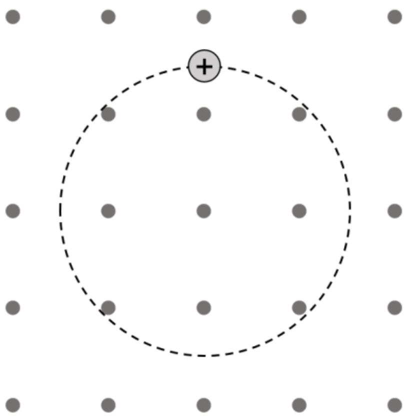


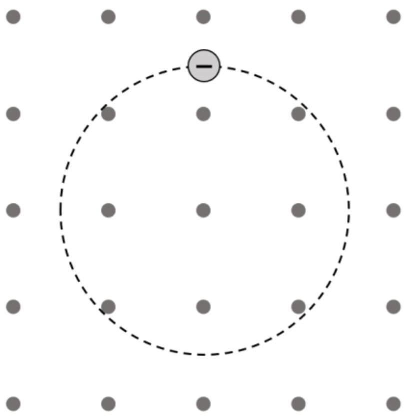
Fig. 16.21b

- Assuming the positive charge (e.g. proton) is moving to the right.
- Using FLHR, the middle finger must point towards the right (**same** direction as the motion of **positive** charge).
- Hence, F_B acts upward, resulting in the circular path as shown.

- Assuming the negative charge (e.g. electron) is moving to the right.
- Using FLHR, the middle finger must point towards the left (**opposite** to the direction of motion of **negative** charge).
- Hence, F_B acts downward, resulting in the circular path as shown.

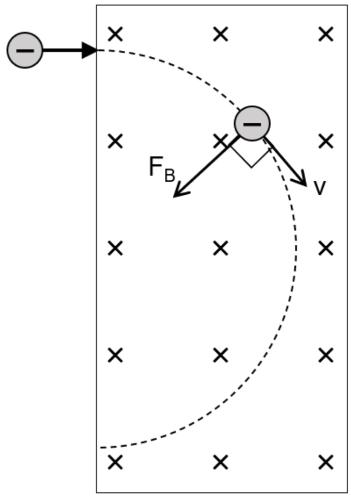
Exercise: Deduce the direction of the F_B and hence the direction of motion of the charge.





Case 2: Moving charge enters a uniform magnetic field from outside: Path will follow a circular arc, but will NOT be a full circle.

Assume a negative charge enters a uniform magnetic field from outside.



Since F_B is always perpendicular to the motion,

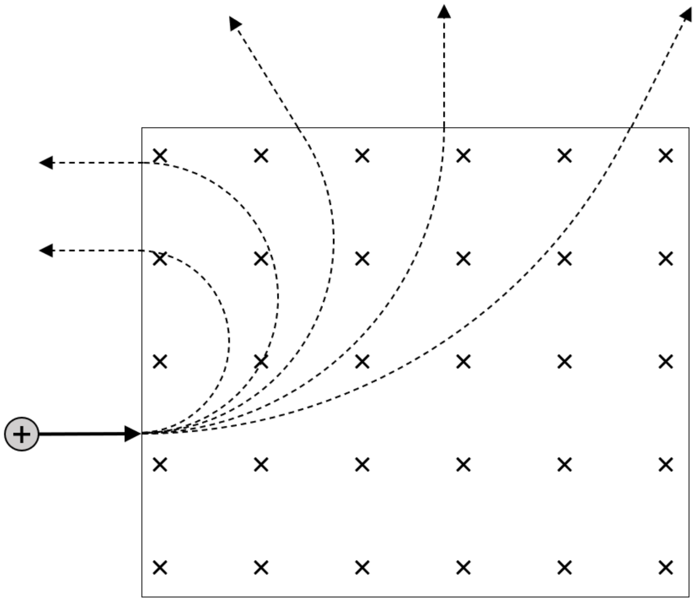
F_B provides for the centripetal force.

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

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

Radius of the circular motion depends on m, v, B and q.

If a charge enters a uniform magnetic field externally, it will not be able to complete a full circle (even though the path still follow a circular arc).



The diagram on the left shows some of the possible paths a positive charge can make when entering a uniform magnetic field pointing into the page.

Note that the charge will move in a straight line after exiting the magnetic field.

3. If 0° < θ < 90°, the charged particle will move in a **helix** / **helical path** (i.e., it spirals forward).

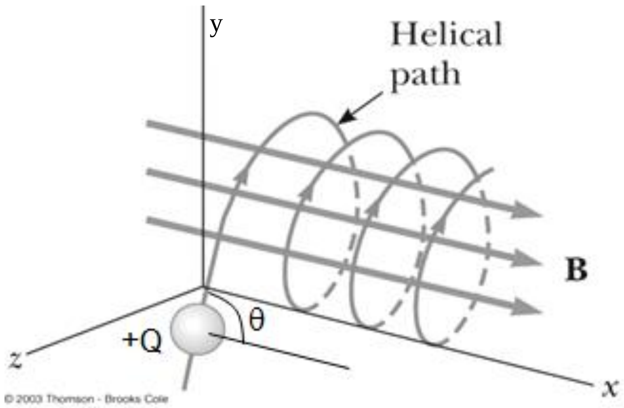
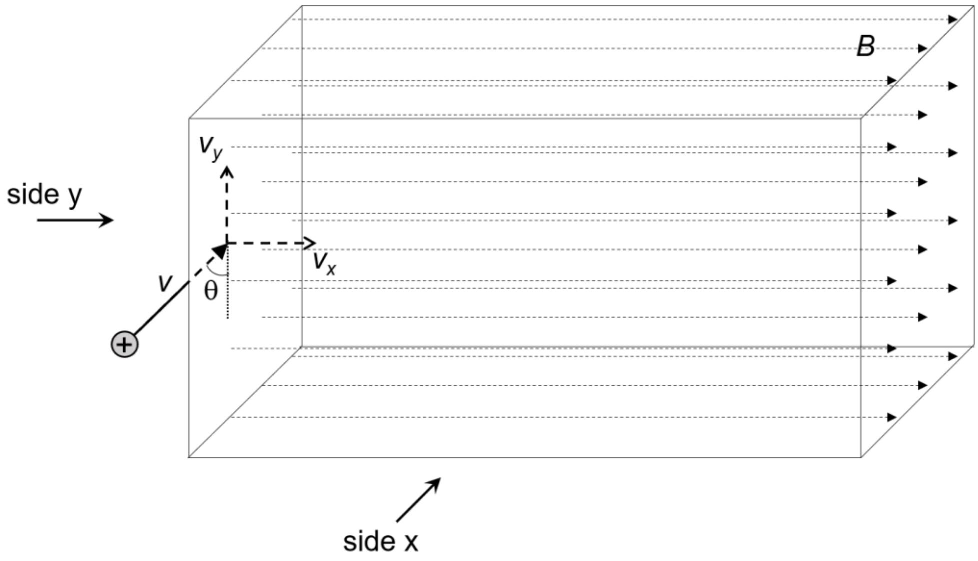


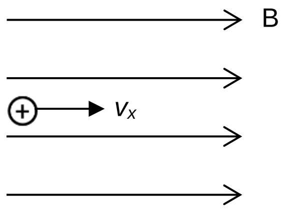
Fig. 16.22: charged particle in a helical path.

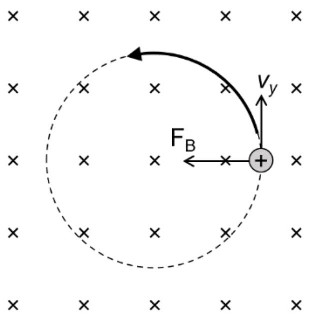


Imagine a charged particle enters a 3-dimensional *B* field with velocity *v* at an angle θ, as shown above.

The velocity *v* can be resolved into a vertical component v_y and horizontal component v_x.

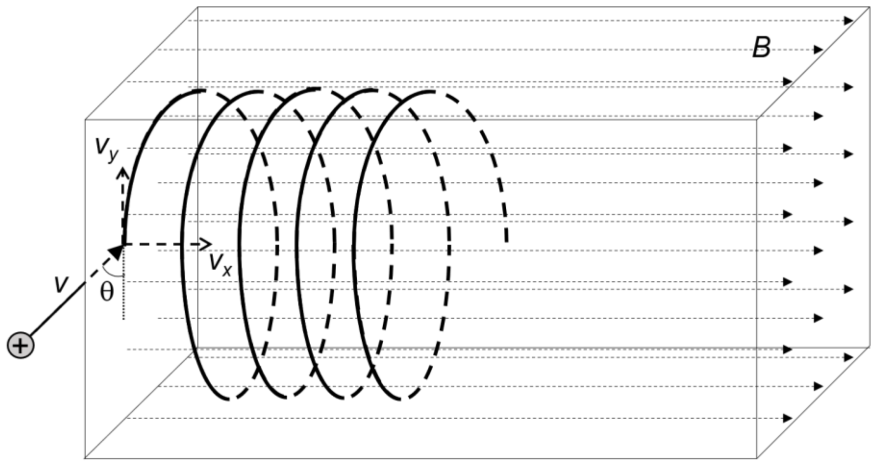
- Viewing from side x, we can see that the horizontal component v_x is <u>parallel</u> to the magnetic flux density *B*.
- Hence, there is <u>no magnetic force</u> induced due to v_x.
- v_x will allow the charged particle to move rightward in a <u>straight line</u>.





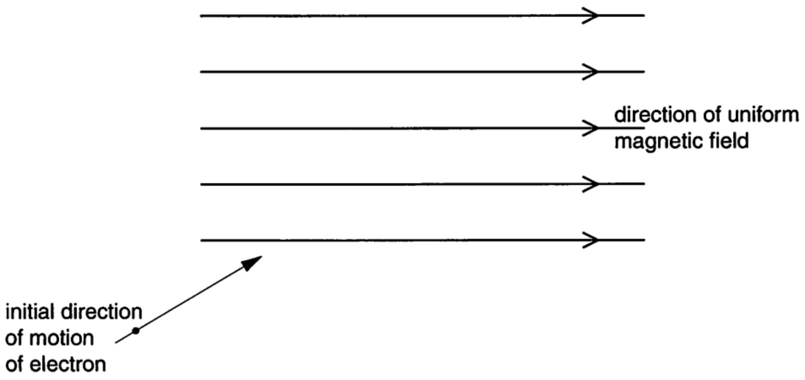
- Viewing from side y, we can see that the vertical component v_y is <u>perpendicular</u> to the magnetic flux density *B*.
- Using FLHR, we can see that a magnetic force F_B will be induced due to v_y, pointing to left.
- v_y will cause the charged particle to move in a <u>circular motion</u> as shown.

Combining the effect due to v_x (straight line) and v_y (circular motion) will result in a helical motion.



Worked Example 11 [N14/III/7e]: Explaining the Helical Path

The initial direction of an electron is directed at an angle to the direction of a uniform magnetic field, as shown in the figure below.



By considering the components of the velocity parallel to the magnetic field and at right-angles to the magnetic field, describe and explain qualitatively the motion of the electron in the field. [4]

Solution:

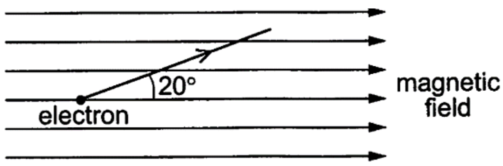
- The component of the velocity at right-angle to the magnetic field causes the electron to experience a magnetic force.
- By Fleming Left-hand rule, the magnetic force is always perpendicular to this component of velocity and causes the electron to move in a circular path in a plane perpendicular to the magnetic field.
- The component of the velocity parallel to the magnetic field is unaffected by the magnetic field and causes the electron to move at constant speed in the direction parallel to the magnetic field.
- The resultant motion is a helical path along the direction of the magnetic field.

Example 12 [N17/I/23]

An electron moves in a vacuum at an angle of 20° to a magnetic field of flux density of 0.088 T.

The force on the electron is 4.3×10^{-14} N.

What is the speed of the electron? [8.9×10^{6} m s^{-1}]



Solution:

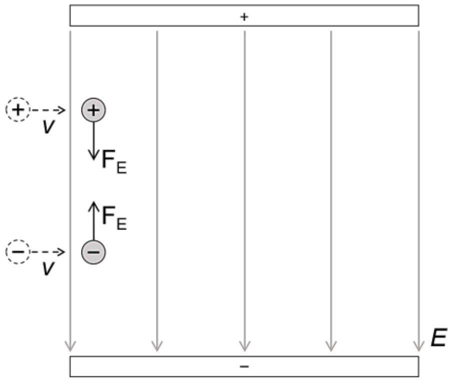
Tutorial qn: Q14, Q16, Q17, Q18, Q19, Q21, Q22

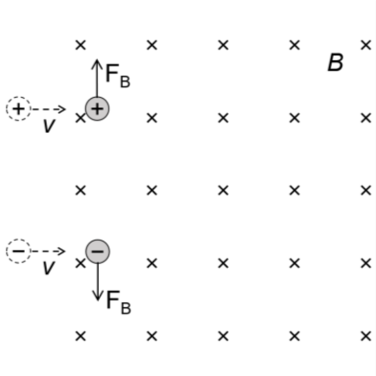
16.7 Use of 'Crossed Fields' to Select a Particular Velocity (Velocity Selector)

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.*

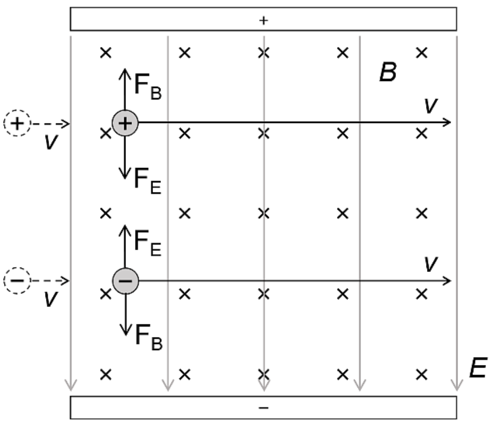
When charged particles pass through an *electric field*, they could be made to move in a **parabolic** path (topic 15); when the same particles pass through a *magnetic field*, they could be made to move in a **circular** path.

- When charges enter an E-field or a B-field, an F_E or F_B exerts on the charges respectively.





- Note that F_E and F_B acts in the opposite direction for the same charge in different fields.

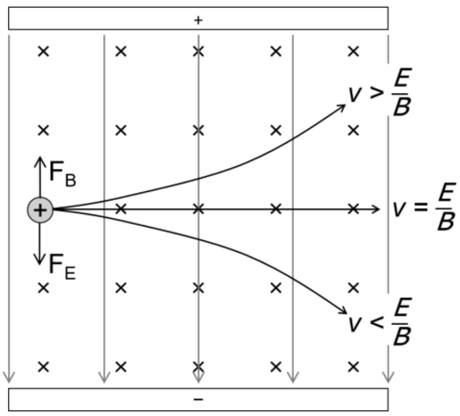


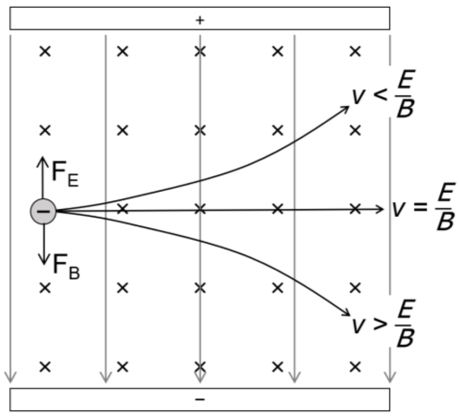
- Imagine we setup both the E- and B- field to exist in the same region (i.e. crossed fields).
- If the charges move at a certain speed, it is possible that the F_E and F_B cancels out each other completely. The charges will then be able to move through the crossed fields at a constant speed
- For $F_E = F_B$, $qE = Bqv$

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

- If the charges are moving at $v = \frac{E}{B}$, the charges will move through the cross field undeflected.

- This is the concept of **velocity selector**, which is a device that makes use of crossed fields to allow charged particles of a particular velocity to pass through undeflected.
- The velocity selected can be adjusted by adjusting the magnitude of E and B.
- If $v \neq \frac{E}{B}$, there will be a deflection. Direction of deflection depends on *v* and the polarity of charge.



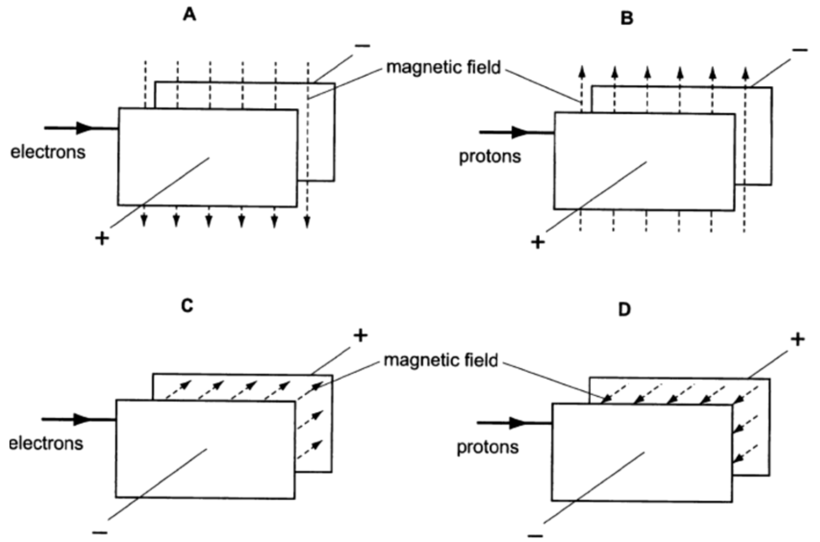


- In general,

Velocity of charged particle	F_B vs F_E	Direction of deflection
$v = \frac{E}{B}$	$F_B = F_E$	Undeflected
$v > \frac{E}{B}$	$F_B > F_E$	Deflected in the direction of F_B
$v < \frac{E}{B}$	$F_B < F_E$	Deflected in the direction of F_E

Example 13

The diagrams show different particle beams entering a region between two metal plates in which there are uniform electric and magnetic fields. In which arrangement would it be possible for the beam to pass through **undeflected**? [N08/1/31]



Ans:

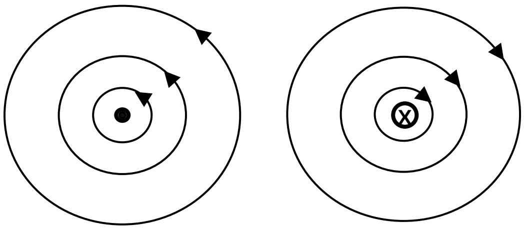
Tutorial qn: Q20, Q23

16.7.1 Comparison Between Deflections of a Charged Particle in B and E Fields

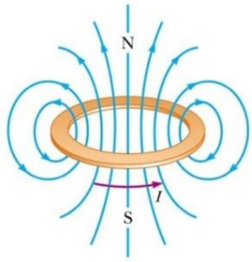
Magnetic Field ($F_B = Bqv\sin\theta$)	Electrical Field ($F_E = qE$)
Magnetic field can exert a magnetic force **only** on a **moving** charged particle.	Electric field can exert an electric force on a **stationary or moving** charged particle.
Magnetic force is **always perpendicular** to the magnetic field and the direction of motion of the charged particle (deduced using **FLHR**)	The electric force acts either **parallel or antiparallel** to direction of the electric field.
Magnitude of magnetic force is **dependent on the speed** and direction of motion of the charged particle ($F_B = Bq\mathbf{v}\sin\theta$)	Electric force is **not dependent on the speed** and direction of motion of the charged particle ($F_E = qE$)
Circular motion is obtained when a charged particle enters a magnetic field perpendicularly.	**Parabolic motion** is obtained when a charged particle enters an electric field perpendicularly

SUMMARY

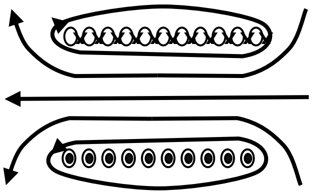
1 Recall magnetic flux patterns: (use Rt Hand Grip Rule)



2 Long Straight Wires (top view)



Flat Circular coil



Long Solenoid

2 **3 Magnetic Field Formulas:** (recall is NOT required; provided in List of Formulae)

2.1 For a **long straight wire**, $B = \dfrac{\mu_o I}{2\pi d}$

2.2 For a **flat circular coil:** at its **centre**, $B = \dfrac{\mu_o NI}{2r}$

2.3 **Within** a **long solenoid**, $B = \mu_o nI$

3 Force on a current-carrying conductor: $\boldsymbol{F = BIL\sin\theta}$

- <u>direction</u> of force found using **Fleming's left-hand rule.**
- Impt to know how to apply FLHR **"indirectly" when B & $\boldsymbol{I}$** are **NOT at 90^0**

4 **Define magnetic flux density** (***B***) as the <u>force acting per unit current</u> on a <u>wire</u> of <u>unit length</u> placed *at <u>right-angles</u>* <u>to the field</u>, ie $\boldsymbol{B = \frac{F}{IL\sin\theta}}$ { 3 mark quest}

- To det B using a **Current Balance:** apply **principle of moments** after disrupted rotational equilibrium is restored.

5 Use of **RHG Rule & FLH Rule** to explain/predict for **2 parallel, long straight conductors**:

If currents in the <u>same</u> direction, ⇒ <u>attractive</u> forces betw conductors;
If currents in <u>opposite</u> directions, ⇒ <u>repulsive</u> forces betw conductors.

6 Force on a **Moving** Charge: $\boldsymbol{F_B = Bqv\ sin\theta}$, where θ is angle between *B* and *v.*

- If v or **θ = 0**, ⇒ $F_B = 0$
- use Fleming's left-hand rule to find direction of F_B
- if θ = **0°**, charged particle takes a **straight path (** ie **undeflected)**
- if **θ** = **90°**, charged particle takes a **circular path (or an arc of a circle)**
- if **0° < θ < 90°:** particle takes a **helical path/helix**

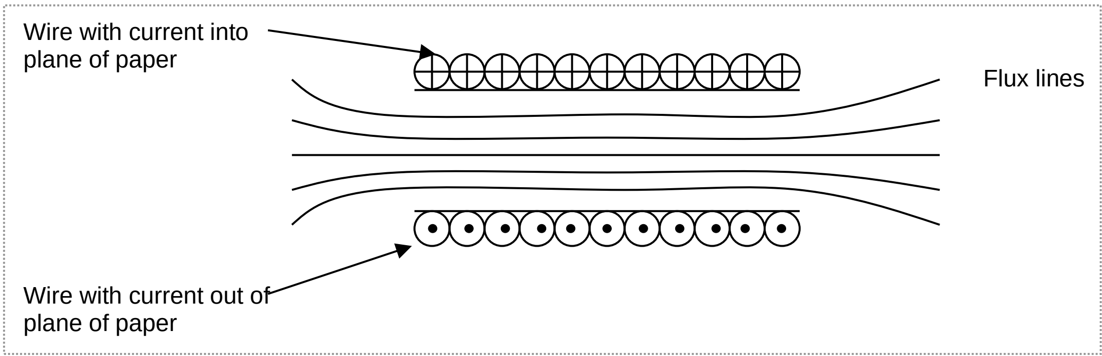
7 **Use of Cross Fields in Velocity Selector**:

- motion of charged particle is **undeflected**
  if magnetic force = electric force on charged particle,
  $\Rightarrow \boldsymbol{v = \frac{E}{B}}$ (ie particles with this speed are selected,
  ie only these can travel out of device)

TUTORIAL 16: ELECTROMAGNETISM

Magnetic Field, Field Lines, Flux Patterns & 3 Field Formulae

(L1) 1. The diagram below illustrates the pattern of the magnetic flux due to a current in a solenoid.



On the diagram,

(a) Draw arrows to show the direction of the magnetic field in the solenoid. [1]

(b) 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. [1]

[J97/II/3]

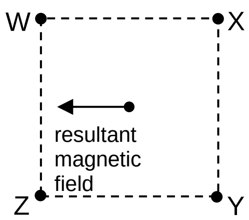
(L1) 2. Sketch the resultant fields around two long wires carrying currents of the same magnitudes. The directions of the currents are as shown in the figures:

(a) Currents in the same direction [2]

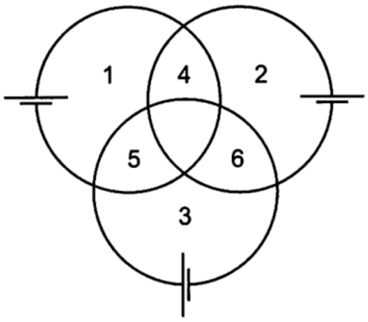
(b) Currents in opposite directions [2]

(L2) 3. 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? [J96/I/18, 2005P1Q25]

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



(L2) 4. Three separate coils of insulated wire are connected by cells as shown. They are placed on a table on top of each other, partially overlapping.



Six of the seven areas formed within the coils are numbered.

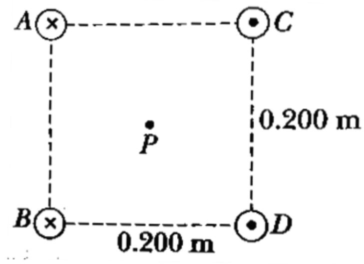
In which areas do the magnetic fields of all the coils reinforce each other?

A 1 and 6 **B** 2 and 5 **C** 3 and 4 **D** 4 and 6

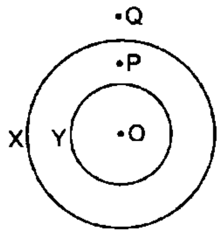
[2015/1/Q30]

(L2) 5. Four long, parallel conductors carry equal currents of $I = 5.00$ A through four corners of a square, with their directions as indicated in the diagram.

Calculate the magnitude and direction of the magnetic field at point *P*, located at the centre of the square with edge of length 0.200 m. [2]



(L2) 6. X and Y are two coaxial circular coils lying on a table. O, P and Q are three points on the table.



Initially, there is a constant current in coil X and no current in Y. A small current is now passed through coil Y, which **decreases** the magnitude of the magnetic flux density at O.

How does the magnitude of the flux density change at P and Q? [2019/P1/Q26]

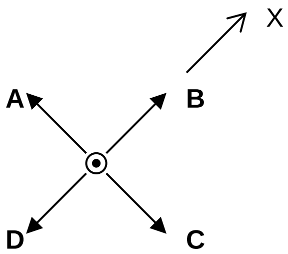
	P	Q
A	decrease	decrease
B	decrease	increase
C	increase	decrease
D	increase	increase

(L2) 7. By reference to the flux pattern of the magnetic field in a solenoid, suggest the difference, if any, between the magnitude of the flux density at the ends of the solenoid compared with at the centre. [2019/P3/Q6(a)(ii)]

Magnetic Force on a Current-Carrying Conductor

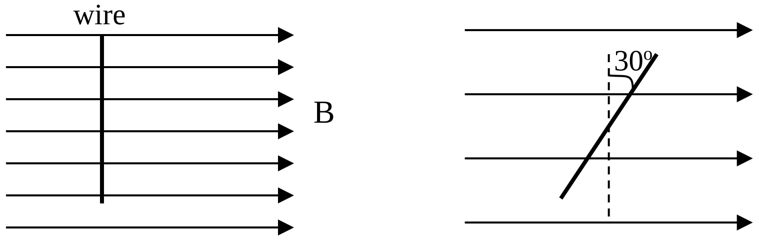
(L1) 8. The diagram shows cross-section of a straight wire that carries a steady current out of the plane of the paper towards the observer. The arrows represent the directions of four magnetic fields, A, B, C and D.

Which field causes the wire to move towards the point X? [J01/I/18]



(L1) 9. 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.

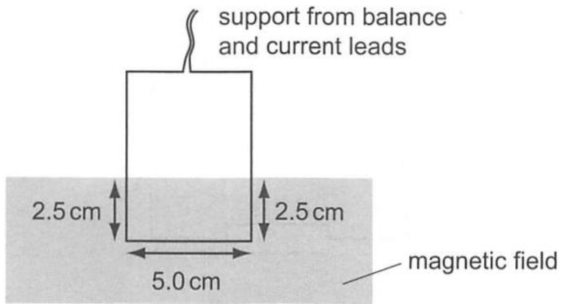
The wire is rotated, in its horizontal plane, through 30º as shown. The flux density of the magnetic field is halved.



What is the vertical force on the wire? [N02/I/25]

A 2.0 mN **B** 3.5 mN **C** 4.6 mN **D** 8.0 mN

(L2) 10. A single-turn rectangular wire loop hangs from a balance reading in grams so that its lower part is in a region of uniform magnetic field. The direction of the field is at right-angles to the plane of the loop. The arrangement is as shown in the diagram. [N07/I/Q30]



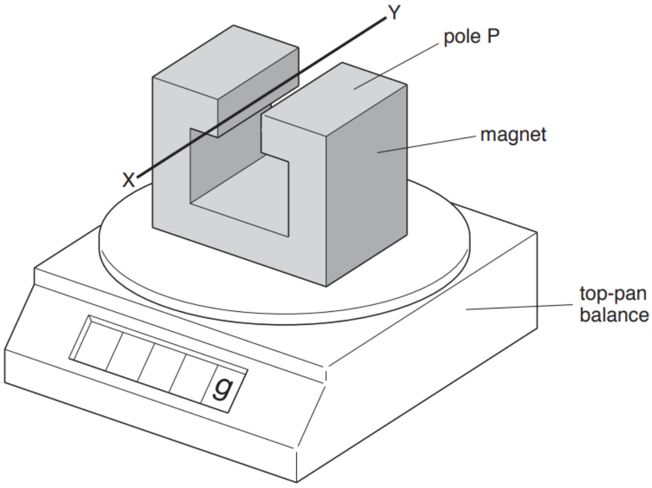
When there is no current in the loop, the reading of the balance is 10.060 g.

When the current in the loop is 3.0 A, the balance reading is 10.040 g.

What is the magnitude of the flux density of the field?

A 6.5×10^{-4} T **B** 1.3×10^{-3} T **C** 1.3×10^{-2} T **D** 6.6×10^{-1} T

(L2) 11. A horseshoe magnet rest on a top-pan balance with a wire situated between the poles of the magnet. With no current in the wire, the reading on the balance is 142.0 g. With a current of 2.0 A 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?

[N04/I/24]

A 138.1 g **B** 140.7 g **C** 145.9 g **D** 148.5 g

(L2) 12. **(a)** A coil of 1500 turns of insulated wire is tightly wound on a non-metallic tube to make a solenoid of mean radius 22 mm, as shown below. The wire itself has a radius 0.86 mm and is made of a material of resistivity $1.7 \times 10^{-8}\ \Omega$ m. The coil is connected to a supply of e.m.f. 12 V and negligible internal resistance.

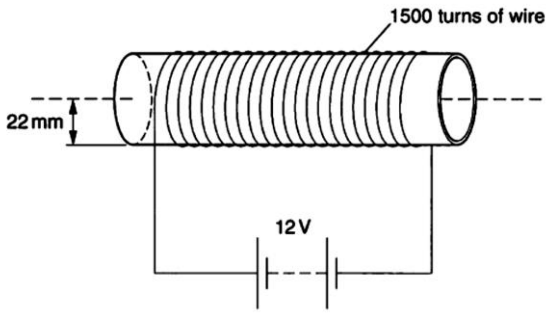


Fig. 12.1

Calculate

(i) the total length of wire in the coil [2]

(ii) the total resistance of the coil [3]

(iii) the current in the coil [2]

(b) On Fig. 12.1, draw the pattern of the magnetic field within and around the solenoid. Use arrows to show the direction of the field inside the solenoid. [3]

(c) The magnetic flux density in the solenoid is measured using a current balance. The current balance is a U-shaped piece of stiff wire ABCDEF pivoted at BE, as shown in Fig. 12.2.

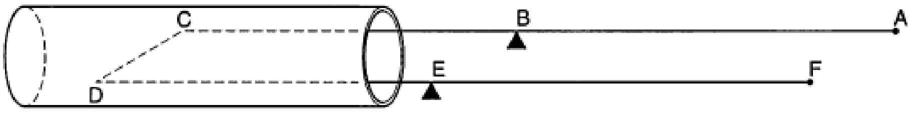


Fig. 12.2

When in use, there is a turning force on the stiff wire caused by a current in CD.

(i) Explain why currents in CB and DE do not contribute to the turning force. [1]

(ii) Explain why the current in CD causes a turning effect. [3]

(iii) CD has length 25 mm, CB and DE each have length 106 mm.
The stiff wire is first balanced when there is no current in it.

A current of 4.9 A is then passed through CD and, in order to rebalance the stiff wire, a force of 5.7×10^{-4} N is then applied at a distance of 77 mm from the pivot, as shown in the side view of the balance, Fig. 12.3.

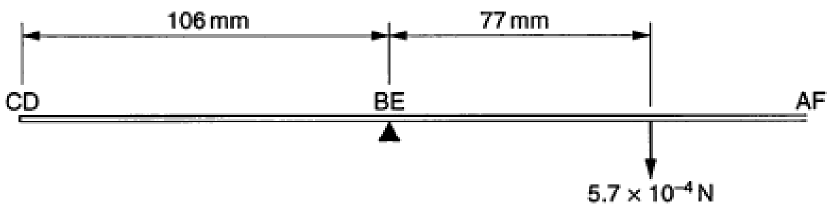


Fig. 12.3

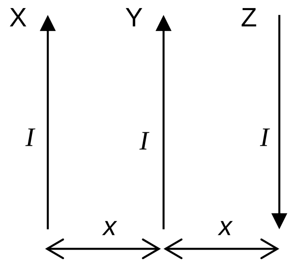
1. What is the direction of the current in CD? [1]

2. Calculate the magnetic flux density in the solenoid. Give the full name of the unit for magnetic flux density. [5]

[H1 N10/II/7]

(L1) 13. 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

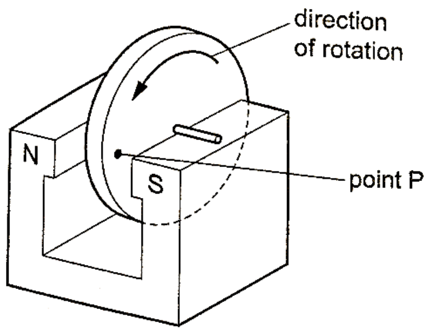


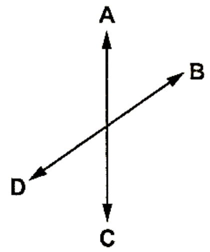
[N99/I/18]

Force betw Current-Carrying Conductors, Force on a Moving Charge & the Velocity Selector

(L1) 14. A metal disc rotates between the poles of a horseshoe magnet as shown in the diagram.

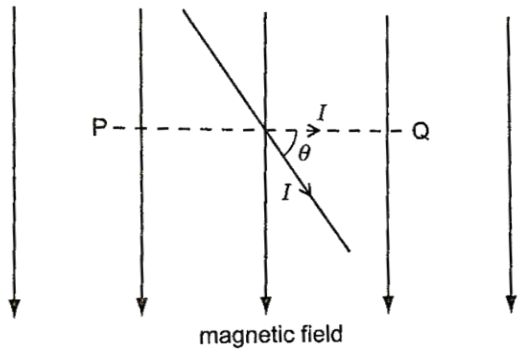
In which direction is the electromagnetic force on a free electron at point P in the disc?





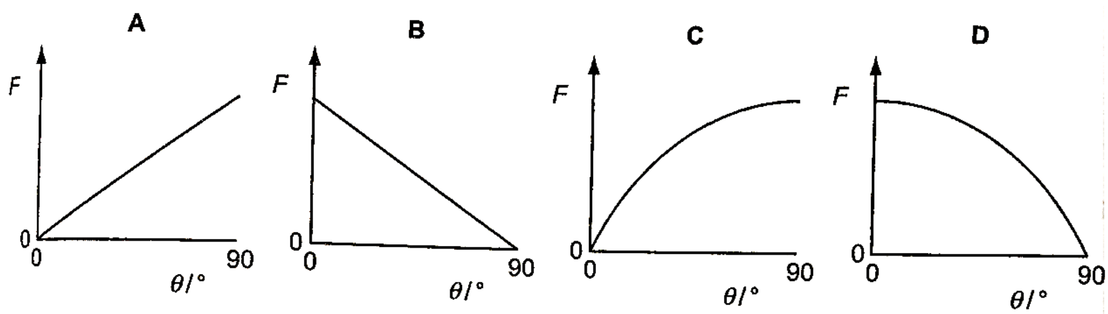
[N16/I/30]

(L1) 15. A straight wire PQ carrying a constant current I is placed at right angles to a uniform magnetic field, as shown by the dotted line in the diagram.

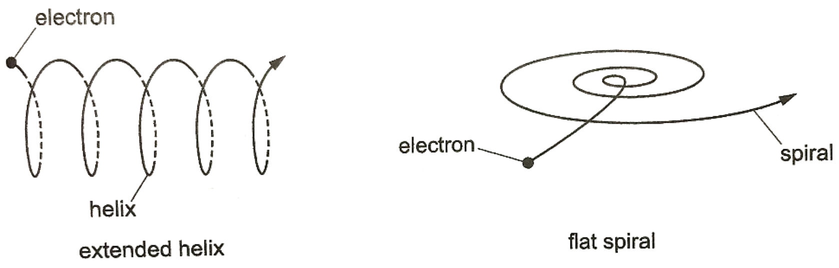


The wire is then rotated through an angle θ about an axis perpendicular to the plane of the diagram.

Which graph shows how the magnitude of the magnetic force F on the wire varies with θ in the range 0° to 90°? [N06/I/23]



(L2) 16. The force on an electron is 7.3×10^{-16} N when moving at an angle of 23° to a uniform magnetic field of magnetic field strength 0.084 T. [N16/I/31]



What is the speed of the electron and what is the shape of the path of the electron?

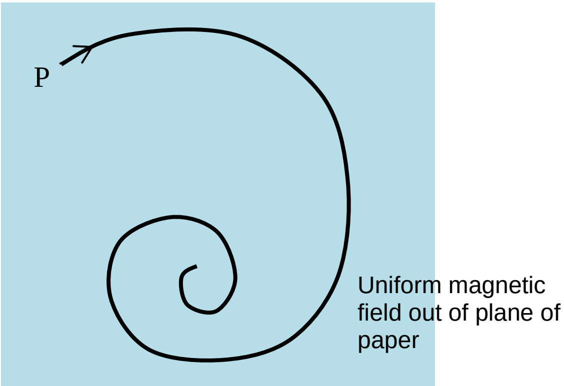
A 1.4×10^{5} m s^{-1} in a helix

B 1.4×10^{5} m s^{-1} in a spiral

C 2.1×10^{4} m s^{-1} in a helix

D 2.1×10^{4} m s^{-1} in a spiral

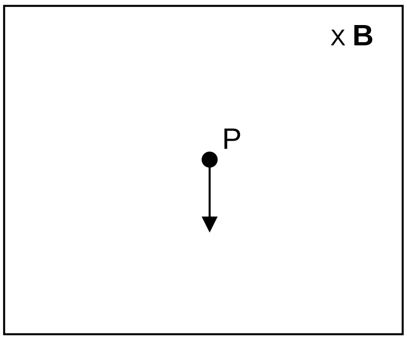
(L2) 17. A charged particle is moving in a region where there is a uniform magnetic field acting out of the plane of the paper. The path of the particle begins at P and is as shown. [N09/1/30]



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

(L2) 18. 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 2.9×10^{7} m s^{-1} in the direction shown. This is normal to the magnetic field.



region of magnetic field into the plane of the paper

(a) On the figure, sketch the path of the electron, assuming that it does not leave the region of the magnetic field. [2]

(b) Calculate, for the electron,

(i) the force on it due to the magnetic field, [2]

(ii) the radius of its path, [2]

(iii) the time taken for it to complete half a revolution, [2]

(iv) its kinetic energy. [1]

(c) Determine the potential difference required to accelerate the electron to this speed from rest. [1]

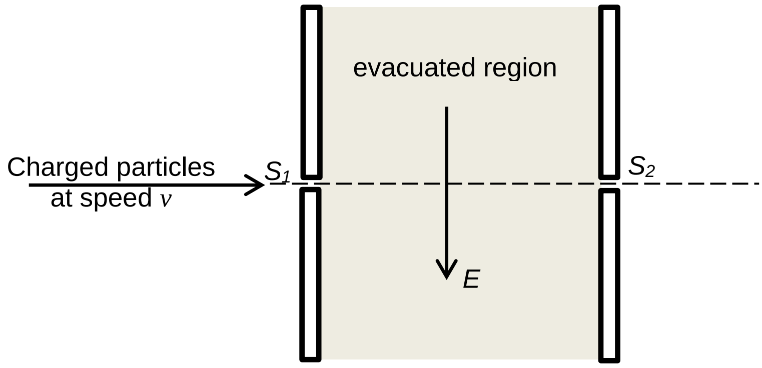
[N03/2/6b mod]

(L2) 19. A charged particle, initially travelling in a vacuum in a straight line, enters a uniform field. This causes the particle to travel in a curved path that is not the arc of a circle. Which type of field, and which initial direction of the particle with reference to the field, causes this to happen?

[N08/P1/30]

	field type	initial direction of the particle compared to the field
A	electric	parallel
B	electric	perpendicular
C	magnetic	parallel
D	magnetic	perpendicular

(L2) 20. A narrow parallel beam of charged particles, each with speed v_1, passes through a slit of S_1 into an evacuated region, moving in the direction towards slit S_2. The evacuated region is shown shaded below.

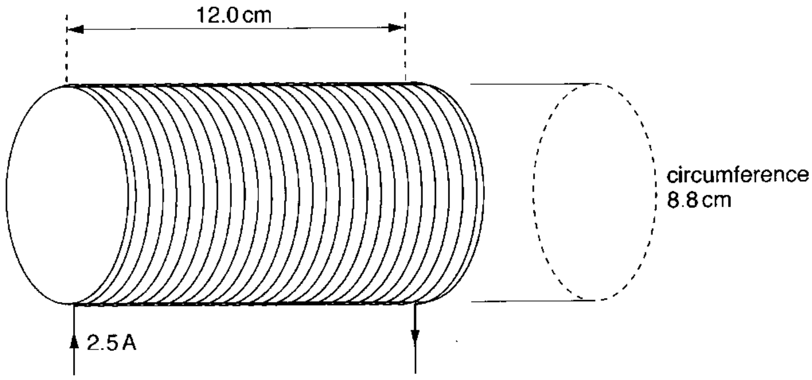


Uniform magnetic and electric fields are applied in the same evacuated region, with the electric field E in the direction shown. The particles continue to exit through slit S_2.

What is the magnitude and direction of the magnetic field? [N11/P1/29]

	Magnitude	Direction
A	$\frac{E}{v}$	into the plane of the paper
B	$\frac{E}{v}$	out of the plane of the paper
C	Ev	into the plane of the paper
D	Ev	out of the plane of the paper

(L2) 21. A student makes a solenoid with insulated copper wire. The solenoid has length 12.0 cm and average length of one turn of wire on the solenoid is 8.8 cm as shown in the figure below.



The copper wire has a circular cross-section of diameter 0.60 mm. The resistivity of copper is 1.6×10^{-8} Ω m. It is found that the current in the solenoid is 2.5 A when the potential difference across the terminals is 4.5 V.

(a) **(i)** Calculate, for the solenoid, the resistance of the wire. [1]

(ii) Use your answer in **(i)** in order to calculate the total number of turns on the solenoid. [3]

(iii) Use your answer in **(ii)** to show that the number of turns per metre length of the solenoid is 3000. [1]

(b) Calculate the magnetic flux density in the solenoid. [1]

(c) The solenoid in is in a vacuum. An electron is injected into the magnetic field of the solenoid with a speed of 4.0×10^7 m s^{-1} at an angle of 30° to its axis, as shown in Fig. 18.2.

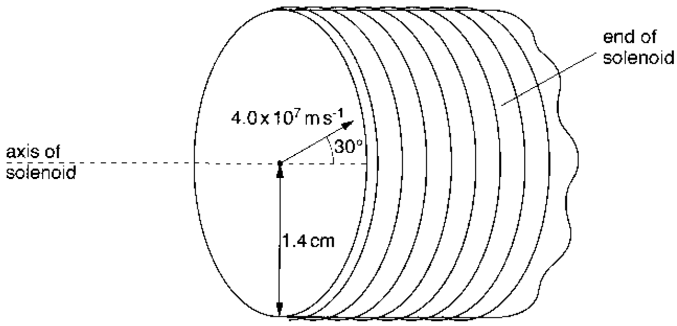


Fig 18.2

Calculate the magnitude of the component of the electron's velocity

(i) along the axis of the solenoid, [1]

(ii) normal to the axis of the solenoid. [1]

(d) A particle of mass *m* and charge *q* is moving with speed *v* normal to a magnetic field of flux density *B*. Show that the particle will move in a circular path of radius *r* given by the expression

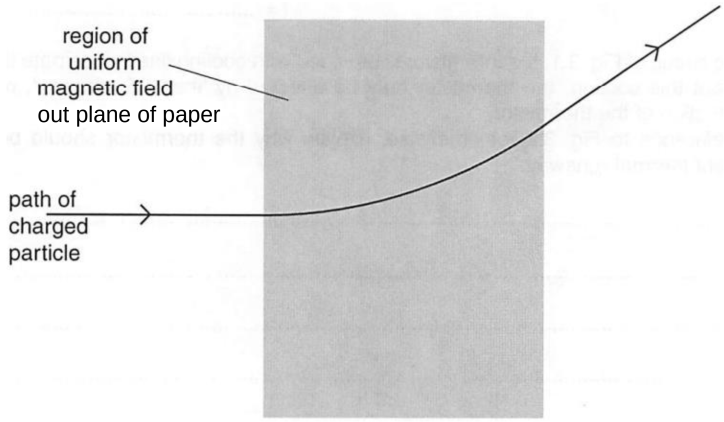
$$r = \frac{mv}{Bq}$$

Explain your working. [3]

(e) The radius of the cross-section of the solenoid in **(c)** is 1.4 cm. Use data from **(c)** and **(d)** to determine quantitatively whether the electron will travel down the length of the solenoid or will collide with its wall. [3]

[N09/P3/2]

(L2) 22. A charged particle is travelling with momentum *p* in a vacuum. It enters a region of uniform magnetic field directed perpendicularly out the plane of the paper.



When the charged particle is in the magnetic field, it is travelling at right-angles to the direction of the field.

(i) Explain why the path of the particle in the magnetic field is an arc of a circle. [2]

(ii) State the sign of the charged particle. [1]

(iii) A second particle has a greater momentum. The second particle has charge of equal magnitude but opposite sign, and is travelling along the same path towards the magnetic field.

Draw the path of this second particle as it passes through and leaves the region of the magnetic field. [2]

(L2) 23. A chlorine gas consists of two types of atoms: chlorine-35 and chlorine-37, of different masses. A researcher wants to separate these two atoms. He does this by using a device called the mass spectrometer as shown in Fig. 6.1.

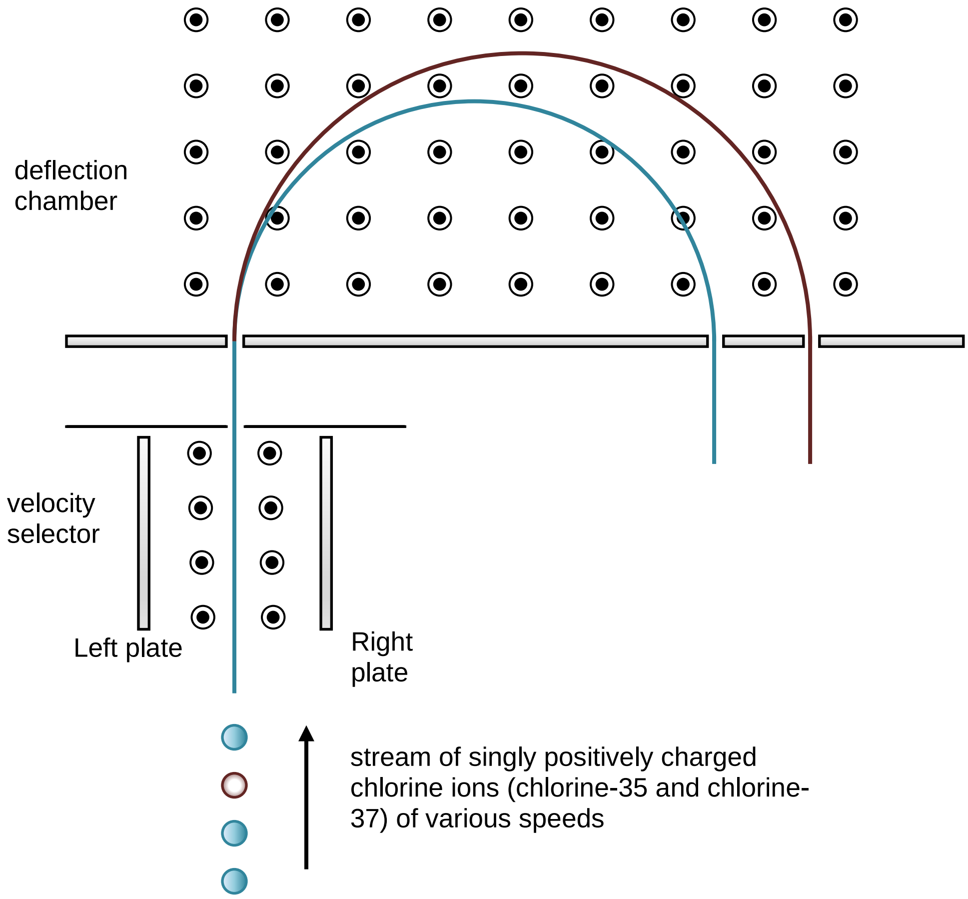


Fig. 6.1 Mass spectrometer

The researcher first ionises all the atoms into singly positively charged ions, and then sends the individual ions of various speeds through the velocity selector. The emerging ions then enter the deflection chamber where they are deflected by a uniform magnetic field.

(a) The first part of the device is the velocity selector where there is a uniform magnetic field, two charged parallel plates, and a slit to allow undeflected ions to emerge through, as shown in Fig. 6.1.

(i) State whether the left plate is at a higher or lower electric potential, explain your answer. [2]

(ii) The flux density of the magnetic field in the velocity selector is 0.020 T. The field strength of the electric field between the plates is 1.50×10^4 V m^{-1}.

Calculate the speed of the emergent ions as they pass undeflected in the velocity selector. [2]

(iii) Describe what happens to those ions that do not have the speed as calculated in **(a)(ii)** and suggest why it is called the velocity selector. [2]

(b) The second part of the device is the deflection chamber where the flux density of the magnetic field is 0.020 T. The two different types of ions, chlorine-35 and chlorine-37, are deflected with different radii and hence are separated. Given that Chlorine-35 atom has a mass of 35*u* and chlorine-37 atom has a mass of 37*u*.

(i) Calculate the radius of the semi-circular path of the chlorine-35 ions. [2]

(ii) Given that the mass of the ions are unchanged, state the effect on your answers to **(a)(ii)** and **(b)(i)** if

1. the ions are singly negatively charged,

effect on **(a)(ii)** : ....

effect on **(b)(i)** : .... [1]

2. the ions are still positively charged but are doubly charged.

effect on **(a)(ii)** : ....

effect on **(b)(i)** : .... [1]

[TMJC 2020/3/Q6]

Numerical Answers:

5. 20.0×10^{-6} T, vertically downwards, in the plane of the paper

9. 3.5 mN

10. 1.3×10^{-3} T

11. 138.1 g

12. (a) (i) 207 m (ii) 1.52 Ω (iii) 7.89 A (c) (iii) 3.38×10^{-3} Tesla

16. 1.4×10^{5} m s^{-1}

18. (b)(i) 6.96×10^{-15} N (ii) 0.11 m (iii) 1.19×10^{-8} s (iv) 3.83×10^{-16} J

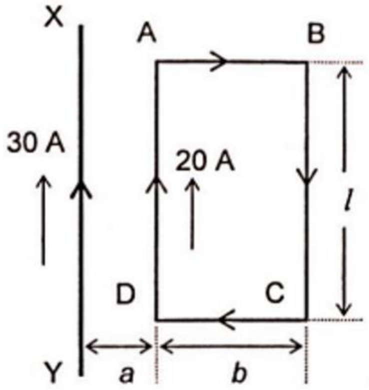
(c) 2400 V

21. (a)(i) 1.8 Ω (ii) 361 turns (b)(i) 9.43×10^{-3} T (c)(i) 3.46×10^{7} m s^{-1} (ii) 2.00×10^{7} m s^{-1}

23. (a)(ii) 7.5×10^{5} m s^{-1} (b)(i) 13.6 m

ADDITIONAL QUESTIONS

1 The figure shows a long wire XY carrying a current of 30 A. The rectangular loop ABCD carries a current of 20 A. Given that a = 1.0 cm, b = 8.0 cm and l = 30 cm,



(a) Calculate the magnetic flux density B due to the current in XY along

(i) AD

B_{AD} = ……………………….. T

(ii) BC

B_{CD} = ……………………….. T

(b) Calculate the resultant force acting on the loop. State the direction of the resultant force.

resultant force = …………………….. N

direction = ………………………………….

(c) State and explain if there are any forces acting on the sides AB and CD and hence, any resultant force acting on the loop along the direction XY.

………

………

………

RJC 2020 P2 Q5

2 A cloud chamber consists of a rectangular box saturated with alcohol vapour. When a charged particle enters the cloud chamber, it interacts with the vapour and leaves a trail, indicating its path in the chamber.

A student designed a cloud chamber with a detector for the charged particles placed at one side of the chamber. A sample which emits identical charged particles is placed at a small opening through one side of the chamber. The charged particles are all emitted with the same speed. A uniform vertical magnetic field of flux density *B* is directed perpendicularly through the entire chamber.

Fig. 5.1 shows the top view of the chamber and the dotted line represents the path of a charged particle entering the chamber and moving on a horizontal plane in the chamber.

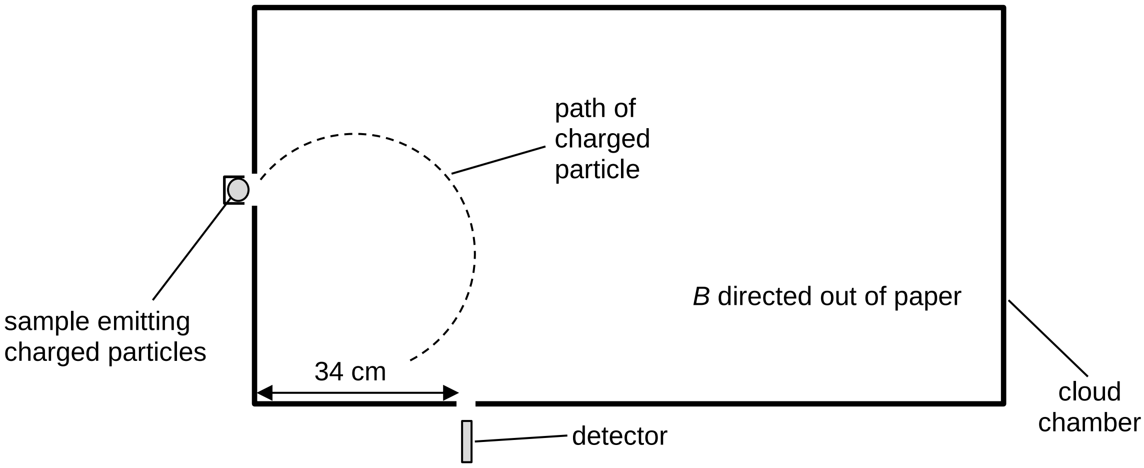


Fig. 5.1 (top view)

(a) **(i)** Define magnetic flux density.

....

....

.... [2]

(ii) State if the charged particle is positively or negatively charged.

.... [1]

(b) The design of the cloud chamber is refined so that particles only enter perpendicularly, as shown in Fig. 5.2.

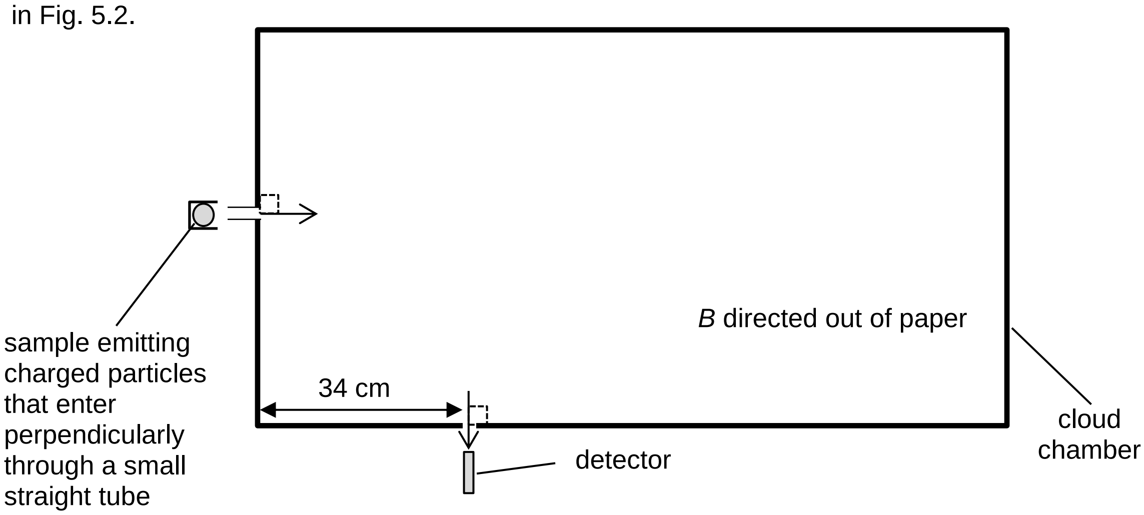


Fig. 5.2 (top view)

The magnitude of B is adjusted so that the particles with the same speed as in Fig. 5.1 will exit perpendicularly through a small opening on another side where the detector is placed. The detector is placed 34 cm from the corner of the chamber.

(i) Derive an expression for B in terms of mass m, speed v and charge q of a charged particle and the radius r of its circular path in the chamber.

[2]

(ii) Deduce whether the magnitude of B has increased or decreased.

....

.... [1]

(iii) Given the magnitude of B is 7.6×10^{-3} T, and each particle has a charge of magnitude 3.2×10^{-19} C and mass 6.6×10^{-27} kg, determine the speed of the charged particle that reaches the detector.

speed = ... m s^{-1} [2]

(c) The design of the cloud chamber is further amended so that particles which enter perpendicularly will move though the chamber undeflected. This is achieved by simultaneously applying a uniform electric field across the chamber.

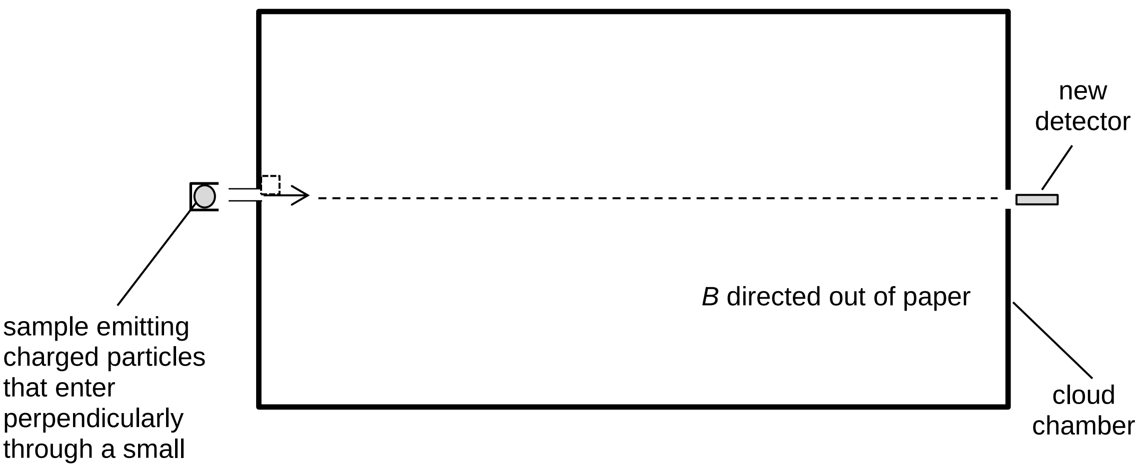


Fig. 5.3 (top view)

(i) State and explain the direction of the electric field.

....

....

.... [2]

(ii) The sample is now placed in the centre of the cloud chamber. Fig. 5.4 shows the direction of speed *v* of one of the emitted charged particles.

With the electric and magnetic fields still applied in the same directions in the cloud chamber as in **(c)(i)**, draw arrows to represent the electric force and the magnetic force acting on the particle at this instant. Label the forces.

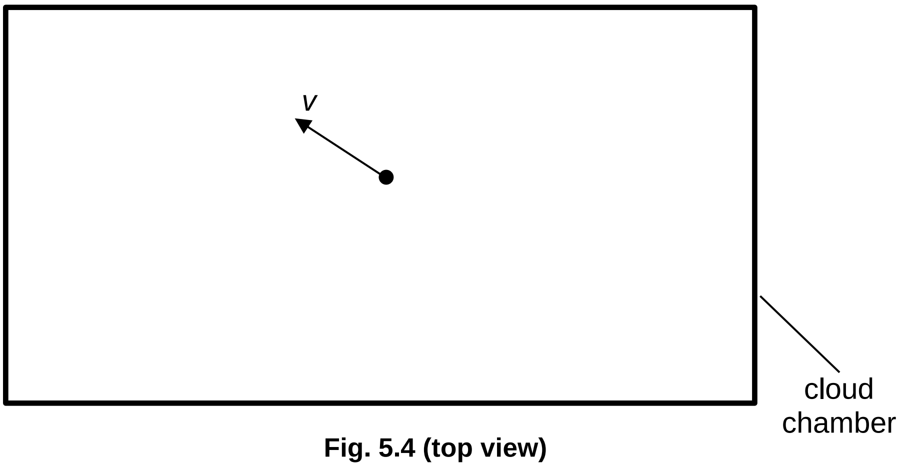


Fig. 5.4 (top view)

[2]

SAJC 2021 P3 Q6

3 **(a)** A slice of a conducting material has its face QRLK normal to a uniform magnetic field of flux density B, as illustrated in Fig. 6.1.

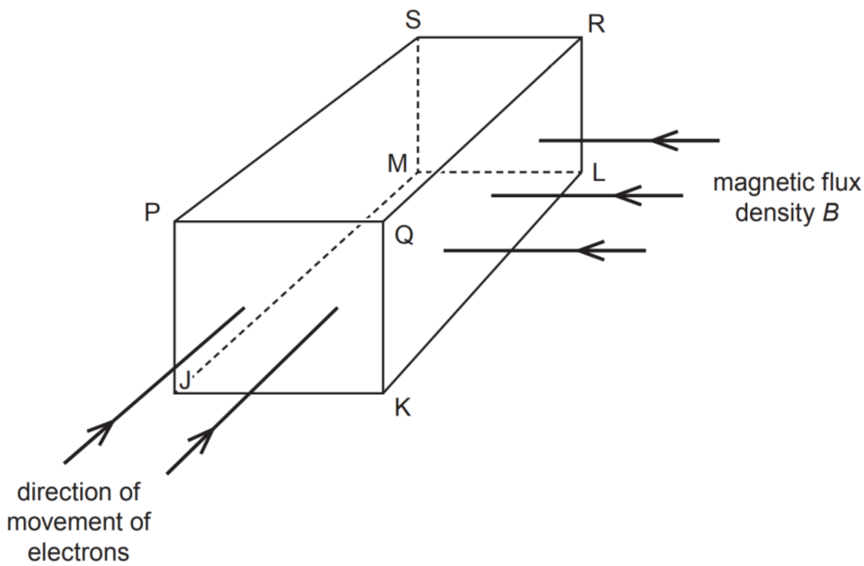


Fig. 6.1

Electrons enter the slice travelling perpendicular to face PQKJ.

(i) For the free electrons moving in the slice:

1. identify the faces, using the letters on Fig. 6.1, between which a potential difference is developed. State its polarity.

face: ………………, polarity: ………………

and face: ………………, polarity: ……………… [2]

2. Explain your answers above.

………………………………………………………………………………………………

…………………………………………………………………………………………… [1]

(ii) Considering the forces acting on the electrons, explain why the potential difference between the faces identified reaches a maximum value.

………………………………………………………………………………………………

………………………………………………………………………………………………

…………………………………………………………………………………………….. [2]

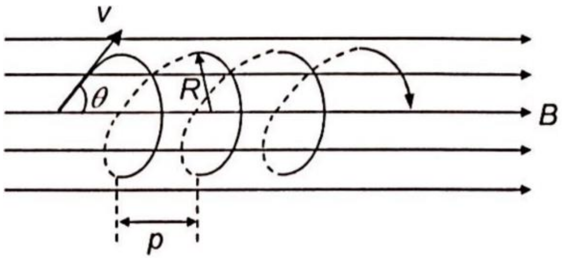
(iii) The number of free electrons per unit volume n in the slice of conducting material is 1.3×10^{29} m^{-3}.
The thickness PQ of the slice is 0.10 mm.
The magnetic flux density B is 4.6×10^{-3} T.
The current I is 6.3×10^{-4} A.

Using $I = nAve$, where A is the cross-sectional area PQJK, and v is the drift velocity of the electron,

calculate the maximum potential difference across the slice.

maximum potential difference = ……………………….. V [3]

4 A uniform magnetic field B of flux density 3.0×10^{-5} T is directed along the positive x-axis. An electron is injected at a speed v of 6.7×10^{6} m s^{-1} and an angle of θ of 40° to the x-axis. It describes a helical path as shown in the figure.



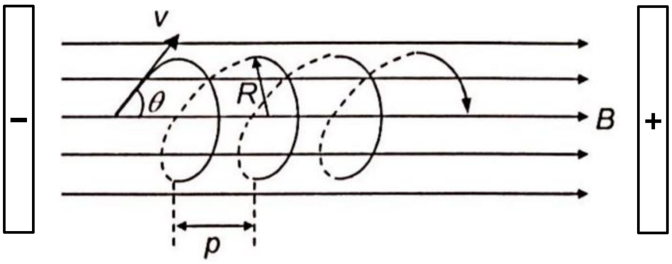
(a) **(i)** Calculate the radius R of the helical path.

(ii) Calculate the time T for the electron to complete one revolution in the helix.

(iii) The distance p shown in the diagram is known as the pitch of the helix.

Calculate the pitch p of the helix. (the pitch p is the distance, measured along the axis, between two successive turns of the curve)

(b) A set of parallel plates are now placed at the ends, as shown in the figure below, such that a uniform electrical field point from right to left is set up.



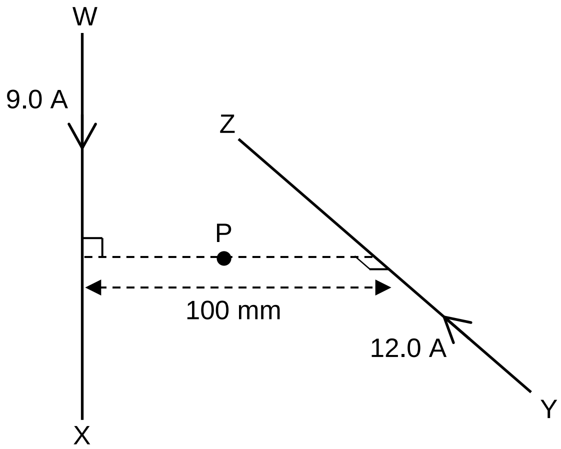
State and explain what will happen to the pitch p of the helix.

………

………

………

5 The figure below shows a long straight, vertical wire WX, carrying a current of 9.0 A downwards. A second long straight wire YZ is placed horizontally and carries a current of 12.0 A in the direction as shown. The perpendicular distance between the wires is 100 mm. P is the point 50 mm from YZ along the perpendicular distance between the wires.



(a) Calculate the magnitude of the magnetic flux density at point P. State the direction.

magnitude of magnetic flux density at P = ……………………….. T

direction = ……………………………

(b) The wire YZ is to remain fixed in position, but the orientation and position of the wire WX can be changed. The current in the two wires remain the same as before, and point P remains 50 mm away from YZ.

Calculate the distance of WX away from YZ where WX should be placed.
State the orientation of WX and the direction of its current with respect to YZ.

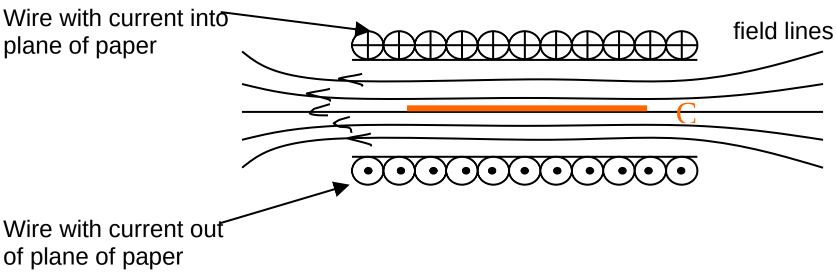
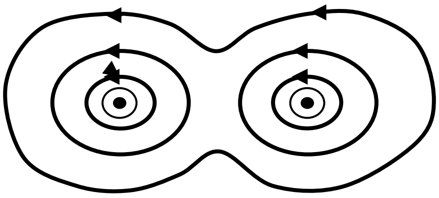
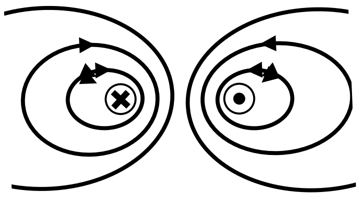
distance = ……………………….. mm

orientation = …………………………………..

direction of current = …………………………………..

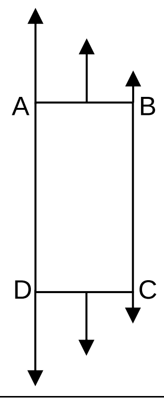
TUTORIAL 16: ELECTROMAGNETISM SOLUTIONS

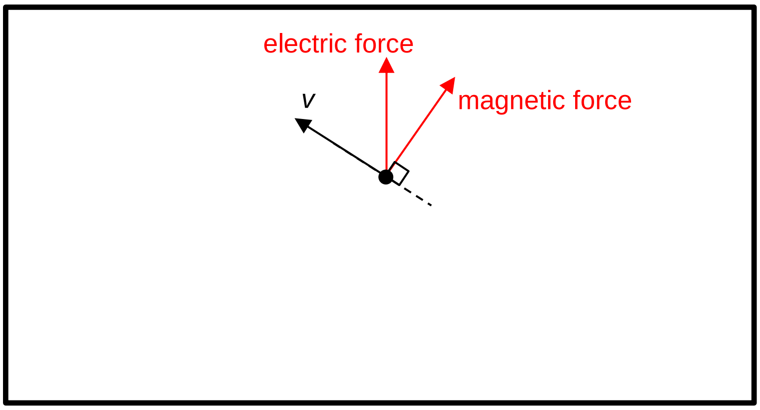
<u>Level 1 Solutions</u>

1(i) & (ii)	 • field lines are evenly-spaced & parallel to axis of solenoid • C parallel to field lines (deduced fr FLHR)	 [1] [1]
2(a)	 [1m for correct shape] [1m for correct direction and *<u>increasingly spread out</u>*; **why?**]	[1] [1]
(b)	 [1m for correct shape] [1m for correct direction and increasingly spread out]	[1] [1]
8	**C** Use Fleming's left-hand rule, the force points towards point X, the current flows out of the paper, and thus the B field must point towards arrow C.	
9	**B** $F_1 = BIL \sin 90°$ $8.0 \times 10^{-3} = BIL$ ------ (1) After rotation: angle between B & current is 60° (**NOT** 30°). $F_2 = (\frac{B}{2})(I)(L \sin 60°) = ½\,(8.0 \times 10^{-3})(\sin 60°) = 3.5$ mN	
13	**B** (Refer to sect. 16.5.2 for explanation in terms of RHGR & FLHR) X and Y are "like currents", so X attracts Y to the left. Z and Y are "unlike currents", so Z repels Y to the left also. Thus resultant: to left. **Note:** Not allowed to explain using following mnemonic in non-MCQ questions: mnemonic: "Like currents" (in direction) attract; Unlike currents repel"	

14	**B** Use FLHR. Current should be pointing upward since electron is moving downward as the wheel turns.	
15	**D** The standard formula F = BIL sin θ applies only if θ is the angle between B and I. However, in this question, θ is NOT the angle between B and I. Hence, the correct formula to apply in this case is F = BIL sin (90° - θ) = BIL cos θ. Thus answer is a cosine graph.	

Solutions to Additional Questions

1(a)(i)	$B_{AD} = \frac{\mu_0 I}{2\pi r}$ $= \frac{(4\pi \times 10^{-7})(30)}{2\pi(0.010)}$ $= 0.00060$ T	
(a)(ii)	$B_{BC} = \frac{\mu_0 I}{2\pi r}$ $= \frac{(4\pi \times 10^{-7})(30)}{2\pi(0.090)}$ $= 0.0000667$ T	
(b)	Resultant force $= B_{AD}IL - B_{BC}IL$ $= (0.00060)(20)(0.30) - (0.0000667)(20)(0.30)$ $= 0.0032$ N Direction = towards the left (force on AD is repulsive and on BC is attractive since like current attracts and unlike current repel, respectively)	
(c)	The magnetic flux induced by XY acting on the loop ABCD is perpendicularly into the page, decreasing in magnitude further away from XY. Using Fleming's Left hand rule, magnetic force acting on AB will be upward while magnetic force acting on CD will be downward, but equal in magnitude. Hence, there is no resultant force acting on the loop along the direction XY even though there are forces acting on AB and CD individually.  	
2(a)(i)	The magnetic flux density of a magnetic field is numerically equal to the <u>force per unit length</u> of a <u>long straight conductor</u> carrying a <u>unit current</u> at <u>right angles</u> to a <u>uniform</u> magnetic field.	
(ii)	The particle is <u>positively charged</u>.	
(b)(i)	<u>Magnetic force provides for the centripetal force</u>. $Bqv = \frac{mv^2}{r}$ $B = \frac{mv}{rq}$	

(ii)	From $B = \dfrac{mv}{rq}$, since the radius has increased, B has decreased.	
(iii)	$v = \dfrac{Brq}{m}$ $= \dfrac{(7.6\times10^{-3})(34\times10^{-2})(3.2\times10^{-19})}{6.6\times10^{-27}}$ $= 1.253\times10^{5} = 1.25\times10^{5}$ m s^{-1}	
(c)(i)	Since the magnetic force is directed to the right of the particle's path, the electric force will have to be to the left of its path (so that resultant force equals zero). Electric force on a positively charged particle is in the same direction as the electric field. Hence the electric field is to the left of the path of the particle. (allow using "upwards" / "downwards" but direction has to be consistent with the drawing in **(c)(ii)**.)	
(c)(ii)	 • Forces labelled • Electric force in the correct direction • Magnetic force perpendicular to v, in the correct direction • Length of $F_E = F_B$	
3(a)(i)	1. face: PQRS, polarity: positive face: JKLM, polarity: negative	[1] [1]
	2. Using Fleming's Left Hand Rule, force on electrons is downward / electrons will accumulate on the face JKLM.	[1]
(ii)	(As charges separates,) an electric field is created between PQRS and JKLM Maximum value is reached when electric force on electron is equal and opposite to magnetic force on electron.	[1] [1]
(iii)	Using $I = nAvq$ $6.3\times10^{-4} = (1.3\times10^{29})(d)(0.10\times10^{-3})(E / B)(1.6\times10^{-19})$ $3.0288\times10^{-10} = (d)(E)(1 / B)$ $3.0288\times10^{-10} = (d)(\Delta V / d)(1 / B)$ $\Delta V = (3.0288\times10^{-10})(B)$ $= (3.0288\times10^{-10})(4.6\times10^{-3})$ $= 1.4\times10^{-12}$ V	[1] [1] [1]

4(a)(i)	Magnetic force provides for the centripetal force. $Bqv_y = \frac{mv_y^2}{r}$ $(3.0 \times 10^{-5})(1.6 \times 10^{-19})(6.7 \times 10^6 \times \sin 40°) = (9.11 \times 10^{-31})(6.7 \times 10^6 \times \sin 40°)^2 / r$ $r = 0.817$ m	
(ii)	$v_y = r(2\pi / T)$ $6.7 \times 10^6 \times \sin 40° = (0.81737)(2\pi / T)$ $T = 1.19 \times 10^{-6}$ s	
(iii)	Using $s_x = u_x t$, $p = (6.7 \times 10^6 \times \cos 40°)(1.19249 \times 10^{-6})$ $p = 6.12$ m	
(b)	With the parallel plate, a uniform E-field will set up such that there is now a horizontal electrical force acting on the electron towards the right. Hence, the electron will now accelerate horizontally, resulting in increasing horizontal component of its velocity. With *T* being constant, the pitch *p* will increase.	
5(a)	B due to WX $= \frac{\mu_0 I}{2\pi d}$ $= \frac{(4\pi \times 10^{-7})(9.0)}{2\pi(50 \times 10^{-3})}$ $= 0.000036$ T, out of the page B due to YZ $= \frac{\mu_0 I}{2\pi d}$ $= \frac{(4\pi \times 10^{-7})(12.0)}{2\pi(50 \times 10^{-3})}$ $= 0.000048$ T, vertically upward Resultant B $= \sqrt{0.000036^2 + 0.000048^2}$ $= 6.0 \times 10^{-5}$ T Direction $= \tan^{-1}\left(\frac{0.000048}{0.000036}\right)$ $= 53.1°$ above the horizontal	
(b)	Since P is still 50 mm away from YZ, B due to YZ remains at 0.000048 T. To get resultant B = 0 at point P, B due to WX must be equal to 0.000048 as well. Hence, B due to WX $= \frac{\mu_0 I}{2\pi d}$ $0.000048 = \frac{(4\pi \times 10^{-7})(9)}{2\pi(d)}$ $d = 37.5$ mm Therefore, distance of WX away from YZ = 50 + 37.5 = 87.5 mm away from YZ orientation of WX should be parallel to YZ direction of current to be in the same direction as current in YZ	