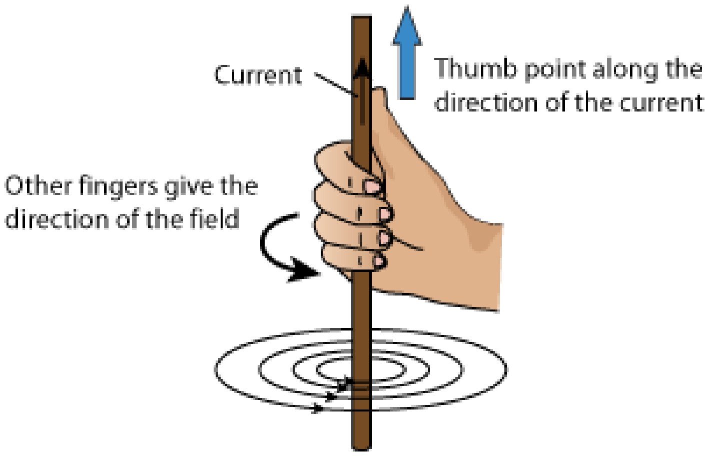
MOTORS AND GENERATORS

CURRENTS AND MAGNETIC FIELDS (PRELIMINARY COURSE REVIEW)

An electrical current produces a magnetic field that is directed around it.

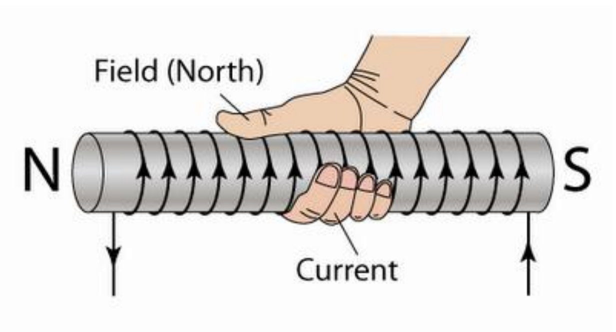
Conventional current is the flow of positive charge. Hence, it is directed from the positive terminal of the power supply, through the circuit load and back to the negative power supply terminal. When we talk about the direction of current flow, we are referring to the conventional current.

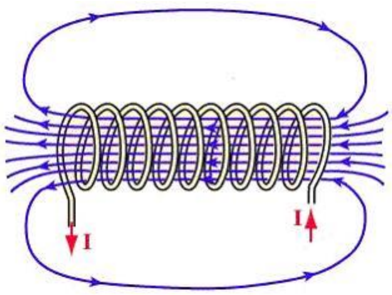
The direction of the magnetic field around a current-carrying conductor can be predicted using the 'Right Hand Grip Rule'; when the thumb of the right hand points in the direction of the conventional current, the fingers point in the direction of the magnetic field around it.



Right Hand Grip Rule

This rule may also be used 'in reverse' to determine the direction of the magnetic field within a current-carrying coil (solenoid). Here, the fingers of the right hand curve in the direction of the current in the coil windings, and the thumb points in the direction of the magnetic field.





Note that a current-carrying solenoid produces a dipole field similar to that of a bar magnet. The field is uniform within the coil.

THE MOTOR EFFECT

A conductor that carries current across a magnetic field will experience a magnetic force. *This phenomenon is known as the Motor Effect.*

Applications of the Motor Effect include electric motors, galvanometers and loudspeakers. It is important to realise that, in these devices, the Motor Effect facilitates the transformation of electrical energy into mechanical energy. The Motor Effect in these devices involves current-carrying wires; however, the same phenomenon also operates on freely moving charges, such as the electrons in cathode rays.

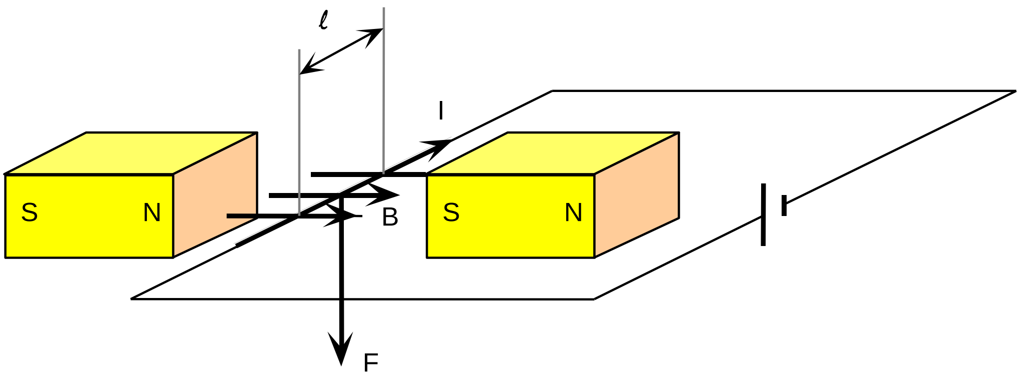
If the current is flowing in a direction that is parallel to the magnetic field, there will be no magnetic force acting on the conductor. The current must be crossing the field.

The *magnitude* of the force is given by:

$$F = BIl\sin\theta$$

Where:

F = force exerted on the conductor (Newtons, N)
B = magnetic field strength, or magnetic flux density (Tesla, T)
I = electric current (Amperes, A)
l = length of conductor within the magnetic field (Metres, m)
θ = angle between B and I



Note: In perspective diagrams, such as the one above, the z-axis (into/out of the page) is represented on the diagonal. E.g. in the above diagram, the current, I, should be thought of as being directed into the page.

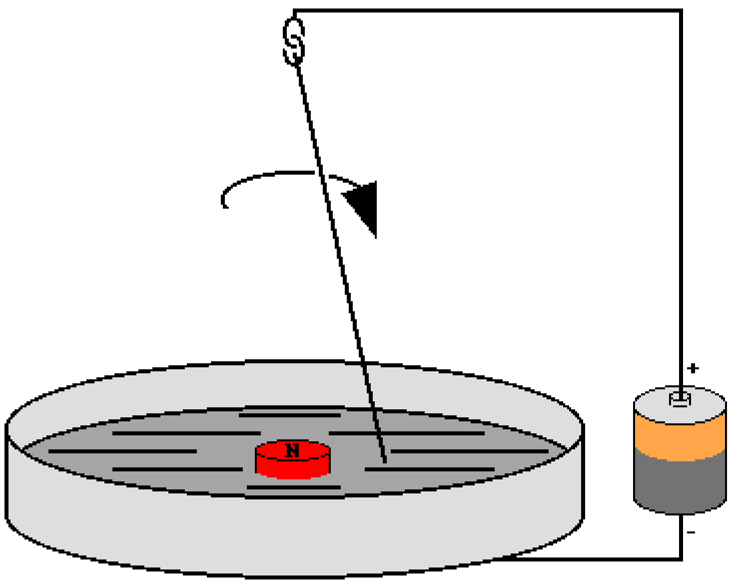
The *direction* of the force can be determined using the **Right Hand Rule** (RH Rule):

*When the **fingers** of the **right hand** point in the direction of the **magnetic field** (B), and the **thumb points in the direction of conventional current** flow (I), the **force** (F) is directed perpendicularly **out from the palm** (as if you were pushing something with your hand).*

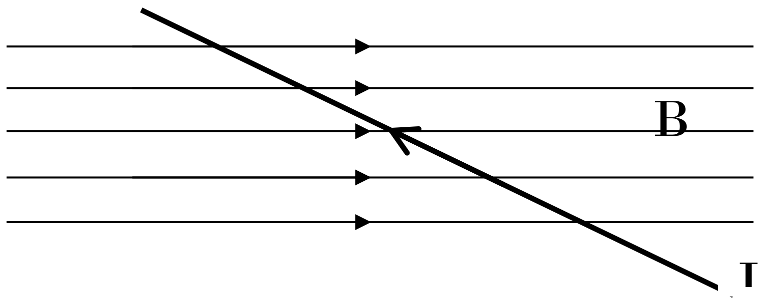
Note that:

- If B and I are parallel (i.e. θ = 0 or 180°) then F = 0 (i.e. there is no force).
- F is at a maximum when $\theta = 90^o$ (since sin θ is maximum when $\theta = 90^o$).
- When $\theta = 90^o$ the equation $F = BIl\sin\theta$ simplifies to F = BIl, since sin 90° = 1.

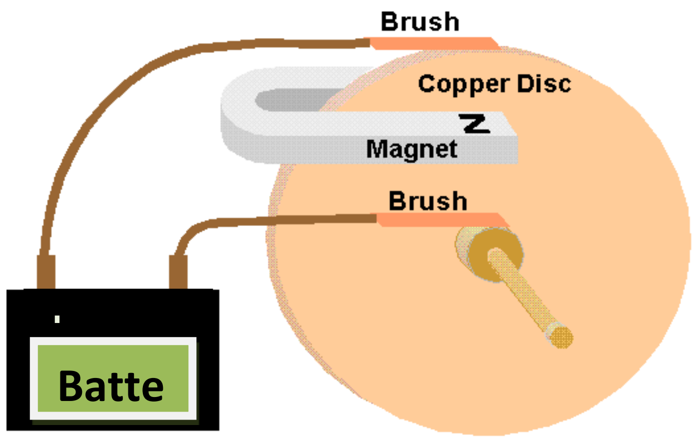
FARADAY'S MOTOR



Using a labelled diagram, **explain** why the wire rotates in the direction shown above.



Direction of the force? (Which way does I cross B?)



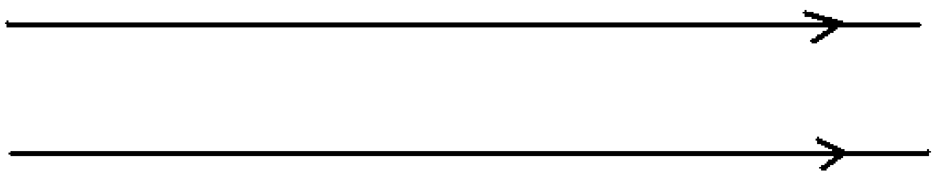
Explain why the disc will stop?

THE FORCE BETWEEN PARALLEL CURRENT-CARRYING CONDUCTORS (AMPERE'S LAW)

A current in a conductor produces a magnetic field around it. This was discovered by Oersted and covered in the Preliminary topic 'Electrical energy in the Home'. The direction of this field can be predicted using the Right Hand Grip Rule (If the thumb of the right hand points in the direction of conventional current flow, the curving fingers point in the direction of the magnetic field around the conductor).

When two current-carrying conductors lie parallel with one another, each conductor rests in the magnetic field produced by the current in the other conductor. Thus each conductor experiences a force due to the Motor Effect.

Two parallel conductors, A and B, have current flowing from left to right. What is the direction of the force that conductor A exerts on conductor B?



Consider the magnetic field produced by the current in A. The RH Grip Rule indicates that in the region below conductor A (i.e. where conductor B is) this field is directed into the page. According to the Right Hand Rule, the resulting force on conductor B is up the page, towards conductor A. That is, it is attracted to A. Newton's 3rd Law tells us that the force on conductor A is equal and opposite. That is, down the page, towards conductor B.

- Wires carrying currents in the same direction attract
- Wires carrying currents in opposite directions repel

The *magnitude* of the force can be calculated using Amperes Law:

$$F = \frac{kI_1 I_2 l}{d}$$

Where:

F = force (Newtons)

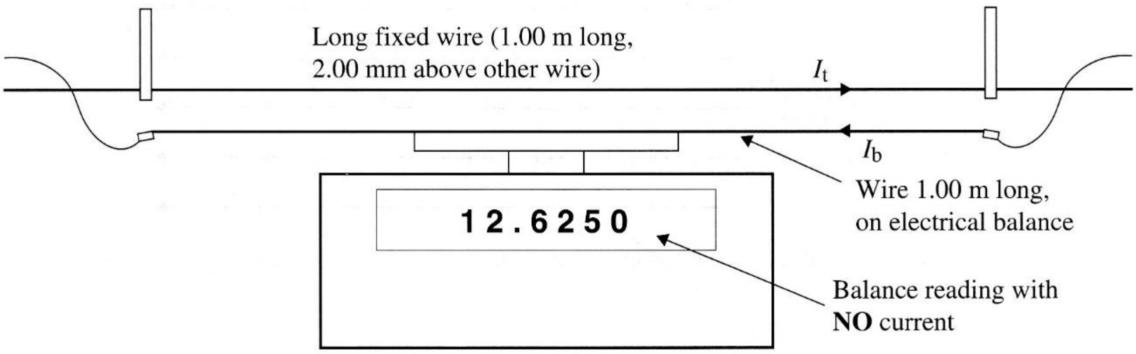
k = 2×10^{-7} NA^{-2} (This is the magnetic force constant, supplied in the HSC Exam.)

I_1 = current in the first conductor (Amps)

I_2 = current in the second conductor (Amps)

d = distance between wires (metres)

EXAMPLE 1
A metal wire, 1.00 m long, is placed onto an electronic balance such that it sits horizontally at rest. The electronic balance records the mass of the metal wire as 12.6250 g. A second long wire is then fixed in position, parallel and 2.00 mm directly above the wire on the balance. A set of very light electrical leads is supported, attached to the ends of each of the wires, such that current flows along the wires in the directions shown in the diagram.



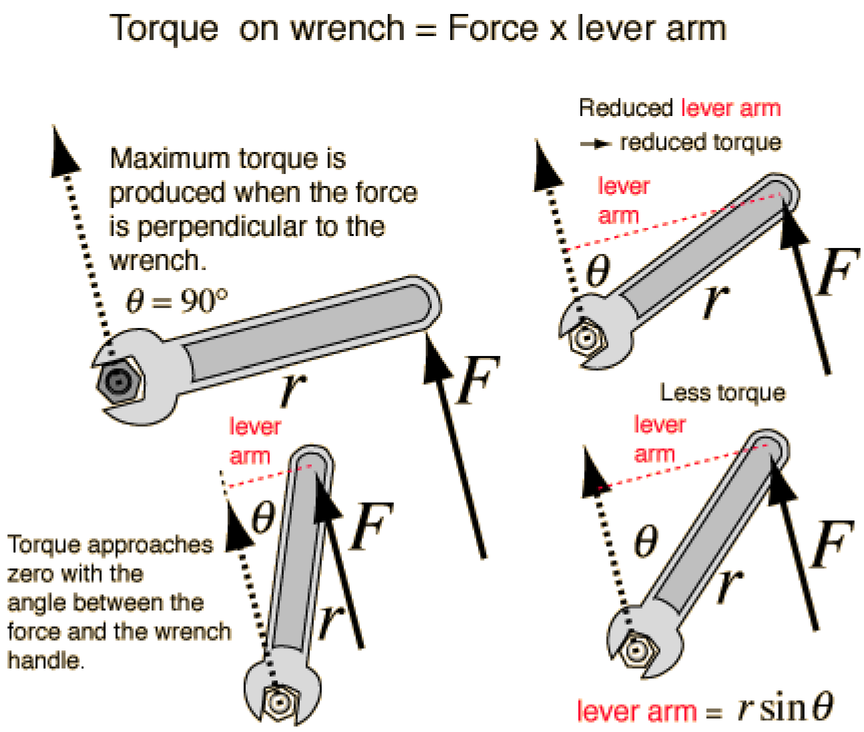
If, when the power is switched on, the current flowing through each wire is 10 A in the directions shown, the reading on the electronic balance will be closest to:

A 12.6250 g
B 12.6350 g
C 13.6454 g
D 11.6046 g

TORQUE

Torque is the turning effect of a force. It is defined as the **turning *moment* of a force**.

The torque produced by a force depends on both the magnitude of the force and the perpendicular distance between of the line of action of the force and the axis of rotation (the pivot or fulcrum). This distance is known as the lever arm.

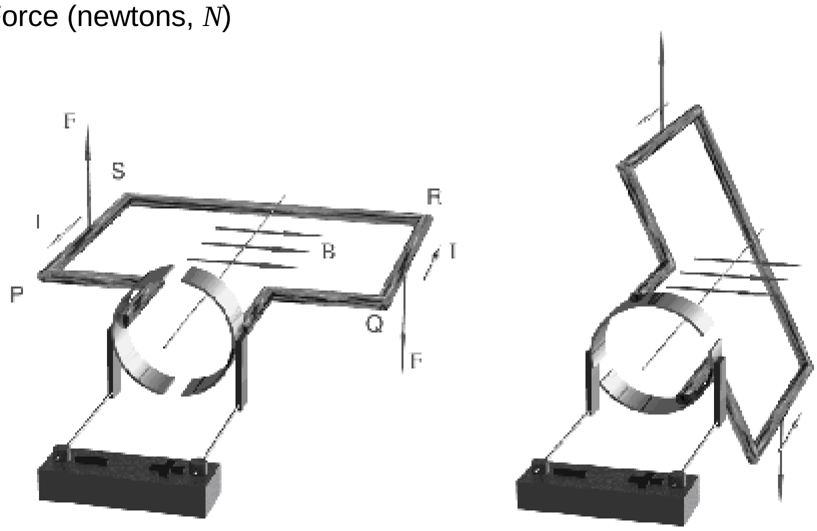


The magnitude of the torque produced by a force is given by: $\tau = Fd$

Where τ = Torque (Newton-metres, Nm)

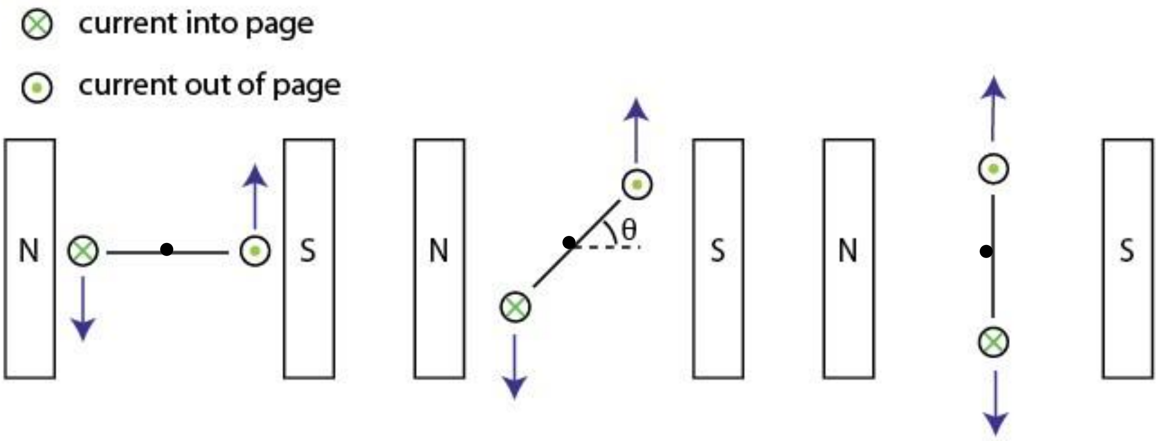
d = Perpendicular distance between the axis of rotation and the line along which the force acts (metres, m)

F = Force (newtons, N)



The diagrams show that for a given force, the torque will be at maximum when the coil is in the first position shown, since this is when the perpendicular distance from force to axis is at a maximum*. Note that in this position of maximum torque, the plane of the coil is parallel with the magnetic field.*

If the coil was to rotate 90^o from this first position, the line along which the force acts (its 'line of action') would pass through the axis of rotation, and thus the perpendicular distance, d, between them would be zero. There would thus be zero torque in such a position. That is, there is no torque on a coil when the plane of the coil is perpendicular to the field.



Maximum Torque

Zero Torque

The magnitude of the torque acting on a current-carrying coil in a magnetic field is given by:

$$\tau = BAIn.\cos\theta$$

Where:

τ = Torque (Nm)
B = Magnetic field strength (T)
A = Area of coil (m^2)
I = Current (A)
θ = Angle between plane of coil and magnetic field
n = Number of turns in coil

Syllabus Dot-Point:

Describe the forces experienced by a current-carrying loop in a magnetic field and describe the net result of the forces.

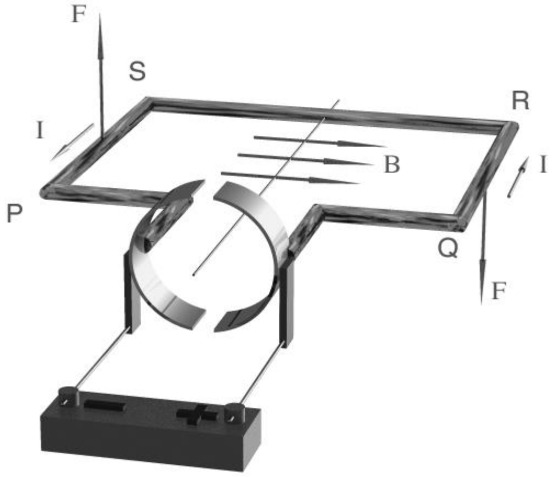
Net force?

(The net force is zero, as the forces acting on each side of the coil are equal and opposite.)

Net Torque?

(The net torque, $\tau = BAIn.\cos\theta$, and is only zero if the plane of the coil is perpendicular to the magnetic field.)

THE D.C MOTOR



The diagram above shows a simplified D.C. motor. Note that in the position shown, the plane of the coil is *parallel* to the magnetic field.

- Current flows around the coil, and thus flows in opposite directions on each side of the coil.

- The current is always at right angles to the field and this produces opposite forces on each side of the coil. The magnitude of these forces does not change as the coil rotates. These forces result in a torque, which causes the coil to rotate. Torque is at a maximum in the position shown.

- As the coil rotates from this position, the torque decreases until, at a position 90^o to the one shown, the torque becomes zero. Although the forces have not changed, the perpendicular distance of these forces from the axis of rotation has reduced to zero.

- As the momentum of the coil carries it past this position (i.e. >90^o past the position shown), then, if the current continued to flow in the same direction, the direction of the torque would reverse. To maintain the torque in the same direction, the direction of current flow in the coil is reversed using the split-ring commutator and brushes. It reverses again after each additional 180^o of rotation.

  Note: **The commutator does not 'keep the torque constant' (it varies with θ), but it does keep the *direction of the torque* constant.**

INCREASING THE TORQUE OF THE MOTOR

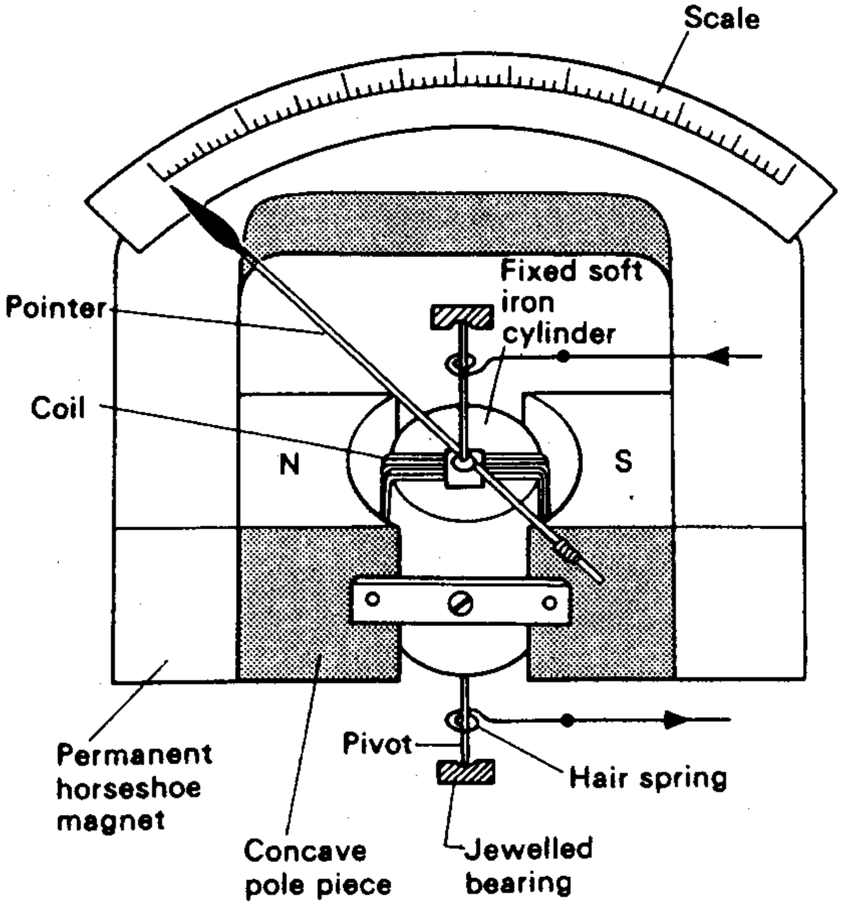
- Increase the magnetic field strength (B) by using stronger stator magnets, and adding a soft iron core (armature).
- Increase the area of the coil (A) (i.e. use a larger coil).
- Increase the current (I).
- Increase the number of turns in the coil (n).

So that the torque of a motor remains high at any angle of rotation, three or more coils are used, offset at different angles. When the torque on one coil drops to zero (when it is perpendicular to the field), the torque on the other coils ensures that sufficient torque is still produced by the motor.

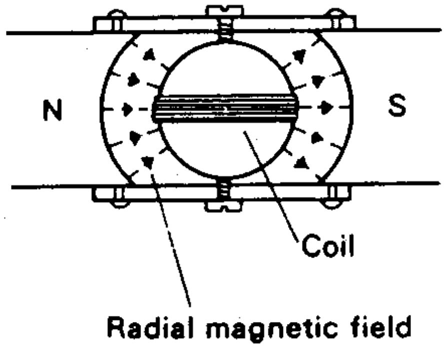
OTHER APPLICATIONS

THE GALVANOMETER

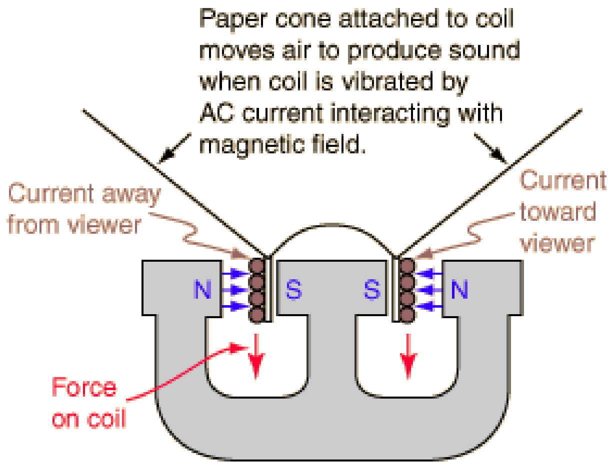
The curved magnet poles and the cylindrical iron core create a *radial* magnetic field. This ensures that, as the coil rotates through a limited angle (around 90^o), the plane of the coil remains parallel to the field. That is, the θ in $\tau = BAIn.\cos\theta$ remains at a constant 0^o. This ensures that the torque remains proportional to the current. This torque deflects the coil and its attached pointer against a restoring torque provided by a torsional spring. Since this deflection is proportional to the torque, it is also proportional to the current.

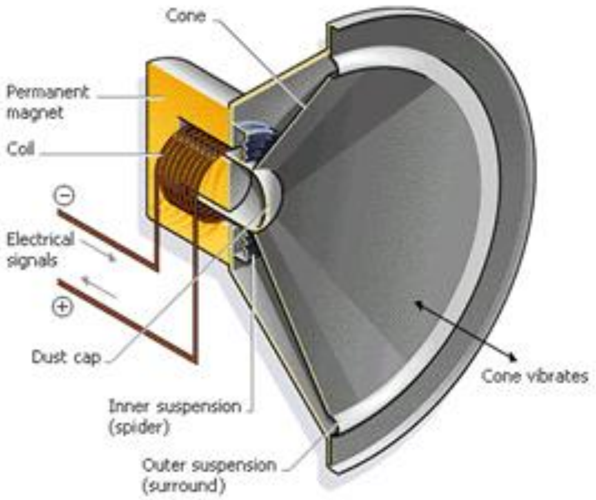


PLAN VIEW



THE SPEAKER





- A coil, known as the voice coil, is suspended between an inner magnetic pole and an outer pole that surrounds it. The radial field of the magnet crosses every part of the coil at right angles.
- When an alternating current, with the same waveform as the sound to be generated, is passed through the coil, the Motor Effect results in a force that moves the coil in and out of the magnet.
- A cone attached to the voice coil does work on the surrounding air, creating compressions and rarefactions, thus creating sound waves.

EXAMPLE 2
An electric DC motor consists of 500 turns of wire formed into a rectangular coil of dimensions 20 cm $\times$10 cm. The coil is in a magnetic field of $1\times10^{-3}T$. A current of 4.0 A flows through the coil.

What is the magnitude of the maximum torque, and the orientation of the plane of the coil relative to the magnetic field when this occurs?

A 0.04 Nm, parallel to the field
B 0.04 Nm, perpendicular to the field
C 0.4 Nm, parallel to the field
D 0.4 Nm, perpendicular to the field

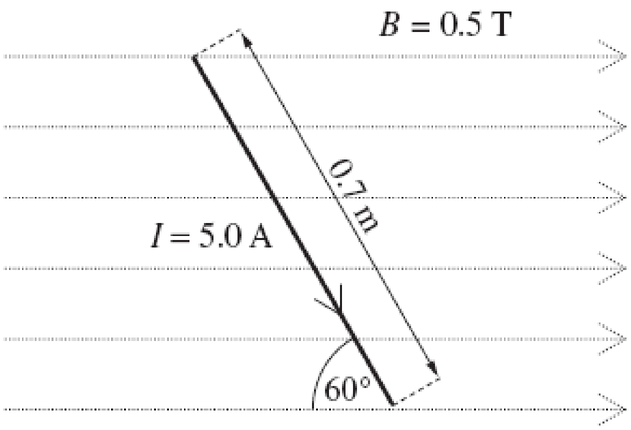
Solution

Maximum torque occurs when the perpendicular distance between the line of force is and the axis of rotation is at a maximum. That is, when the plane of the coil is parallel to the field.

Note that the standard unit of area is m^2 (not cm^2), thus the area of the coil must be calculated in m^2 by converting the dimensions to metres before calculating the area.

Correct answer is A.

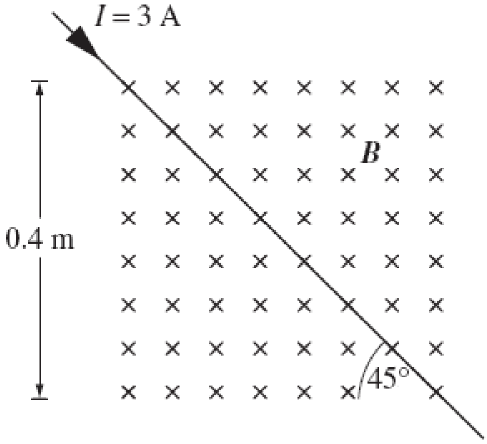
QUESTION 1
A current of 5.0 A flows in a wire that is placed in a magnetic field of 0.5 T. The wire is 0.7 m long and it is placed at an angle of 60º to the field.



What is the approximate magnitude of the force on the wire?

A 0 N
B 0.9 N
C 1.5 N
D 1.8 N

EXAMPLE 3
A current-carrying conductor passes through a square region of a magnetic field, magnitude 0.5 T, as shown in the diagram. The magnetic field is directed into the page.



What is the magnitude of the magnetic force on the conductor?

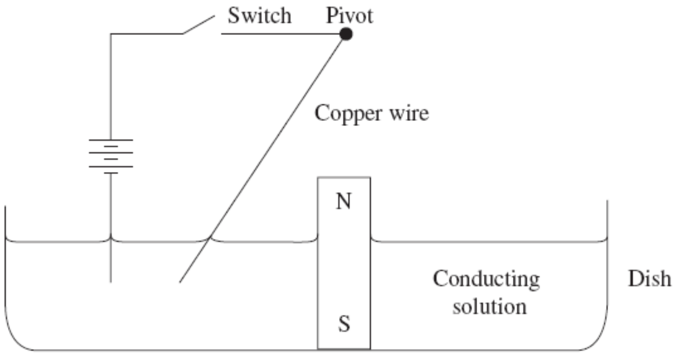
A 0.170 N
B 0.424 N
C 0.600 N
D 0.849 N

Solution

This question requires you to use $F = BIl\sin\theta$; however, **don't assume that any supplied angle represents θ**. Here, the 45° angle does not represent the angle between the current and the magnetic field. This angle, θ, is 90° is this example. The 45^o angle in this example is merely used to determine the length of wire in the field: $l = \dfrac{0.4}{\sin 45^o}$.

Correct answer is D.

QUESTION 2
The diagram shows a magnet standing on the bottom of a dish filled with a conducting solution. A copper wire is suspended freely from a point above the magnet, with its tip in the conducting solution. It is held in the position shown.



The switch is closed and the wire released. Which of the following will be observed?

A The wire will rotate in a clockwise direction around the magnet as viewed from above.

B The wire will rotate in an anti-clockwise direction around the magnet as viewed from above.

C The wire will be attracted to the magnet.

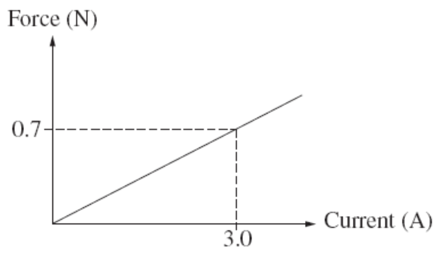
D The magnet will rotate about its vertical axis.

Hint:

Draw a labelled diagram of the situation above as a TOP VIEW.

EXAMPLE 4
A student performed an experiment to measure the force on a long current-carrying conductor, perpendicular to an external magnetic field.

The graph shows how the force on a 1.0 m length of the conductor varied as the current through the conductor was changed.



What was the magnitude of the external magnetic field in this experiment?

A 0.23 T
B 1.1 T
C 2.1 T
D 4.3 T

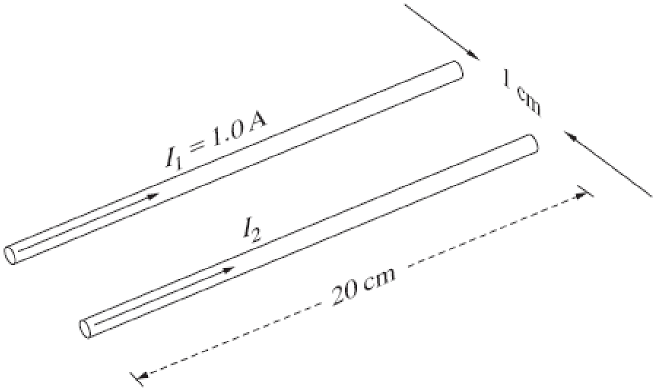
Solution

The equation relating the magnetic field to the force here is $F = BIl\sin\theta$.

Since the length is 1 and the angle is 90°, F= BI. Therefore $B=F/I$, which is the gradient of this graph. The gradient is 0.7/3 = 0.23.

The correct answer is A.

QUESTION 3
The diagram shows part of an experiment designed to measure the force between two parallel current carrying conductors.

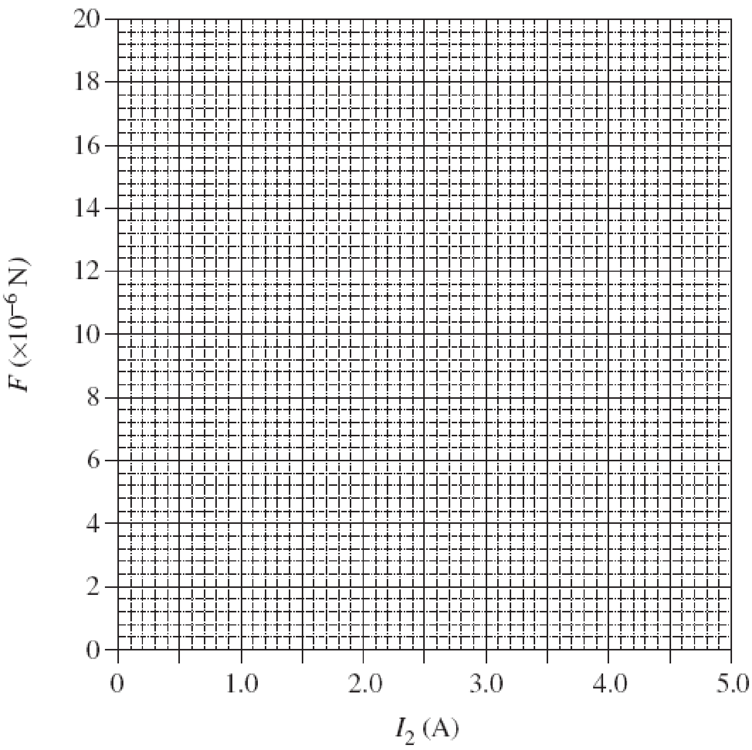


The experimental results are shown below.

I_2 (A)	Force ($\times 10^{-6}$ N)
0	0
2.0	7
3.0	11
4.0	14
5.0	18

(a) Plot the data on the graph paper below.

2 marks



(b) Calculate the gradient of your line.

1 mark

(c) Write an expression for the magnetic force constant, k, in terms of the force constant and other variables.

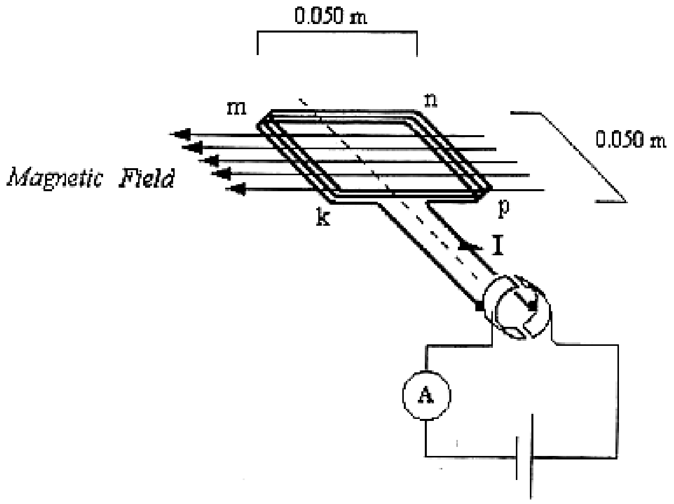
1 mark

(d) Use this expression and the gradient calculated in part (b) to determine the value of the magnetic force constant, k.

2 marks

QUESTION 4

The diagram below shows a simple D.C. motor. There are 500 turns on the rotor, carrying a current of 2 A. The side length of the square coil is 0.050 m. The magnetic field is 0.2 T.



(a) Identify the direction of the force on side np in the position shown. 1 mark

(b) Calculate the magnitude of the torque on the coil in the position shown. 2 marks

(c) Determine the magnitude of the force on side mk after the coil has rotated 90^{o} from the position shown. 2 marks

Solution