elevate

# YEAR 12 PHYSICS

## MODULE 6

### LESSON FOUR

# THEORY

# Electromagnetic Induction

## BACKGROUND

Recall that it was Hans Christian Oersted who discovered that an electric current produced a magnetic field.

This led Michael Faraday to put forward the hypothesis that the reverse should also be true – that is, a magnetic field produces an electric current. This would eventually become the principle of **electromagnetic induction.**

To test this hypothesis, Faraday conducted three key experiments.

### Wooden Block

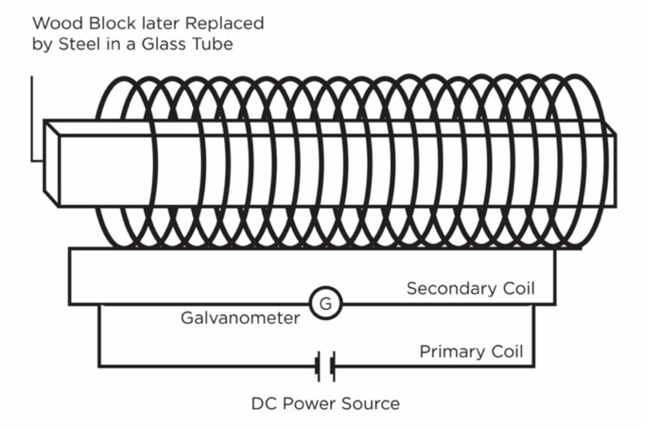
Faraday wound a copper wire around a piece of wood and connected it to a DC power source. This was the *primary coil.* He then wound a *secondary coil* of wire between the spaces of the first wire (insulated by twine) and attached it to a galvanometer (a type of early ammeter).

When he switched on the DC power source for the primary coil, there was a momentary deflection in the needle of the galvanometer in one direction. This indicated that a **very small current** was **temporarily** created in the secondary circuit.

However, the needle restored to its original position and remained there while the switch in the primary coil was left on.

When the current in the primary circuit was stopped, there was again a momentary deflection in the galvanometer's needle, equal in magnitude to the first deflection but opposite in direction. Again, this showed that a **very small current** was **temporarily** created in the secondary circuit.

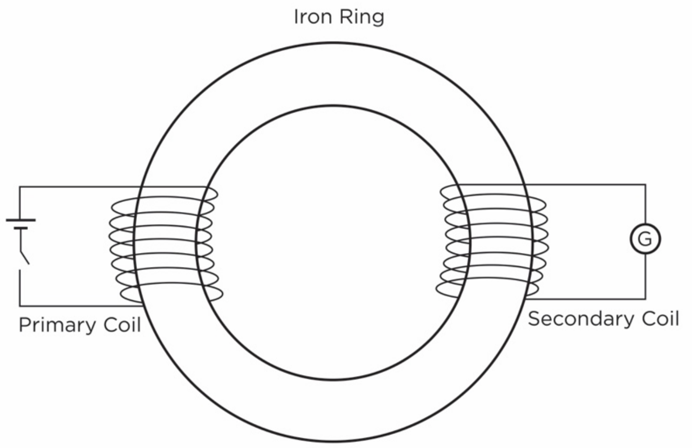
∴ He concluded that the electromotive force (emf) generated was associated with the **changing current** in the circuit as it was switched on and off.



# THEORY

## Iron Ring

Faraday later modified his experiment to further test the findings from the previous experiment which indicated that the induced emf was related to a changing current.

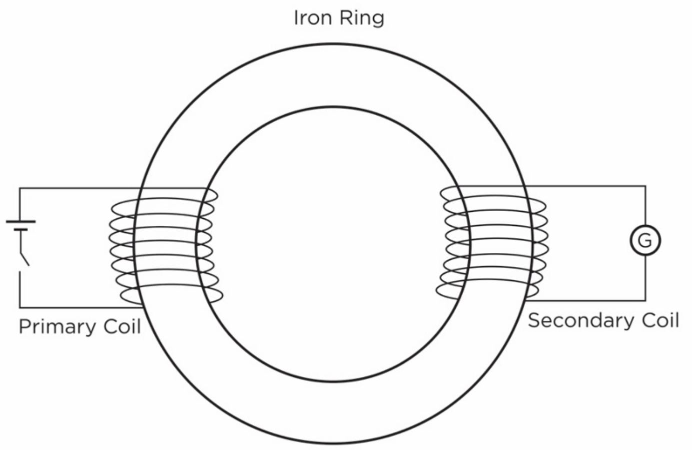



He used iron, a material of high magnetic permeability to obtain efficient transferal of magnetic flux from primary to secondary coil. He similarly wound the two coils of wire on either side of the iron ring. The primary coil (connected to DC power source) on one side was opposite the secondary coil (connected to Galvanometer).

When he switched on the current in the primary coil on, a current briefly appeared in the secondary coil as shown by the deflection of galvanometer needle. The galvanometer needle then restored to its initial position.

When the current in the primary coil was stopped, a current briefly appeared again in the secondary coil as shown by the deflection of galvanometer. However, the deflection (and current) was in a direction opposite to that when the current in primary coil was turned on.

∴ Concluded that the current induced in the secondary coil was due to a **changing magnetic field** rather than a changing current, which is created by switching the currents on and off.



# THEORY

## Moving Magnet

Faraday was also able to show that moving a magnet near a coil could generate an electrical current in the coil.

He set up a coil of wire set up like a solenoid but connected it to a galvanometer.

When he brought a N pole of a bar magnet near the coil, the galvanometer momentarily deflected in one direction, indicating that a small current had been momentarily created. The needle then restored to its original position.

When the N pole of magnet is held without moving near the end of the coil, the needle does not deflect, conferring, no induced current.

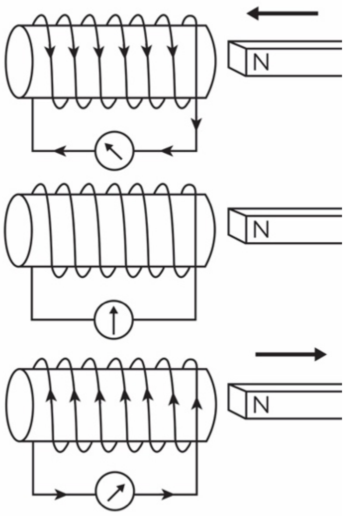
When the N pole of magnet is taken away from the end of the coil, the galvanometer again deflects momentarily but in the opposite direction. This deflection is indicative of momentary induced current which flows in the opposite direction to when the N pole is brought towards the coil.

When he moved it **faster** (towards or away), the magnitude of the galvanometer needle's deflection and generated current is **greater**. Similar results were obtained when the coil was moved towards a stationary magnet – indicating it was **relative motion** which induced the emf.

∴ He concluded that:

- To induce a current, a conductor must experience a change in magnetic flux over a period of time.
- The magnitude of the induced emf and hence current depends on the rate at which magnetic flux changes, or the speed of relative motion between conductor and magnet.

# THEORY



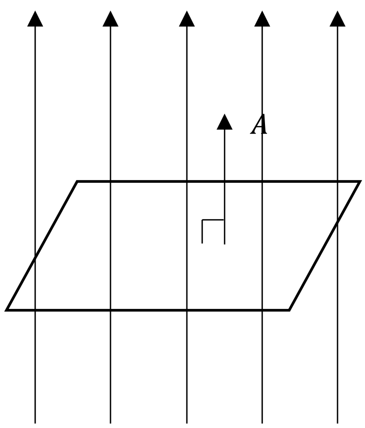

Note: a change in magnetic flux can be obtained by *rotation* of the magnet as well – an example of which will be explored in this lesson.

## 6.3.1 Describe how magnetic flux can change, with reference to the relationship [equation]

With the conclusions of Faraday's experiments above, we must understand the concept of magnetic flux and how it may 'change'.

**Flux** in physics, is the rate of flow of a fluid, radiation, or particles.

**Magnetic flux** ($\phi_B$) is defined as the number of magnetic field lines threading a given area or imaginary surface



# THEORY

It is given by the equation:

.................................................................................................................................................................................

Where:

- $\phi_B$ is the magnetic flux (Wb)
- $B_{\parallel}$ is the strength of the magnetic field parallel to the area vector (T)
- $A$ is the area vector ($m^2$)
- $\theta$ is the angle between the magnetic field lines and the area vector (°)

The S.I unit of magnetic flux $\phi_B$ is the Weber (Wb).

Consequently, the magnetic field strength $B_{\parallel}$ can be measured in terms of:

.................................................................................................................................................................................

Whilst the S.I unit of magnetic field strength is the $Tesla$ $(T)$, the expression above has an equivalent unit $Wbm^{-2}$.

In addition, the direction of the **Area vector** is at a **normal** to the plane of the area and its direction relative to the magnetic field lines are fundamental to finding the angle $\theta$.

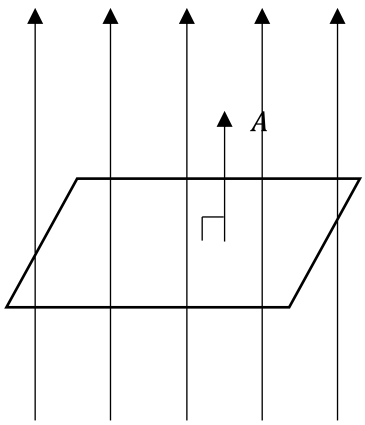
See the example questions below.

# THEORY

## EXAMPLE QUESTION

Find the magnetic flux 'threading' each of the following coils if a field of strength 0.10T is incident upon a $30\text{cm} \times 30\text{cm}$ coil in the orientations shown below:

1.

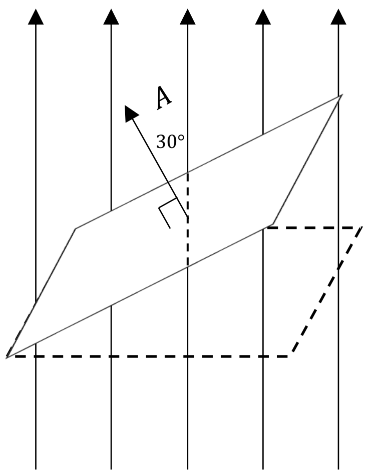



......................................................................................................................................................................................

......................................................................................................................................................................................

......................................................................................................................................................................................

2.



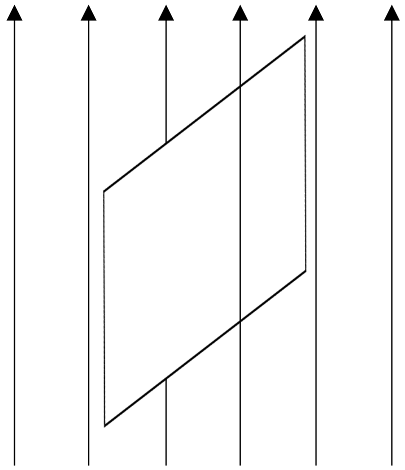

......................................................................................................................................................................................

......................................................................................................................................................................................

......................................................................................................................................................................................

# THEORY

3.



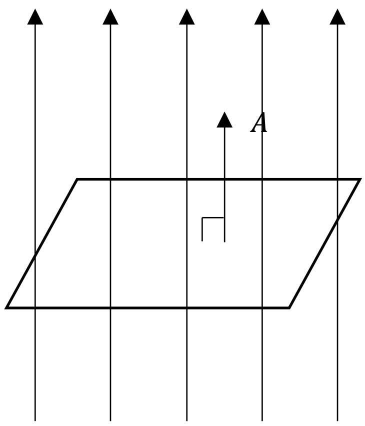
........................................................................................................................................................................................................

........................................................................................................................................................................................................

........................................................................................................................................................................................................

Find the magnetic flux density in the following scenarios:

a. $2.5 \times 10^{-4}\ Wb$ threads a square wire of side length 10cm in the manner shown below:



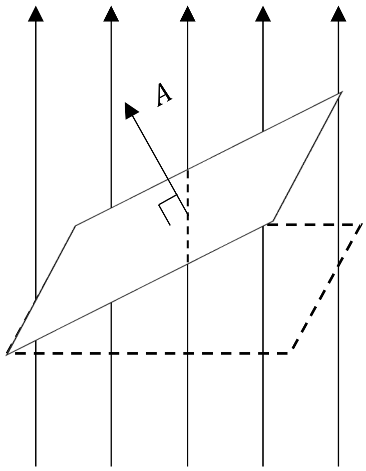

........................................................................................................................................................................................................

........................................................................................................................................................................................................

........................................................................................................................................................................................................

# THEORY

b. A square coil of side length 10.0cm is threaded by $1.7 \times 10^{-3}\ Wb$ when the angle between the *plane of the coil* and the magnetic flux is $60°$.

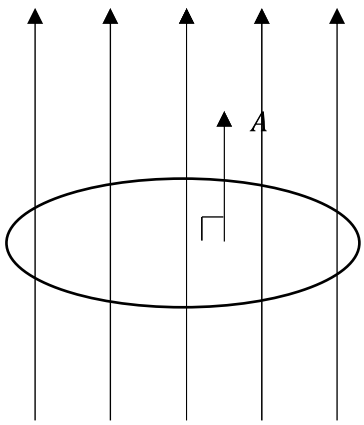



.................................................................................................................................................................

.................................................................................................................................................................

.................................................................................................................................................................

c. $1.5 \times 10^{-3}\ Wb$ of magnetic flux threads a circular coil of radius 5cm in the manner shown below.




.................................................................................................................................................................

.................................................................................................................................................................

.................................................................................................................................................................

Note: whilst the $Tesla\ (T)$ and $Wm^{-2}$ are equivalent units, they are not interchangeable. If a question asks for:

- The magnetic field strength, answer in $Tesla\ (T)$
- The magnetic flux density, answer in $Wbm^{-2}$

# THEORY

6.3.2 Analyse qualitatively and quantitatively, with reference to energy transfers and transformations, examples of faraday's law and lenz's law [equation], including but not limited to: the generation of an electromotive force (emf) and evidence for Lenz's Law produced by the relative movement between a magnet, straight conductors, metal plates and solenoids, the generation of an emf produced by the relative movement or changes in current in one solenoid in the vicinity of another solenoid

## FARADAY'S LAW

Based on the conclusions from his experiment, Faraday's law of electromagnetic induction was born:

This can be summarised by the expression:

Where:

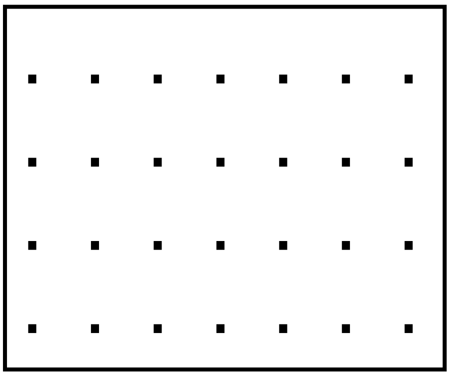
- $n$ is the number of loops
- $\varepsilon$ is the emf (V)
- $\phi_B$ is the magnetic flux (Wb)
- $t$ is time (s)

The negative sign defines the direction of the induced emf and has more to do with **Lenz's Law** which will be learnt later.

# THEORY

## EXAMPLE QUESTION

A magnetic field of strength 0.30mT threads a square coil of side length 30cm as shown below. The magnetic field is switched off over a period of 0.3s.



a. Calculate the change in flux.

...................................................................................................................................................................................

...................................................................................................................................................................................

...................................................................................................................................................................................

b. Calculate the *magnitude* of the induced emf.

...................................................................................................................................................................................

...................................................................................................................................................................................

...................................................................................................................................................................................

## LENZ'S LAW

Recall that emf stands for 'electromotive force' and is a force which propels the movement of charged particles, ultimately giving rise to a current.

Importantly however, for an electromotive force to give rise to a current, there must be a complete circuit.

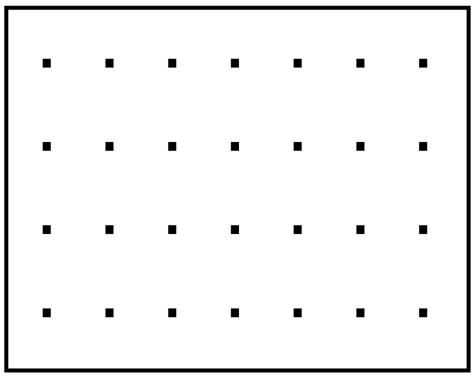
In the absence of a complete circuit, an emf can still be induced provided that the conductor experiences a change in flux (Faraday's law). This emf will not however, give rise to a current.

# THEORY

When a current is produced, we can use Lenz's law to determine the direction of the current flow:

**EXAMPLE QUESTION**

**For the same question above, explain the direction of current flow if the magnetic field were to be 'switched-off' over a period of 0.3s.**



As seen above, we may use the **right-hand solenoid rule** to aid in determining current flow relative to magnetic poles produced.

Furthermore, we may explore why the induced current must produce a magnetic field which ***opposes*** the original change in flux by considering the alternate scenario.

If the induced current produced a magnetic field in the same direction as the original change in flux, this new flux would *itself* cause a change in flux which would give rise to a larger current. This larger current would then in turn, give rise to a larger change in magnetic flux, which would drive the production of an even larger current.

This violates the ***law of conservation of energy (LOCOE)*** as this implied energy is being 'created' – which cannot be true.

# THEORY

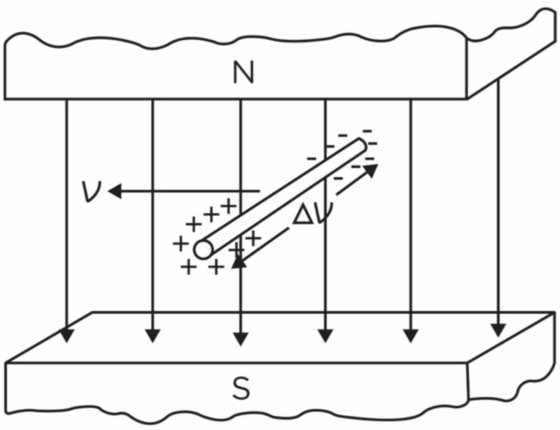
In fact, the production of an electrical current, a form of *electrical energy*, is an example of an **energy transformation** from the *mechanical work* done in creating relative motion between conductor and magnetic field.

See further scenarios and example questions below:

## Straight Conductors

When a conducting rod is moved through a magnetic field, the rod experiences a change in flux and hence, an emf is produced.

However, since there is an absence of a complete circuit, this emf does not give rise to a current.




We may use a different technique to determine the direction of the emf. Imagine a single electron which is in the metal rod.

As the rod moves to the left, the negatively charged electron experiences a force into the page (RHPR). Consequently, the end of the rod that is 'in the page' accumulates negative charge and acquires a negative (-) polarity.

..............................................................................................................................................................................

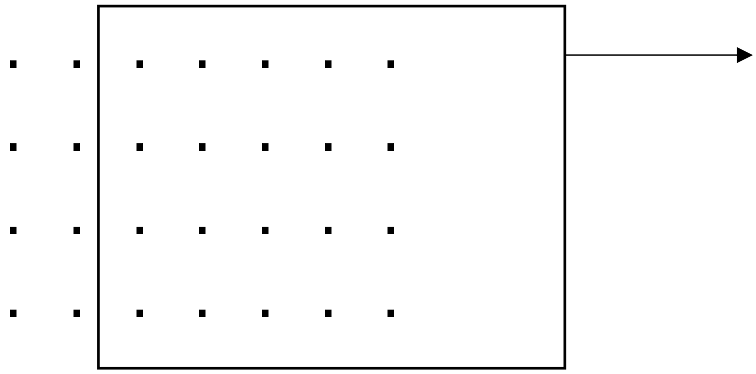
..............................................................................................................................................................................

This can be understood by thinking that the end that is 'out of the page' is positive due to a 'lack of negative charge' as the electrons have migrated into the page.

# THEORY

## Metal Plates

Now consider a metal plate which is removed from a magnetic field as shown below:



As the metal plate is a conductive surface which experiences a change in flux, an emf will be produced **(Faraday's Law).**

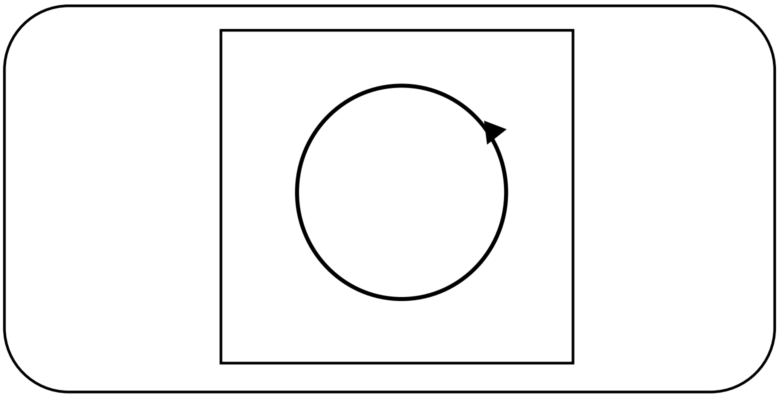
There technically isn't a clearly defined circuit, which may lead some to argue that the emf doesn't give rise to a current.

........................................................................................................................................................

........................................................................................................................................................

## EXAMPLE QUESTION

**Draw the direction of the flow of any eddy currents produced in this example. Explain your reasoning.**



........................................................................................................................................................

........................................................................................................................................................

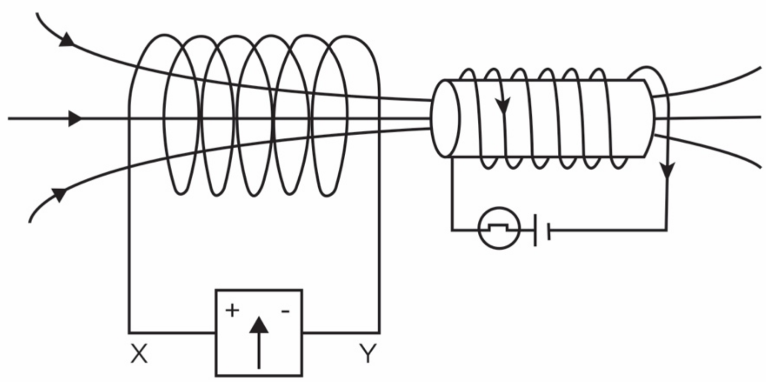
........................................................................................................................................................

# THEORY

## Solenoids

Like the way Faraday was able to induce a current within a solenoid by moving a bar towards and away from it, the same can be achieved with two solenoids whereby:

- One solenoid is connected to a galvanometer
- The other is connected to a DC power source.




This is true if there is **relative change in magnetic flux**.

The **right-hand solenoid rule** may be used to determine the direction of induced current flow.

See the example questions below.

### EXAMPLE QUESTION

**Explain the direction of current flow in terms of X and Y if the solenoid connected to the power source is:**

a. Switched from off to on.

.............................................................................................................................................................

.............................................................................................................................................................

.............................................................................................................................................................

# THEORY

b. Switched from on to off.

......................................................................................................................................................................

......................................................................................................................................................................

......................................................................................................................................................................

c. Moved towards the solenoid connected to the galvanometer.

......................................................................................................................................................................

......................................................................................................................................................................

......................................................................................................................................................................

d. Moved away from the solenoid connected to the galvanometer.

......................................................................................................................................................................

......................................................................................................................................................................

......................................................................................................................................................................

e. Rotated clockwise

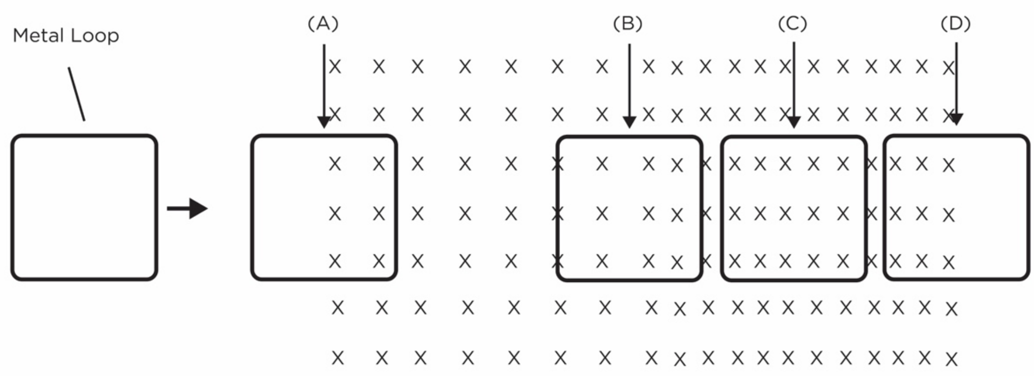
......................................................................................................................................................................

......................................................................................................................................................................

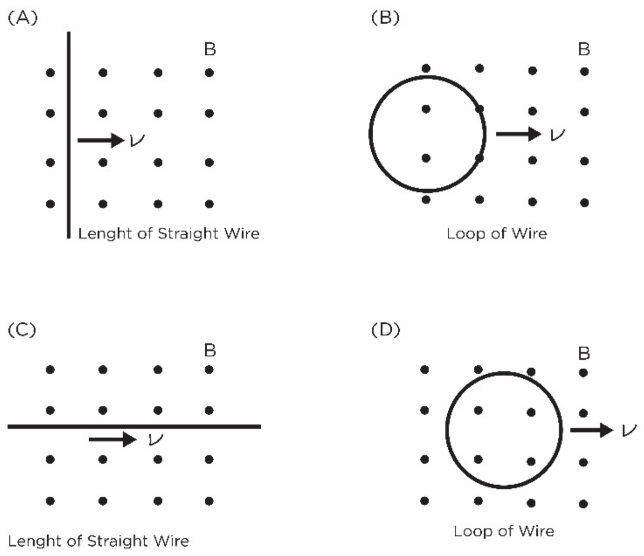
......................................................................................................................................................................

# PRACTICE QUESTIONS

1. Determine the point at which the induced current will be of the greatest magnitude if a conducting metal loop is moved through the magnetic field below at a constant velocity.




2. Choose the option in which a current is induced at the instant shown. The loops and wires are moving at a constant velocity.

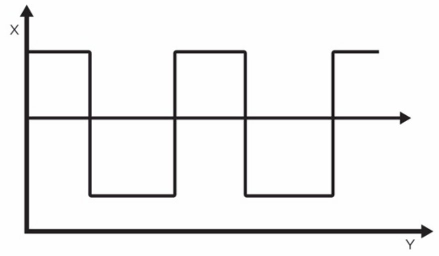



3. Calculate the average emf produced in a square coil of side length 12cm if a magnetic field of strength 5 mT is removed over a period of 0.5s. The coil consists of 15 turns of wire.
   a. 2.16 mV
   b. 0.144 mV
   c. 2.16 V
   d. 21.6 V

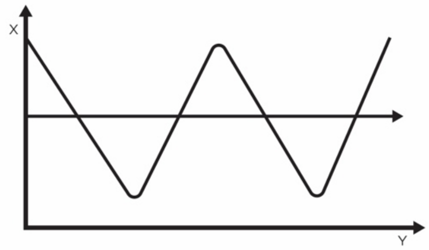
# PRACTICE QUESTIONS

4. Timothy moves a bar magnet in and out of a nearby solenoid which is connected to a cathode ray oscilloscope (CRO), a device capable of representing voltage as a function of time. Which of the following graphs best represents the trace displayed by the CRO?

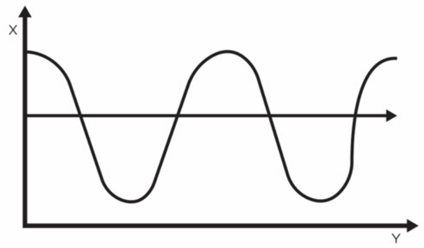
a.



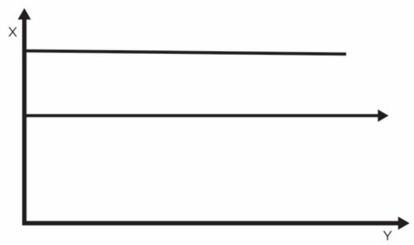

b.




c.

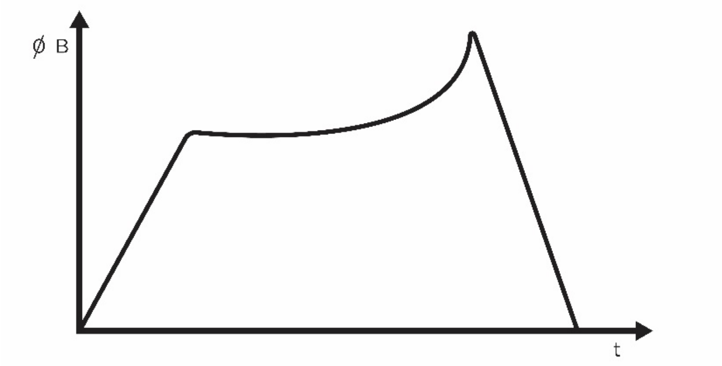



d.



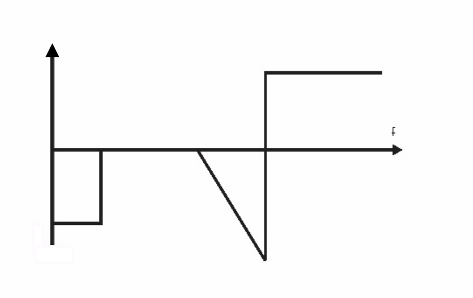
# PRACTICE QUESTIONS

5. The graph below shows the change in magnetic flux through a coil over a period of time.

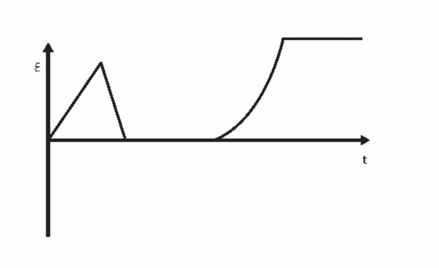



Choose the graph which best represents the emf produced in the coil during this time.

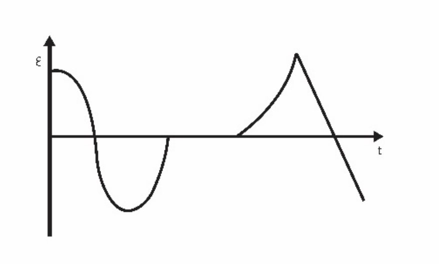
a.



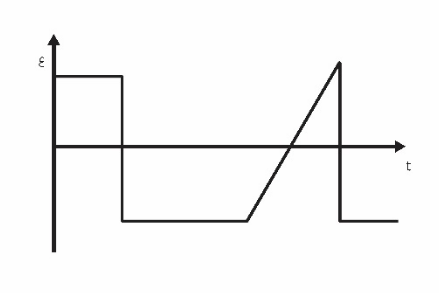
b.




c.




d.

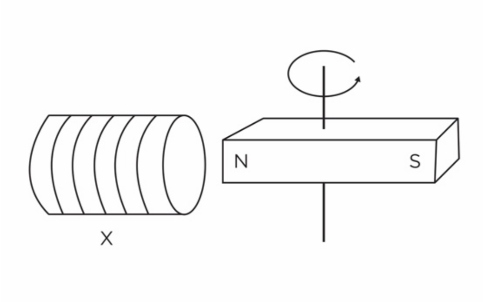


# PRACTICE QUESTIONS

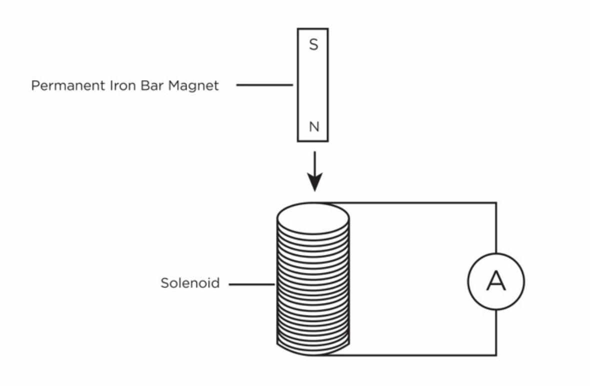
6. **Draw the direction of flow of induced current at the instant shown in each of the following examples.**

**(1 mark each)**

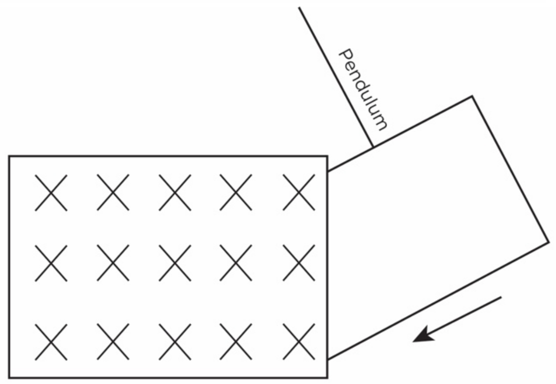
a.



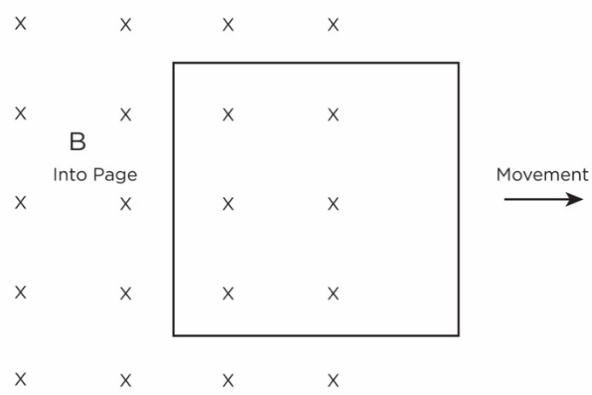

b.




c.

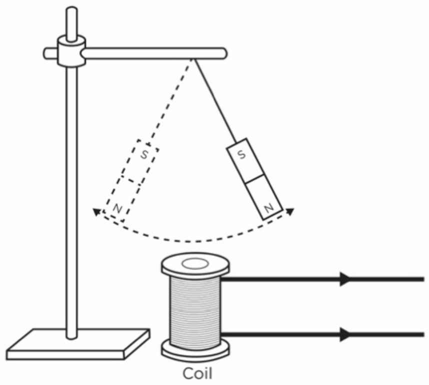



d.



# PRACTICE QUESTIONS

e. For the purpose of the question below, the coil is swinging from right to lef




7. **Amy makes the following statement:**

*"Lenz's law states that the induced current sets up a magnetic field in the same direction as the original change in flux."*

**Evaluate the accuracy of the statement above with reference to any relevant physics principles.**

**(4 marks)**

..........................................................................................................................................................................

..........................................................................................................................................................................

..........................................................................................................................................................................

..........................................................................................................................................................................

..........................................................................................................................................................................

..........................................................................................................................................................................

..........................................................................................................................................................................

..........................................................................................................................................................................

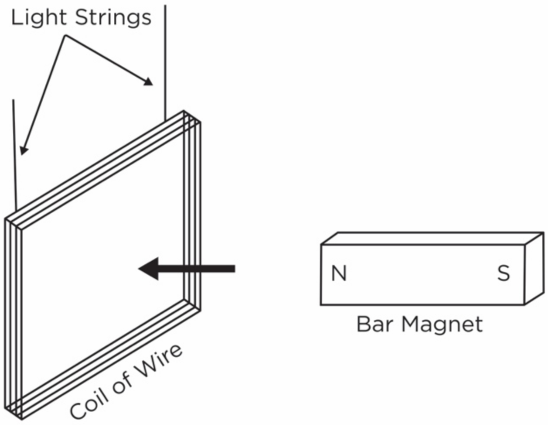
..........................................................................................................................................................................

..........................................................................................................................................................................

# PRACTICE QUESTIONS

8. Explain with reference to any relevant principles, what would happen if a bar magnet were moved rapidly towards a coil of wire suspended from the roof by a set of lightweight strings.

(3 marks)




..........................................................................................................................................................................................

..........................................................................................................................................................................................

..........................................................................................................................................................................................

..........................................................................................................................................................................................

..........................................................................................................................................................................................

..........................................................................................................................................................................................

..........................................................................................................................................................................................

..........................................................................................................................................................................................

..........................................................................................................................................................................................

..........................................................................................................................................................................................

..........................................................................................................................................................................................

..........................................................................................................................................................................................

# PRACTICE QUESTIONS

9. A circular conducting loop of radius 7.5cm has a magnetic field of strength of strength 0.30 mT threading it before it is expanded such that radius is doubled over a period of 0.2 seconds. Calculate the magnitude of the emf produced.

(3 marks)

..................................................................................................................................................................

..................................................................................................................................................................

..................................................................................................................................................................

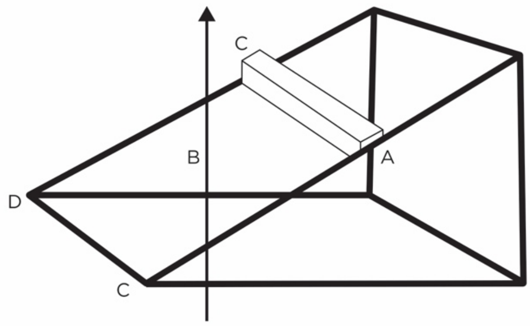
..................................................................................................................................................................

..................................................................................................................................................................

..................................................................................................................................................................

# HOMEWORK

1. **The inclined surface has a conducting loop *abcd* of which the side *ab* is free to move. A uniform magnetic field threads the loop as shown in the diagram below.**




   a. Explain the direction of current flow within the loop as the side ab slides down the inclined plane with reference to physics principles.

   (4 marks)

   b. Describe any changes in the rate at which ab slides down the inclined. plane.

   (3 marks)

# HOMEWORK

c. Explain whether the magnetic flux density threading the loop increases, decreases, or remains the same as ab moves down the inclined plane.

(2 marks)

....................................................................................................

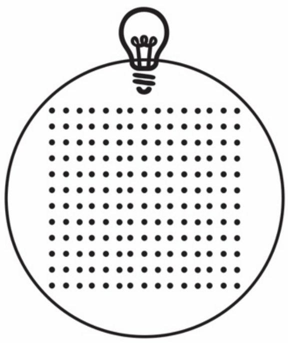
....................................................................................................

....................................................................................................

....................................................................................................

....................................................................................................

**2. A school student varied the magnetic flux threading the loop below and observes that the light bulb turns on when she does so.**



a. Explain how a change in flux may cause the light bulb to shine.

(2 marks)

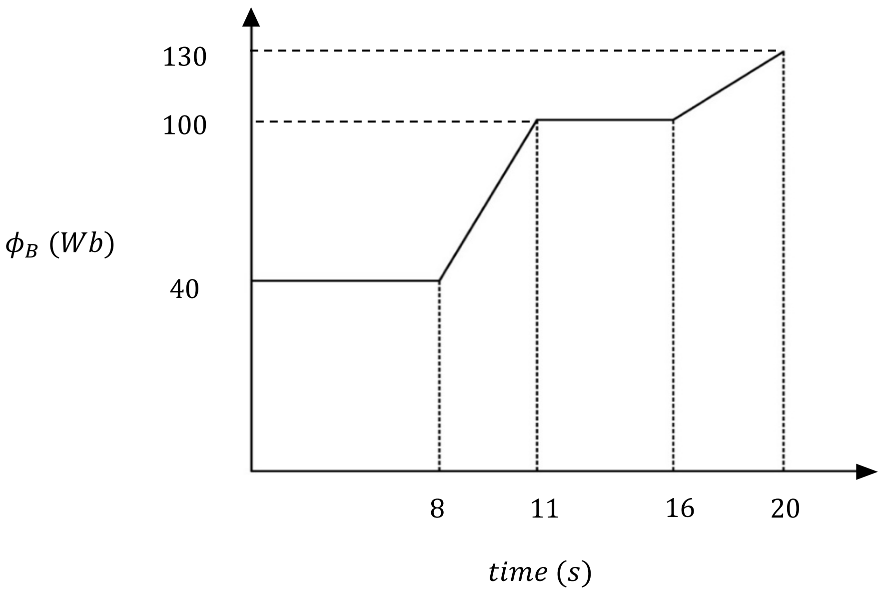
....................................................................................................

....................................................................................................

....................................................................................................

# HOMEWORK

b. The graph below shows how the magnetic flux varies over a 20 second period.




Analyse how the induced emf varies throughout the period shown.

(4 marks)

..............................................................................................................................................

..............................................................................................................................................

..............................................................................................................................................

..............................................................................................................................................

..............................................................................................................................................

..............................................................................................................................................

..............................................................................................................................................

..............................................................................................................................................

..............................................................................................................................................

..............................................................................................................................................

..............................................................................................................................................

c. The student noticed that the bulb turned on in the first period where she varied the flux, but that it was much dimmer the second time. Explain why this may be the case.

(2 marks)

..............................................................................................................................................

..............................................................................................................................................

..............................................................................................................................................

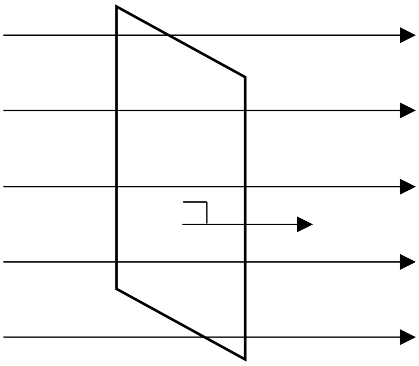
# HOMEWORK

......................................................................................................................................................

......................................................................................................................................................

......................................................................................................................................................

**3. A thin metal conductor is rotated in a clockwise direction within the magnetic field shown below.**



a. Sketch a graph of emf vs time to represent how the induced emf varies throughout one full rotation.

(1 mark)

b. Explain the shape of the curve of the graph drawn above.

(2 marks)

......................................................................................................................................................

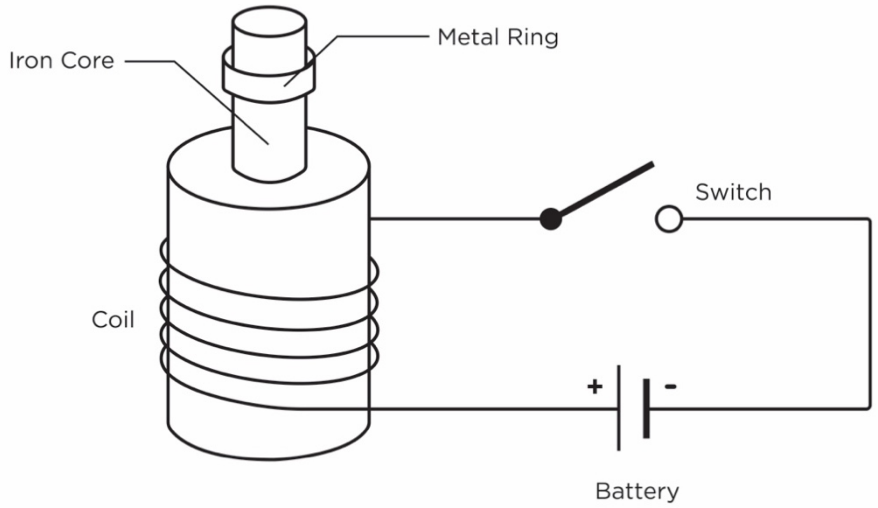
......................................................................................................................................................

......................................................................................................................................................

# HOMEWORK

4. A metal ring is freely suspended above a solenoid as shown below. Explain the motion of the ring, if any, when the switch is closed.

(4 marks)




..................................................................................................................................................

..................................................................................................................................................

..................................................................................................................................................

..................................................................................................................................................

..................................................................................................................................................

..................................................................................................................................................

..................................................................................................................................................

..................................................................................................................................................

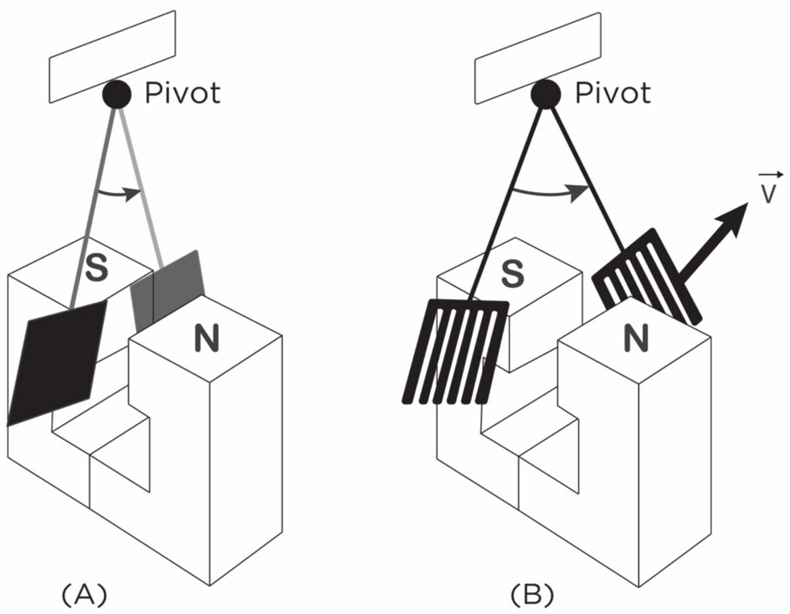
..................................................................................................................................................

..................................................................................................................................................

..................................................................................................................................................

# HOMEWORK

5. See pendulums A and B below. Both are made of conducting metal sheets, where pendulum B has a sheet with slits in it.

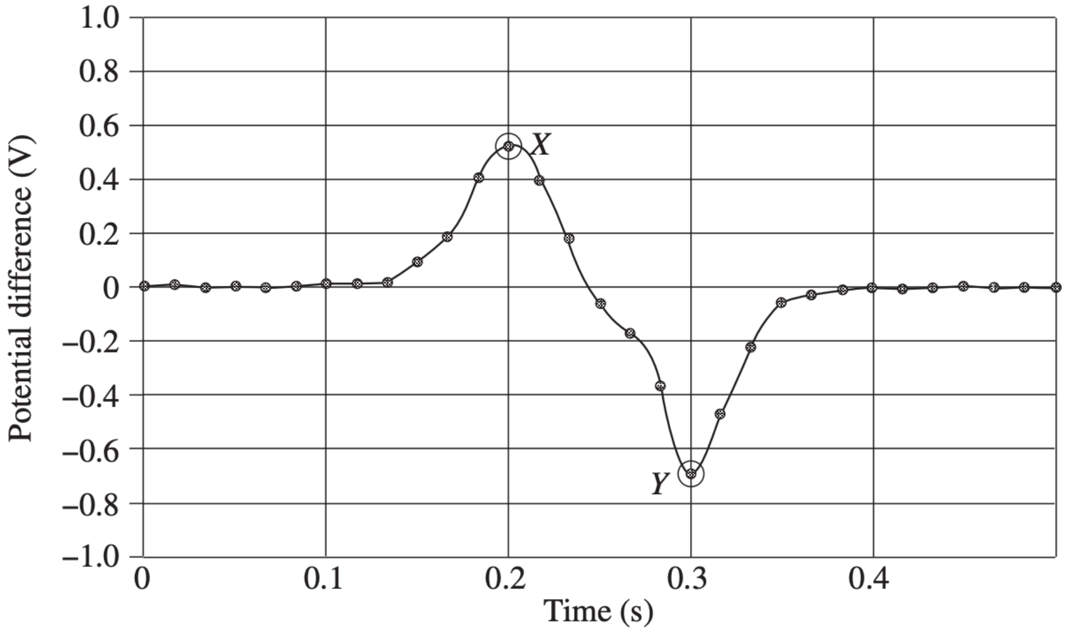



Explain the difference in the motions undergone by the two pendulums.

(5 marks)

# HOMEWORK

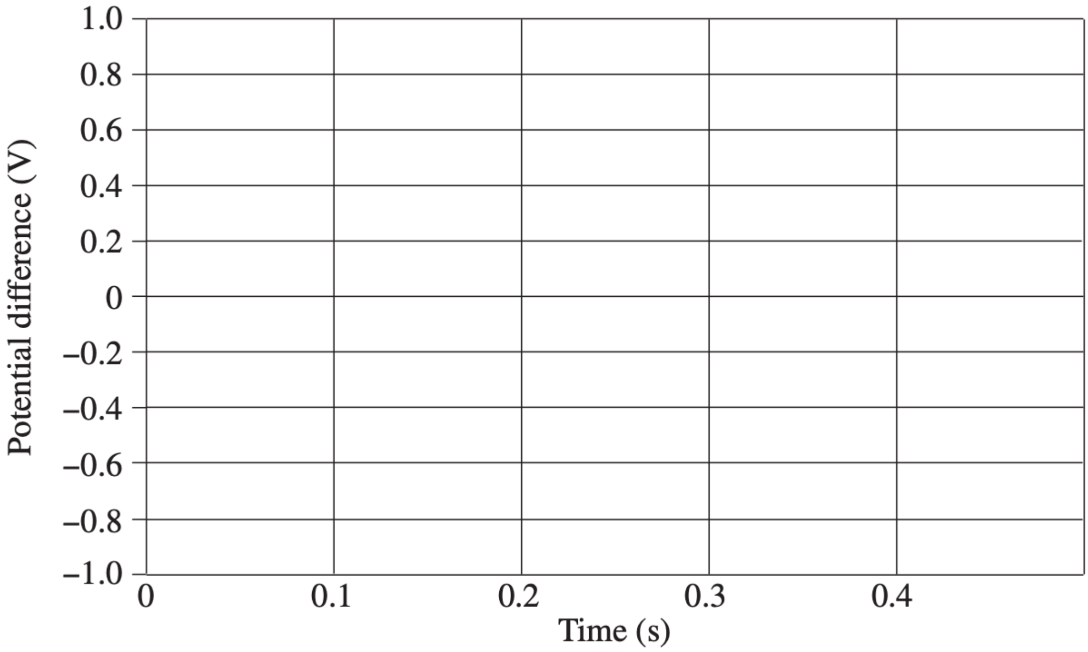
6. A bar magnet is dropped from rest from a height through a solenoid. The solenoid is connected to a data logger which outputs the following graph:




Assume that the point X represents the point at which the bottom of the magnet is at the same vertical position as the top of the solenoid and has a Y-coordinate of 0.5V.

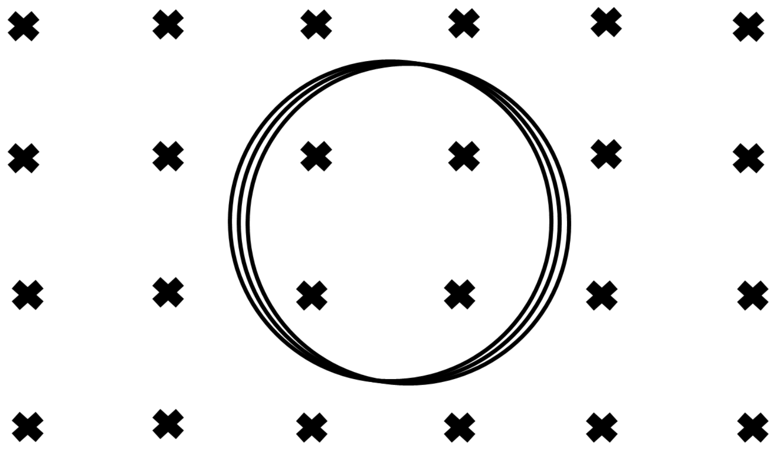
Draw a graph representing the outcome when the magnet is dropped from twice as high. Label numerically the Y-coordinate of point X.

(2 marks)



# HOMEWORK

7. **A year 12 physics class is investigating the concept of electromagnetic induction. They place a coil of wire in a uniform, variable magnetic field generated by an electromagnet and measure the current through the coil.**



**Initially, the coil is at rest and the magnetic field is kept constant. The class carries out the following steps:**

1. Increase the magnetic field strength
2. Decrease the magnetic field strength
3. Rotate the coil around an axis pointing into the page
4. Rotate the coil around a vertical axis
5. Accelerating the coil into the page

a. What is the current in the coil initially?

(1 mark)

..........................................................................................................................................................................

..........................................................................................................................................................................

b. Which of their actions will change the current that they measure? Justify your answer.

(3 marks)

..........................................................................................................................................................................

..........................................................................................................................................................................

..........................................................................................................................................................................

..........................................................................................................................................................................

..........................................................................................................................................................................

..........................................................................................................................................................................

..........................................................................................................................................................................

..........................................................................................................................................................................

..........................................................................................................................................................................

# HOMEWORK

**8. A square coil of conducting wire with 250 turns is held in a uniform magnetic field of strength 700 mT. The coil has side length 12 cm and is made of a material with resistance r = 0.0034 Ω/m. The magnetic field is decreased at a constant rate until it reaches zero 3.6 seconds later.**

a. Calculate the magnitude of the emf induced in the coil.

(2 marks)

b. Calculate the current induced in the coil.

(2 marks)

c. If the coil was replaced by one made of plastic, what would happen to the induced emf and induced current in the coil?

(2 marks)

# HOMEWORK

**9. A magnet is dropped from rest. It falls 4 metres before entering a vertical copper tube. As it passes through the tube, the magnet slows down until it is falling at a constant velocity.**

a. Describe the forces on the magnet as it falls.

(3 marks)

..........................................................................................................................................................

..........................................................................................................................................................

..........................................................................................................................................................

..........................................................................................................................................................

..........................................................................................................................................................

..........................................................................................................................................................

..........................................................................................................................................................

..........................................................................................................................................................

..........................................................................................................................................................

..........................................................................................................................................................

b. Analyse the energy transformations in this scenario.

(4 marks)

..........................................................................................................................................................

..........................................................................................................................................................

..........................................................................................................................................................

..........................................................................................................................................................

..........................................................................................................................................................

..........................................................................................................................................................

..........................................................................................................................................................

..........................................................................................................................................................

..........................................................................................................................................................

..........................................................................................................................................................

# HW ANSWERS

## Module 6 Lesson 3

**1.**

| | |
|---|---|
| 2 | Explains how each wire is affected by the magnetic field of the other<br><br>• Let the wire on the left be named Wire A and the wire on the right be named Wire B<br>• Wire A produces a magnetic field which permeates Wire B into the page by right hand grip rule<br>• This creates a force towards the left for Wire B by right hand palm rule<br>• Wire B produces a magnetic field which permeates Wire B out of the page by right hand grip rule<br>• This creates a force towards the right for Wire A by right hand palm rule |
| 1 | Draws a relevant diagram or draws on the given diagram supporting the above<br><br>• Diagram may include crosses on Wire B and dots on Wire B<br>• Vector arrows showing the force on the two wires |
| 1 | States that the force between the two wires is attractive, equal and opposite |

**2.**

| | |
|---|---|
| 1 | Calculates the force on the bottom-right wire exerted by the bottom-left wire<br><br>• $F = 2 \times 10^{-7} \times \frac{I_1 \times I_2}{r} \times l$<br>• $F = 2 \times 10^{-7} \times \frac{2 \times 7}{0.3} \times 1 = 9.33 \times 10^{-6} N$ towards the right |
| 1 | Calculates the force on the bottom-right wire exerted by the top wire<br><br>• $F = 2 \times 10^{-7} \times \frac{I_1 \times I_2}{r} \times l$<br>• $F = 2 \times 10^{-7} \times \frac{5 \times 7}{0.3} \times 1 = 2.33 \times 10^{-5} N$ at $60^o$ below the horizontal |
| 2 | Successfully uses vector addition and trigonometry to determine the correct net force acting on the bottom-right wire with the correct direction.<br><br>• The use of a diagram is highly recommended<br>• By cosine rule…<br>• $x^2 = (9.33 \times 10^{-6})^2 + (2.33 \times 10^{-5})^2 - 2 \times (9.33 \times 10^{-6}) \times (2.33 \times 10^{-5}) \times \cos 120$<br>• $x = 2.9 \times 10^{-5} N$ (2sf)<br>• By sin rule…<br>• $\frac{\sin\theta}{2.33 \times 10^{-5}} = \frac{\sin 120}{2.9 \times 10^{-5}}$<br>• $\theta = 44^o$<br>• Therefore, the force is $2.9 \times 10^{-5} N$ at $44^o$ degrees below the horizontal |

# HW ANSWERS

| mass $(\times 10^{-3}\text{g})$ | $\text{I(A)}$ | $\text{I}^2(\times 10^3\text{A}^2)$ |
|---|---|---|
| 1.0 | 50 | 2500 |
| 1.2 | 55 | 3025 |
| 1.5 | 60 | 3600 |
| 1.7 | 65 | 4225 |
| 2.0 | 70 | 4900 |

**4a.**

| | |
|---|---|
| 4 | Fills in the table above with the correct values for the 4th column |
| 3 | Fulfils all the following criteria<br>• Labels the graph with an appropriate title<br>• Labels the y axis with E strength and x axis with B strength<br>• Labels the axis with correct units<br>• Accurately plots points with crosses and a suitable line of best fit<br>• Uses an appropriate scale and take at least 3/4 of the graphing space |
| 2 | Fulfils 3-4 of the following criteria<br>• Labels the graph with an appropriate title<br>• Labels the y axis with E strength and x axis with B strength<br>• Labels the axis with correct units<br>• Accurately plots points with crosses and sketches a suitable line of best fit<br>• Uses an appropriate scale and takes at least 3/4 of the graphing space |
| 1 | Fulfils 1-2 of the following criteria<br>• Labels the graph with an appropriate title<br>• Labels the y axis with E strength and x axis with B strength<br>• Labels the axis with correct units<br>• Accurately plots points with crosses and a suitable line of best fit<br>• Uses an appropriate scale and take at least 3/4 of the graphing space |

**b.**

| | |
|---|---|
| 1 | Uses the gradient formula to calculate the gradient of the line of best fit<br>• Gradient $= \frac{\Delta y}{\Delta x} = \frac{(1.85-1.1)\times 10^{-3}}{67.5-52.5} = 5 \times 10^{-5}$<br>• Two points must be chosen that are not the given data points and must be decently far apart on the line of best fit |
| 1 | Derives a value which is in the correct solution range<br>• Any value from $4.9\ \times 10^{-5}$ to $5{,}1\ \times 10^{-5}$ |

# HW ANSWERS

**c.**

| | |
|---|---|
| 3 | Equates the measured "weight force" on the wire with the force due to the interaction of the two wires, and rearranges the formula to match the gradient<br>• $F = 2 \times 10^{-7} \times \frac{I^2}{r} \times l$ (Keep in mind $I_1 = I_2$)<br>• This force is equal to the measured "weight" force...<br>• $mg = 2 \times 10^{-7} \times \frac{I^2}{r} \times l$<br>• $\frac{m}{I^2} = 2 \times 10^{-7} \times \frac{l}{r}$ |
| 1 | Substitutes the gradient and length of wire into the formula to determine the distance<br>• $5 \times 10^{-5} = 2 \times 10^{-7} \times \frac{0.1}{r}$<br>• $r = \frac{2\times10^{-7}\times0.1}{5\times10^{-5}} = 4.0 \times 10^{-4}$m (2sf) |

**d.**

| | |
|---|---|
| 1 | Recognises the use of $\frac{F}{l} = \frac{\mu_0 I_1 I_2}{2\pi r}$ |
| 1 | Correctly substitutes values into the question to determine the correct solution<br>• $F = 2 \times 10^{-7} \times 80 \times 40 \times 0.1 \times \frac{1}{4\times10^{-4}}$<br>• $F = 0.16N$<br>• Therefore, the balance will read 0.016kg (2sf) |

**5a.**

| | |
|---|---|
| 1 | Recognises that the current flow will anti-clockwise in accordance with right-hand palm rule since a downward force is present |

**b.**

| | |
|---|---|
| 1 | Determines the added force due to the magnetic field<br>• $(0.675 - 0.2) \times 9.8 = 4.655N$<br>12. |
| 2 | Uses the force on a current carrying conductor equation to determine the correct magnetic field strength<br>• $F = BIl$<br>• $4.655 = B(30)(0.3)$<br>• $B = 0.52$ T (2sf) |

6a.

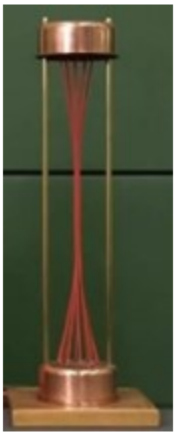
| | |
|---|---|
| 1 | Identifies the direction of the force on each wire. They carry current in the same direction so the forces between the wires are attractive. The force on the upper wire is directed downwards and the force on the bottom wire is directed upwards. |
| 1 | Explains that force from the lower wire pulls the top wire straight downwards, which is the same direction as the force that is already on it due to gravity so it will remain in the same position (assuming the cables cannot stretch). |
| 1 | Explains that the lower wire is pulled upwards by the force due to the current, opposing gravity. When the current flows, the direction of the net force on the wire will change from downward to upwards if the current is high enough, making it move. |

b.

| | |
|---|---|
| 1 | The force per unit length on the wire is given by: $$\frac{F}{l} = \frac{\mu_0}{2\pi}\frac{I_1 I_2}{r}$$ Recognises that, at the maximum current, the force upwards balances the weight force downwards and substitutes $F = mg$ $\frac{mg}{l} = \frac{\mu_0}{2\pi}\frac{I_1 I_2}{r}$ |
| 1 | Rearranges the above equation, letting $I_1 = I_2 = I_{max}$ to show that: $$I_{max} = \sqrt{\frac{2\pi rmg}{\mu_0 l}}$$ |
| 1 | Calculates the maximum current in each wire. Substitute r = 1m, m = 16kg, $l$ = 10m $$I_{max} = \sqrt{\frac{2\pi \times 1 \times 1.6 \times 9.8}{4\pi \times 10^{-7}}}$$ = 94.1 A |

# HW ANSWERS

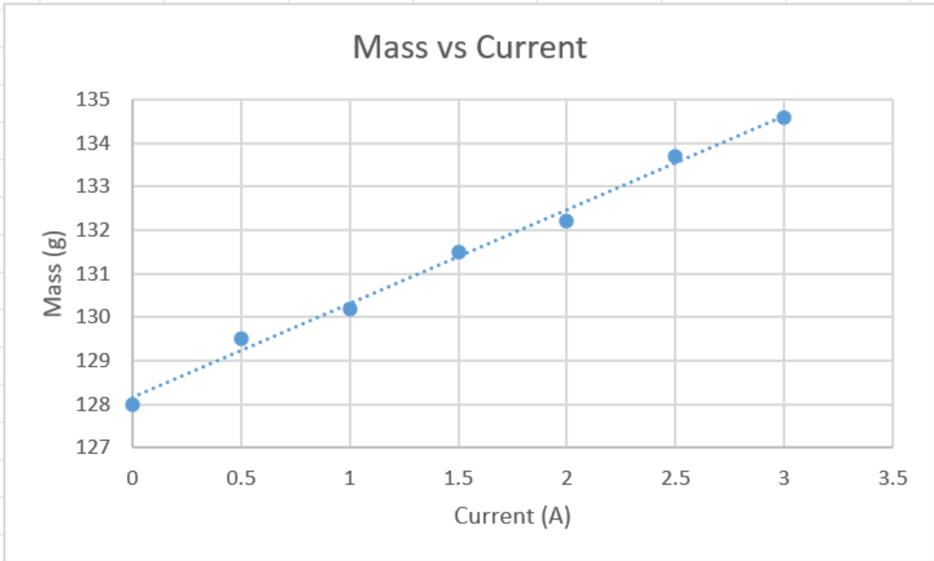
7.

| | |
|---|---|
| 1 | Draws a diagram in which the wires are collected in the centre of the circle. The diagram should look like this:<br> |
| 1 | Explains that the current in each wire produces a magnetic field, which exerts a force on each of the other current-carrying wires. |
| 1 | Recognises that the force between each pair of wires is attractive because the currents are all in the same direction due to the right hand rule. |
| 1 | Explains that the wires are all drawn inwards, pinching together as a result of their attraction to each other wire. |

# HW ANSWERS

8a.

Example graph:




| | |
|---|---|
| 1 | Appropriately sized graph<br><br>Data points should fill a significant portion of the space provided |
| 1 | Title and axis labels with units |
| 1 | Appropriate scales on axes<br><br>- Scale should be consistent and fit all of the data<br><br>Note that the x and y axis scale do not need to be the same and do not need to start at 0 |
| 1 | Correctly plots data points with crosses |
| 1 | Draws an appropriate line of best fit |

b.

| | |
|---|---|
| 1 | Uses two points on their trendline to calculate the gradient of their graph (do not use points straight from the table)<br><br>Gradient should be around 2.2 g/A = 2.2 x $10^{-3}$ kg/A |
| 1 | Correct units |

# HW ANSWERS

c.

| | |
|---|---|
| 1 | Recognises that the force can be calculated from the mass shown by the balance by F = mg |
| 1 | Substitutes F = mg into the equation F = BIL and rearranges to find an expression for the magnetic field strength<br><br>mg = BIL<br><br>$$B = \frac{m}{I}\frac{g}{L}$$ |
| 1 | Substitutes g = 9.8 m/s$^2$, L = 0.05m and their value of the gradient $\frac{m}{I}$ = 2.2 x 10$^{-3}$ kg/A<br><br>$$B = \frac{m}{I}\frac{g}{L}$$<br>$$B = 2.2 \times 10^{-3}\ kg/A\ \times \frac{9.8\ m/s^2}{0.05\ m}$$<br>B = 0.43 T |

elevate