Phone: (02) 8007 6824
Email: info@dc.edu.au
Web: dc.edu.au

2018 HIGHER SCHOOL CERTIFICATE COURSE MATERIALS

HSC Physics

Motors and Generators

Term 1 – Week 3

Name ……………………………………………………….

Class day and time ……………………………………………

Teacher name ……………………………………………...

Term 1 – Week 3 – Theory

THE RELATIVE MOTION BETWEEN A CONDUCTOR AND MAGNETIC FIELD IS USED TO GENERATE AN ELECTRICAL VOLTAGE.

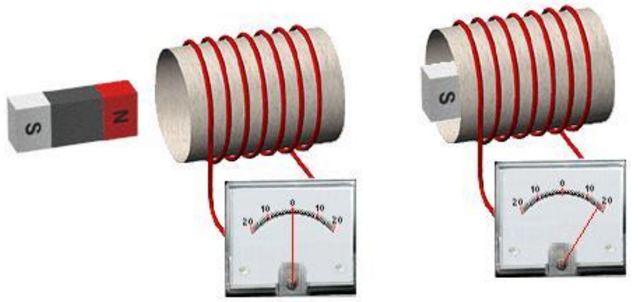
- **Outline Michael Faraday's discovery of the generation of an electric current by a moving magnet**

FARADAY'S FIRST EXPERIMENT

In 1831, Michael Faraday discovered that by moving a magnet towards and away from a coil of wire, an electric current was produced in the coil. His experiment involved moving a permanent magnet in and out of a coil connected to a galvanometer.

Faraday found that the pointer in the galvanometer deflected in one direction as a magnet was moved towards the coil. The pointer returned to its rest position when the magnet was stationary. The pointer deflected in the opposite direction as the magnet was moved away from the coil. Also, the deflections caused by moving a north pole and moving a south pole towards the coil were in opposite directions.

Faraday's magnet / coil experiment



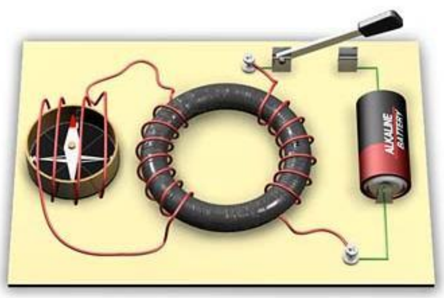
Faraday connected a coil to a galvanometer (to measure current). Only as he moved a magnet towards and away the coil, he noticed a spike in current.

There was no current produced when the magnet was not moving relative to the coil.

FARADAY'S SECOND EXPERIMENT

Faraday also experimented with an apparatus which consisted of two coils of wire looped wound around opposite sides of a soft iron ring. One coil was attached to a source of DC current and the other was connected to a galvanometer. When the current in the first coil was switched on or off, there was a momentary deflection of the pointer before it returned to rest. When the current was repeated switched on and off, a current was induced in the second coil.

Faraday's coil / coil experiment



Faraday's second experiment involved winding 2 independent coils around a soft-iron ring. He connected one coil to a battery and the other coil to a galvanometer.

He noticed that as he switched on the battery coil, the galvanometer measured a current in the second coil, but only momentarily.

Current was momentarily measured when the battery was switched off.

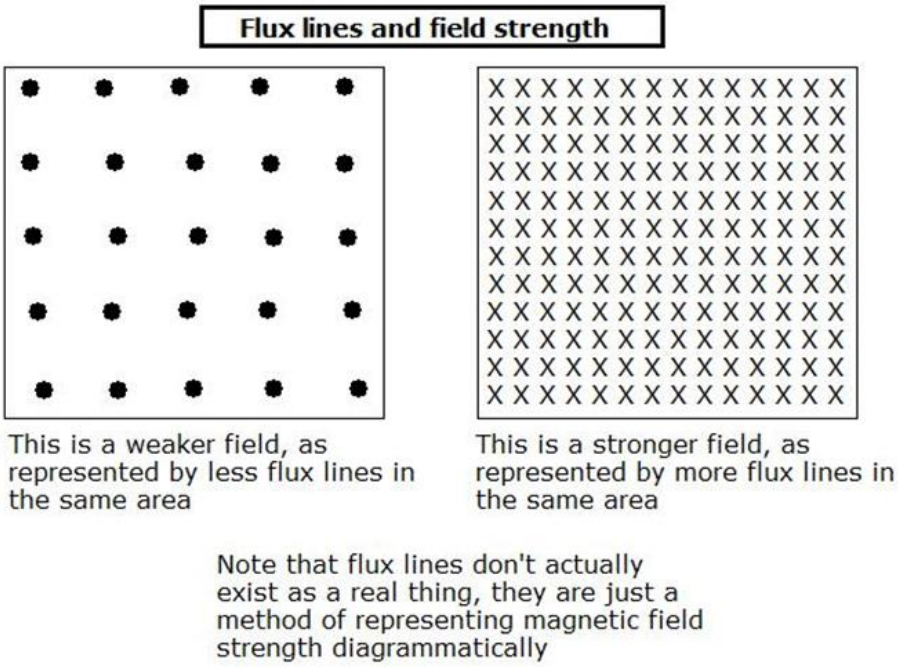
CONCLUSION FROM HIS EXPERIMENTS

Faraday concluded that a changing magnetic field can generate an electric current in a coil. This changing magnetic field could be produced by relative movement of a permanent magnet near a conductor, or by switching an electromagnet on and off, as per the second experiment. The magnitude of the potential difference is dependent upon the rate at which the magnetic field changes. The faster the field changes, the higher the potential difference and current induced.

Faraday's experiments led to the discovery of **electromagnetic induction**, which is the core principle behind generators and transformers.

- **<u>Define magnetic field strength B as magnetic flux density</u>**
- **<u>Describe the concept of magnetic flux in terms of magnetic flux density and surface area</u>**

Magnetic flux, Φ, is the amount of magnetic field permeating a given area. It is measured in Weber (Wb). The stronger a magnetic field is at a particular region, the higher the flux density is. The magnetic flux of a given area depends on the area, the magnetic field strength and the angle which the area makes with the magnetic field. Magnetic flux can be presented diagrammatically by the amount of flux lines in an area.



Magnetic field strength, B, is also known as magnetic flux density. This is the amount of magnetic flux passing through one square metre, measured in tesla (T) or weber per square metre (Wb m^{-2}). Hence, one tesla equals one weber per square metre.

$\Phi_B = B_\perp A$ shows the relationship between magnetic flux, magnetic flux density and area perpendicular to the field. (Note that this equation is **not required for the HSC**. Students need to be able to qualitatively describe the concept of flux and the relationship between flux density and perpendicular surface area)

For example, (a) and (c) have the same magnetic flux but different magnetic flux density. (b) and (c) have the same magnetic flux density but different magnetic flux.

- **Describe generated potential difference as the rate of change of magnetic flux through a circuit**

FARADAY'S LAW OF INDUCTION

Generated potential difference (or induced Electromotive Force, termed **'EMF'**) can be defined as the rate of change of magnetic flux through a circuit. (Recall the definitions for potential difference in the Preliminary course as $V = Ed$, $V = IR$ etc, they are still all true) This is called Faraday's law of induction, and can be mathematically expressed as:

$$Induced\ EMF = -\frac{Change\ in\ Magnetic\ Flux\ in\ Webers}{Time\ in\ seconds} \times (Number\ of\ turns\ in\ the\ coil)$$

The negative sign is due to the direction of the induced EMF (see next dot point).

An EMF is induced in a conductor when it is in relative motion to a magnetic field and/or when it is positioned in a changing magnetic field. In both situations, the conductor passes through the magnetic flux.

FACTORS AFFECTING INDUCED EMF

The induced EMF increases if you:

- Increase in the number of **turns in the coil**
- Increase the **strength of the magnet**
- Increase the **speed** of the relative moment
- Set the **angle** between the coil and magnetic flux to 90°

Also, decreasing the distance between the coil and the magnet will result in an increased rate of change of magnetic flux.

- **Account for Lenz's Law in terms of conservation of energy and relate it to the production of back EMF in motors**
- **Explain that, in electric motors, back EMF opposes the supply EMF**

Lenz's Law: *An induced EMF always gives rise to a current that produces a magnetic field that opposes the original change in magnetic flux in the circuit.*

Why is Lenz's Law true? A proof by contradiction

The Law of Conservation of Energy states that **energy cannot be created nor destroyed**, only transformed from one form to another.

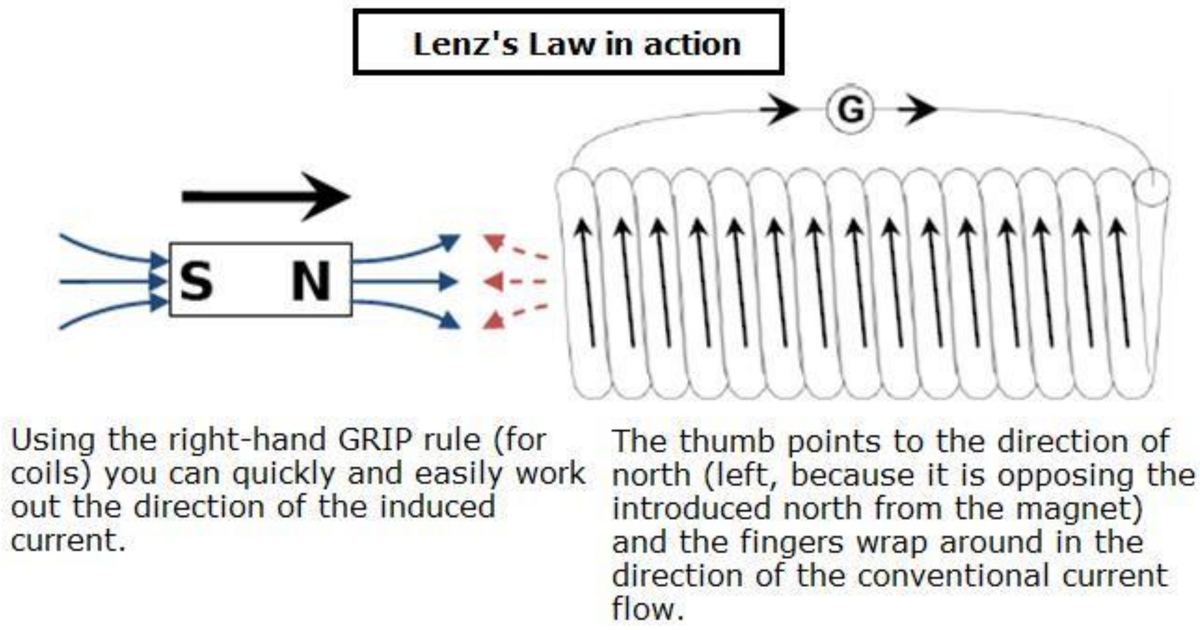
If we assume the opposite of Lenz's Law was correct, a magnetic flux change would induce a current that creates a magnetic field in the same direction as the original magnetic flux. This would result in a greater change in flux passing through the coil, which would lead to an even larger current that creates an even greater magnetic field in the same direction.

The ever increasing change in flux would lead to an ever increasing induced current which further increases the change in flux. The cycle continues, producing infinite energy and breaking the law of conservation. Thus, the opposite of Lenz's Law violates the principle of conservation of energy. Since there are only 2 possibilities (2 ways a current can flow, and 2 directions of magnetic field), Lenz's law must be true.

USING LENZ'S LAW

Lenz's Law can be used to determine the direction of an induce EMF. In the diagram below, the north pole of a bar magnet is moved towards a coil.

According to Lenz's Law, the change in magnetic flux in the coil will induce a current that creates a magnetic field which **opposes the original change in flux**. Hence, the coil will induce a magnetic field that repels the approaching north pole. An opposing north pole therefore would be induced on the left end of the coil in the diagram. Using the right-hand grip rule for coils (recall from the Preliminary course, or ask your tutor), with the thumb pointing in the direction of the north magnetic field (towards the left), the curl of the fingers indicates the direction of the induced current in the coil.



BACK EMF

Back EMF is the **induced EMF that opposes the external supply EMF** in motors. In electric motors, an input voltage is used to produce a current in a coil which then rotates in an external magnetic field. Since the amount of magnetic flux in the coil is continually changing as the coil rotates, an EMF is induced in the coil. The induced EMF opposes the supply EMF by Lenz's Law.

If this was not true, the EMF and current in the coil would increase, the coil would rotate faster and result in a greater induced EMF. This cycle would continue and the coil would rotate faster and faster without any further energy input. In the same way as before, this violates the Law of Conservation of Energy.

When a motor is turned on and if there is absolutely no load or friction to slow it down, the speed of the coil increases until the back EMF is equal to the supply EMF (actually this is an asymptote). At this point, there will be no net voltage and hence no current in the coil. The coil would rotate at a constant speed as there is no net torque acting on it. This makes logical sense because if the coil is spinning only because of its existing momentum, no power is needed to keep it spinning, therefore no current is being used.

When a load is placed on the motor, the motor slows down. This results in the reduction of back EMF to enable more current to flow through the coil in order to support the load. The net EMF (supply EMF minus Back EMF) and resultant current is what is being used to move the load.

Note that in reality, all motors experience at least a load from air resistance, bearing friction (from the axle and front bearing), and the brushes rubbing against the split-ring commutator. Therefore motors use a bit of energy as long as it's spinning, even if not connected to any external load. If there is an external load, the net EMF will increase since the extra load will cause back EMF to decrease further. This means more energy (more net EMF results in more current flowing through the coils) will be used to pull the greater load, which makes sense because more work is being done.

Worked example

In an electric motor, the armature winding has a resistance of 10 Ω. When the motor is connected to a 240V supply and is operating normally, the current is 3 A. Calculate the current that flows through the motor when it is first started. Calculate the back emf of the motor when it is operating.

Solution:

$Initial\ current = I = \frac{V}{R}$ (Ohm's law)

$= 240 \div 10$

$= 24A$

Difference in initial current and operating current:

$= 24 - 3 = 21A$

$Back\ EMF = IR = 10 \times 21 = 210V$

Therefore the majority of the initial 240V is pushed back by back EMF.

SAFETY MEASURES

In some motors, a resistor is built in to limit the current flow in the coil until it is spinning fast enough for the back EMF to counter the supply EMF. This prevents the motor from burning out due to excessive current in the coil when the motor is accelerating from a standstill. Also, if a motor is held stationary so that it cannot turn, the current in the coil would increase dramatically because the stationary coil does not cut flux and hence, no back EMF is produced. In this situation, the motor's coil is essentially a short circuit, which is dangerous and can damage the power source as well as the motor. A resistor in this situation would prevent the motor from burning out.

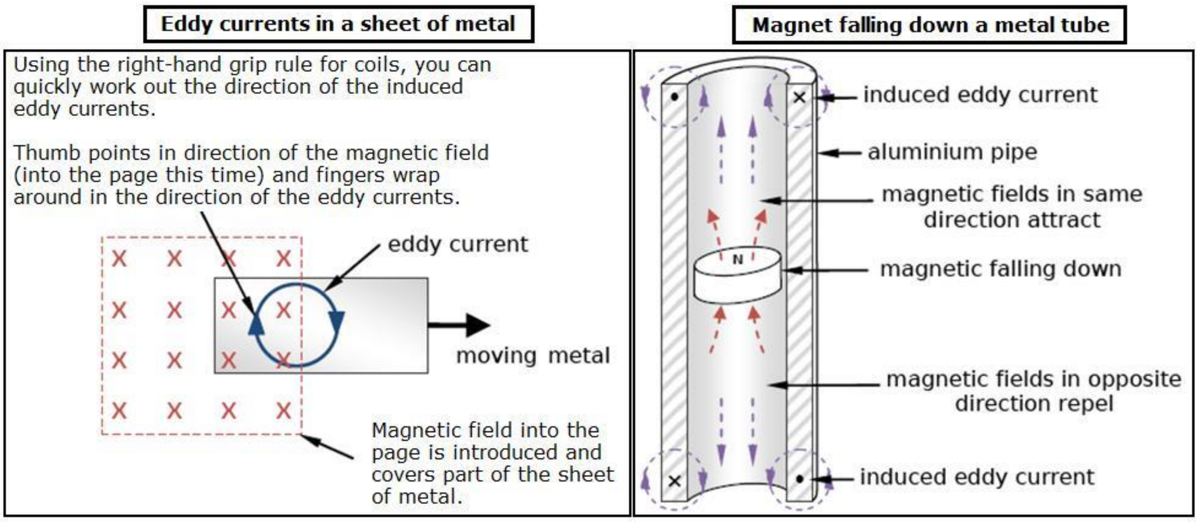
Note that the net EMF of the coil in a motor is equal to the input the supply EMF minus the back EMF.

- **Explain the production of eddy currents in terms of Lenz's Law**

Eddy currents are circular or whirling currents within a conducting material, induced by a change on magnetic flux through the conductor. Eddy currents are produced when a conductor is subjected to a changing magnetic field or when a conductor is moving through a magnetic field.

Eddy currents, like all currents, produce magnetic fields in accordance with Lenz's Law. Eddy currents are formed so that they flow in a direction which produces a magnetic field that **opposes the original change in magnetic flux**.

The following two diagrams show the production of eddy currents.



EDDY CURRENTS IN A MOVING SHEET OF METAL

The first diagram shows a metal sheet being moved out of a magnetic field. As you pull the metal out of the field going into the page, you are effectively removing the magnetic field. To oppose this change (according to Lenz's Law), an eddy current will be produced which creates a magnetic field going into the page to replace the removed field. Using the right-hand grip rule for coils, the direction of the eddy current can easily be found (clockwise in this case).

Note you can also use the right-hand palm rule, but it is slower and more complicated – we recommend using the grip-rule for coils for eddy currents.

MAGNET FALLING DOWN A METAL TUBE

The second diagram shows a strong magnet being dropped into an aluminium pipe (cross-section shown). The north is pointing up and the south is pointing down. As the magnet falls, it is introducing "south" into the sections of the pipe beneath it, and removing "north" from the sections of the pipe above it.

To oppose both changes, the sections of the pipe above and beneath the magnet will have eddy currents flowing in such a way as to induce south pushing against the introduced south beneath the magnet, and north opposing the removal of north above the magnet. This is clear from the diagram's labelled current flow.

The net effect of this is that the magnet's descent is slowed significantly. In fact, if you did this as an experiment in class, the magnet will take a full 5 to 10 seconds to fall a tube of 1 metre!

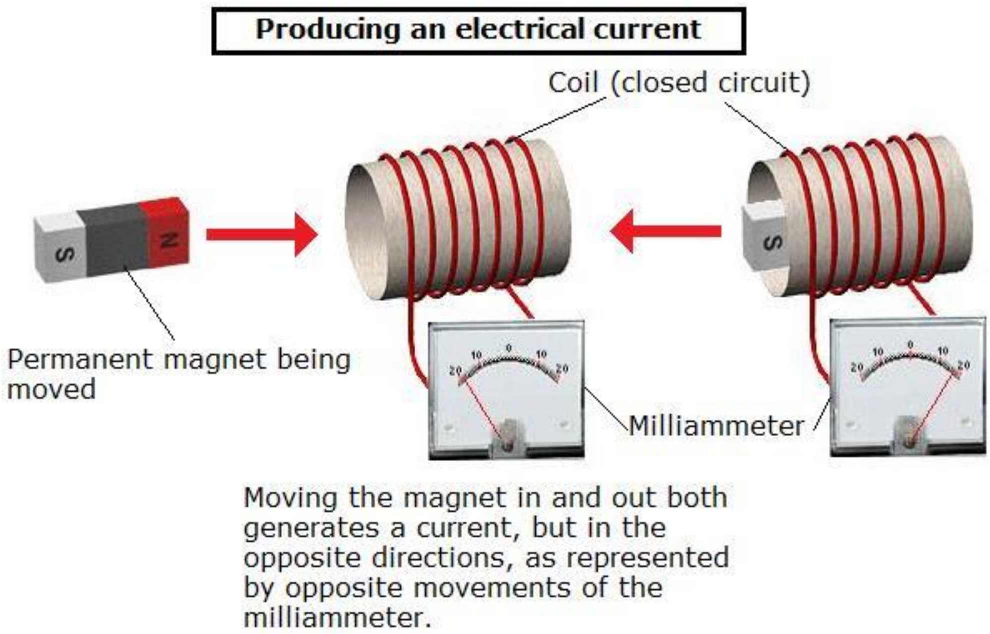
- **<u>Perform an investigation to model the generation of an electric current by moving a magnet in a coil or a coil near a magnet.</u>**
- **<u>Plan, choose equipment or resources for, and perform a first-hand investigation to predict and verify the effect on a generated electric current when:</u>**
    - **<u>The distance between the coil and magnet is varied</u>**
    - **<u>The strength of the magnet is varied</u>**
    - **<u>The relative motion between the coil and the magnet is varied</u>**

These dot-points require students to be able to recall an experiment they did at school which used a coil and magnet to generate a current. We describe here one method of demonstrating the generation of a current.

GENERATING THE CURRENT

A solenoid was connected to a milliammeter (this is needed as the induced currents will be so small, a normal ammeter can't detect it). The north pole of a bar magnet was moved into the solenoid, held stationary and moved out of the solenoid. The movement of the pointer in the milliammeter was observed and recorded at each stage.

The bar magnet was then held stationary while the solenoid (still connected to the milliammeter) was moved towards the north pole, held stationary and moved away from the north pole. The deflections of the pointer were observed. The entire process was repeated for the south pole of the magnet.



Testing at different distances

The bar magnet was held 5cm from the solenoid and then moved 5 cm towards it. Then, the bar magnet was held 10cm from the solenoid and then moved 5 cm towards it. Approximate readings of the milliammeter were taken.

Testing different magnet strengths

The bar magnet was held 5cm from the solenoid and then moved 5 cm towards it. This was repeated for three of the same bar magnets strapped together to provide a stronger magnetic field. (Alternatively, a stronger bar magnet may be used.) Approximate readings of the milliammeter were taken.

Testing different speeds of movement

The bar magnet was held 5 cm from the solenoid and then moved slowly towards it. The bar magnet was held 5 cm from the solenoid and then moved towards it at a faster speed. Approximate readings of the milliammeter were taken.

RESULTS AND ANALYSIS

Effect of polarity and direction: When the north pole was moved towards the solenoid, the pointer moved left. When the magnet was held still, the pointer returned to its rest position. When the north pole was moved away from the solenoid, the pointer moved to the right. For the same movement, the deflections caused by the south pole were in the opposite direction than those caused by the north pole.

The movement of the pointer indicated that there was an induced current. The pointer only moved when there was relative motion between the solenoid and the magnet because electromagnetic induction only occurs when there is a change in magnetic flux.

Effect of distance: *The larger the distance between the magnet and the solenoid, the smaller the generated current*. This is because the magnetic flux is greater near the magnet and so the solenoid would cut less flux lines when the distance is larger.

Effect of strength of field: *The greater the strength of the magnetic field, the larger the generated current*. This is because a stronger magnetic field will have more flux lines than a weak magnetic field in an identical area. The solenoid would cut more flux lines when a stronger magnet is used, generating a greater current.

Effect of speed of motion: *The greater the speed of relative motion between the magnet and the coil, the larger the generated current*. This is because more turns of the solenoid cut flux lines in a given length of time when the relative motion is faster.

Term 1 – Week 3 – Homework

- **Outline Michael Faraday's discovery of the generation of an electric current by a moving magnet**

1. Outline what Faraday concluded from his experiments. **[2 marks]**

……

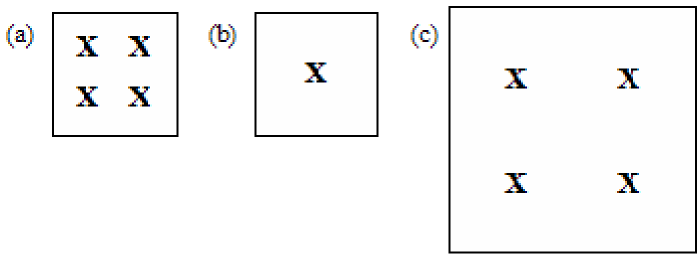
……

……

……

- **Define magnetic field strength B as magnetic flux density**
- **Describe the concept of magnetic flux in terms of magnetic flux density and surface area**

1. Qualitatively describe the magnetic flux and the magnetic flux density for the three given areas. Assume box (a) is 50 cm × 50 cm and the diagrams are drawn to scale. **[3 marks]**



……

……

……

……

……

……

……

……

……

……

- **<u>Describe generated potential difference as the rate of change of magnetic flux through a circuit</u>**

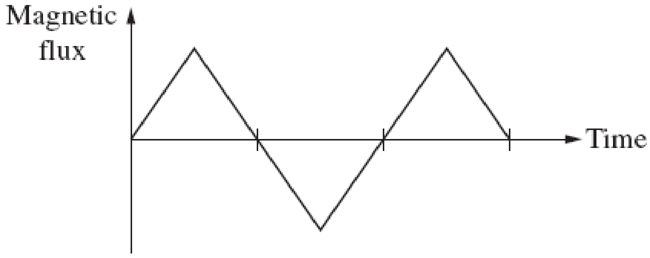
1. Define generated potential difference. **[1 mark]**

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

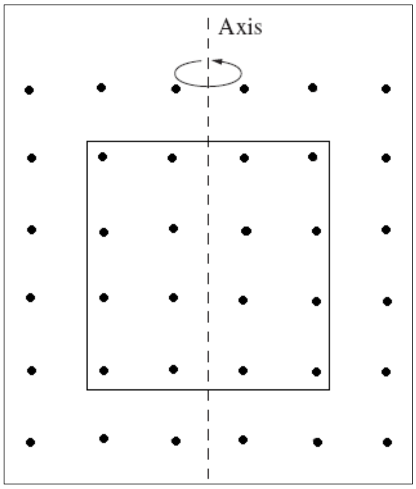
2. State the factors which influence the magnitude and direction of a generated potential difference. **[3 marks]**

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

3. [2007 HSC] The variation in magnetic flux through a coil is shown below. Sketch a graph to represent the corresponding induced EMF in the coil. **[2 marks]**



4. [2006 HSC] A square loop of wire, in a uniform magnetic field, is rotating at a constant rate about an axis as shown. The magnetic field is directed out of the page as shown. At time $t = 0$ the plane of the loop is perpendicular to the magnetic field and the left side is moving out of the page. Construct a graph to represent the variation of the magnetic flux through the loop with time. **[2 marks]**



- **Account for Lenz's Law in terms of conservation of energy and relate it to the production of back EMF in motors**
- **Explain that, in electric motors, back EMF opposes the supply EMF**

1. State Lenz's Law. **[1 marks]**

....

....

....

....

....

....

....

....

2. For each of the following, determine the direction of the induced EMF in the wire. **[1 mark each]**

   (a) magnetic field into the page, wire lays horizontal, wire is moved down the page

   (b) magnetic field out of the page, wire lays vertical, wire is moved to the right

   (c) magnetic field out of the page, wire lays horizontal, wire is moved up the page

   (d) magnetic field into the page, wire lays vertical, wire is moved to the left

....

....

....

....

....

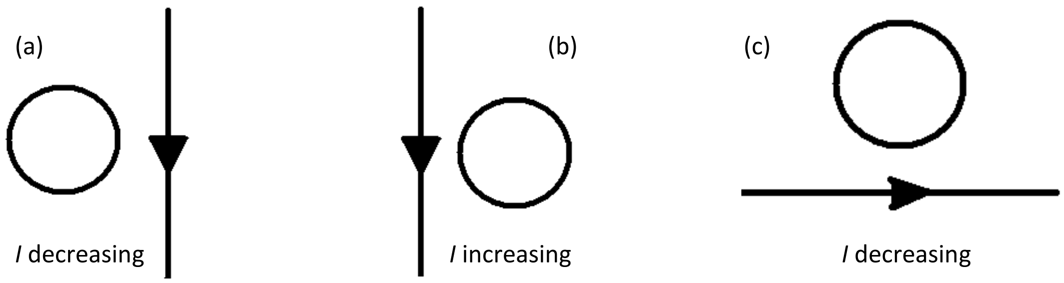
....

....

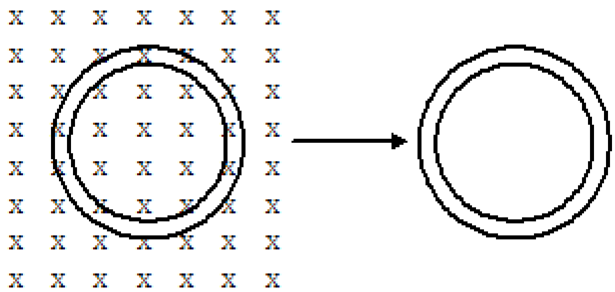
....

....

3. For each of the following, determine the direction of the induced current in the wire. **[1 mark each]**



4. A metallic ring lies in a uniform magnetic field. The ring is then moved out of the magnetic field, as shown. Deduce the direction of the induced current in the ring. Explain how you arrived at your answer. **[3 marks]**

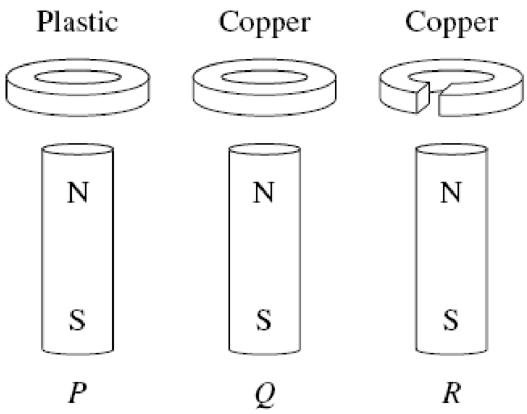


5. An electric motor is turned on and allowed to run freely. Then, a load is placed on the motor. Describe what happens inside the motor in relation to the coil, the supply EMF and the back EMF. **[3 marks]**

6. [2004 HSC] An ammeter was used to measure the current through a small DC motor. While it was running freely, a current of 2.09 A was recorded. When the motor was running, the axle of the motor was held firmly, preventing it from rotating, and the current was then recorded as 2.54 A. Explain this observation. **[3 marks]**

- **<u>Explain the production of eddy currents in terms of Lenz's Law</u>**

1. [2005 HSC] Three rings are dropped at the same time over identical magnets as shown below. State the order in which the rings *P, Q* and *R* reach the bottom of the magnets. Explain your reasoning. **[4 marks]**



....

....

....

....

....

....

....

....

....

....

....

....

....

....

- **<u>Perform an investigation to model the generation of an electric current by moving a magnet in a coil or a coil near a magnet.</u>**

- **Plan, choose equipment or resources for, and perform a first-hand investigation to predict and verify the effect on a generated electric current when:**
    - **The distance between the coil and magnet is varied**
    - **The strength of the magnet is varied**
    - **The relative motion between the coil and the magnet is varied**

1. [2003 HSC] Describe a first-hand investigation to demonstrate the effect on a generated electric current when the strength of the magnet is varied. In your description, include a labelled sketch of the experimental set-up, how you varied the magnetic field strength, and how other variables were controlled. **[4 marks]**

………

………

………

………

………

………

………

End of homework