TOPIC 11.1: Electromagnetic Induction

Physical Laws of electromagnetic induction

11.1 Electromagnetic Induction

- Describe the production of an induced emf by a changing magnetic flux and within a uniform magnetic field
- Solving problems involving magnetic flux, magnetic flux linkage and Faraday's Law
- Explaining Lenz's Law through the conservation of energy

11.1 Electromagnetic Induction

- Quantitative treatments will be expected for straight conductors moving at right angles to magnetic fields and rectangular coils moving in an out of fields and rotating in fields

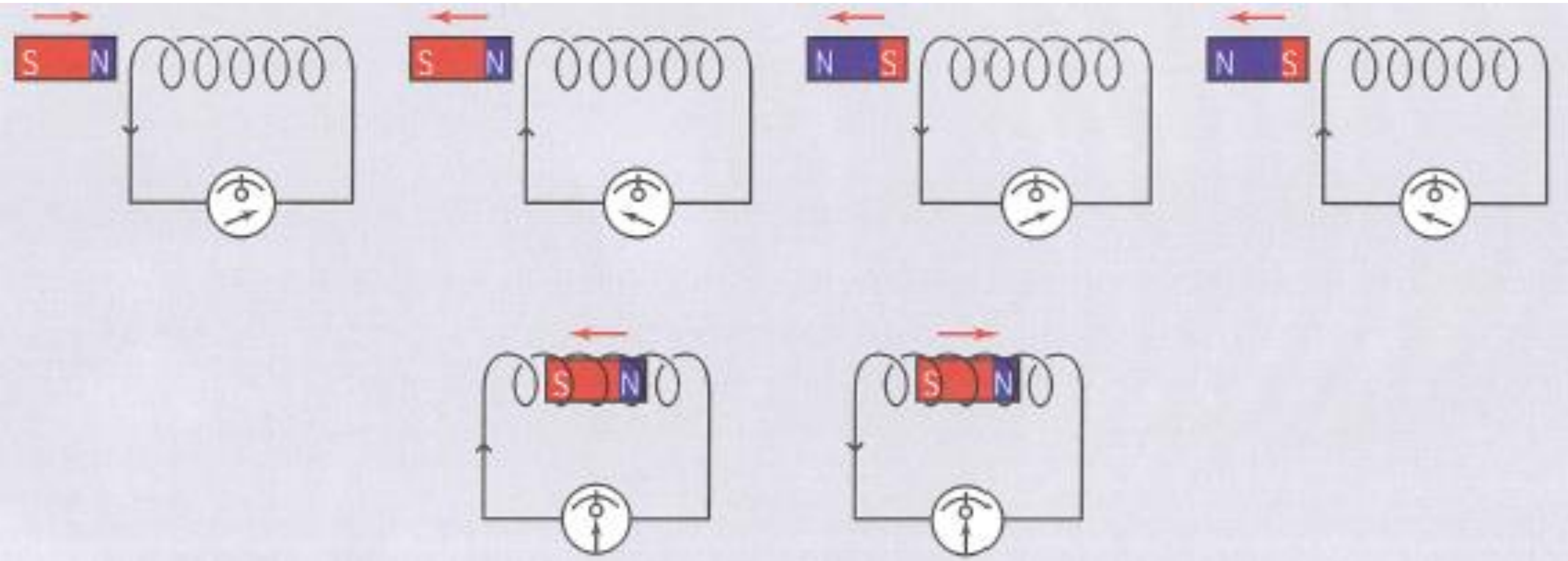
- Qualitative treatments only will be expected for fixed coils in a changing magnetic field and a.c. generators

11.1 Electromagnetic Induction

- Data booklet reference

Sub-topic 11.1 – Electromagnetic induction
$\Phi = BA\cos\theta$
$\varepsilon = -N\frac{\Delta\Phi}{\Delta t}$
$\varepsilon = Bvl$
$\varepsilon = BvlN$

Production of an induced e.m.f. within a uniform magnetic field



1. Induced current only appears when there is relative motion between the coil and the magnet
2. Moving the coil or magnet at greater speeds increase the current
3. Direction of current reverses whenever either the pole of magnet facing the coil reverses, or the direction of movement of the magnet relative to the coil reverses.

Production of an induced e.m.f. within a uniform magnetic field

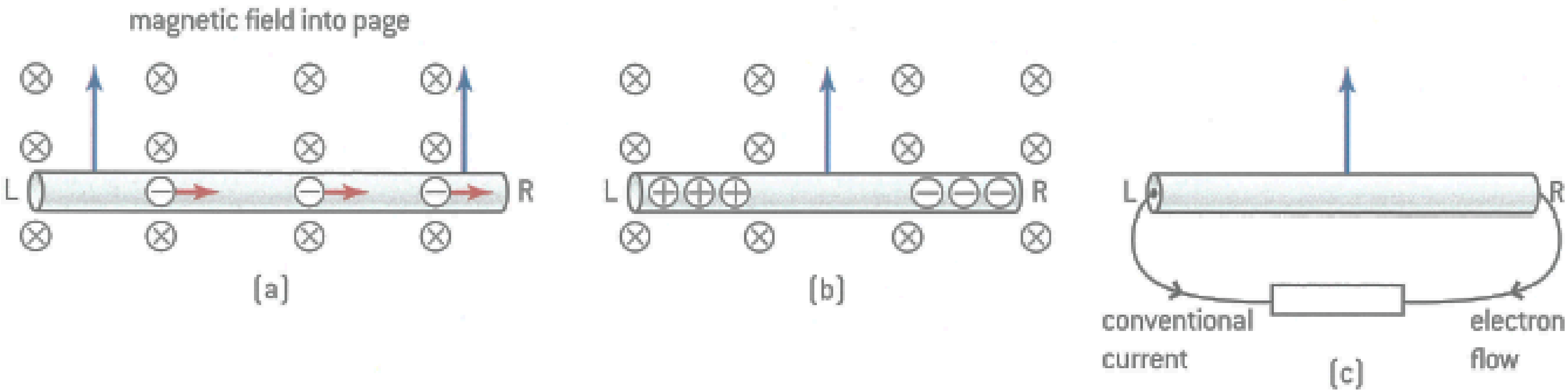
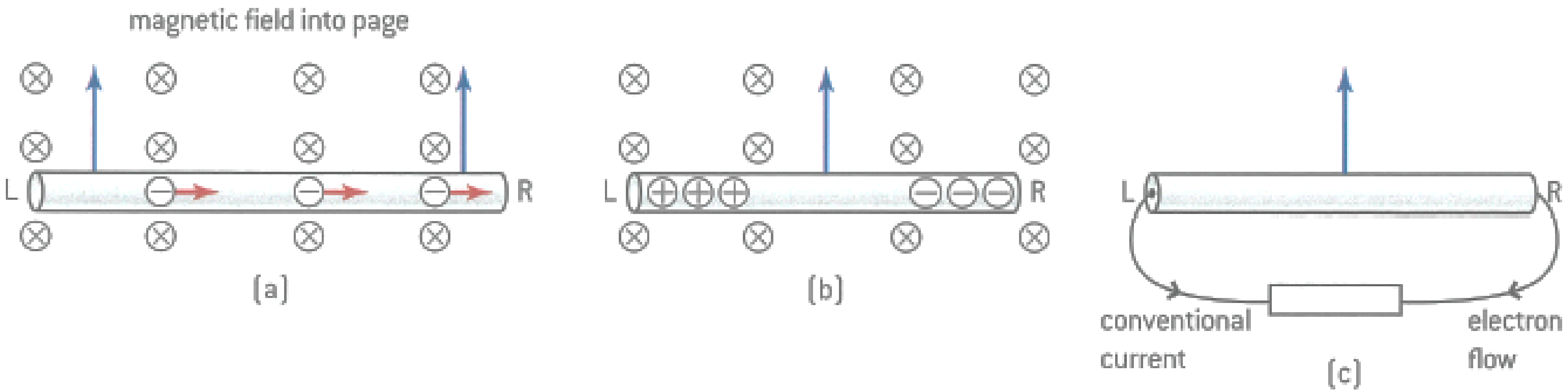


Figure 2 Electrons forced to move in a magnetic field experience a force.

Diagrams show what happens to the electrons in a metal rod that is moving through a <u>uniform</u> , unchanging magnetic field.

1. Free electrons in the wire are moving upwards with the rod in an external magnetic field that acts into the page. A force acts on each electron to the right. (Fleming's left hand rule) *(B-into page; v – upwards /blue arrow; hence F is right/red arrow)*
2. Electrons accumulate at the right end (R) of the rod making it negatively charged, and a lack of electrons at the left end (L) makes it positive.

Production of an induced e.m.f. within a uniform magnetic field

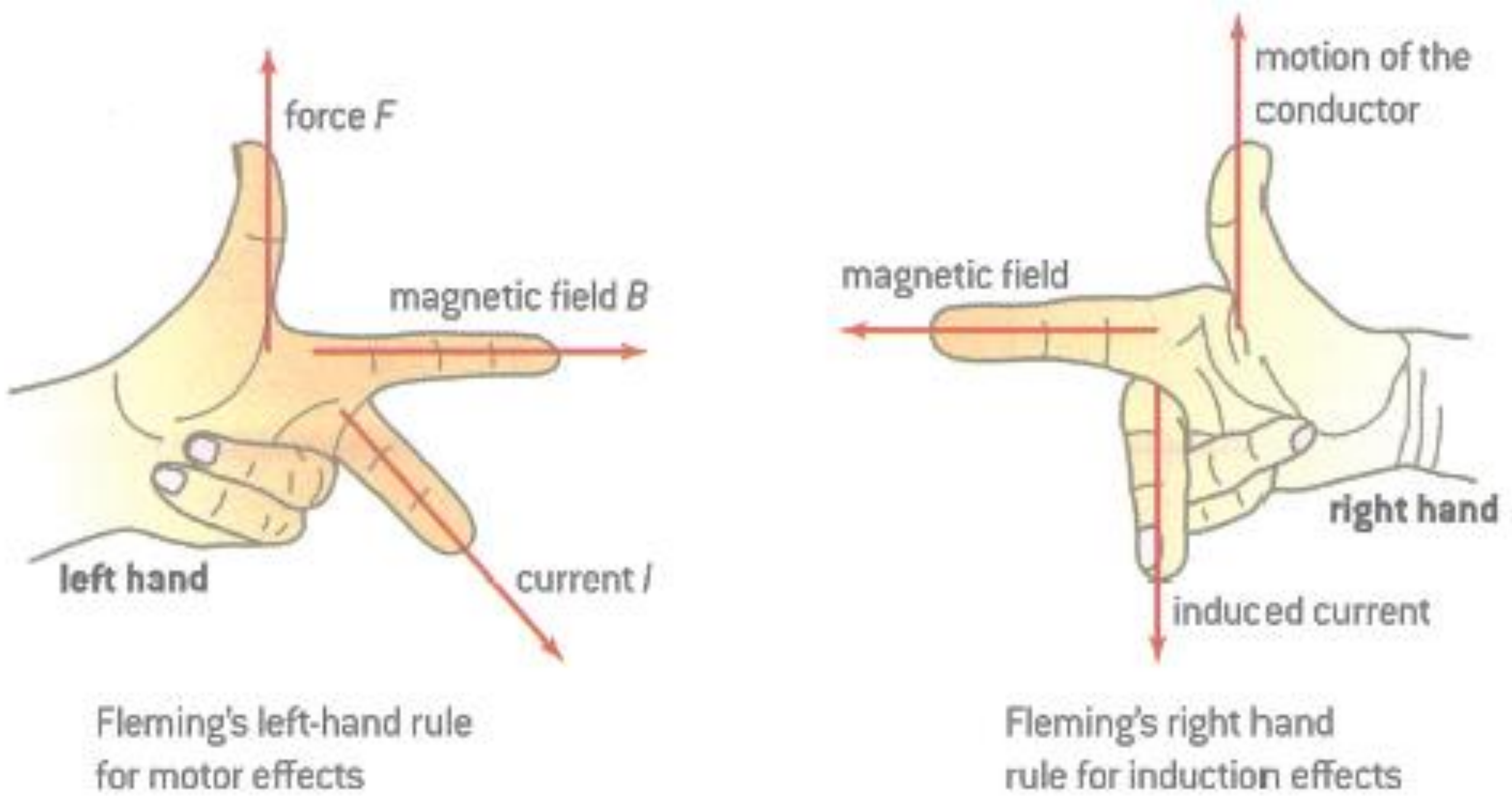


▲ Figure 2 Electrons forced to move in a magnetic field experience a force.

3. Hence a potential difference exists between L and R, L being at the higher electric potential. When there is no external connection between L and R, no current will flow. If the circuit is closed between L and R, a current will flow. A current has been generated, or induced.

4. When the ends of the rod are connected to an external resistor, the rod behaves as a source of electrical energy which drives the electrons around the resistor. Since the rod provides the energy to the electrons, it is said to have an induced emf within its ends. (just like sources of electrical energy as batteries have emf within them)

Lenz's law



▲ Figure 3 Fleming's rules.

The direction of the flow of electrons / conventional current / within the rod (previous example) can be deduced in two ways. Either use Fleming's left-hand rule to work out the force direction from first principles; or use Fleming's right-hand rule on the given B-direction and F-direction on the rod to determine the direction of conventional current I. Electron current is then opposite in direction to the conventional current .

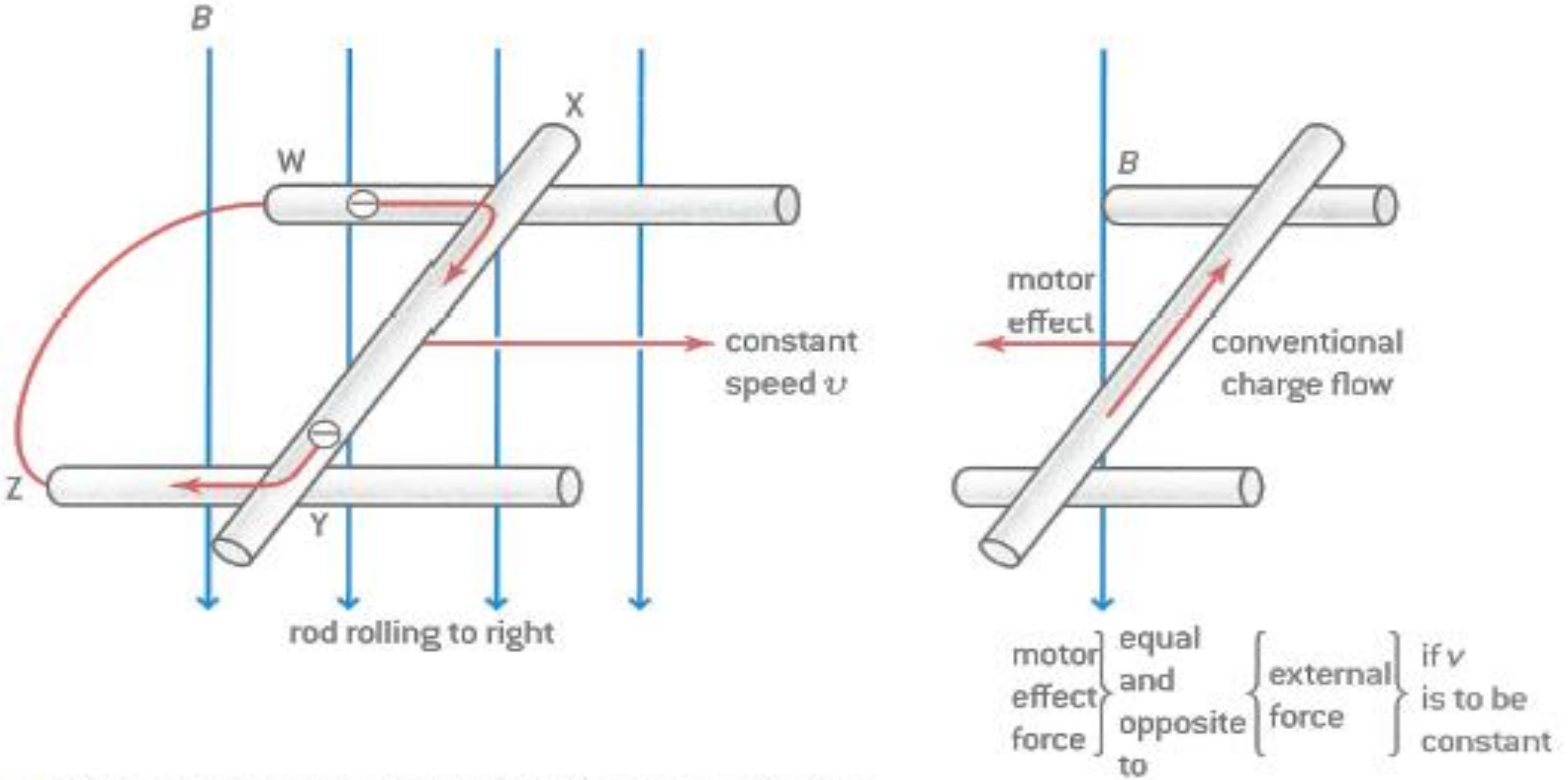
Lenz's law

The direction of the induced emf is such as to oppose the change in magnetic flux that causes it ('it' refers to the induced emf).

In fact, Lenz's law is little more than the conservation of energy. Suppose that, rather than opposing the induced effect, the change were to enhance it. This would imply an attraction instead of a repulsion between magnet and coil; the magnet would be pulled into the coil, accelerating as it goes. This would increase the speed and lead to an even greater acceleration. The magnet would move faster and faster into the coil, gaining kinetic energy from nowhere. Conservation of energy tells us this cannot happen.

Another way to look at the consequences of Lenz's law is to realize that you cannot do work without having some opposition. The induced current in the coil is such that the induced field produced by this current opposes the motion of the magnet you are holding. If the circuit is open, there is no current, no opposition, and no electric energy produced. If you move the magnet very fast you will clearly feel the opposite force acting on you!

Lenz's law applied to a conducting rod



▲ Figure 4 Conducting rod rolling in a magnetic field.

The work done by the external force to keep the conductor moving at a constant speed appears as electrical energy in the conductor.

use Fleming's left-hand rule you will see that the induced current leads to a motor effect (a force) acting to the left in figure 4,

Magnetic flux and magnetic flux density

In the earlier example, an applied force on a rod moves it and cuts the magnetic field strength at right angle.

Since the rod moves at a constant speed v , the applied force must overcome an opposing force produced by the induced current on the rod. This opposing force is actually the magnetic force given by BIl, where I is the induced current, B the magnetic field strength and l the length of the rod.

Hence the energy needed to supply in a time Δt to move the rod is *force x distance* $= Bil\,\Delta x$; *where* Δx is the distance moved in Δt.

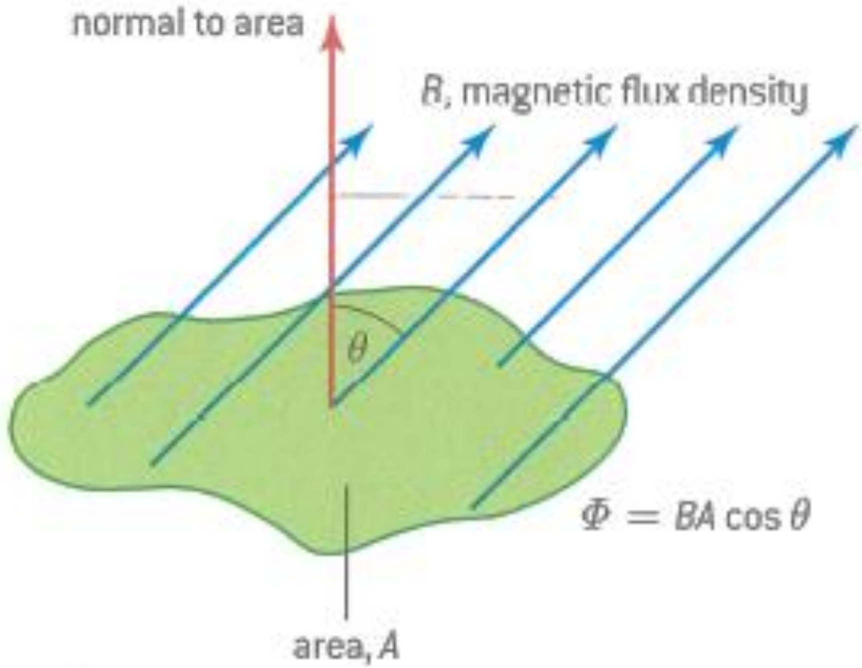
Therefore induced emf ε = energy supplied ÷ charge moved

$= BIl\Delta x / I\Delta t = Blv$; since $v = \Delta x/\Delta t$.

$$\varepsilon = Blv$$

Magnetic flux and magnetic flux density

The magnetic field strength *B* is numerically equal to the *magnetic flux density*.



▲ Figure 5 Flux and flux density.

The *magnetic flux* ϕ is defined as the magnetic flux density passing through a *plane area normal* to the direction of the flux density.

Mathematically, the flux density *B* at right angle (i.e. normal) to the plane area *A* is $B\cos\theta$; where θ is the angle between the directions of B and the normal line to the plane area A.

Hence $\phi = B\,A\cos\theta$

Magnetic flux and magnetic flux density

1. When the direction of flux density B is parallel to the normal line to the plane area A; $\theta = 0^o$. The magnetic flux is maximum; $\phi = BA \cos 0^o = BA$.

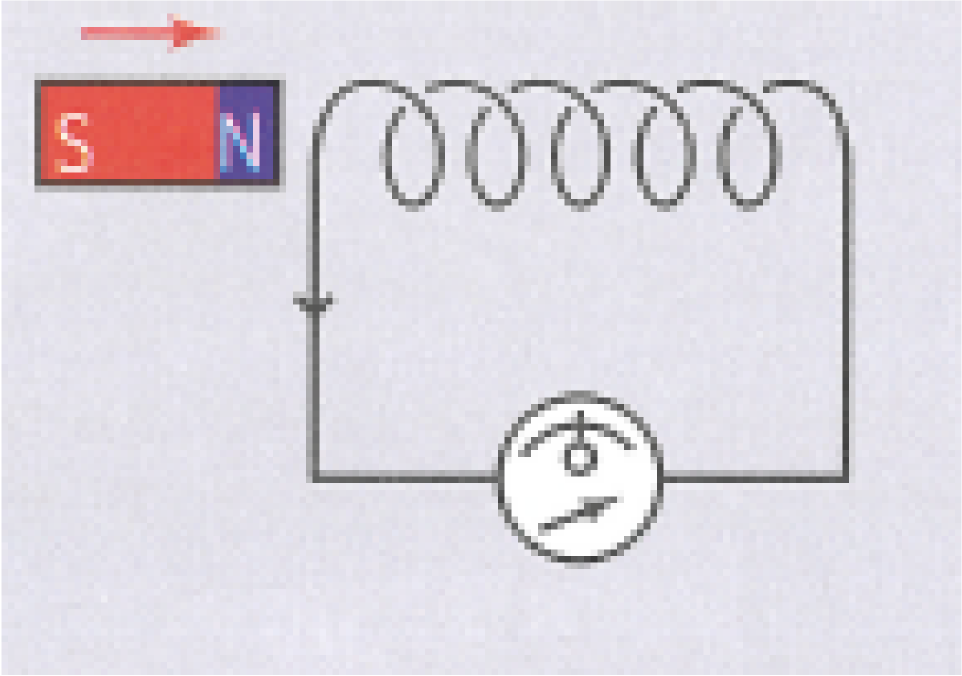
2. When the direction of flux density B is at right angle to the normal line; $\theta = 90^o$. The magnetic flux is minimum at $\phi = 0$.

3. *B* is measured in units of the Tesla (T); and area in units of m^2; hence the units of magnetic flux ϕ is in units of Tm^2 or Weber (Wb). One Wb is equivalent to 1 Tm^2.

4. Since $B = \phi / A$. ($1\ T = 1\ Wb\ m^{-2}$). This explains why *B* is known as the flux density (flux per unit area).

Magnetic flux and magnetic flux linkage

In the case of a solenoid with N number of turns, each turn has a plane area A; then the sum of flux through all the turns is the *magnetic flux linkage* $\Phi = N\phi$. The units of Φ is still Wb.



Laws of electromagnetic induction

Faraday's Law

The magnitude of the *induced e.m.f*. is directly proportional to the *rate of change of magnetic flux linkage*

Lenz's Law

The direction of the induced e.m.f. is such that if an induced current were to flow, it would oppose the change in magnetic flux which causes it.

Mathematically, the law is expressed as:

$$\varepsilon = -\frac{N\Delta\phi}{\Delta t}$$

The negative sign expresses Lenz's law.

Laws of electromagnetic induction

From the expression in the previous slide, an induced e.m.f. can be produced in a coil in several ways.

- A wire or coil cuts an unchanging magnetic field (e.g. a moving rod)

- A changing magnetic field changes its strength as it passes a stationary coil (e.g. a magnet is moved through a solenoid)

- A coil can change its size or orientation in an unchanging magnetic field (e.g. a.c. generator)

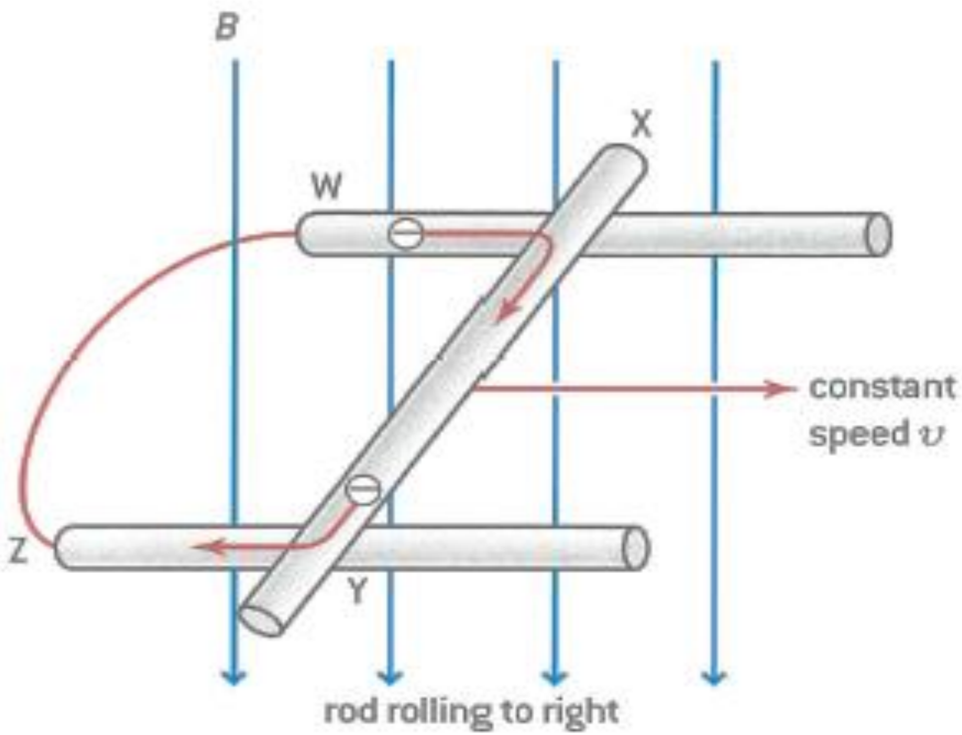
- Combinations of these changes can occur

Faraday’s Law of Induction; Lenz’s Law

Problem Solving: Lenz’s Law

1. **Determine whether the magnetic flux is increasing, decreasing, or unchanged.**
2. **The magnetic field due to the induced current points in the opposite direction to the original field if the flux is increasing; in the same direction if it is decreasing; and is zero if the flux is not changing.**
3. **Use the right-hand rule to determine the direction of the current.**
4. **Remember that the external field and the field due to the induced current are different.**

Laws of electromagnetic induction



▲ Figure 4 Conducting rod rolling in a magnetic field.

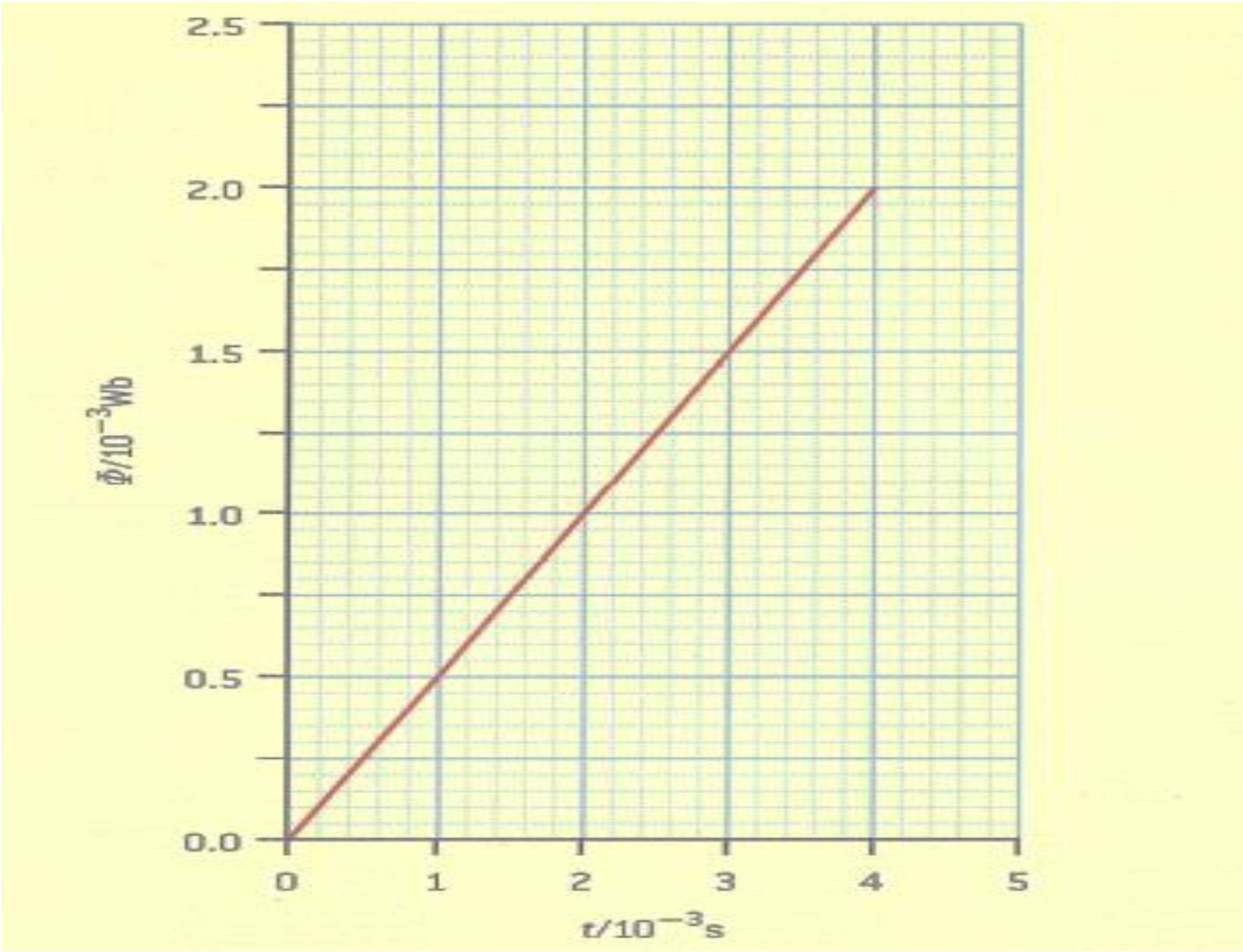
We can use Faraday's law to derive the expression of the induced emf in a moving rod; $\varepsilon = Blv$

$\varepsilon = \frac{B\Delta A}{\Delta t} = \frac{Bl\Delta x}{\Delta t}$; where l is the length of the rod XY, Δx is the horizontal distance the rod travelled along the two rails in a short time of Δt.

Since $v = \frac{\Delta x}{\Delta t}$; as the rod moves at a constant speed, we get $\boldsymbol{\varepsilon = Blv}$

Worked Examples

1. The graph shows the variation of magnetic flux with time through a coil of 500 turns. Calculate the magnitude of the emf induced in the coil. (250V)



2. A flat circular coil of diameter 30 mm has 500 turns and is situated so that the plane of the coil is at right angle to a uniform magnetic field of flux density 20 mT. The flux density is reduced to zero and then increased to 20 mT in the opposite direction at a constant rate. The time taken for the whole operation is 60 ms. What is the average value of the e.m.f. induced in the coil? (0.24V)

Question 3

A small cylindrical magnet and an aluminum cylinder (which is non-magnetic) of similar shape and mass are dropped from rest down a vertical copper tube of length 1.5 m.

a) Show that the aluminum cylinder will take about 0.5 s to reach the bottom of the tube.

b) The magnet takes 5 s to reach the bottom of the tube. Explain why the objects take different times to reach the bottom.