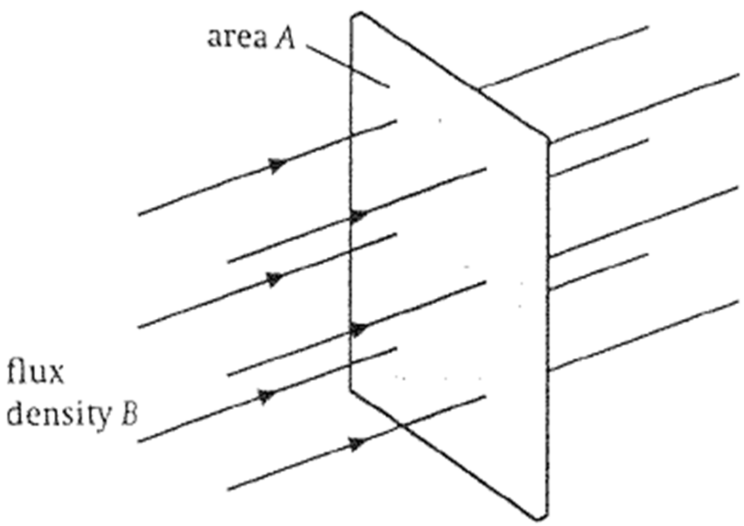
Electromagnetic Induction

Content

23.1 Laws of electromagnetic induction

Magnetic flux



$\Phi = BA$

$B = \Phi / A$

The unit of magnetic flux is Weber, Wb.
It is a scalar quantity.

1 T = 1Wbm^{-2}

- ***Magnetic flux density, B*** is defined from the equation F = BIL.
- Now we go on to define ***magnetic flux*** as a quantity.
- We can think of magnetic flux density as a measure of how closely spaced the lines of magnetic flux are, in other words, how concentrated they are as they pass through a particular area. (amount of flux per metre square)
- Therefore, we can say that the total amount of flux (Φ) is equal to the flux density (B) multiplied by area (A) through which it is flowing.
- Magnetic flux (Φ) is the product of flux density (B) and the area (A), when the flux is at right angles to the area.
- Otherwise we would have to consider the component of B perpendicular to A.

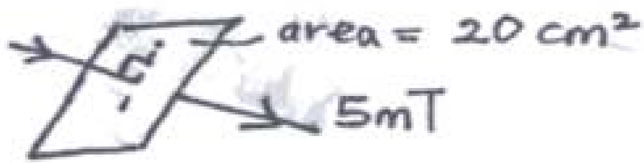
Magnetic Flux Linkage

- If a coil has more than 1 turn, then the flux through the whole coil is the sum of the fluxes through each individual turns.
- We called this the **magnetic flux linkage** through the whole coil.
- The flux through 1 turn is given by $\Phi = BA$
- Therefore, if the coil has N turns, the total flux linkage is given by:

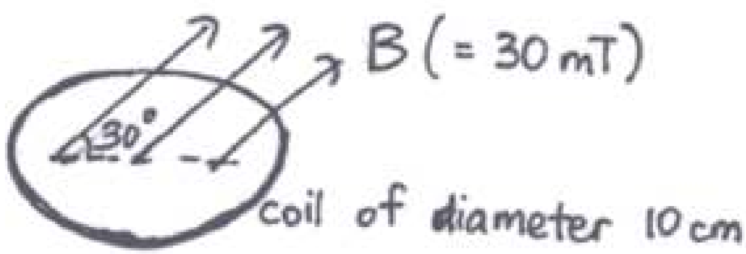
$$\boxed{\textbf{Flux Linkage} = N\Phi = NBA}$$

Example 1

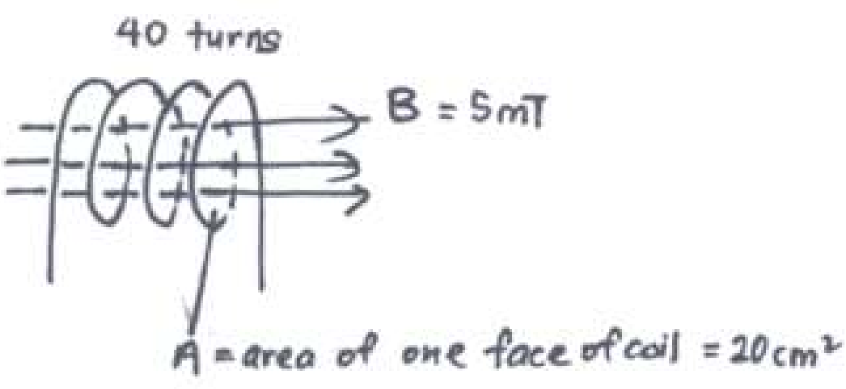
- Find the flux through the frame



- Find the flux through the coil



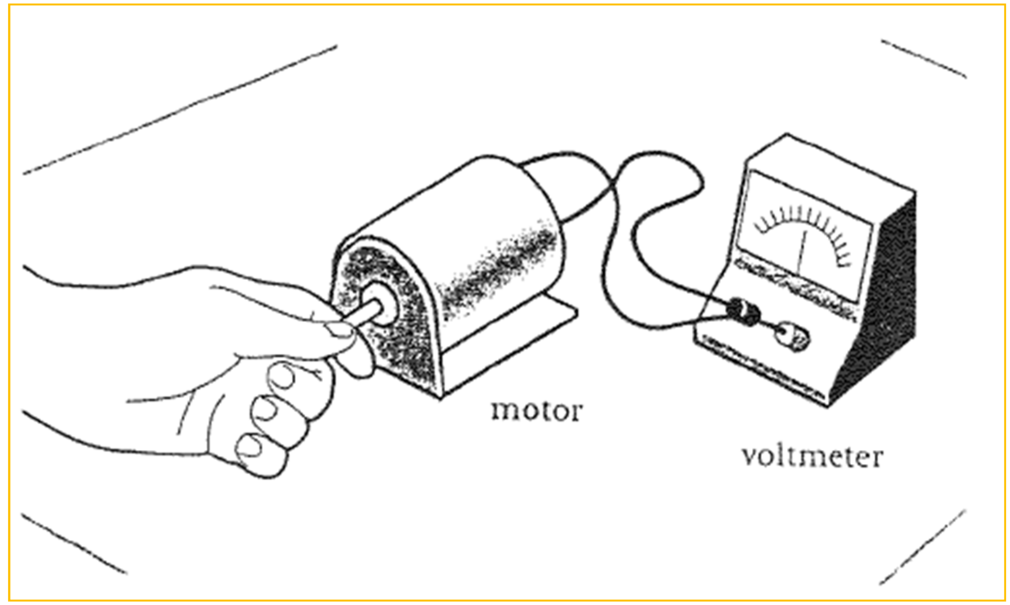
- Find the magnetic flux linkage through the solenoid



Examples of Electromagnetic Induction

Experiment 1:

- Connect a small electric motor to a voltmeter.
- Spin the shaft of the motor and meter will show a deflection.
- Usually we connect a motor to the voltage provided by a power supply and it turns.
- In this experiment, we turn the motor, it generates a voltage.
- When a motor is working in reverse or in this way, we call it a generator.

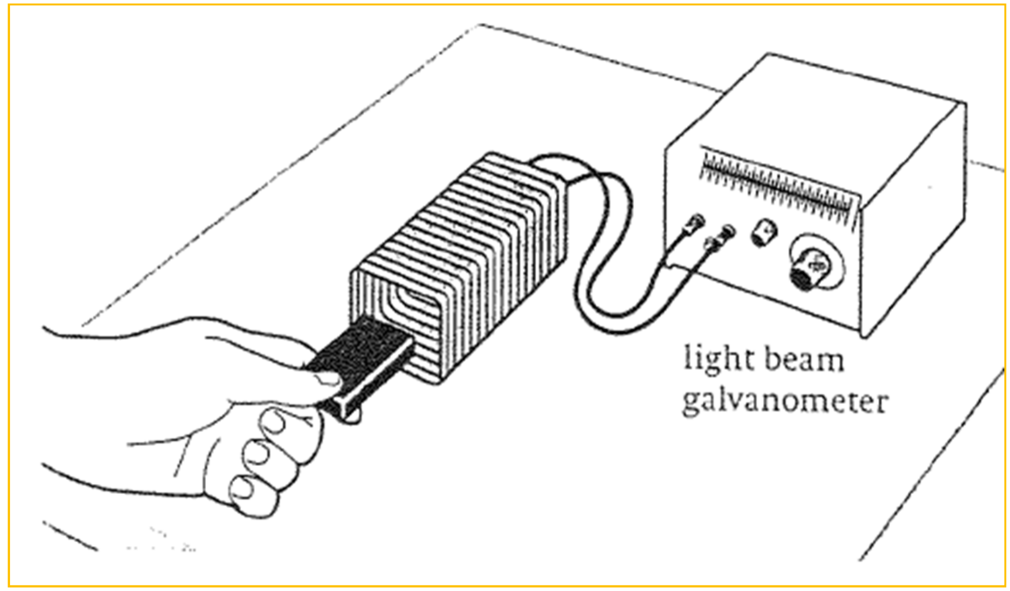


A motor work in reverse is called a generator

Examples of Electromagnetic Induction

Experiment 2:

- Connect a solenoid to a galvanometer.
- Move a bar magnet in towards the coil.
- The meter will show a deflection only if the bar magnet is moving in the solenoid.

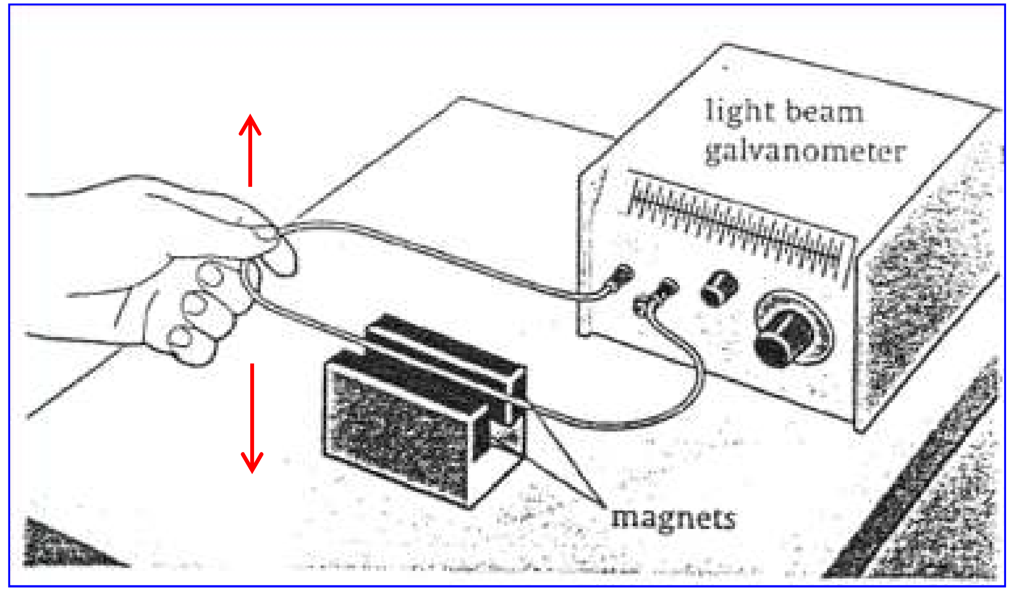


A moving magnet near a coil generates a small current

Examples of Electromagnetic Induction

Experiment 3:

- Connect a long wire to the galvanometer.
- Move the middle section up and down between the poles of a horseshoe magnet.
- The meter will show deflection when the wire is moved between the magnet.



Investigating the current induced when a wire moves through a magnetic field

Explaining Electromagnetic Induction

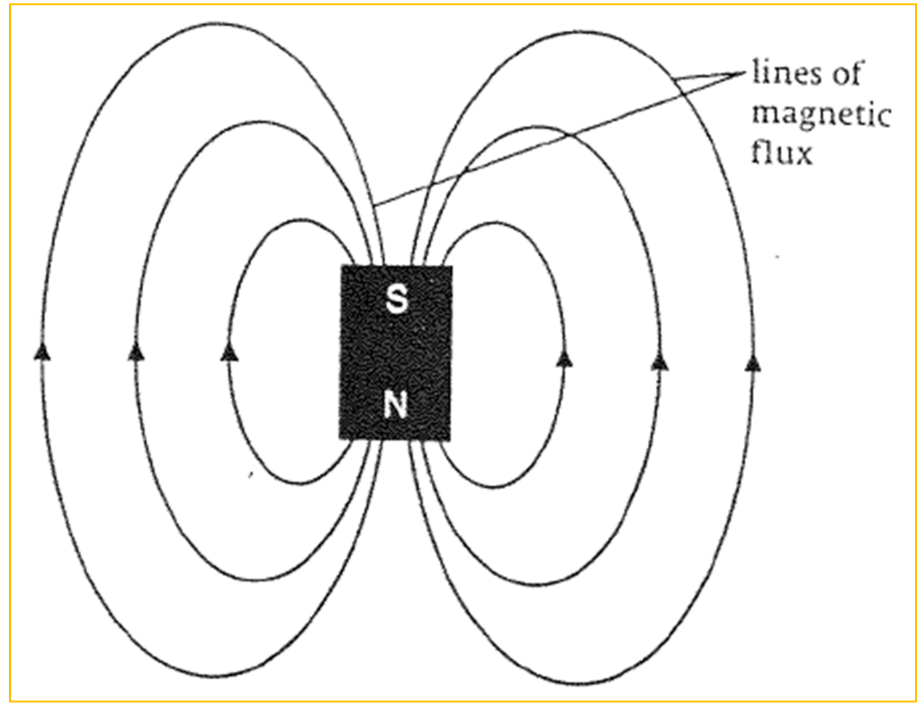
- We have seen that relative movement of a conductor and a magnetic field induces a current in the conductor when it is part of a complete circuit.

- Now we need to think about how to explain this observations, using what we know about magnetic fields.

- We start by thinking about a simple magnet bar. It creates a magnetic field in the space around it

- We represent this field by lines of force called magnetic flux.

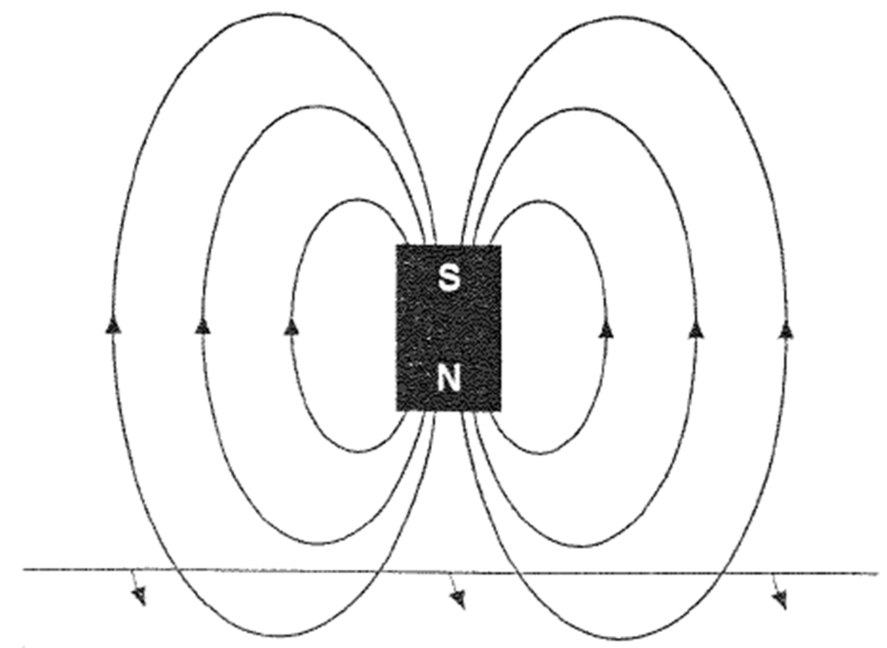
- “Flux” means something that flows, and we picture magnetic flux flowing out of the north pole of the magnet round to the south pole.



Magnetic flux around a permanent magnetic bar

Explaining Electromagnetic Induction

- Now think about what happens when a wire is moved into the magnetic field.
- As it moves, it cuts across the magnetic flux. Remove the wire from the field, and again it must cut across the flux, but in the opposite direction.
- We think about this cutting of flux by a conductor as the effect that gives rise to an induced current flowing in the conductor.
- It doesn't matter whether the conductor is moved through the field, or the magnet is moved past the conductor, the result is the same – an induced current flows.



Moving wire cuts across magnetic flux

Inducing a current by moving a wire through a magnetic field

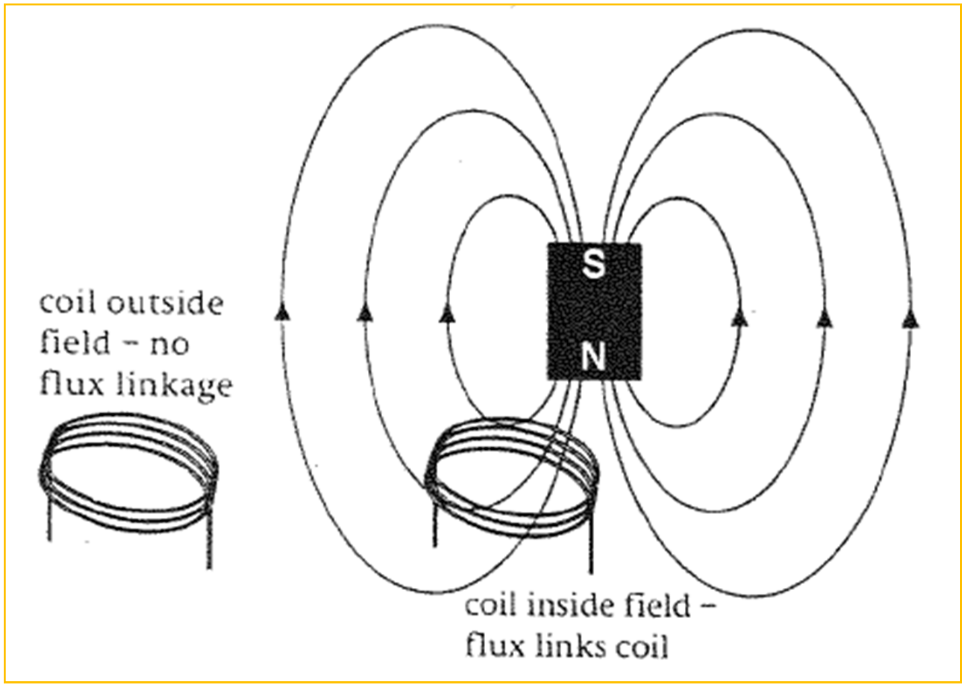
Explaining Electromagnetic Induction

- The effect is magnified if we use a coil of wire. Each bit of wire cuts across the magnetic flux, and so each contributes to the induced current.

- For a coil of N turns, the effect is N times greater than for a single turn of wire.

- When the coil is outside the field, no flux links it. When it is inside the field, flux links it by flowing through it.

- Moving the coil in and out of the field changes the flux linkage, and this induces a current.



The flux linking a coil changes as it is moved in to and out of a magnetic field

Explaining Electromagnetic Induction

Conclusion:

- In all these experiments, electric current or an emf is induced.
- In each case, there is a magnetic field and conductor.
- When you move the magnet or conductor, there is an induced current. When you stop, the current stops.

For a coil of wire, the MAGNITUDE of the induced emf depends on:

- Magnitude of magnetic flux density. (B)
- Cross sectional area of the coil. (A)
- Number of turns of wire of the coil. (N)

$$\boxed{E = -\frac{d\phi}{dt} = -\frac{N\,d(BA)}{dt}}$$

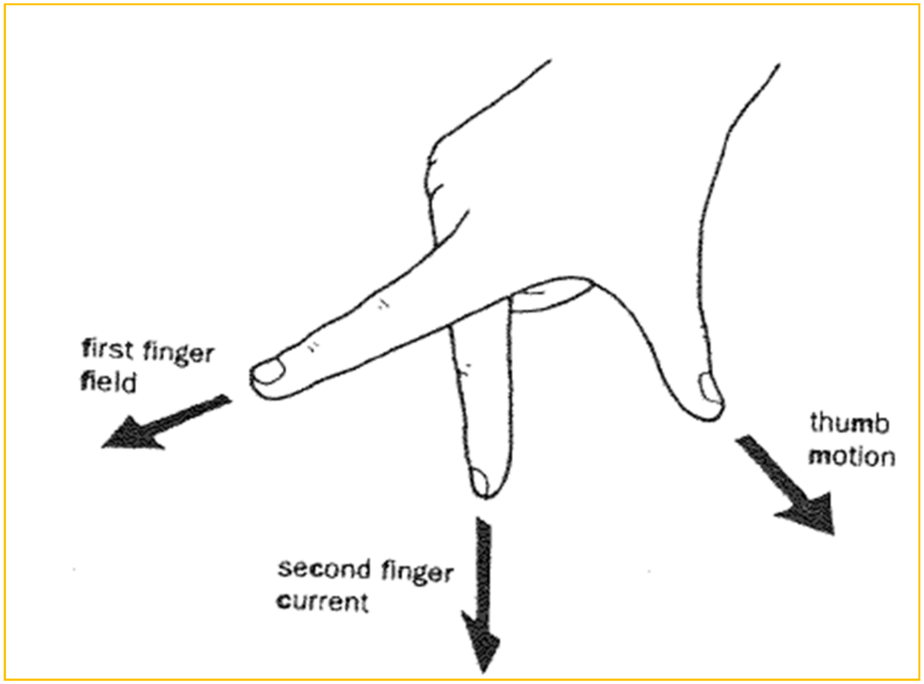
For straight wire, the MAGNITUDE of the induced emf depends on:

- Magnitude of magnetic flux density. (B)
- Length of the wire in the field. (L)
- Speed on movement of the wire. (v)

$$\boxed{E = Bvl}$$

Determining the Direction of Induced Current

- How can we predict the direction of the induced current?
- In the previous Chapter of Electromagnetism, we determine the direction of force by using Fleming Left Hand Rule.
- Electromagnetic induction is like the mirror image of it.
- Instead of a current producing a force on a current carrying conductor in a magnetic field, we provide an external force (motion) on a conductor by moving it through the magnetic field and this induces a current in the conductor.
- For this, we use the mirror image of the left hand rule: **Fleming's Right Hand Rule.**
- Generally, Fleming's Left hand Rule is for the motor effect,
- while Fleming's Right hand Rule is for the generator effect.



Fleming's Right Hand Rule.
The 3 fingers represent the same thing again.

Faraday's Law of Electromagnetic Induction

- Faraday's Law states that **"the magnitude of the induced emf is proportional to the rate of change of flux cutting, or to the rate of change of flux linkage."**

$$\boxed{E = - d(\Phi) / dt}$$

- For a coil having N turns of wire, the emf will be N times greater than for a single turn.

$$\boxed{\begin{array}{l} E = - N\, d(\Phi) / dt \\ E = - N\, d(BA) / dt \end{array}}$$

- The minus sign indicates that ***the induced e.m.f. causes effects to oppose the change producing it.*** This minus sign represents Lenz's Law, which will be dealt with later.

Example 2

- The uniform flux density between the poles of a magnet is 0.080 T. A small coil of area of cross-section 6.5 cm^2 has 250 turns and is placed with its plane normal to the magnetic field. The coil is withdrawn from the field in a time of 0.26 s.

Determine:

(a) the magnetic flux through the coil when it is between the poles of the magnet

(b) the magnetic flux linkage under the same condition as (a)

(c) the change in magnetic flux linkage when the coil is removed from the field

(d) the magnitude of the average e.m.f. induced in the coil whilst it is being withdrawn

Solution

Example 3

- A wire of length 10 cm is moved through a distance 2.0 cm in a direction at right angles to its length in the space between the poles of a magnet, and perpendicular to the magnetic field. The flux density is 1.5 T. If this takes 0.5 s, calculate the average e.m.f. induced across the ends of the wire.

Solution

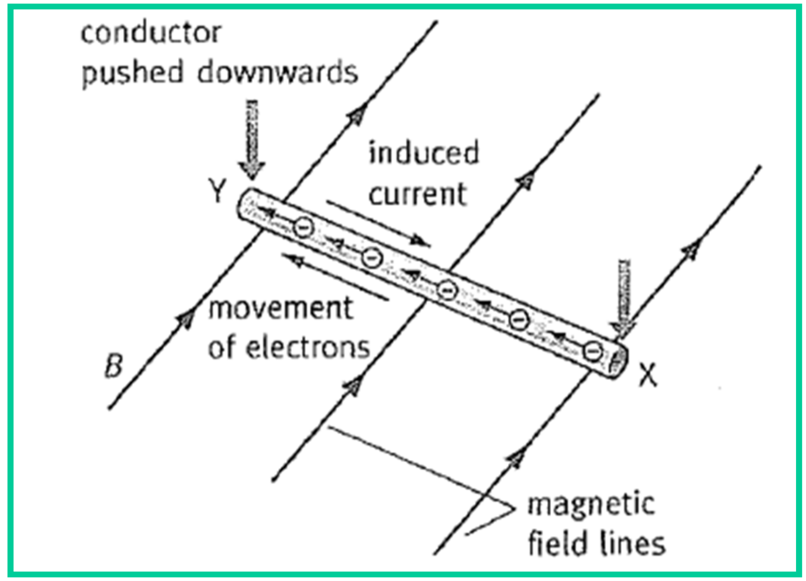
Example 4

- A search coil having 2000 turns and of area 1.2 cm^2 , placed between the poles of a strong magnet. The ends of the coil are connected to a voltmeter. The coil is then pulled out of the magnetic field, and the voltmeter records an average emf of 0.40 V over a time interval of 0.20 s. Calculate the magnetic flux density between the poles of the magnet.
- **Solution**

Lenz's Law

The origin of electromagnetic induction

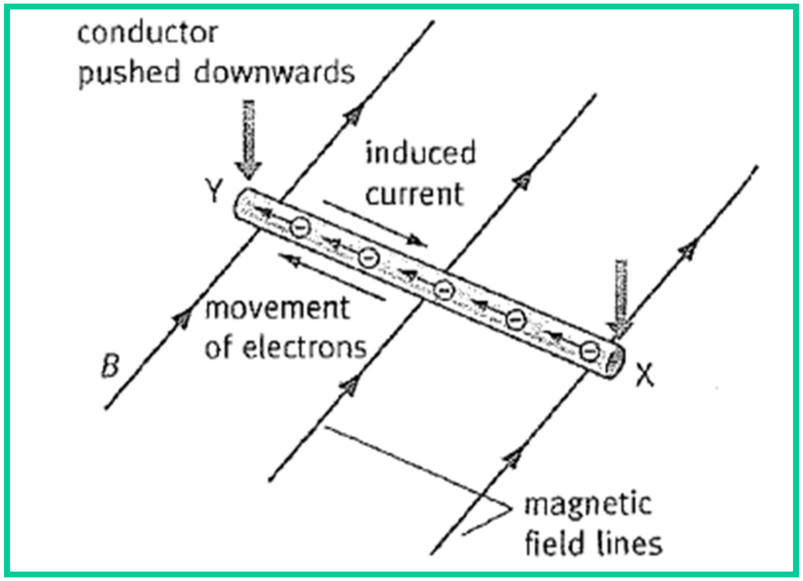
- We use Faraday's Law to calculate the magnitude of an induced emf.
- Now we go on to think about the direction of the emf - in other words, which end of the wire or coil moving in the magnetic field becomes positive and which becomes negative.
- So far we have not given an explanation of electromagnetic induction.
- We have seen, from the experiments at the beginning of this chapter that it does occur, and we know the factors that affect it.
- ***But what is the origin of the induced current?***
- Figure on the right gives an explanation.
- A straight wire XY is being pushed downwards through a horizontal magnetic field of flux density B.
- Now think about the free electrons in the wire. They are also moving downwards, so they are in effect an electric current.
- The conventional current moves upwards.



Lenz's Law

The origin of electromagnetic induction (Cont.)

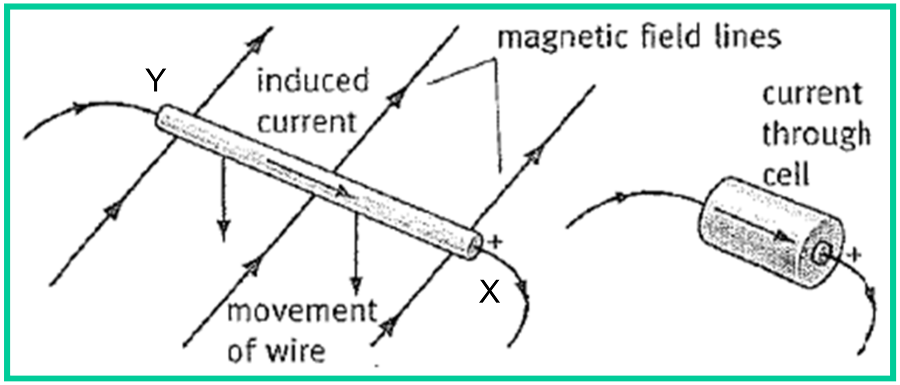
- We now have current flowing across the magnetic field, and the motor effect will therefore come into play.
- Each electron experiences a force of magnitude Bqv. Using Fleming's left hand rule, we can find the direction of the force on the electrons.
- The diagram shows that the electrons will be pushed in the direction from X to Y. So current has been induced to flow in the wire; the direction of the conventional current is from Y to X.
- Now we check that Fleming's right hand rule gives correct direction for the motion, field and current, which indeed it does.
- To summarize, there is an induced current because electrons are pushed by the motor effect.
- Electromagnetic induction is simply a consequence of the motor effect.



Lenz's Law

The origin of electromagnetic induction (Cont.)

- In the previous figure, it is found that electrons accumulate at Y. This end of wire, Y is thus the negative end of the emf and X is positive.
- If the wire was connected to an external circuit, electrons would flow out of Y, around the circuit, and back into X.
- Figure below shows how the moving wire is equivalent to a cell. (or any other source of emf.)

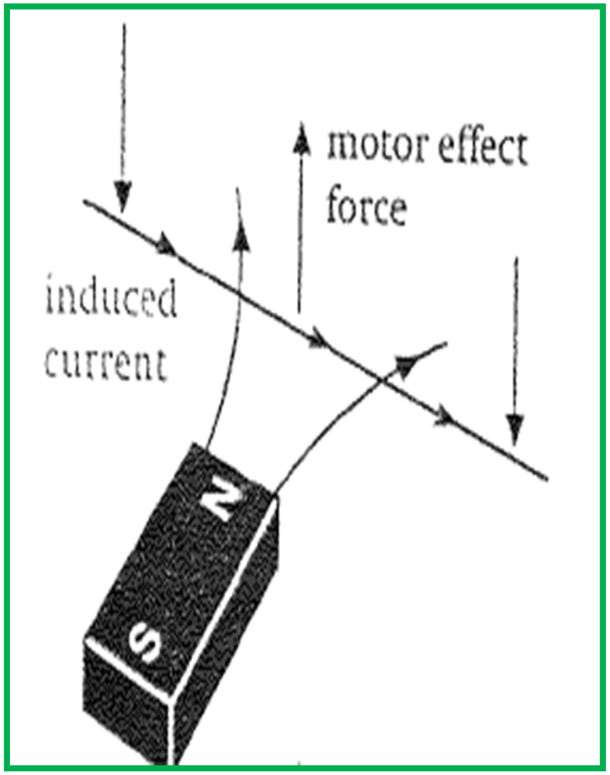


- Now, since there exist an induced current flowing from Y to X across the magnetic field, a force will act on it (the motor effect), and we can use Fleming's left hand rule to deduce its direction.

Lenz's Law

- It shows that this motor effect force that results would be in the direction as to oppose / against the direction that you are trying to move the wire.
- This clearly reveal to us that we need to do work to move the wire, in order to generate electric energy.
- Lenz's Law basically summarizes the principle of conservation of energy.
- The direction of the induced current is such that it always produces a force that opposes to this, we would be getting energy for nothing.
- Lenz's Law states that **" any induced current or induce emf will be established in a direction so as to produce effects which opposes the change that is producing it."**
- The idea of this opposition to change is encapsulated in the minus sign in the equation for Faraday's Law:

$$\boxed{E = -\,N d(\Phi) / dt}$$

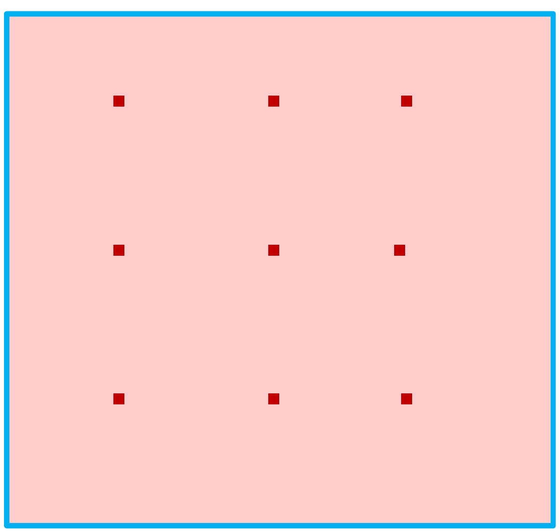


Example 5

- Consider a flat square coil with N = 5 loops. The coil is 20 cm on each side, and has a magnetic field of 0.3 T passing through it. The plane of the coil is perpendicular to the magnetic field. The magnetic field is then increased uniformly from 0.3 T to 0.8 T in 1.0 s.

  a.) What is the induce emf in the coil?

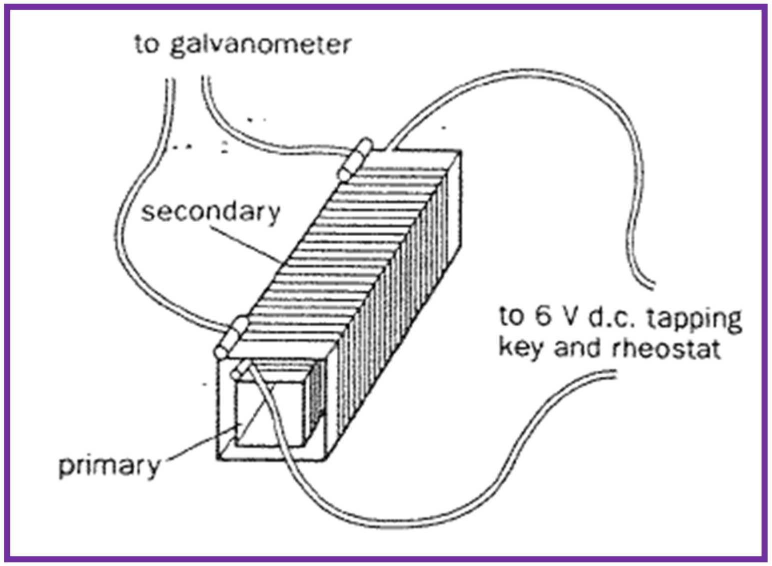
  b.) The induced emf in the coil causes a current to flow. Does the current flow clockwise or counter-clockwise around the coil?



Applications of electromagnetic induction

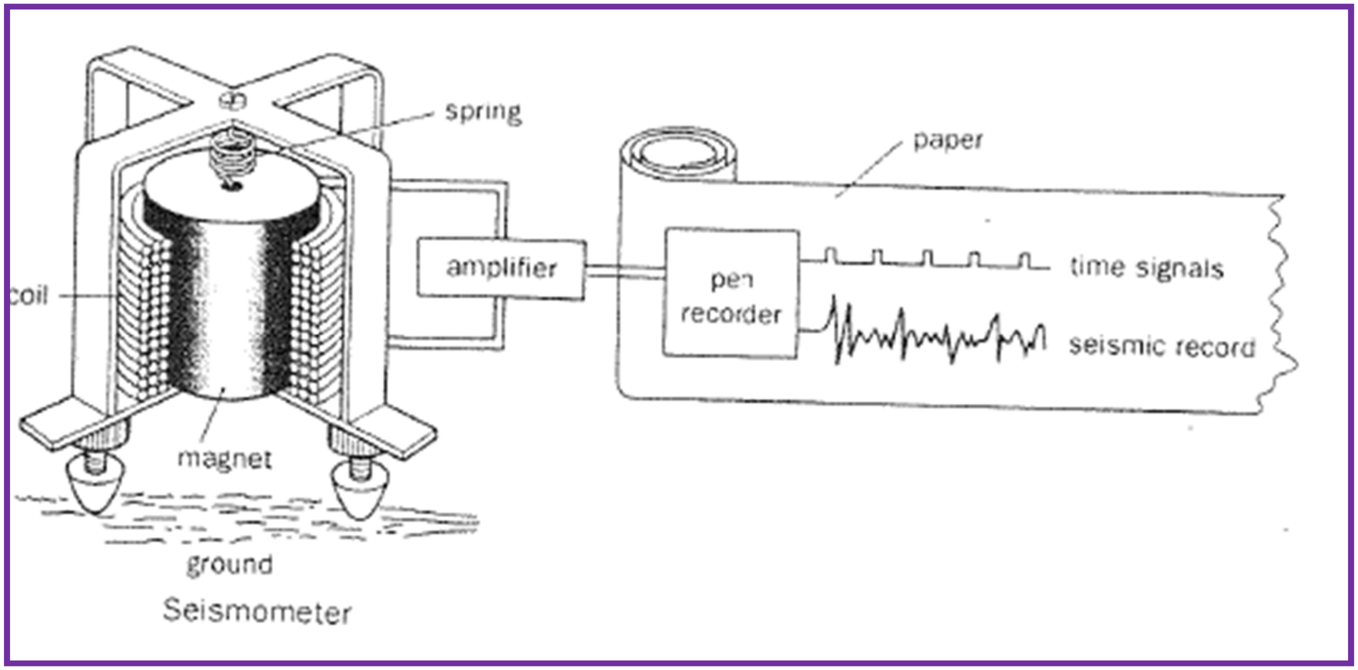
A.) <u>The transformer effect</u>

- In this case, 2 coils are arranged one inside the other.
- One coil is called primary, is in series with a 6V d.c. supply and a rheostat.
- The other, called the secondary, is connected to a galvanometer.
- Switching the current on and off in the primary coil causes current to be induced in the secondary coil.
- Varying the primary current by quickly altering the value of the rheostat will give the same effect.
- Cases of electromagnetic induction in which current changes in one circuit cause induced emfs / current in a neighboring circuit (not connected to the first), are examples of mutual induction or the transformer principle.



Applications of electromagnetic induction

B.) Seismometer



- This earthquake detecting instrument is a good example of an application of electromagnetic induction.
- Any movement or vibration of the rock on which the seismometer rests (buried in a protective case) results in relative motion between the magnet (suspended by a spring from the frame) and the coil (also attached to the frame)
- The emf induced in the coil is directly proportional to the displacement associated with the earthquake and, after amplification, causes a trace on the paper of a pen recorder.

Eddy Current

- Any piece of metal moving in a magnetic field, or exposed to a changing one, has emfs induced in it, as we might expect.
- These can cause currents, called Eddy currents, to flow inside the metal and they may be quite large because of the low resistance of the paths they follow.
- Their magnetic and heating effects may be both helpful and troublesome.
- On its magnetic effect, Eddy current helps the moving coil meters to take up its deflected position quickly, without overshooting and oscillating about its final reading.
- On its heating effect, Eddy current causes heating and dissipation of energy on electric motors, transformers, and generators. To minimize energy loss through Eddy currents, the iron parts consists of sheets called lamination, insulated from each other by a thin paper, varnish or some other insulator.