Cambridge Internatinoal
AS & A Level

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Candidate's Name: ____

23 Electromagnetic induction

Electromagnetic induction provides the basis of an important means of generating electrical power. In this topic, the laws of electromagnetic induction are developed.

	Learning outcomes Candidates should be able to:
23.1 Laws of electromagnetic induction	**a) define magnetic flux and the weber** **b) recall and use $\Phi = BA$** **c) define magnetic flux linkage** **d) infer from appropriate experiments on electromagnetic induction:** **• that a changing magnetic flux can induce an e.m.f. in a circuit** **• that the direction of the induced e.m.f. opposes the change producing it** **• the factors affecting the magnitude of the induced e.m.f.** **e) recall and solve problems using Faraday's law of electromagnetic induction and Lenz's law** **f) explain simple applications of electromagnetic induction**

<u>For a straight wire, when moves inside a magnetic field, the induced current or e.m.f. depends on:</u>

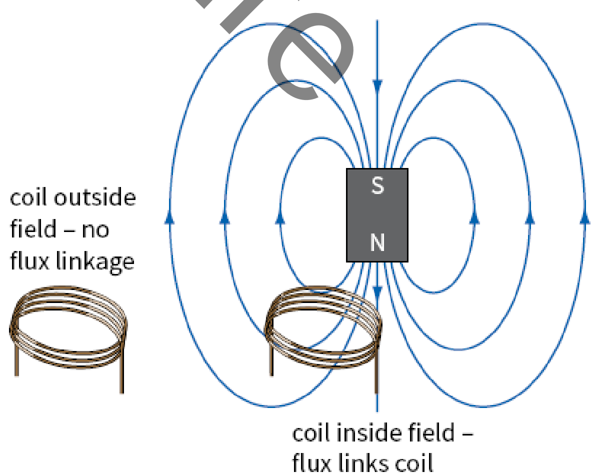
- the magnitude of the magnetic flux density
- the length of the wire in the field
- the speed of movement of the wire.

<u>For a coil of wire, when rotates in a magnetic field, the induced current or e.m.f. depends on:</u>

- the magnitude of the magnetic flux density
- the cross-sectional area of the coil
- the number of turns of wire
- the rate at which the coil turns in the field.

- We think of this cutting of a magnetic field by a conductor as the effect that gives rise to an induced current 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 – there will be an induced current.

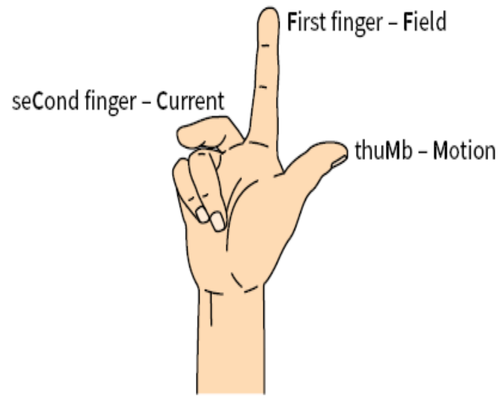
- Figure below shows a coil near a magnet.
- When the coil is outside the field, there are no magnetic field lines linking the coil.
- When it is inside the field, field lines link the coil.
- Moving the coil into or out of the field changes this linkage, and this induces an e.m.f. across the ends of the coil.



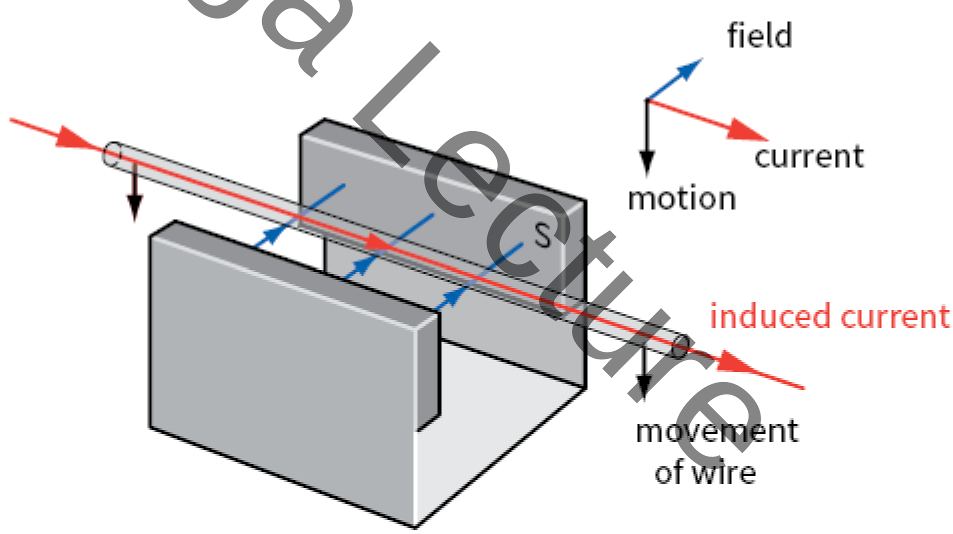
Current direction (Fleming's Right Hand rule)

The three fingers represent the same things again

- thuMb – direction of Motion
- First finger – direction of external magnetic Field
- seCond finger – direction of (conventional) induced Current



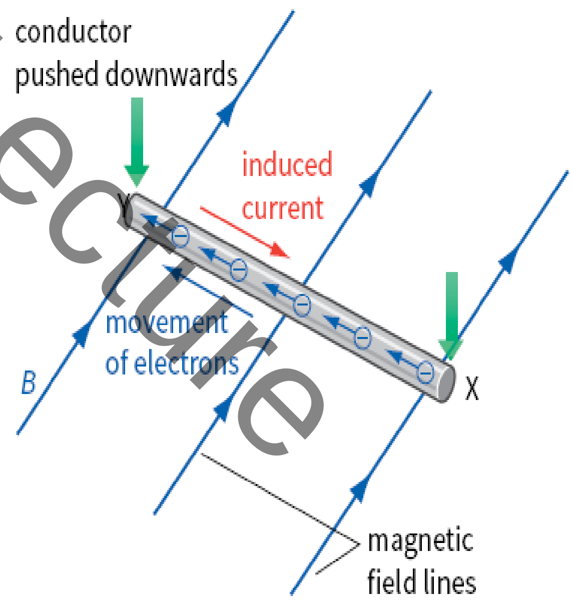
Deducing the direction of the induced current using Fleming's right-hand rule:



What causes these electrons to move?

- Moving the conductor is equivalent to giving an electron within the conductor a velocity in the direction of this motion.
- This electron is in an external magnetic field and hence experiences a magnetic force *Bev* from right to left.

- **Figure below** gives a complete 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 moving downwards, so they are in effect an electric current.
- Of course, because electrons are negatively charged, the conventional current is flowing upwards.
- We now have a current flowing across a magnetic field, and the motor effect will therefore come into play.
- Each electron experiences a force of magnitude *Bev*.
- 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 a current has been induced to flow in the wire; the direction of the conventional current is from Y to X.
- Now we can check that Fleming's right-hand rule gives the correct directions for motion, field and current, which indeed it does.
- So, to summarise, there is an induced current because the electrons are pushed by the motor effect.
- Electromagnetic induction is simply a consequence of the motor effect.



Magnetic flux and magnetic flux linkage:

The magnetic flux Φ through area A is defined as:

$$\boldsymbol{\Phi = B\,A}$$

where B is the component of the magnetic flux density perpendicular to the area.

To find the magnetic flux in general, we need to find the component of the magnetic flux density perpendicular to the area.

$$\textbf{Magnetic flux} = (B \cos \theta) \times A$$

or

$$\textbf{Magnetic flux} = BA \cos \theta$$

(Note that, when $\theta = 90°$, flux = 0; and when $\theta = 0°$, flux = BA.)

For a coil with N turns,

the magnetic flux linkage is defined as the product of the magnetic flux and the number of turns;

that is:

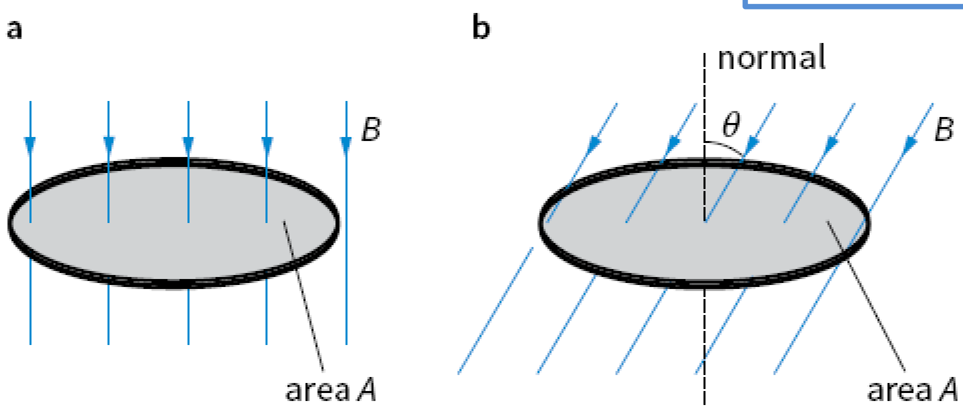
$$\textbf{Magnetic flux linkage} = N\Phi$$

$$\textbf{Magnetic flux linkage} = BAN \cos \theta$$

The unit for magnetic flux or flux linkage is the weber (Wb).

One weber (1 Wb) is the flux that passes through an area of 1 m^2 when the magnetic flux density is 1 T.

$$\mathbf{1\ Wb = 1\ T\ m^2.}$$



Comments:

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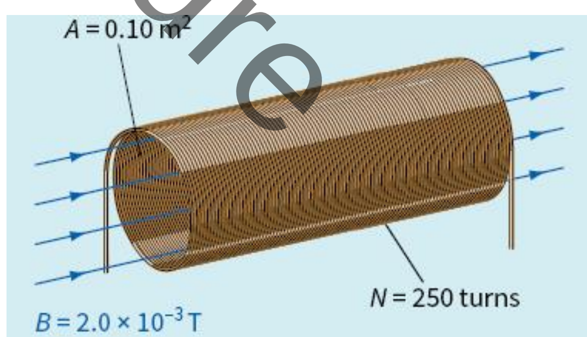
Figure shows a solenoid with a cross-sectional area 0.10 m^2. It is linked by a magnetic field of flux density 2.0×10^{-3} T and has 250 turns. Calculate the magnetic flux and flux linkage for this solenoid. [5.0×10^{-2} Wb]



Laws of Electromagnetic Induction:

1. **Faraday's Law** allows us to calculate the *magnitude* of the induced e.m.f.;
2. The *direction of Induced EMF* is given by **Lenz's law**.

Faraday's law of electromagnetic induction

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

We can write this mathematically as:

$$E \propto \frac{\Delta(N\Phi)}{\Delta t}$$

- $\Delta(N\Phi)$ is the change in the flux linkage in a time Δt.
- Working in SI units, the constant of proportionality is equal to 1.

Therefore:

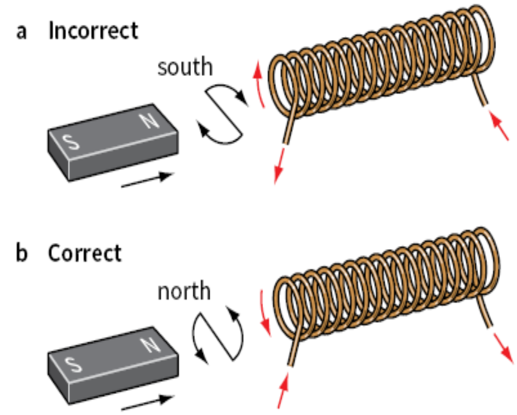
$$E = \frac{\Delta(N\Phi)}{\Delta t}$$

Lenz's law:

Any induced current or induced e.m.f. will be established in a direction so as to produce effects which oppose the change that is producing it.

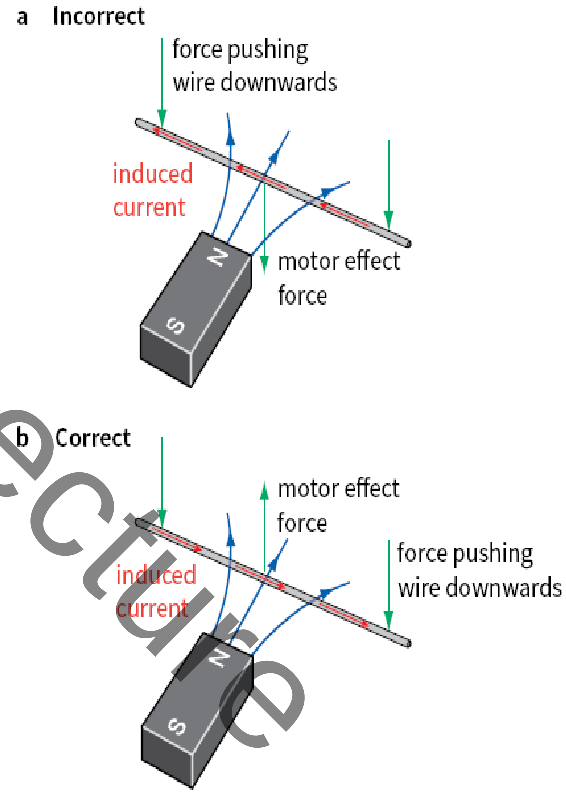
1st Interpretation of Lenz's Law:

Remarks:

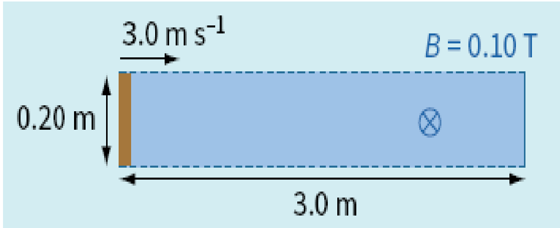


2nd Interpretation of Lenz's Law:

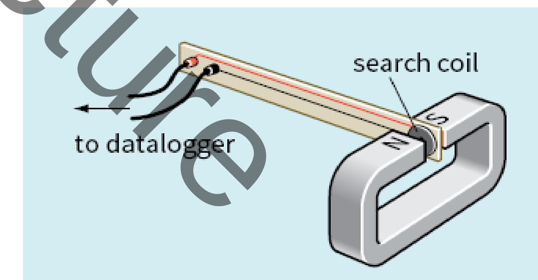
- Figure shows how we can apply the same reasoning to a straight wire being moved in a downward
- direction through a magnetic field.
- There will be an induced current in the wire, but in which direction?
- Since this is a case of a current across a magnetic field, a force will act on it (the motor effect), and we can use Fleming's left -hand rule to deduce its direction.
- First we will consider what happens if the induced current is in the wrong direction.
- This is shown in Figure **a**.
- The left -hand rule shows that the force that results would be downward – in the direction in which we are trying to move the wire.
- The wire would thus be accelerated, the current would increase, and again we would be getting both kinetic and electrical energy for no energy input.
- The induced current must be as shown in Figure **b**.
- The force that acts on it due to the motor effect pushes against you as you try to move the wire through
- the field.
- You have to do work to move the wire, and hence to generate electrical energy.
- Once again, the principle of energy conservation is not violated.



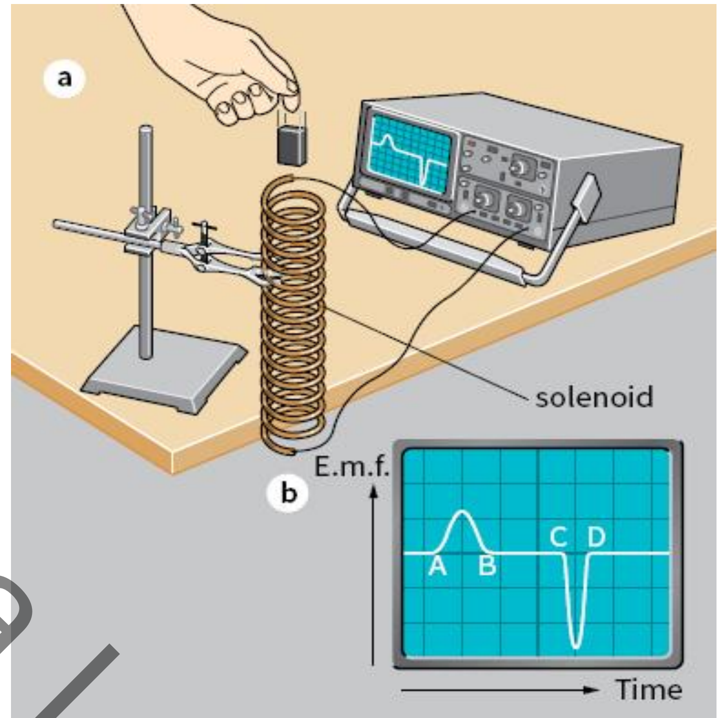
A straight wire of length 0.20 m moves at a steady speed of 3.0 m s−1 at right angles to a magnetic field of flux density 0.10 T. Use Faraday's law to determine the e.m.f. induced across the ends of the wire. [6.0 × 10−2 Wb]



A search coil of wire having 2500 turns and of area 1.2 cm^2 is placed between the poles of a magnet so that the magnetic flux passes perpendicularly through the coil. The flux density of the field is 0.50 T. The coil is pulled rapidly out of the field in a time of 0.10 s. What average e.m.f. is induced across the ends of the coil?



Q: A bar magnet is dropped vertically downwards through a long solenoid, which is connected to an oscilloscope Figure. The oscilloscope trace shows how the e.m.f. induced in the coil varies as the magnet accelerates downwards.



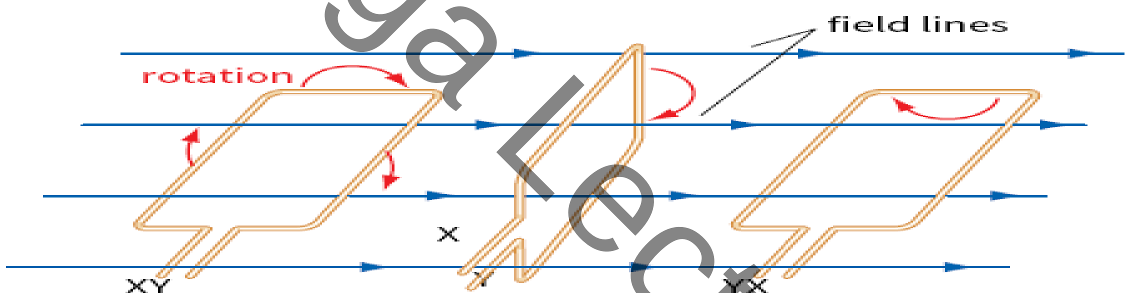
(a) Explain why an e.m.f. is induced in the coil as the magnet enters it (section AB of the trace).

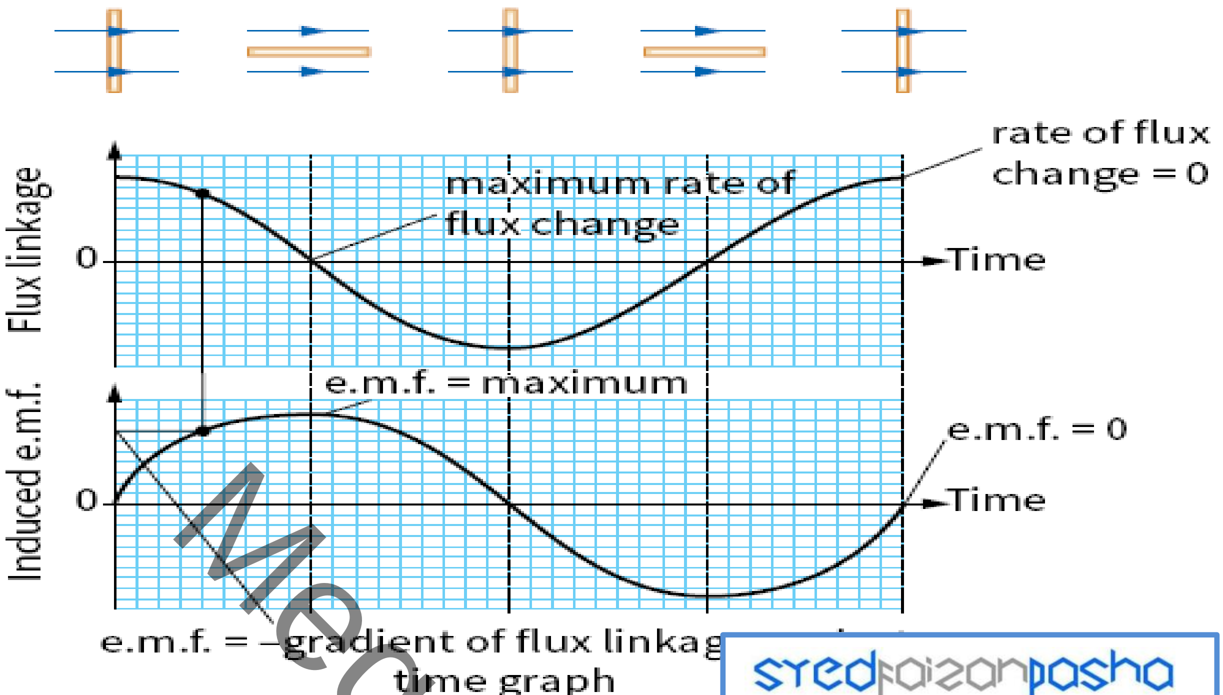
(b) Explain why no e.m.f. is induced while the magnet is entirely inside the coil (section BC).

(c) Explain why section CD shows a negative trace, why the peak e.m.f. is greater over this section, and why CD represents a shorter time interval than AB.

Generators:

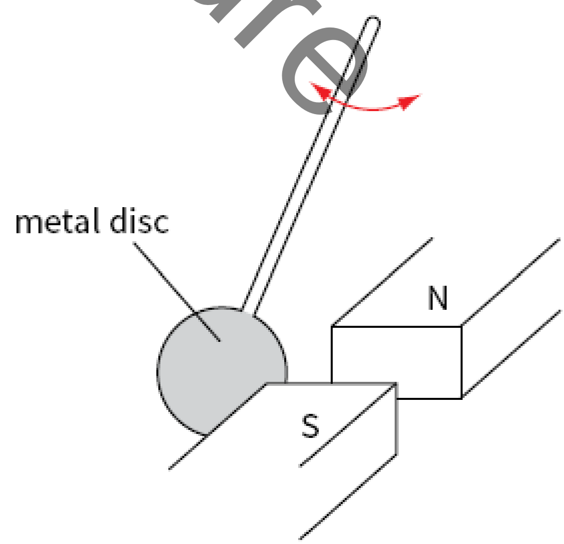
- We can generate electricity by spinning a coil in an magnetic field.
- This is equivalent to using an electric motor backwards.
- Figure shows such a coil in three different orientations as it spins.
- Notice that the rate of change of flux linkage is maximum when the coil is moving through the horizontal position – one side is cutting rapidly downwards through the field lines, the
- other is cutting rapidly upwards.
- In this position, we get a large induced e.m.f.
- As the coil moves through the vertical position, the rate of change of flux is zero – the sides of the coil are moving parallel to the field lines, not cutting them, so that there is hardly any change in the flux linkage.





Eddy currents:

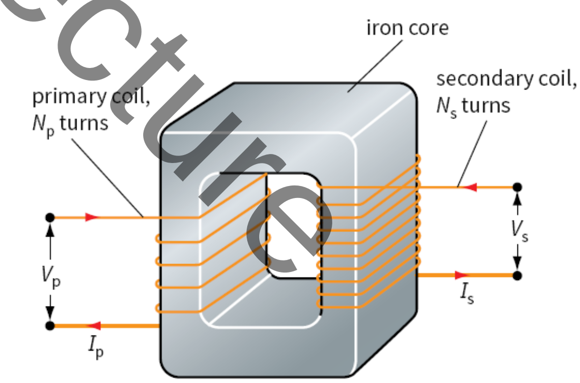
- Consider the demonstration shown in Figure.
- A metal disc on the end of a rod swings freely between two opposite magnetic poles.
- Without the magnets, the disc oscillates from side to side for a long time.
- This is because air resistance is small and it takes a long time for the energy of the disc to be lost.
- When the magnets are present, the oscillation of the disc dies away quickly.
- As the disc enters the magnetic field, one side of the disc is cutting the magnetic field lines and so an induced e.m.f. is created in that side but not in the side that has not yet entered.



- Since the disc is a conductor, the induced e.m.f. creates currents in the disc itself.
- These currents are known as eddy currents.
- They flow in a circular fashion inside the disc.
- Lenz's law predicts that the induced currents that flow in the disc will produce a force that opposes the motion.
- Eddy currents, like other electrical currents, cause heating and the energy of the oscillation dies away quickly. The oscillation is damped by the eddy currents.

Transformers

- Figure shows the construction of a simple transformer.
- The primary coil of *N*p turns of wire is wound around an iron core.
- The secondary coil of *N*s turns is wound on the opposite side of the core. (Many different configurations are possible, with different shapes of core and with the coils wound separately, or one on top of the other.)



- The p.d. *V*p across the primary coil causes an alternating current *I*p to flow.
- This produces an alternating magnetic field in the soft iron core.
- The secondary coil is thus in a changing magnetic field, and an alternating current *I*s is induced in it.
- There is thus an alternating e.m.f. *V*s across the secondary coil.

- There is no electrical connection between the primary coil and the secondary coil.
- Energy is transferred from one to the other via the magnetic field in the core.
- We can write an equation relating the voltages across the coils to the number of turns in each coil:

$$\frac{V_s}{V_p} = \frac{N_s}{N_p}$$

- A transformer with fewer turns on the secondary coil than on the primary coil is described as a **step-down transformer.**
- A transformer with fewer turns on the primary coil than on the secondary coil is described as a **step-up transformer.**