Chapter 28: Electromagnetic Induction

Please remember to photocopy 4 pages onto one sheet by going A3→A4 and using back to back on the photocopier.

Changing flux ⇒ induced emf ⇒ induced current ⇒ magnetic field

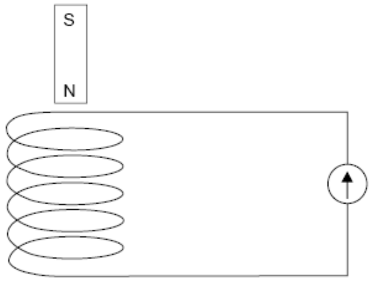
Electromagnetic Induction occurs when an emf is induced in a coil due to a changing magnetic flux.

We have seen from the last two chapters that **Electricity** and **Magnetism** are inter-linked.

The English scientist Michael Faraday investigated this relationship.
He found that if you moved a magnet in or out of a coil of wire, a voltage was generated (more properly called an emf (electromotive force).
He also realised that the quicker you moved the magnet (or the coil), the greater was the emf generated.
This is now known as Faraday's Law of Electromagnetic Induction.

Demonstrating Faraday's Law

1. Move the magnet in and out of the coil slowly and note a slight deflection.
2. Move the magnet quickly and note a greater deflection.



Later on it was found that the direction of the emf could also be predicted.
This is known as Lenz's Law.
The two laws together are known as the laws of Electromagnetic Induction

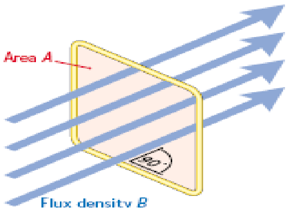
The Laws of Electromagnetic Induction.

1. **Faraday's Law** states that ***the size of the induced emf*** is proportional to the rate of change of magnetic flux.
2. **Lenz's Law** states that the ***direction of the induced emf*** is always such as to oppose the change producing it.*

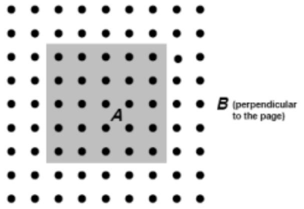
Magnetic Flux

To calculate the size of the induced emf we need one more concept; *magnetic flux*.
The symbol for magnetic flux is Φ (pronounced "sigh").
The unit of magnetic flux is the Weber (Wb)*

To introduce the idea of magnetic flux consider an area, A in a uniform magnetic field.
When the magnetic force lines are perpendicular to this area (see diagram) the total magnetic flux (Φ) through the area is defined as the product of B and A.



$$\boxed{\Phi = BA}$$



The magnetic flux, Φ, can be visualised as the number of magnetic field lines passing through a given area.
The number of magnetic field lines per unit area, i.e. B, is then referred to as the density of the magnetic flux or, more properly, the *magnetic flux density*.

Now we are in a position to *calculate* the induced emf:

Remember Faraday's Law: The size of the induced emf is proportional to the *rate of change of flux.*
In this case the proportional constant turns out to be 1 (remember where we came across this before? Hint: F = ma)

So

$$\boxed{\text{Induced emf} = -\frac{\text{final flux} - \text{initial flux}}{\text{time taken}}}$$

(the minus sign is a reference to *Lenz's Law*)

In symbols (this is the version that you'll see in the log tables:

$$\boxed{E = \frac{d\Phi}{dt}}$$

Finally, this formula assumes the coil has only one turn. If there are *N* turns, then the formula becomes

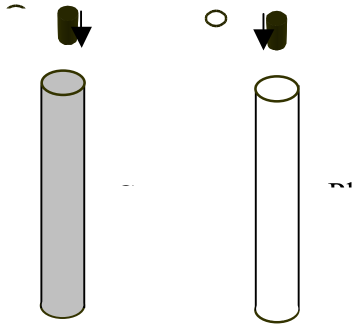
$$\boxed{\text{Induced emf} = -\,(N)\left[\frac{\text{final flux} - \text{initial flux}}{\text{time taken}}\right]}$$

Lenz's Law

Lenz's Law states that the direction of the induced emf is always such as to oppose the change producing it.

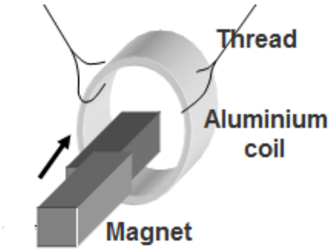
Explanation
We know that when a magnet and coil move relative to each other, an emf is induced.
Now if the coil is a conductor the induced emf will drive a current around the coil.
This current has a magnetic field associated with it.
The direction of this magnetic field will always be such as to oppose the change which caused it.

Demonstrating Lenz's Law (i): Magnet, Plastic and Copper Tubes*



Apparatus
Copper pipe, plastic pipe, stopwatch, strong neodymium magnet, piece of neodymium, or iron, (same size as magnet).
Procedure
Drop the neodymium magnet down both tubes and compare the time taken for each for each.
Observation
The time taken for the magnet to fall down through the copper tube is much longer than the time taken for the magnet to fall down the plastic tube.
Explanation
The falling magnet creates a changing magnetic flux in both tubes.
An emf is therefore induced in both tubes.
But current flows in only the copper tube because this is the only material that is a conductor.
This induced current generates a magnetic field which oppose the motion of the falling magnet.

Demonstrating Lenz's Law (ii): Magnet and Aluminium Ring

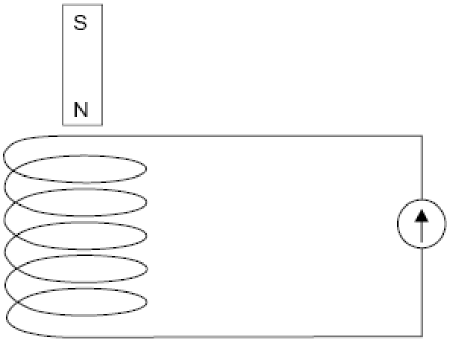


Apparatus
Aluminium ring, magnet, thread, retort stand.
Procedure
1. Move one end of the bar magnet towards and into the ring. The ring moves away from the magnet.
2. Hold the magnet in the ring and quickly pull it away. The ring follows the magnet.

Observation
When the magnet moves, the ring responds by moving in the same direction.
Explanation
The moving magnet causes a changing magnetic flux in the ring.
An emf is therefore induced in the ring and this emf in turn generates a current.
This current creates a magnetic field that exerts a force to oppose the motion of the magnet. The magnet exerts an equal and opposite force on the ring and so the ring moves foward.

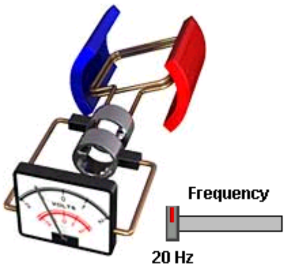
Now have a go at the exam questions on this section

Electric Generators

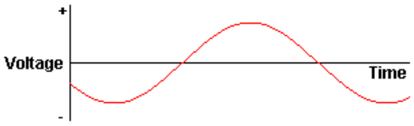


Let’s take a look at that very first diagram again:
Here mechanical energy is being converted to electrical energy.
This is the action which is responsible for almost all our electricity generation (solar energy being the main exception).
If you follow the electric wires in your house back to their source you will find at the other end a generating station which has either a magnet moving in and out of a coil of wire, or more likely, a coil of wire rotating in a magnetic field.

An Electric Generator is a device that converts mechanical energy to electrical energy.

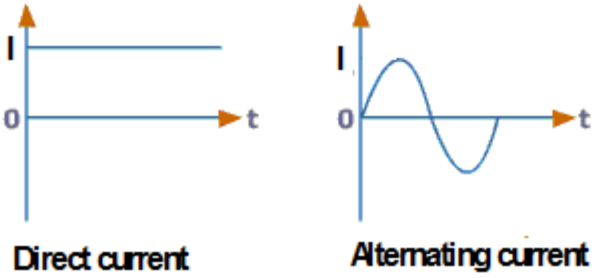


Note that in the diagrams on the right the voltage is changing direction in a sine-wave fashion.
The generators in power plants are designed to change direction 50 times a second (frequency = 50 Hertz).
Because the voltage drives the current it follows that the current also changes direction 50 times a second.



Alternating Current (A.C.)*
Alternating current is current which continually changes direction.
Mains electricity consists of current which changes direction between 40 and 50 times a second.

Comparing alternating voltage and current to direct voltage and current
We have a problem.
If the current (or voltage) is constantly changing, how can we say what its value is?
We can’t take the average value because it’s zero.
We could take the height of the wave – but this keeps changing with time.
We could take the maximum height – but if the maximum height is say 3 Amps, it still won’t have the same heating effect as a direct current of 3 Amps.



To solve the problem we use a little mathematical trickery:
We use what’s known as the root mean square value ($V_{r.m.s.}$)
This is obtained by dividing the maximum value (V_{max}) by √2.

$$\boxed{V_{rms} = \frac{V_{max}}{\sqrt{2}}} \qquad \boxed{I_{rms} = \frac{I_{max}}{\sqrt{2}}}$$

We do this because the magnitude of the *r.m.s. alternating current* will have the same power output as a *direct current* of the same magnitude.
e.g. If the r.m.s. value of an *alternating current* is 2 Amps, it will the same heating effect as 2 Amps *direct current.*

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Explain why it is necessary to use rms values when comparing a.c. and d.c. electricity.
So as to make the power output equivalent between a.c. and d.c.

Mutual Induction

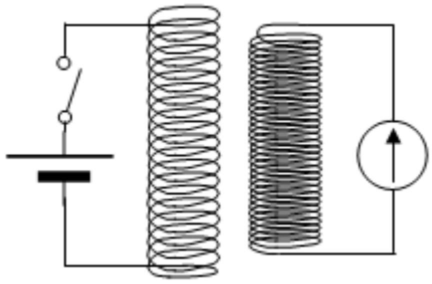
When the emf field in one coil changes, an emf is induced in the other.

Changing emf (in first coil) ⇒ changing current (in first coil) ⇒ changing magnetic flux (in first coil) ⇒ induced emf (in second coil). This in turn can induce a current if the second circuit is complete.

To Demonstrate Mutual Induction

Procedure

- Set up two coils side by side as shown.
- Close the switch – a deflection is seen on the galvanometer.
- Open the switch – a larger deflection is observed.



Observation

Each time the circuit is completed or broken, a deflection is obtained on the galvanometer. The deflection at the break is greater than at the make.

Explanation

At the make and break of the circuit there is a change in the magnetic flux linking the coils and so an emf is induced in the secondary coil.

The deflection is greater at the break because the current drops more quickly than it increases.

Mutual Induction and the Transformer

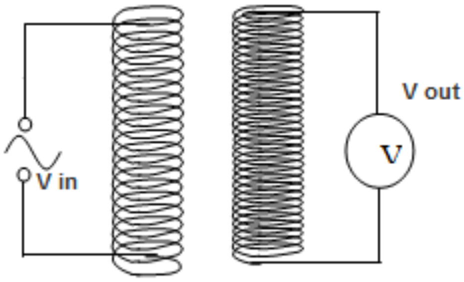
Constantly changing emf (in first coil) ⇒ constantly changing current (in first coil) ⇒ constantly changing magnetic field (in first coil) ⇒ constantly changing induced emf (in second coil) ⇒ constantly changing current (in second coil if it's a complete circuit).

Apparatus

6 V a.c. power supply, coils of wire – 400 turns and 800 turns, soft iron core, two a.c. voltmeters.

Procedure

1. Set up the apparatus as shown.
2. Switch on the a.c. supply (left hand side)..



Observation A continuous reading is obtained on the voltmeter at the right hand side.

The size of the induced emf may be increased by

1. Having the coils nearer each other
2. Winding the coils on the same soft iron core

This is the principle behind how a transformer works

The relationship between Voltage out and Voltage in for a Transformer

The relationship between voltage across the secondary coil (V_s) and voltage across the primary coil (V_p) is determined by the ratio of the number of turns on the secondary coil (N_s) to the number of turns on the primary coil (N_p)

V_s = voltage across the secondary coil, V_p = voltage across the primary coil
N_s = Number of turns in secondary, N_p = Number of turns in primary coil

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

Note

If the voltage is increased, the transformer is called a 'Step-Up Transformer'
If the voltage is decreased, the transformer is called a 'Step-Down Transformer'

Uses of transformers
Transformers are used in generating stations to step up the voltage from about 20 kV to anything up to 400 kV (can you remember why? Hint: Joules' Law)
This has then to be dropped down to 230 Volts before it enters the home.
Many household appliances run on lower voltages again, and so a second transformer is required. This is usually inside the appliance (e.g. a radio).

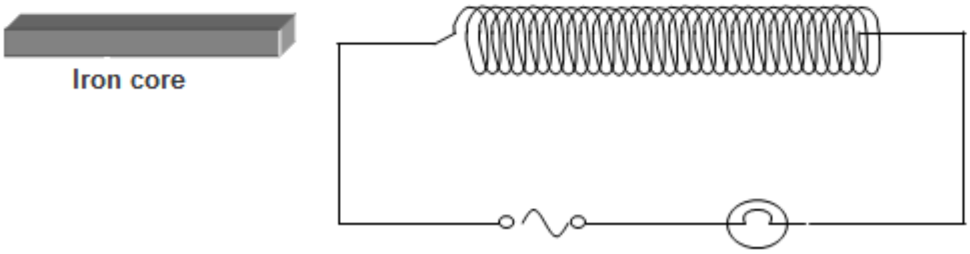
Question to make you think (otherwise known as WTF?)
According to this, if the voltage out is 100 times greater than the voltage in, then the current out is 100 times *less* than the current in.
But from Ohm's Law (V = IR) if the voltage increases then so also does the current.
What gives??

Self-Induction
A changing emf in a coil induces a changing magnetic field in the coil itself. This changing magnetic field in turn induces a second emf (in the coil itself) which is opposite in direction to the driving emf.

This induced emf is known as back-emf (because it is acting 'backwards')

Changing emf ⇒ changing current ⇒ changing magnetic field ⇒ induced changing emf (in opposite direction to original) ⇒ induced changing current (in opposite direction to original) {all in the same coil}

To Demonstrate Self-Induction (Back Emf)
Apparatus
6 V a.c. power supply, coil of wire with 1200 turns, soft iron core, 6 V filament lamp.



Procedure
1. Connect the bulb, coil and a.c. supply in series.
2. Switch on the power supply. The lamp lights.
3. Insert the iron core into the coil. The lamp becomes dimmer.

Explanation
The a.c. produces a changing magnetic field in the coil.
This induces an emf and hence a current that opposes the applied current.
The iron core increases the magnetic flux and hence the induced opposing current is increased.
The resultant current in the circuit is reduced and the bulb becomes dimmer.

Note
If this circuit is set up using a d.c. power supply, no dimming occurs with the core in the coil as there is no changing magnetic field.

It should now be apparent that a coil of wire can be used to reduce alternating current in the same way that a normal resistor is used to reduce Direct Current.
The coil, when used in this fashion, is known as an inductor.

An inductor is an electrical component used to reduce the flow of alternating current.
An example of an inductor is the dimmer switch used in stage lighting.

Leaving Cert Physics syllabus

Content	Depth of Treatment	Activities	STS
4. Electromagnetic induction	Magnetic flux $\Phi = BA$ Faraday's law.	Demonstration of the principle and laws of electromagnetic induction. **Appropriate calculations.**	Application in generators.
	Lenz's law. Change of mechanical energy to electrical energy.		
5. Alternating current	Variation of voltage and current with time, i.e. alternating voltages and currents. **Peak and rms values of alternating currents and voltages.**	Use oscilloscope to show a.c. **Compare peak and rms values.**	National grid and a.c.
6. Concepts of mutual induction and self-induction	**Mutual induction (two adjacent coils): when the magnetic field in one coil changes an emf is induced in the other, e.g. transformers.** **Self-induction: a changing magnetic field in a coil induces an emf in the coil itself, e.g. inductor.**	**Demonstration**. **Demonstration**.	
	Structure and principle of operation of a transformer.	Demonstration. Appropriate calculations (voltage).	Uses of transformers.
	Effects of inductors on a.c. (no mathematics or phase relations).		Dimmer switches in stage lighting – uses of inductors.

Extra Credit

Lenz's Law states that the ***direction of the induced emf*** is always such as to oppose the change producing it.*
An alternative (less formal) definition is to say that the direction *of the induced magnetic field* will always be such as to oppose the change producing it. We don't specify magnetic field, because there will only be an inducted magnetic field if there is an induced current, which will only happen if there is a complete circuit, whereas there will *always* be an induced emf.
This is a consequence of the conservation of energy – if the induced magnetic field attracted the magnet, then the magnet would move faster, resulting in a greater induced emf and magnetic field, resulting in magnet moving faster still, and eventually would break the speed of light!

The unit of magnetic flux is the Weber (Wb)*
Named after Professor Weber – he was a professor who lectured Albert Einstein. Einstein held him in contempt because Weber refused to give any time to recent developments in Physics, developments which contradicted – or at the very least questioned – the traditional teachings.
Einstein refused to address Weber by his proper title Herr Professor Weber, instead he addressed him as Herr Weber.
Weber in turn refused to write a reference for Einstein (mind you the fact that Einstein couldn't be bothered going to Weber's lectures probably didn't help).
End result?
Einstein could only get a job as a lowly clerk in a patent office. This did have the advantage of providing Einstein with a lot of free time to think, time which he appears to have put to good use.

*Demonstrating Lenz's Law (i): Magnet, Plastic and Copper Tubes

A practical use of this in the real world is in the design of elevators.
They have strong magnets attached to their outer walls, and the lift shafts have copper linings, so even if the elevator becomes detached from its cable, it cannot fall faster than the eddy currents and Lenz's Law will allow.
There is a model of this in the *Science in Action* video: "Electricity and Magnetism", where Howie investigates the Trocadero Centre in London.
The S*heer Drop* amusement rides use permanent magnets to bring the ride to rest at the end of the fall.

*Alternating Current

"Trust you will avoid the gigantic mistake of alternating current".
Lord Kelvin (1824-1907)
Tesla (remember him) was generating electricity in the form of alternating current, but his great rival at the time was Edison, who favoured direct current. Edison roped in Kelvin to back him (Kelvin was recognised as the greatest living scientist at the time), but even with the backing of Kelvin he still lost out to Tesla (this one time).

A good analogy to help you understand the flow of the electrons caused by potential difference is to imagine *pushing* a stiff bicycle chain around and around.
Each link is an electron, and they all move at the same speed.
Alternating Current is therefore analogous to pushing *and pulling* the chain, switching directions 50 times a second (alternating current alternates at a frequency of 50 hertz).

Why aren't Laptops allowed to be used on airplanes?
The rate of change of flux generated by the new generation of computer chips can be very significant- not because the strength of the magnetic field is significant, but because the frequency is so high (2 GHz plus).

The airline world isn't absolutely sure what does, or doesn't, constitute a threat to safety.
And the evidence of problems is largely anecdotal.
Their best policy is to ban ALL electronic devices other than their own built in systems which have, of course, been subject to flight testing.

A source of High Voltage but Low current is the Van de Graff generator
A source of High Current but Low Voltage is the Transformer used to melt nails.

Activities

Take a battery with a wire on each terminal; Attach one end to a metal file.
Scrape the end of the other wire along the file beside an AM radio and listen to the crackles... furthermore; radio the old-fashioned way began with sparks.

Make radio waves by switching off an electric circuit, and detecting them as "crackle" on a long-wave radio.