A2 Level Physics

Chapter 12 – Magnetic Fields

12.3.1 Electromagnetism

Notes

Magnetic Flux

A magnetic field is a region around a magnet in which magnetic forces are exerted. It was once considered that there must be something 'flowing' through this magnetic field region from N-pole to S-pole.

The flowing quantity was given the name, Magnetic Flux and while it does not exist, the idea is very useful for explaining magnetic fields.

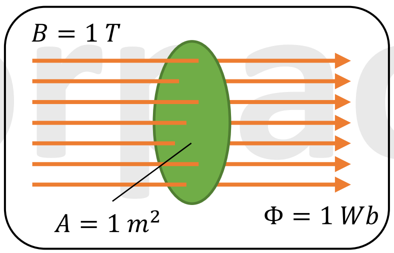
The amount of flux flowing through a unit cross-sectional area can be used to visualise the strength of a magnetic field (i.e. measure of the concentration of flux).

If a uniform magnetic field of strength (B) acts perpendicular to an area (A), the magnetic flux (Φ) passing through the area is given by:

$$\boldsymbol{\Phi = BA}$$

Where:

- Φ = magnetic flux in Wb (webers)
- B = magnetic flux density in T
- A = area in m^2



1 WEBER (Wb) is the amount of magnetic flux flowing perpendicularly through an area of $1m^2$ in a magnetic field of flux density $1T$.

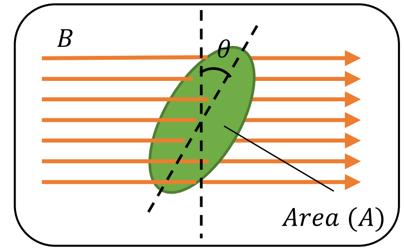
And since $B = \frac{\Phi}{A}$, magnetic field strength can be re-defined as magnetic flux density.

Magnetic flux density (B) at a point in a magnetic field is the magnetic flux perpendicular to unit area (A).

Magnetic Flux

If the area (A) of a single loop of wire has rotated through an angle (θ) from its original position, less magnetic flux goes through it, and the magnetic flux (Φ) is given by:

$$\boldsymbol{\Phi = BAcos\theta}$$



Where:

- Φ = magnetic flux in Wb (webers)
- B = magnetic flux density in T
- A = area in m^2
- θ = angle between the normal to the plane of the coil and the magnetic field in degrees, °

- When the flux is perpendicular to the area (A):

$\theta = 0°$, and $cos\theta = \cos 0° = 1$

So: $\Phi = BA$

- When the flux is parallel to the area (A) :

$\theta = 90°$, and $\cos\theta = \cos 90° = 0$

So: $\Phi = 0$

Magnetic Flux Linkage

Since motor and generator coils include many turns of wire, we need to know how much flux flows through and so 'links with' all the turns.

When a coil of wire is moved in a magnetic field an electromotive force (e.m.f.) is induced. The magnitude of the induced e.m.f. is determined by the magnetic flux passing through the coil, (Φ), and the number of turns on the coil cutting the flux. The product of these is called the flux linkage, $N\Phi$.

Consider a coil with (N) turns and area (A) that is perpendicular to a uniform magnetic field of flux density (B).

The magnetic flux which links with the coil is called the magnetic flux linkage and is given by:

$$\boldsymbol{Flux\ linkage = N\Phi = BAN}$$

Where:

- $N\Phi$ = Flux linkage in Wb (webers)
- Φ = magnetic flux in Wb (webers)
- B = magnetic flux density in T
- A = area in m^2
- N = number of turns on the coil cutting the flux

In a loop of wire, a change in flux linkage of one weber per second induces an e.m.f. of 1V.

The rate of change in flux linkage determine the strength of the e.m.f. in volts.

Magnetic Flux Linkage at an angle

We can use the same concept for a coil with N turns as we did for a single loop of wire when B is not perpendicular to the area. As a result, the flux linkage of a coil that has turned through an angle θ from the original position can be found using the equation:

$$\boldsymbol{N\Phi = BANcos\theta}$$

Where:

- $N\Phi$ = Flux linkage in Wb (webers)
- Φ = magnetic flux in Wb (webers)
- B = magnetic flux density in T
- A = area in m^2
- N = number of turns on the coil cutting the flux
- θ = angle between the normal to the plane of the coil and the magnetic field in degrees, °

Electromagnetic induction – Experimental

A voltage can be produced when a magnet moves in a coil of wire or when a conductor moves in a magnetic field. This process is called the electromagnetic induction and the effect is known as the dynamo effect.

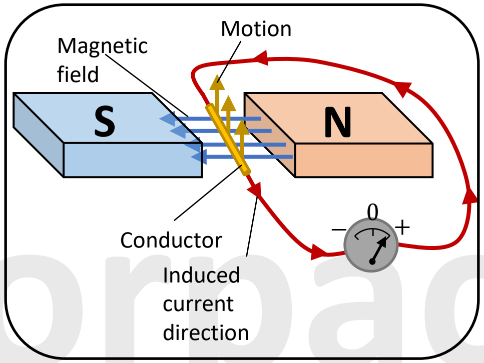
Stationary field moving conductor

When a conductor passes through a magnetic field, a voltage is induced in it. The same effect can be achieved by keeping the wire stationary while moving the magnet.

If the conductor is part of a complete circuit, the induced voltage will produce an induced current.

In order to increase the size of the induced voltage or current, increase:

- The speed (v) of motion of the conductor.
- The length (L) of the conductor in the magnetic field.
- The magnetic field strength (B).



By reversing the following, the direction of the induced voltage or current is reversed:

- The direction of the magnetic field.
- The direction of motion of the conductor.

If the wire is held stationary within the magnetic field, no voltage or current is induced (i.e. no motion – no induced current).

Electromagnetic induction – Experimental

Stationary conductor moving field

A current is induced in a coil when a magnet is moved into or out of it. The diagrams below show how the galvanometer deflects in one direction when the S-pole of the magnet is plunged into the coil, and reverses when the S-pole is pulled out of the coil.

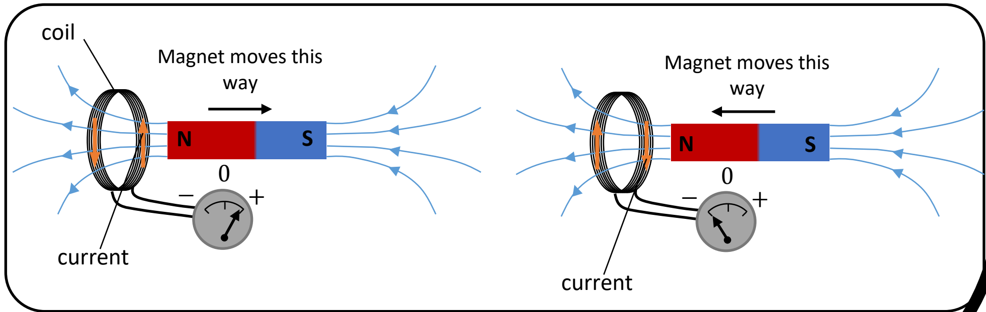
The faster the magnet is moved, the greater is the deflection and when the magnet is held stationary inside the coil, there is no deflection. The deflection can be increased by using a coil with a larger number of turns.

When there is relative motion between the magnet and the coil, a voltage (and current) is induced in the coil. This is due to a change in the amount of magnet flux linking with the coil as a result of the motion.

The direction of induced voltage and current is determined by the magnet pole that is being moved into the coil and its motion.

In order to increase the size of the induced voltage and current, increase:

- The speed of motion of the magnet.
- The number of turns of the coil.



The movement of a magnet towards and away from a coil results in the induction of an e.m.f. and current.

Faraday's Law

Electromagnetic induction occurs whenever there is relative motion between a conductor (or a set of conductors) and magnetic field.

The rate at which magnetic flux is 'cut' or 'linked' determines the magnitude of the induced voltage (or current).

Michael Faraday demonstrated that the induced e.m.f. (electromotive force) increased as the magnet was moved faster. (E.m.f. is another term for voltage.) This is because the motion between the magnet and wire causes a change in flux linkage.

Faraday summed up his findings and came up with Faraday's law which states:

Induced e.m.f. or voltage is directly proportional to the rate of change of magnetic flux linkage.

The size of the induced emf is also determined by Faraday's law:

Magnitude of induced e.m.f. = rate of change of flux linkage

Or:

$$\varepsilon = \frac{N\Delta\Phi}{\Delta t}$$

Where:

ε = magnitude of induced e.m.f. in V

N = number of turns on the coil

$\Delta\Phi$ = change in magnetic flux in Wb

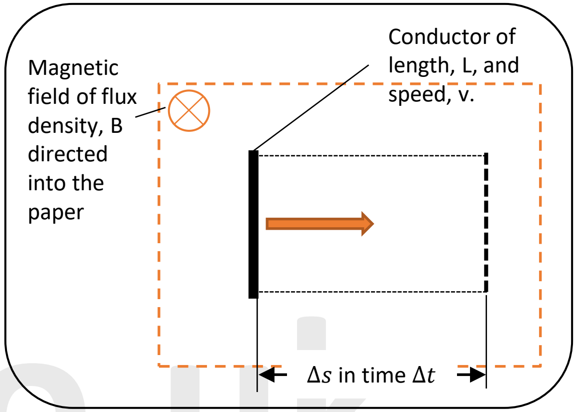
Δt = time taken for flux to change in s

Examples of the Use of Faraday's Law

Conductor moving at 90° to a magnetic field

Consider a conductor of length (L) moving a constant speed (v) at $90°$ to a magnetic field of flux density (B), covering distance Δs in time Δt. The induced e.m.f. would therefore be:

$$\varepsilon = \frac{\Delta\Phi}{\Delta t} = \frac{\Delta(BA)}{\Delta t}$$



Area $A = L\Delta s$, so

$$\varepsilon = \frac{BL\Delta s}{\Delta t}$$

But velocity $v = \frac{\Delta s}{\Delta t}$, therefore

Induced e.m.f., $\varepsilon = BLv$

Where:

ε = magnitude of induced e.m.f. in V

B = magnetic flux density in T

L = length of the conductor in m

v = speed of the conductor in ms^{-1}

Examples of the Use of Faraday's Law

Rectangular coil moving into a uniform magnetic field

Consider a rectangular coil with (N) turns, length (L) and width (w) moving at constant speed (v) into a uniform magnetic field of flux density (B).

Time for coil to completely enter the field, $\Delta t = \frac{w}{v}$

In this time, flux linkage NΦ increases from 0 to BNLw.

Therefore:

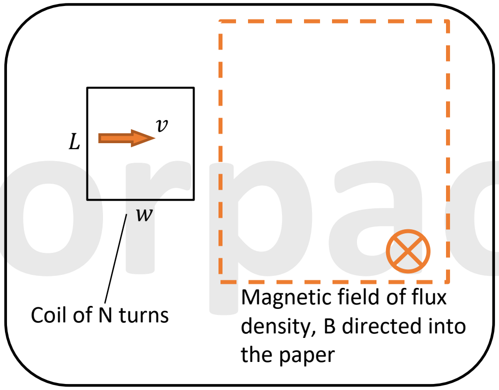
Induced emf, $\varepsilon = change\ of\ flux\ linkage\ per\ sec$

$$\varepsilon = \frac{N\Delta\Phi}{\Delta t}$$

$$\varepsilon = \frac{BNLw}{w/v} = BLvN$$

Simplified the induced emf is,

$$\varepsilon = BLvN$$



Where:

ε = magnitude of induced e.m.f. in V

B = magnetic flux density in T

L = length of the conductor in m

v = speed of the conductor in ms^{-1}

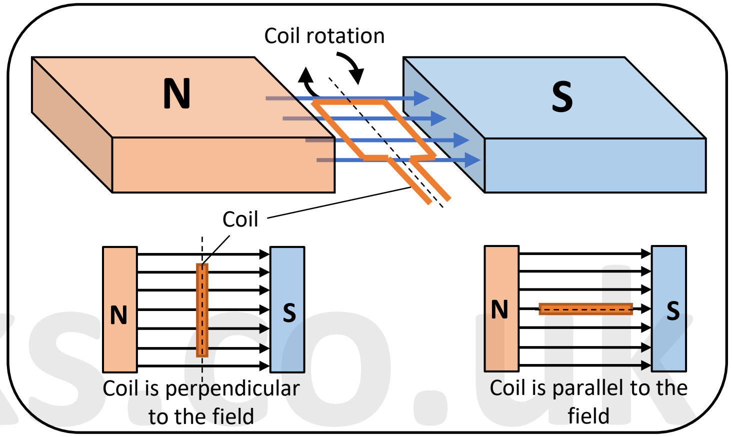
N = number of turns on the coil cutting the flux

There is no change in the flux linkage once the coil is completely inside the field, so the induced emf drops back to 0.

Coil rotating in a uniform magnetic field

Rotating a coil in a magnetic field is another way to produce a change in magnetic flux linkage.

When the plane of the coil is perpendicular to the field, the flux linkage is at its highest, and when the plane of the coil is parallel to the field, the flux linkage is reduced to zero. The diagram below demonstrates this.



Worked example:

A circular coil of 25 turns and radius 15 cm is situated with its plane perpendicular to a magnetic field of flux density 0.50T. Calculate the e.m.f. induced in the coil if it is rotated through 90° in a time of 40ms.

Coil Area, $A = \pi r^2 = \pi \times 0.15m^2 = 0.0707m^2$

Magnetic flux linkage when coil is perpendicular to the field, $N\Phi = BAN = 0.50\ T \times 0.0707\ m^2 \times 25\ = 0.884Wb$

Magnetic flux linkage when coil is parallel to the field, $N\Phi = 0Wb$

So, change in magnetic flux linkage, $N\Delta\Phi = 0.884\ Wb$

Induced e.m.f., $E = \frac{N\Delta\Phi}{\Delta t} = \frac{0.884\ Wb}{40\times10^{-3}\ s} = 22.1V$

Lenz's Law

When a current flows through a wire in a magnetic field, the wire experiences a force. Conversely, when a wire is moved through a magnetic field as part of a complete circuit, electrons flow through it, inducing a current and voltage (or an e.m.f.), and thereby generating electricity in the wire.

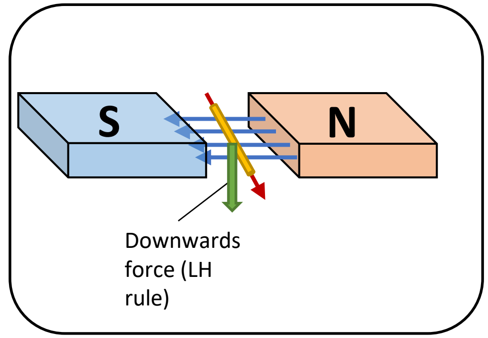
Fleming's left-hand rule is applied to electric motors or the motor effect, which occurs when a current-carrying wire is in a magnetic field and experiences a force. In other words, the current generates a force.

If we consider the principle of "force makes current or induces current," it relates to the Dynamo effect. This phenomenon happens when a magnet moves in a wire coil, resulting in the production of a voltage. This process is referred to as electromagnetic induction. Unlike the motor effect, the Dynamo effect requires the use of Fleming's right-hand rule instead of the left-hand rule. Flemings RH rule is primarily applied to electric generators.

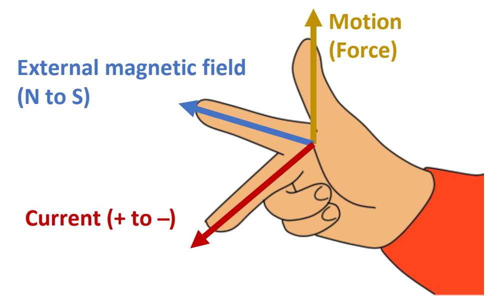
Therefore, the current flowing through a wire causes it to go downwards, because the current produces a force. The issue is that the force, in turn, produces a current, creating a cycle that seems impossible to break. Nevertheless, this paradoxical situation makes sense.

The diagram opposite shows a downward force according to Fleming's LH rule. When a wire moves through a magnetic field, the dynamo effect is created, requiring the use of Fleming's RH rule. As the motion is downwards, the thumb points downwards, and the current flows in the opposite direction to what is shown in the diagram. Therefore, the Dynamo effect opposes the motor effect and tries to stop it.

Lenz's Law

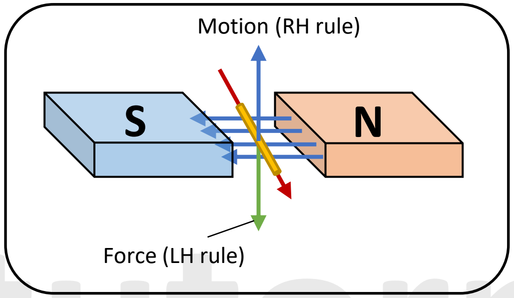


Fleming's right-hand rule is applied to explain how moving a coil through a magnetic field creates a current. This rule is similar to the left-hand rule, and it involves holding the thumb, first, and second fingers at 90 degrees to each other. The thumb represents the conductor's motion, the first finger indicates the magnetic field, and the second finger shows the induced current.



Lenz's Law

The same phenomenon applies in the other situation where a wire is forced upwards. Fleming's RH rule helps to determine the current's direction (as shown below). However, as there is now a current flowing through the wire, Fleming's LH rule is required. This rule shows a force generated in the opposite direction (downwards), and the motor effect opposes the dynamo effect.



This is the concept behind Lenz's law, which states:

The direction of the induced current is always such as to oppose the change which causes the current.

By including a minus sign, Faraday's law incorporates Len's law (which implies that the induced e.m.f. acts in the opposite direction of the change that creates it).

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

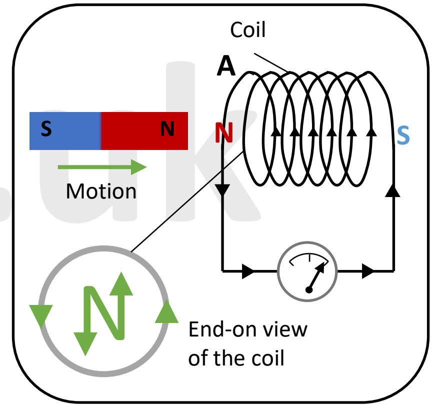
So, we have a wire that we are pulling upwards, which produces a current in the wire, but that current produces its own equal and opposite force, which will try to push it back downwards. As a result, we have two equal and opposing forces.

Lenz's Law

Lenz's law is demonstrated by a solenoid (coil of wire) that is part of a complete circuit, and a magnet is forced through it. As the magnet has its own magnetic field, pushing it through the solenoid causes the flux of the magnetic field to cut through the wire (or the wire cuts through the flux).

When the north end of the magnet is pushed through the solenoid, the wire experiences a flux change, inducing a current that causes electron flow. Simultaneously, the current generates a magnetic field in the solenoid, but the question is which end of the solenoid will be the temporary North and South poles.

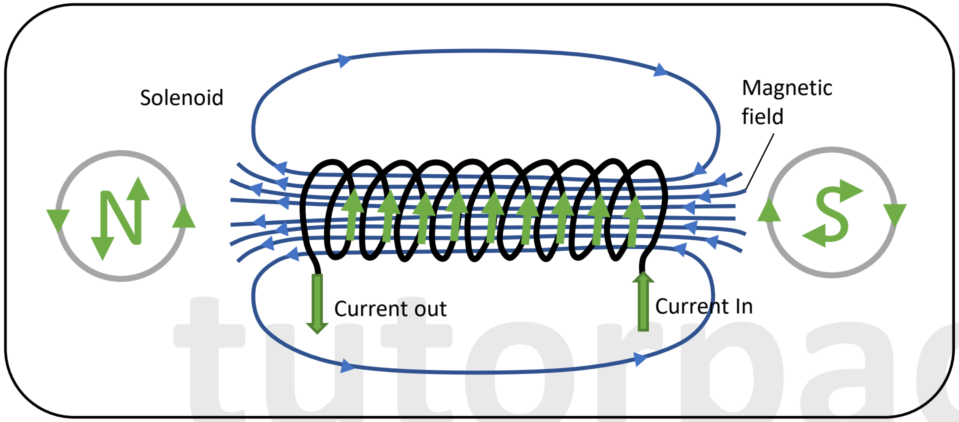
If a magnet with a north pole is pushed through the solenoid and a south pole is induced at point A, the magnet speeds up due to the attraction between opposite poles. The magnetic field generated by the current in the wire also increases, further attracting the magnet. If the south pole is induced at point A, the magnet accelerates, passing straight through the solenoid, defying the principle of energy conservation. This is impossible as the magnet's kinetic energy would continue to rise, and the induced current would increase with no work being done.



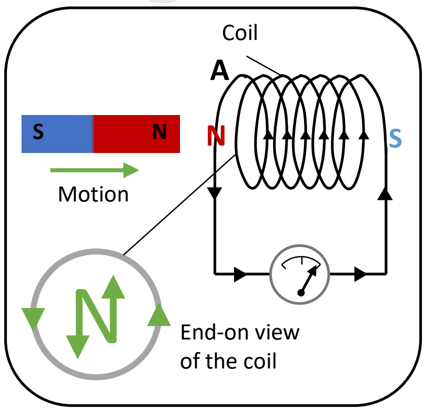
But, as we know from Lenz's law, any induced current will try to stop the change that generated it in the first place, thus it makes sense that if the North end of the magnet is inserted, a North pole will be induced at point A. As a result, a South pole will be induced at the solenoid's opposite end.

Lenz's Law

Determining the direction of the induced current in the solenoid at point A is challenging. However, viewing the solenoid from the end reveals a North pole at point A with anti-clockwise current flow. Conversely, looking at it from the other end (South pole) results in clockwise current flow. This information helps predict the direction of an induced current in a solenoid (see below).



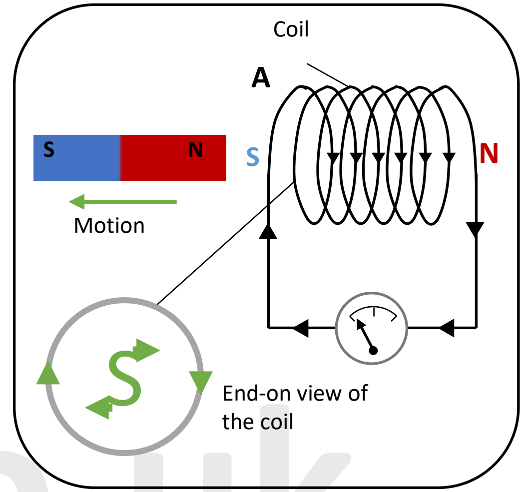
As a result of Lenz's law, if the north pole is induced at point A of the solenoid, we will experience repulsion. In other words, the solenoid does not want the magnet to enter it, thus it tries to prevent it from doing so. In order to push the magnet into the coil against the repulsive force, work must be done. The energy generated by the work done is converted into electrical energy.



Lenz's Law

We also have energy lost as heat due to resistance caused by the electric circuit set up.

Also, due to Lenz's law, if the magnet N-pole were pulled out of the coil instead of pushed into it, the induced current would have an S-polarity at end A.



Once again, the direction of the induced current opposes the change or motion that causes it. To pull the magnet N-pole out of the coil, work must be done against the attraction force.

So the solenoid produces a repulsive force to prevent the magnet from coming in, but it also tries to prevent the magnet from leaving.

Also if the magnet N-pole were pulled out of the coil and we have a S-polarity at end A, this means on the opposite end of the solenoid is the N-pole. As a result, the magnetic field created in the solenoid flips completely between the magnet entering and exiting. Therefore the current must reverse and begin to flow in the opposite direction.

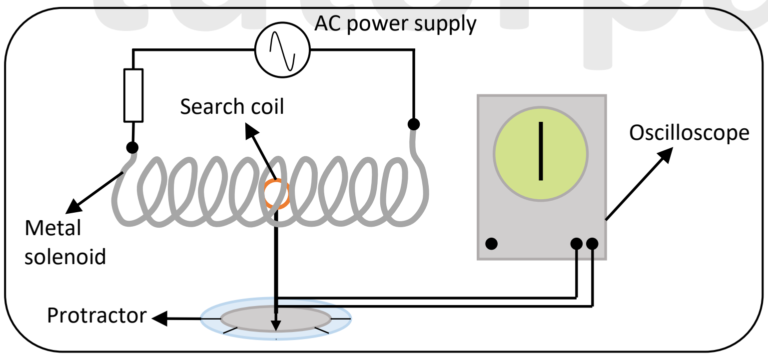
Investigating magnetic flux using search coil

Apparatus:

- Oscilloscope,
- Long wire coil,
- Search coil,
- Stand/support for search coil,
- Low voltage AC supply,
- Connecting leads,
- Protractor.

Method:

Using the setup below, you can observe how the e.m.f. produced in the search coil varies with the angle of the search coil's plane to the solenoid:



An experiment aiming to study how changing the angle between a search coil and the magnetic field affects the magnetic flux linkage.

A search coil is a small, flat coil that can be used to find the magnetic field strength.

Investigating magnetic flux using search coil

- **Step 1:** Link the alternating power supply, to the long wire coil which acts as a solenoid. The alternating supply means that the solenoid's magnetic field is always changing, which means that the flux through the search coil is changing, inducing an e.m.f. Throughout the experiment, make sure the peak of the AC voltage from the AC power supply remains constant.
- **Step 2:** Record the search coils area and number of turns.
- **Step 3:** Link the search coil to the oscilloscope in order to record the induced e.m.f. in the coil. Set up the oscilloscope so that it just displays the e.m.f. amplitude as a vertical line (you'll need to disable the time basis).
- **Step 4:** Use the protractor to calculate the angle between the magnetic field line and the normal to the area of the search coil. See below:
- **Step 6:** Place the search coil inside the solenoid approximately halfway down (but not touching it). A solenoid's magnetic field is strongest inside it, and can be considered to be uniform and parallel.
- **Step 7:** Place the search coil so that its area is perpendicular to the field ($\theta = 0°$). Then, using the amplitude of the oscilloscope trace, record the induced e.m.f. in the search coil.
- **Step 8:** Rotate the search coil by 10 degrees in relation to the solenoid and magnetic flux lines. Record the induced e.m.f. on a table like the one shown on the next page and continue until the search coil has been rotated 90 degrees. As you turn the search coil, you'll see that the induced e.m.f. decreases. This is because the search coil cuts fewer flux lines as the component of the magnetic field perpendicular to the area of the coil decreases, resulting in a reduced total magnetic flux passing through the coil. This indicates that the coil's magnetic flux linkage is reduced.

Investigating magnetic flux using search coil

Angle θ / deg	$sin\ (\theta)$	Peak-to-peak voltage V_P/V	Peak e.m.f. ε_0/V
0			
10			
20			
30			
40			
50			
60			
70			
80			
90			

From oscilloscope

$\frac{V_P}{2}$

Step 9: Plot a graph of induced e.m.f. against θ. This should produce a sinusoidal curve where the induced e.m.f. is a maximum at $0°$, and a zero at $90°$.

Safety:

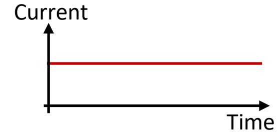
- To avoid damaging the coil, don't exceed the specified current rating.
- To avoid a short circuit or a fire, make sure no wires or connections are broken and that proper fuses are used.
- The larger coil, especially if it is very thin, will heat up as the current passes through it. As a result, don't leave the current running for longer than necessary.

Improvements:

- To reduce parallax error, read the angle from the protractor from above and from the same spot each time.
- Improve reliability by repeating the experiment for a full turn $(\theta = 360°)$.

Simple A.C. generator

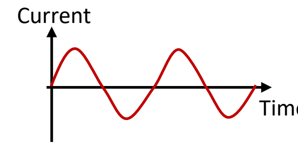
Direct current (D.C.) is the flow of electric charge in one direction only in a conductor.



Graphical representation of a **Direct Current**

When direct current (DC) (for example, from a battery) flows through a wire, the moving electrons that make up the current drift slowly and in a constant direction.

In alternating current (A.C.) the movement of the electric charge periodically changes direction.



Graphical representation of an **Alternating Current**

When alternating current (AC) (for example, from the mains) flows through a wire, the electrons oscillate back and forth about their mean positions rather then drifting along the wire as they do with direct current.

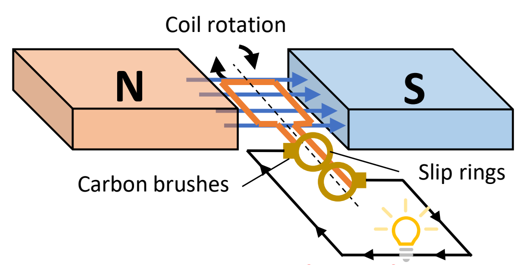
Generators, also known as dynamos, transform kinetic energy into electrical energy by rotating a coil in a magnetic field.

The simple A.C. generator seen in the diagram above consists of a coil that is free to rotate on an axle and is connected to two conducting slip rings that rotate with the coil.

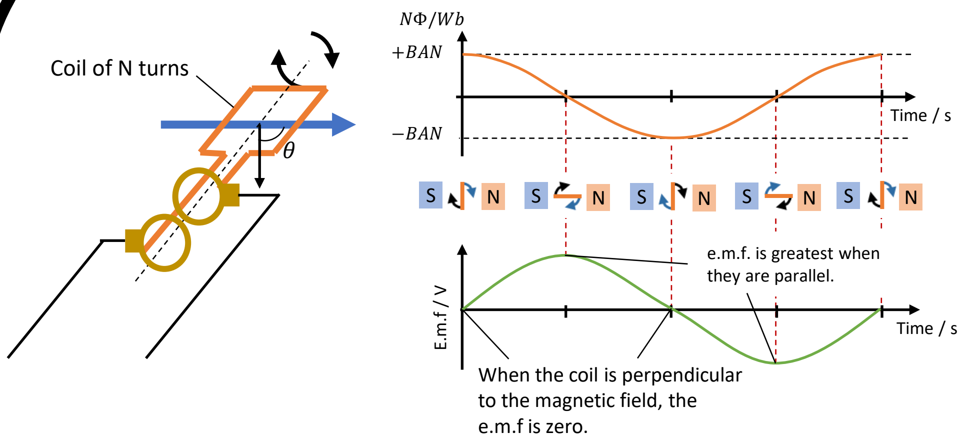
The current generated by rotating the coil between the magnet poles is directed to an external circuit via stationary carbon brushes pressed against the slip-rings.

When this coil rotates uniformly (at a constant speed) in a magnetic field, the coil cuts the flux and an alternating e.m.f. is induced.

Every half-cycle of the rotation, the direction of the induced e.m.f. and thus the induced current reverses, which is why the generator creates alternating current (a.c.).



Simple A.C. generator



The flux (Φ) linking a coil of area (A) with (N) turns rotating through an uniform magnetic field of flux density (B) at any instant is given by:

$$N\Phi = BANcos\theta$$

Where θ is the angle between the plane of the coil and the magnetic flux lines.

- When the plane of the coil is perpendicular to the field, $\theta = 0°$, $cos\theta = 1$ and so the flux linkage is a maximum ($\Phi = BAN$).
- When the plane of the coil is parallel to the field, $\theta = 90°$, $cos\theta = 0$ and so the flux linkage is zero ($\Phi = 0$).

The e.m.f induced in the coil is the rate of change of flux linkage with the coil, which is highest when the flux linkage is zero and zero when the flux linkage is at its maximum value. The gradient of the flux linkage (Φ) graph can be used to calculate the induced e.m.f. (ε).

So, when we have the least amount of flux linkage, we have max e.m.f, and when we have the most amount of flux linkage, we have min e.m.f. This is because the e.m.f. is the rate of change of flux linkage which means from the coil being perpendicular to the magnetic field to the coil being parallel to the magnetic field we produced the max e.m.f.

Simple A.C. generator

How fast θ changes or in other words how quickly the coil rotates depends on the angular speed, ω, of the coil and we know that $\theta = \omega t$. Thus, we can rewrite $N\Phi = BANcos\theta$ to:

$$N\Phi = BANcos\omega t$$

Where:

$N\Phi$ = Flux linkage in Wb (webers)

Φ = magnetic flux in Wb (webers)

B = magnetic flux density in T

A = area in m^2

N = number of turns on the coil cutting the flux

ω = angular speed in $rads^{-1}$

t = time in s

The induced e.m.f., ε, also varies sinusoidally because. Therefore, equation for the e.m.f. at time t can also be written as:

$$\varepsilon = BAN\omega\ sin\omega t$$

Where:

ε = induced e.m.f. in V.

Changing the speed of rotation or the size of the magnetic field can change the shape of the induced e.m.f. graph:

- The frequency and maximum e.m.f. will increase as the rotational speed is increased.
- The maximum e.m.f. will increase as the magnetic flux density B increases, but the frequency will remain unchanged.

The changes are proportional: doubling the rotational speed doubles the maximum e.m.f., and halving the rotational speed halves the maximum e.m.f.

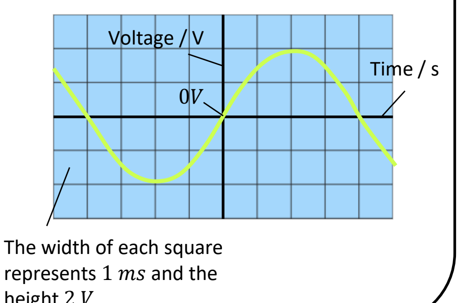
Measuring alternating voltage with an oscilloscope

An oscilloscope can be used to display the voltage of an alternating and direct current.

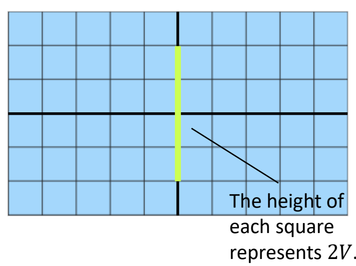
Oscilloscopes are voltmeters in disguise. The input voltage is shown by the vertical height of the trace. The oscilloscope screen has a grid on it; using the Y-gain control dial, you can pick how many volts per division you want the y-axis scale to indicate, for example, 5V per division. Because the height of each square on the grid on some oscilloscopes is 1cm, the scale can be set in terms of V per cm (Vcm^{-1}).

An oscilloscope

Oscilloscope settings:
Y-gain = 2 V per division,
Time base = 1 ms per division

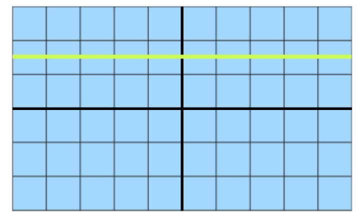


Oscilloscope settings:
Y-gain = 2 V per division,
Time base turned off

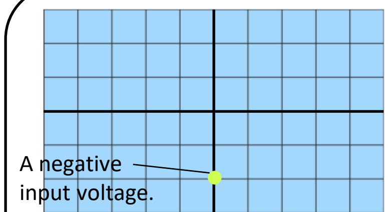


Measuring alternating voltage with an oscilloscope

An AC source produces a sinusoidal waveform that regularly repeats itself. Because the voltage of a DC source is constant, the result is a horizontal line, as seen below. When the time base is turned off, oscilloscopes can display AC voltage as a vertical line and DC voltage as a dot.



DC supply shown on an oscilloscope

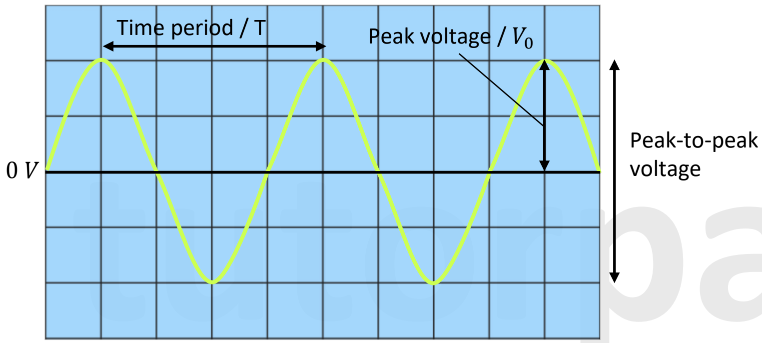


DC supply shown on an oscilloscope with the time base turned off.

Measuring alternating voltage with an oscilloscope

An AC oscilloscope trace can provide three main pieces of information:

- The time period (T),
- Peak voltage, V_0, and
- The peak-to-peak voltage.



The time period is determined by measuring the distance between crest to crest or trough to trough along the time axis (as long as you know the time base setting). This can be used to calculate frequency:

$$Frequency = \frac{1}{time\ period}$$

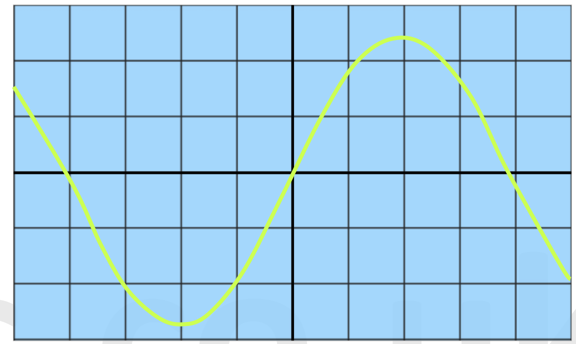
Or,

$$f = \frac{1}{T}$$

Measuring alternating voltage with an oscilloscope

Worked example

The oscilloscope output of an alternating current is shown in the diagram below:



The Y-gain dial is set to 0.10 V per division and the time base is set to 1.0 s per division.

Calculate:

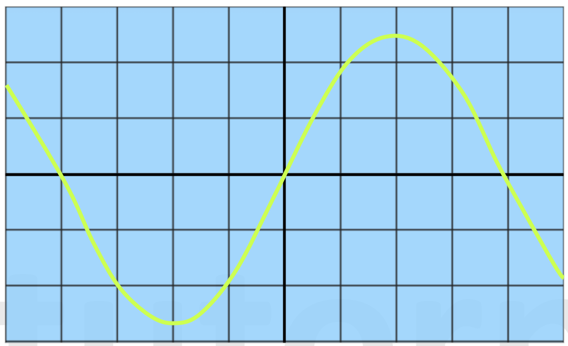
a) The peak voltage of the wave,

b) The frequency of the wave.

Measuring alternating voltage with an oscilloscope

Worked example

The oscilloscope output of an alternating current is shown in the diagram below:



The Y-gain dial is set to 0.10 V per division and the time base is set to 1.0 s per division.

Calculate:

a) The peak voltage of the wave,

b) The frequency of the wave.

Measuring alternating voltage with an oscilloscope

Worked example

a) The distance between the 0V line (horizontal axis) and the top of the peak is known as the peak voltage.

The peak is 2.5 squares high.

So the peak voltage = $2.5 \times 0.10\ V = 0.25\ V$

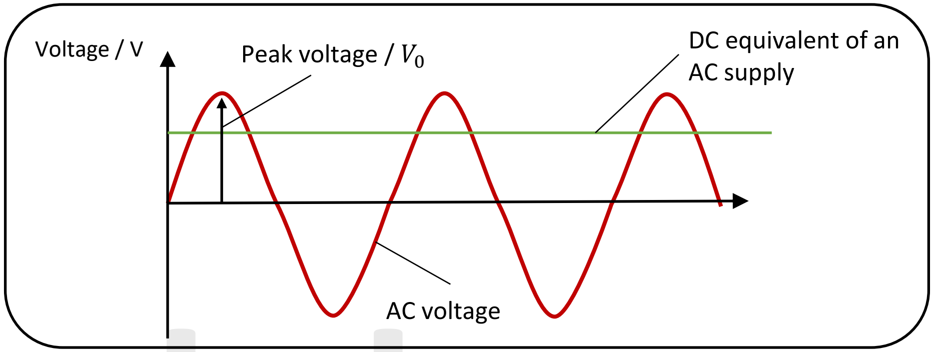
b) First you have to work out the time period of the wave.

The time base is set to 1.0s, so every square on the grid represents 1.0s. The time period of the wave is 8 squares = 8 seconds.

$$\therefore\ Frequency = \frac{1}{time\ period} = \frac{1}{8} = 0.125Hz = 0.13Hz\ (2s.f.)$$

Root Mean Square (rms) voltage (AQA & Edexcel Only)

Most of the time, an AC supply with a peak voltage of 2V will be below 2V. This means it won't produce as much power as a 2V DC supply. In order to compare an AC voltage to a DC voltage or to find the DC equivalent of an AC supply you must find the average of the AC voltage.



Working out an average regularly will not work since the positive and negative values cancel out, .

The root mean square (rms) voltage helps us determine this average AC voltage. For a sine wave, you get the rms voltage, V_{rms}, by dividing the peak voltage, V_0 by $\sqrt{2}$. You do the same to calculate the rms current I_{rms}:

$$V_{rms} = \frac{V_0}{\sqrt{2}}, \quad I_{rms} = \frac{I_{rms}}{\sqrt{2}}$$

Where:

V_0 = peak voltage in volts (V)

I_0 = peak current in Amps (A)

To calculate the rms power for an ac supply, use the formula below:

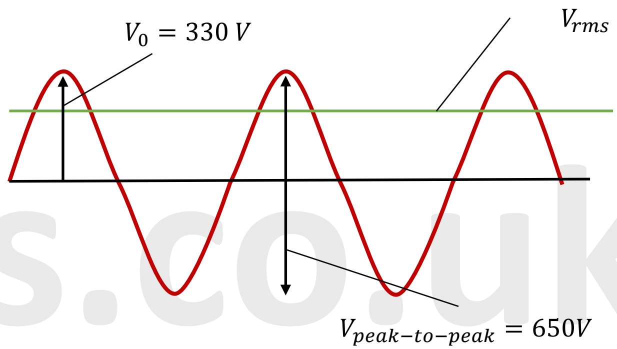
$$Power_{rms} = I_{rms} \times V_{rms}$$

Mains Electricity (AQA & Edexcel Only)

On most power supplies, the rms voltage is provided. The 230V stated for the UK mains power supply is the rms value.

To calculate the peak voltage or peak-to-peak voltage of the UK mains electricity supply, just rearrange $V_{rms} = \frac{V_0}{\sqrt{2}}$ into $V_0 = \sqrt{2}\, V_{rms}$:

$$V_0 = \sqrt{2} \times V_{rms} = \sqrt{2} \times 230 = 325.26 \ldots = 330V(to\ 2s.f.)$$
$$V_{peak-to-peak} = 2 \times V_0 = 2 \times 325.26 \ldots = 650.53 \ldots = 650V(2s.f.)$$



Worked example 1:

A light is powered by a sinusoidal AC power supply with a peak voltage of 4.5V and a root mean square current of 0.80 A.

a) Calculate the root mean square voltage of the power supply.

$$V_{rms} = \frac{V_0}{\sqrt{2}} = \frac{4.5\ V}{\sqrt{2}} = 3.1819 \ldots = 3.18\ V(3s.f.)$$

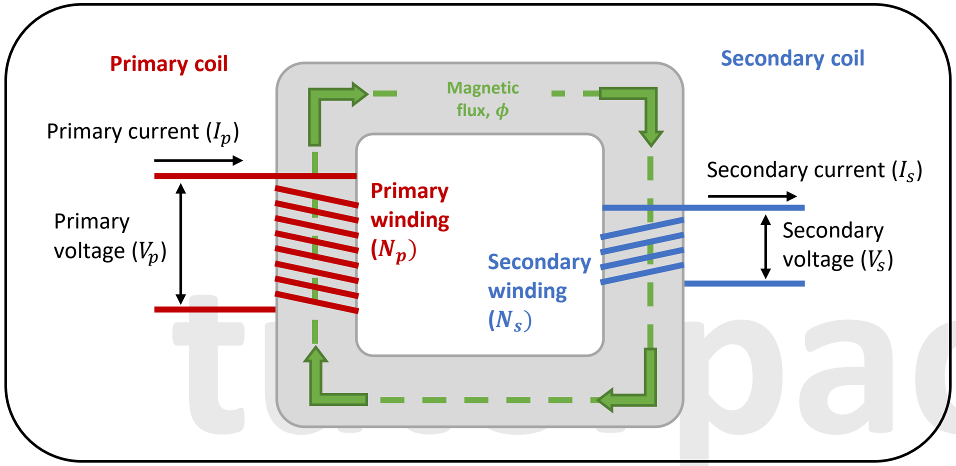
b) Calculate the power of the power supply

$$Power_{rms} = I_{rms} \times V_{rms} = 0.80\ A \times 3.18 \ldots V = 2.5455 \ldots W$$
$$Power = 2.5\ W\ (2s.f)$$

Transformers

Transformers are highly efficient devices that convert alternating p.ds (voltages) from one value to another using the phenomenon of electromagnetic induction.

The transformer is made up of two coils, the primary and secondary, coiled onto a laminated soft iron core in its most simplest form.



When an alternating voltage is applied to the primary coil, an alternating current is generated, which causes an alternating magnetic flux in the core. The magnetic flux is guided around the core by the laminated core, which prevents it from leaving the core. This changing magnetic flux then connects with the secondary coil turns, causing an alternating e.m.f. (or voltage) to be induced across it.

The iron core itself has no current flowing through it.

Transformers

The primary and secondary coil voltages can be calculated using Faraday's law:

Primary coil: $V_p = N_p \frac{\Delta\Phi}{\Delta t}$

Secondary coil: $V_s = N_s \frac{\Delta\Phi}{\Delta t}$

Where:

V_p = voltage across primary coil in V

N_p = number of turns on primary coil

$\frac{\Delta\Phi}{\Delta t}$ = rate of change of flux in $Wb\ s^{-1}$

V_s = voltage across secondary coil in V

N_s = number of turns on secondary coil

Combining these equations gives the equation for an ideal transformer (one that is 100% efficient):

$$V_p = N_p \frac{\Delta\Phi}{\Delta t} \Rightarrow \frac{V_p}{N_p} = \frac{\Delta\Phi}{\Delta t}$$
$$V_s = N_s \frac{\Delta\Phi}{\Delta t} \Rightarrow \frac{V_s}{N_s} = \frac{\Delta\Phi}{\Delta t}$$
$$\frac{V_p}{N_p} = \frac{V_s}{N_s} \left(= \frac{\Delta\Phi}{\Delta t}\right)$$

Rearranging gives:

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

The above is also known as the turns ratio (R):

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

- A step-up transformer has more turns on the secondary coil than on the primary coil, so the secondary voltage is greater than the primary voltage.
  $$N_s > N_p \ so \ V_s > V_p$$
- A step-down transformer has less turns on the secondary coil than on the primary coil, so the secondary voltage is less than the primary voltage.
  $$N_s < N_p \ so \ V_s < V_p$$

Transformers

Calculating Efficiency

Remember that in a circuit power transferred is given by:

$$P = IV$$

Where:

- P = power in W
- I = current in A
- V = voltage in V

So for an ideal transformer:

Electrical power input to the primary coil = electrical power output from the secondary coil

$$Primary\ current \times primary\ voltage = secondary\ current \times secondary\ voltage$$

$$I_p \times V_p = I_s \times V_s$$

$$\frac{I_p}{I_s} = \frac{V_s}{V_p}$$

You can get the following result by combining the two ideal transformer equations:

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

But because not all of the power is transferred, you can calculate the transformer's efficiency by dividing the power out by the power in:

$$efficiency(\%) = \frac{Power\ Out}{Power\ In} \times 100 = \frac{I_s V_s}{I_p V_p} \times 100$$

Where:

- I_s = current across secondary coil in A
- V_s = voltage across secondary coil in V
- I_p = current across primary coil in A
- V_p = voltage across primary coil in V

A transformer will lose energy if it is not 100 % efficient (mostly through heat). The power that isn't transferred to the secondary coil must be transferred to something else. The following equation can be used to calculate the amount of energy that has been 'lost':

$$E = Pt$$

Where:

- E = energy in J
- P = power in W
- t = time in s

Transformers

Inefficiency in a transformer

Transformers are made to keep energy losses to a minimum. The windings, for example, are made **of extremely low-resistance coppers** to minimise energy loss due to heat generated in the coils. The core's shape and material, as well as **the lamination of the core**, ensure that nearly all of the magnetic flux created by the primary coil is sent to the secondary coil.

However, there will **be minor power losses** from the transformer, most of which will be **in the form of heat.**

Resistance in the coils generate heat. **Low-resistance wires** can be used to help with this. Since **copper** has a **low resistivity** (resistivity is a measure of how strongly a substance opposes the flow of electric current), thick copper wire is used for this, and a bigger diameter means less resistance.

The secondary coil of a step-down transformer or the primary coil of a step-up transformer carry a higher current, so using low-resistance wires is very critical.

Eddy currents, which are created by the alternating magnetic field in the primary coil and form a loop, is another cause of energy loss in a transfer. They resist the field that formed them due to Lenz's law, reducing the flux density of the field and generating heat, resulting in energy loss.

The impacts of eddy currents can be managed by using a laminated iron core, which **consists of layers of iron sandwiched between layers of an insulator**. Because eddy currents cannot flow through the insulator, their amplitude is reduced. Eddy currents can also be decreased by using a high-resistance metal as a core.

Also in order to magnetise and demagnetise the core, energy is required, and this energy can be wasted as it heats up the core. A **magnetically soft material** that magnetises and demagnetizes quickly should be used to minimize this effect.

Investigating Transformers

The relationship between turns

Setting up the equipment as illustrated below will allow you to investigate the relationship between the number of turns and the voltages across a transformer's coils:

Step 1: Wrap two wires with ten coils each around an iron core.

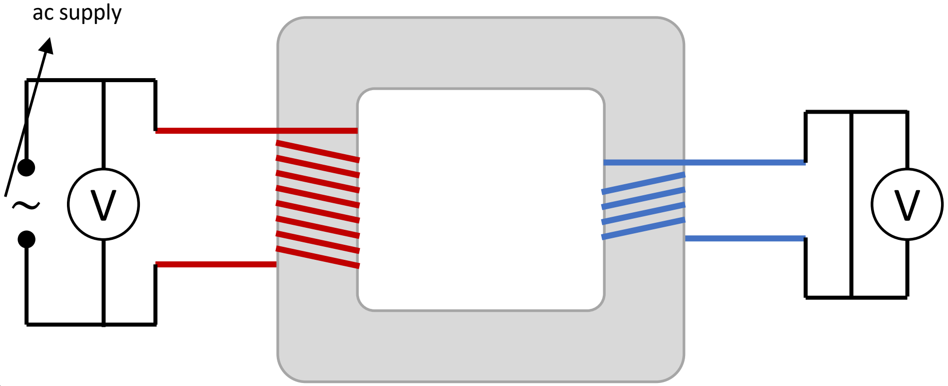
Step 2: In parallel, connect the primary coil to a low voltage ac supply and a voltmeter.

Step 3: Connect a voltmeter to the secondary coil.

Step 4: Record the primary and secondary voltages.

Step 5: Change the number of coils on the secondary coil while keeping V_p and the number of coils on the primary coil the same.

Step 5: Then divide N_s by N_p and V_s by V_p to determine that for each ratio of turns, $\frac{V_s}{V_p} = \frac{N_s}{N_p}$.



Investigating Transformers

You can use the same equipment as before to investigate the relationship between current and voltage in the primary and secondary coils with a specific number of turns, but add a variable resistor to the primary coil circuit and an ammeter to both circuits as shown below.

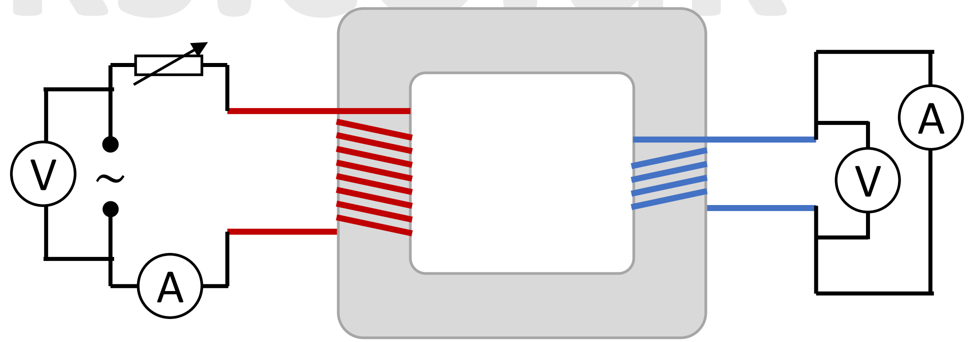
Step 1: Turn on the power supply and record the current flowing through each coil and the voltage.

Step 2: Change the input current by adjusting the variable resistor. Remember not to change the number of turns of the coils.

Step 3: Record current and voltage for each coil for this new input current.

Step 4: Then repeat the steps for a range of input currents.

You should find that for each current, $\frac{I_p}{I_s} = \frac{V_s}{V_p} = \frac{N_s}{N_p}$



Please see '12.3.2 Electromagnetism worked examples' pack for exam style questions.

For more revision notes, tutorials and worked examples please visit www.tutorpacks.co.uk.