keep it simple science®

KEEP IT SIMPLE SCIENCE

PhotoMaster Format

Physics Module 6

Electromagnetism

Topic Outline

1. Electric Charges in Electric & Magnetic Fields
- Revision of electric charges & fields
- Acceleration of charges in electric field
- Trajectory of a charge in electric field
- Revision: currents & magnetic fields
- Force on a moving charge in a magnetic field
- Trajectory

2. The Motor Effect
- Force between 2 wires carrying current
- Force on a wire carrying current in a magnetic field. Direction of force
- Effect of angle and other parameters
- Cause of the “Motor Effect”
- Torque (again)
- Torque on a coil in a field
- Simple electric motors & their parts

3. Electromagnetic Induction
- Revision of solenoids & electromagnets
- Electromagnetic induction
- EM flux & flux change
- EMF & Faraday’s Law
- EMF in a conductor moving in a field
- Lenz’s Law
- Generators
- Transformers

4. Applications of the Motor Effect
- Back-EMF in motors
- Applications of Lenz’s Law
- The induction motor
- Laminations in the core

Attention Teachers & Students

This module might NOT cover all the syllabus content as fully as KISS Resources usually do.
This is due to time constraints, as explained by a notice at our website.

What is this topic about?

To keep it as simple as possible, (K.I.S.S. Principle) this topic covers:

1. Electric Charges Interact with Electric & Magnetic Fields

Revision of electric charges & fields. Energy & voltage. Acceleration of a charge in an electric field. Work done on the charge. Trajectories of charges in & across electric fields. Revision of magnetic field basics. Force on a moving charge in a magnetic field. Trajectories.

2. The Motor Effect

The force between 2 wires carrying a current. Significance to defining the “amp” unit. Force on a wire carrying current through a magnetic field. Direction of the force. Angles & other parameters. Torque reminder. Torque on a loop carrying current through a field. Simple electric motors and their components.

3. Electromagnetic Induction

Revision of magnetic fields produced by solenoids & electromagnets. Electomagnetic induction. Magnetic flux & flux density. EMF & Faraday’s Law. EMF induced in a conductor moving in a field. Lenz’s Law. Back-EMF & eddy currents. Electrical generators. Comparing AC & DC electricity. Transformers & how they work. Step-up & step-down. The transformer equation.

4. More Applications of the Motor Effect

Back-EMF in a motor. Applications of Lenz’s Law... EM braking & induction cooking. The induction motor: parts & features. Why have laminations in the core?

keep it simple science

1. Electric Charges Interact with Electric & Magnetic Fields

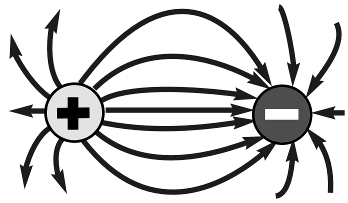
We begin with a revision of some basics covered back in Module 4.

Electrical Forces & Fields

The forces are best explained by imagining that each electrical charge is surrounded by a "FORCE FIELD". Any electrical charge which is placed within the field will experience a force.

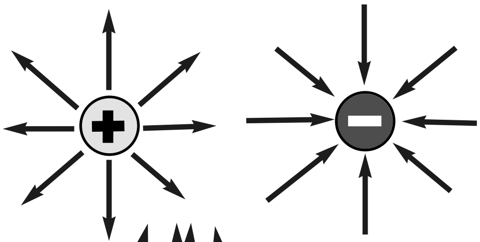
By definition, the direction of the force field lines is the direction a <u>positive</u> (+ve) charge would move if placed in the field.

Field shape between two opposite charges (attracting each other)

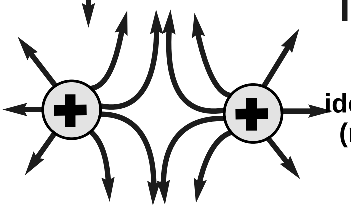


SHAPES OF FIELDS AROUND POINT CHARGES

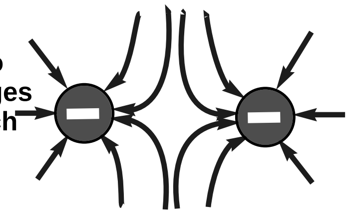
POSITIVE NEGATIVE



Sliding down a plastic "slippery-dip" has charged this girl with "static electricity". Since each hair has the same charge, the hairs repel each other.
Image by Chris Darling. CCA 2.0 licence.



Field shape between two identical charges (repelling each other)

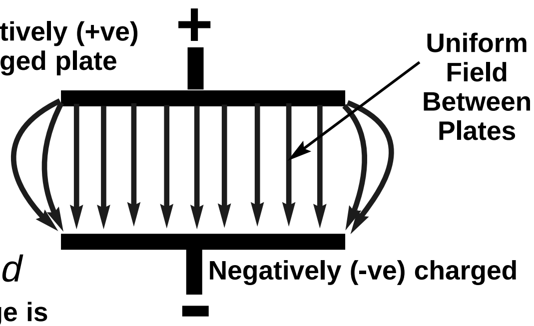


Note that all the electric fields above have irregular shapes and the strength of the field (and any forces that occur) vary from point to point.

Field Between Parallel Charged Plates

The only electrical field that is quite regular and has the same strength at each point is shown.

Oppositely charged metal plates like this are often used in scientific experiments because they have a regular strength and shape. This makes it easier to study the field & behaviour of small electrically-charged objects within it.



Measurement of Electrical Charge & Field

The unit of <u>electric charge</u> is the coulomb (C). 1 coulomb of charge is quite a large amount, so "microcoulombs"(μC) are commonly used.
1 μC = 1 x 10^{-6} C. **("Coulomb" is named in honour of a French scientist.)**

The <u>electric field strength</u> (E) is defined and measured as the force which a charge of +1 C would experience if placed in the field. Electric field is a VECTOR: it has a direction as well as a value. The direction is the way a +ve charge would move.

Since force is measured in newtons (N), and charge is in coulombs (C), it follows that the unit of electric field strength is the "newton per coulomb" (NC^{-1})

This means if a charge "q" experiences an electric force "F", then there must be an electric field present, and its strength is F/q.

Example Problem 1

When an electric charge "q" = 6.50×10^{-4} C is placed in an electric field, it experiences a force of 8.15×10^{-2} N. What is the field strength at that point?

Solution:
E = F / q = 8.15×10^{-2} / 6.50×10^{-4}
E = 125 NC^{-1}

Electric Field = Force / Charge

$$\vec{E} = \frac{\vec{F}}{q} \quad \text{or} \quad \vec{F} = \vec{E}.q$$

Example Problem 2

What force would be experienced by a charge of 4.68×10^{-6} C, when placed in an electric field with strength 3.65×10^{3} NC^{-1}?

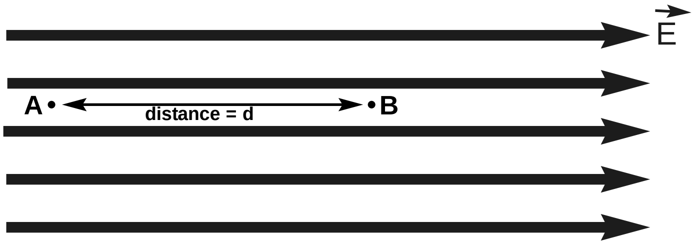
Solution

E = F/q, so F = E.q = $3.65 \times 10^{3} \times 4.68 \times 10^{-6}$
= 0.017082 (= 1.71×10^{-2} N)

Energy & Voltage in an Electric Field

Potential Energy in an Electric Field

Imagine a uniform electric field (E) such as the field produced between 2 parallel metal plates with opposite charges. If an electric charge (q) were to be placed within the field, it will experience a force according to $F = E.q$ as already covered. Remember also, that the vector direction of the field is the direction that a +ve charge would move when acted on by the force.



Now, suppose we could place an electrically charged particle at point A and let it go.

If it is a +ve charge it will experience a force to the right and (if no friction) it will accelerate, thereby gaining a certain amount of kinetic energy by the time it reaches point B.

If it is a negative charge and we want it to go to point B, we would need to supply a force to push it. (against the electric force) Applying a force over a distance means we would have to do "work" and you are reminded that work = energy.

Where is this going?

The points A and B need to be seen as having different amounts of potential energy within the field. Potentially, a (+ve) charge can gain energy by accelerating from A to B, or a (-ve) charge can be pushed from A to B by doing work on it. (If released from point B, the (-ve) charge would use that potential energy to accelerate back to A.)

So, different places "upstream" or "downstream" in the field can be thought of as points of different potential energy. However, exactly how much energy depends on the size of the charge involved.

Time for a new (and very useful) concept...

Voltage ("Potential Difference")

"Voltage" is a word you already know, but perhaps didn't quite understand what it measures.

Voltage is a measure of the amount of energy (either lost or gained) by a charged particle as it moves "upstream" or "downstream" in an electric field.

Since it measures the energy per unit of charge, you might guess that the units of voltage would be joules per coulomb (JC^{-1}). This is correct, but we call this unit the "volt" (V).

It is named after Alessandro Volta, an Italian scientist who was very important in the history of our understanding of electricity... worth researching!

Voltage can be defined in at least 2 different ways:

$$V = \frac{\Delta U}{q}$$

V = voltage, in JC^{-1}, or V.

ΔU = change in potential energy, in joules (J).

q = size of the electric charge involved, in coulombs (C).

$$V = E.d \quad \text{or} \quad E = \frac{V}{d}$$

V = voltage, in JC^{-1}, or V.

E = electric field strength, NC^{-1}.
d = distance between the 2 points being compared within the field, in metres.

Before looking at examples of how to use these equations, let's do a little algebra:

$E = V / d$ and you already know that $E = F / q$.
Therefore, $V / d = F / q$, so $V = F.d / q$.

Also above we have that $V = \Delta U / q$,

Therefore, $F.d / \cancel{q} = \Delta U / \cancel{q}$
Cancelling the charges, gives $F.d = \Delta U$

This says "Work done" = "Change in Energy". Well, we already knew that! The point is, that it proves that these equations are equivalent and inter-changeable. Use whichever applies.

At this point you should note that, if a charge loses potential energy in a field, there must be gain of something else: maybe it accelerates to a higher Kinetic Energy. Energy must be conserved!

Another point to note, by example:
If 2 plates are 10mm apart and have a voltage across them of (say) 200V, there is a change of 20V per mm as you move down the field. Half-way across the voltage is 100V... it is proportional to distance. $V = E.d$

Example Problem

Two parallel charged plates have a uniform electric field of 28,000 NC^{-1} between them. They are 1.0cm apart.
a) What is the voltage across the plates?

b) How much energy would be gained by a charged particle (charge $q = 5.2 \times 10^{-6}$ C) which accelerates from one plate to the other?

Solution:
a) Use $V = E.d = 28{,}000 \times 0.01 = 280$ V

b) Use $V = \Delta U / q$
so $\Delta U = V.q = 280 \times 5.2 \times 10^{-6} = 1.46 \times 10^{-3}$ J.

Another example, next page...

keep it simple science

Using the Voltage Equations (cont.)

Example Problem 2

A uniform electric field is established between 2 metal plates with a potential difference (voltage) of 10,000V across them. The plates are 5cm apart in vacuum. A stream of electrons is accelerating between the plates, gaining a total of 2.5 J of energy per second.
a) What is the strength of the electric field?
b) How <u>many</u> electrons are passing through the field per second?

Solution: **a) $E = V / d = 10{,}000 / 0.05 = 2.0\times10^{5}\ NC^{-1}$.**

b) $V = \Delta U / q$ so $q = \Delta U / V = 2.5 / 10{,}000 = 2.5 \times 10^{-4}$ C.

This is the total charge per second. To find how many electrons, divide by the charge on one electron:
No.electrons = $2.5\times10^{-4} / 1.6\times10^{-19} = 1.56 \times 10^{15}$ electrons

Charge on an Electron. Equipotentials

Charge on an Electron

It should be no surprise to know that the most common charged "particle" you are likely to deal with is the electron. Electrons are the charged particles which create static charges when they transfer from place to place and are the charges which flow in an electric current.

The amount of charge carried by an electron is:

$$q_e = -1.602 \times 10^{-19}\ C$$

You don't need to remember this value... it's on your Data Sheet.

As you might expect, this value is a very small amount of charge. In fact, you cannot get any electric charge smaller than this... it is the "quantum" of electric charge. All electric charges are a multiple of this value.

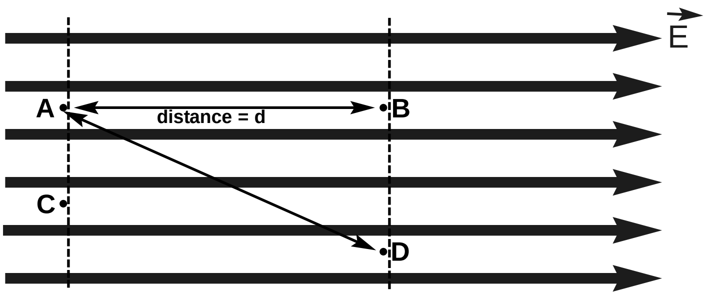
As you might guess, the charge carried by a proton is:

$$q_p = +1.602 \times 10^{-19}\ C$$

Study the example above, then try the worksheets.

Equipotentials

Below is the same diagram from the previous slide, but with extra points "C" & "D" added.



Previously, we considered the energy effects of a charged particle moving from A to B.

What about if it moved from A to D?

The distance A-D is geometrically more than A-B. Does this mean that if a particle moved A-D that you need to put a larger distance into the equation, for example, V = E.d?

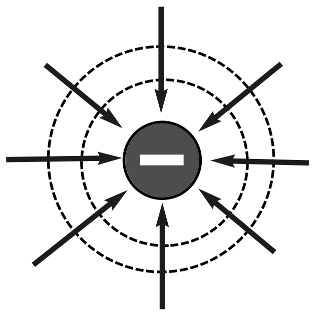
Is more work done (V = F.d / q) moving a charge A-D compared to A-B?

Actually, No! The distance "d" in the equations must (technically) be the <u>vector component of displacement</u> which is <u>parallel</u> to the field. The displacements A-B and A-D are exactly the same in terms of their displacement vector parallel to the electric field. Compared to point A, both points B&D are <u>equivalent</u> in terms of their potential energy within the field.

The dotted line is called an "<u>equipotential</u>". Every point along this line has the same potential and no work is done to move a charge along this line. (Assuming no friction or other forces are acting on the charge particle.) Note that equipotential lines are always perpendicular to electric field lines.

Similarly, point C is equipotential with point A. If a charge was moved from A to C to D to B, the energy change & voltage change would be the same as moving from A-B directly.

As another example, the diagram below shows some equipotentials (dashed lines) in the field surrounding a point charge.



keep it simple science

Acceleration of a Charge within an Electric Field

Hopefully, it is now obvious that a positive charge placed within an electric field will accelerate in the direction of the field lines. A negative charge will accelerate in the opposite direction. Calculating the acceleration (etc) is a simple application of the Dynamics equations.

Example Problem: Acceleration

Two parallel charged plates are separated by a distance of 20mm (0.020m) and have a potential difference of 500V between them.

a) What is the strength of the electric field?

b) How much energy would be gained by a single electron which accelerates from one plate to the other?

c) Starting at rest, at what velocity would the electron strike the positive plate?

d) What was its acceleration rate?

e) Calculate the force acting on the particle using two completely different methods.

Solution

See Data Sheet for charge & mass of electron.

a) $E = V / d = 500 / 0.020 = 2.50\times10^{4}\ NC^{-1}$.

b) Use $V = \Delta U / q$

so $\Delta U = V.q = 500 \times -1.602\times10^{-19} = -8.01\times10^{-17}$ J.

(The negative sign arises because of the electron charge. The sign may be ignored, so long as you understand that the electron has lost that amount of potential energy and gained that amount of E_k.)

c) Gain of $E_k = 1/2.m.v^2 = 8.01\times10^{-17}$

$\therefore v^2 = 2 \times 8.01\times10^{-17} / 9.109\times10^{-31}$

$\therefore v = 1.33 \times 10^{7}\ ms^{-1}$.

d) use $v^2 = u^2 + 2aS$ (and u=0)

so $a = v^2 / 2S = (1.33\times10^{7})^2 / 2 \times 0.020$

$= 4.42 \times 10^{15}\ ms^{-2}$.

e) <u>method 1</u>. Use $F = ma = 9.109\times10^{-31} \times 4.42\times10^{15}$

$= 4.03 \times 10^{-15}$ N

<u>method 2</u>. Use $F = E.q = 2.50\times10^{4} \times -1.602\times10^{-19}$

$= -4.0 \times 10^{-15}$ N

(Again, the negative sign arises from the charge sign. It may be interpreted as meaning the force vector is in the opposite direction to the field.)

Work Done on the Charge

Following on from the worked example above:

1.
Energy gained / lost by the electron was calculated in part (b).
The electron lost 8.01×10^{-17} J of potential energy and gained the same amount of kinetic energy. This resulted in it gaining a very high velocity as calculated in part (c).

2.
In part (e) it was calculated that the force acting on the electron was 4.0×10^{-15} N. Since the electric field is uniform, this force would be constantly applied across the 20mm between the plates, and since

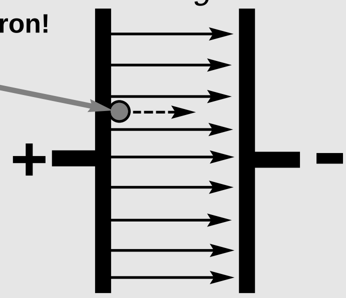
Work = Force x distance $= 4.0 \times 10^{-15} \times 0.020$
$= 8.0 \times 10^{-17}$ Nm (J)

Sure enough, this agrees with the amount of energy lost / gained by the electron. Once again, we have confirmed the equivalence of Work = Energy

Example Problem with a +ve Charge

Enough study of a measly electron!

This speck of dust with a mass of 0.040g and carrying an electric charge $q = +\ 8.4\times10^{-6}$ C was sitting on this plate (in vacuum) when the power was switched on, creating a field $E = 7{,}400\ NC^{-1}$.



a) If the plates are 12mm apart, what is the voltage?

b) How much kinetic energy would the particle gain as it travelled between the plates?

c) With what velocity would it hit the other plate?

Solution

a) $V = E.d = 7{,}400 \times 0.012 = 89$ V.

b) $\Delta U = V.q = 89 \times 8.4\times10^{-6} = 7.5 \times 10^{-4}$ J
This is potential energy lost = E_k gained.

c) Gain of $E_k = 1/2.m.v^2 = 7.5\times10^{-4}$

$\therefore v^2 = 2 \times 7.5\times10^{-4} / 4.0\times10^{-5}$ (mass in kg)

$\therefore v = 6.12\ ms^{-1}$.

keep it simple science

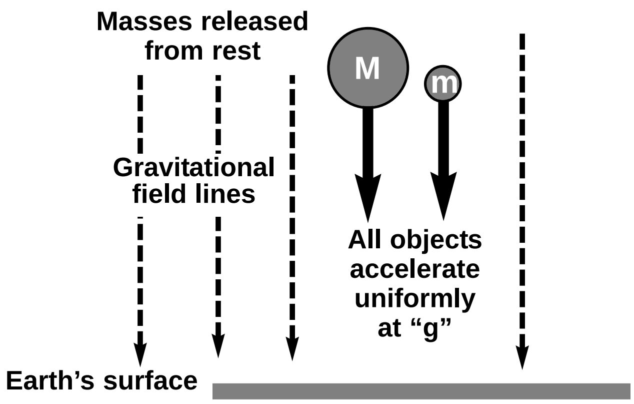
Trajectory of Charges in an Electric Field

How does the trajectory of a charged particle in an electric field compare to that of a projectile in a gravitational field? We will consider 2 simple scenarios...

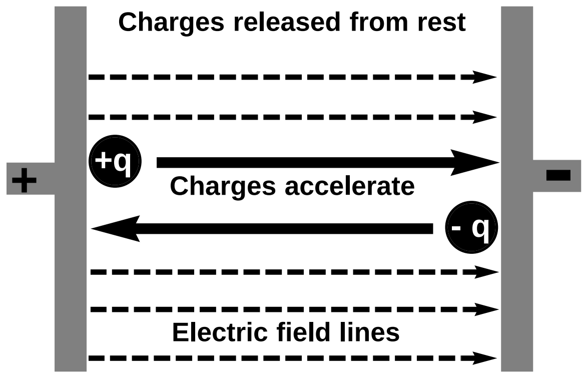
Scenario 1: Charge Released from Rest in a Field

This compares to the case of releasing a mass in a uniform gravity field (e.g. near the surface of the Earth) and letting it fall.

Mass in a Gravity Field



Charge in an Electric Field



Comparison of These Motions

Similarities

• **In both fields, acceleration is uniform and parallel to the field lines.**

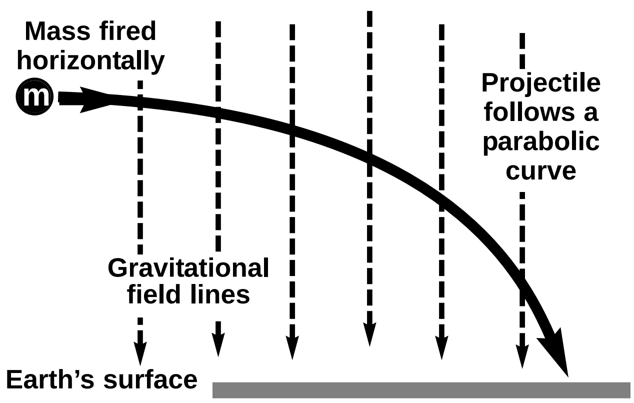
Differences

• **Gravity is always attractive. Electrical forces can attract or repel.**
• **Positive & negative charges accelerate in opposite directions.**
• **All masses accelerate at the same rate in the gravitational field. In an electric field, equal charges feel the same force, but will accelerate at different rates if their masses are different.**

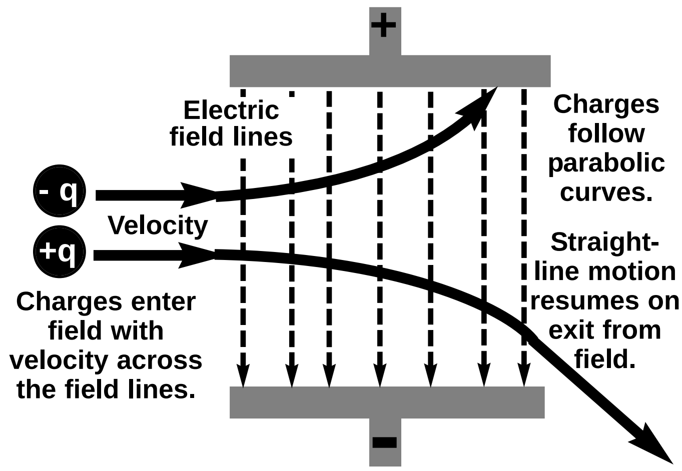
Scenario 2: Charge with a Velocity Perpendicular to Field

This compares to the case of launching a projectile horizontally near the surface of the Earth.

Projectile in a Gravity Field



Moving Charges in Electric Field



Comparison of These Motions

Try Worksheet 1

Similarities

• **In both fields, the trajectories are parabolic.**

This occurs when there is constant acceleration parallel to field lines AND constant velocity at right angles to field lines.

Differences

• **Gravitational trajectory depends only on initial velocity and angle of launch; mass is irrelevant.**

• **Exact electric field trajectories depend on velocity, polarity and magnitude of charge AND mass.**

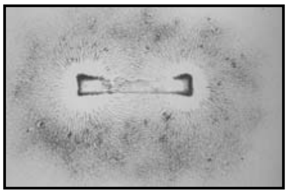
keep it simple science®

Electric Charges in Magnetic Fields

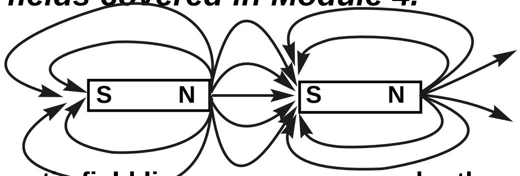
First, a quick revision of magnetic fields covered in Module 4.

Magnetic Field Made Visible

If a magnet is covered with a sheet of stiff paper (or clear plastic) and small iron particles sprinkled on top, the iron powder lines up with the magnetic field.

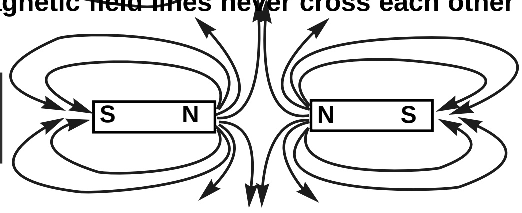


Fields Attracting



Notice that magnetic field lines never cross each other

Fields Repelling

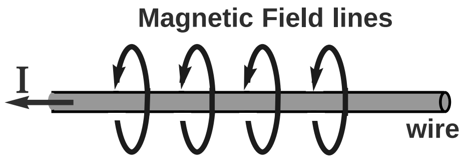


Electric Currents Create Magnetic Fields

After all that, you now need to realise that permanent magnets are quite trivial compared to what electricity can do to produce magnetic fields.

Magnetic Field Around a Wire Carrying Current

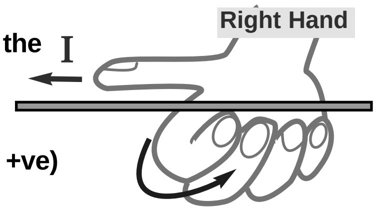
Every electric current produces a magnetic field. A wire carrying a current has a circular magnetic field wrapped around it as shown.



To predict the shape of such a field, use the "<u>Right-Hand Grip Rule</u>". Pretend you are gripping the wire with your thumb pointing in the direction of the flow of <u>conventional current</u> (+ve towards -ve).

The curling fingers show the direction of the field.

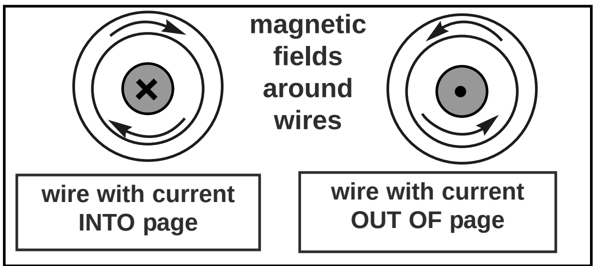
If you wish to use the <u>real current</u> (-ve towards +ve) then use your left hand.

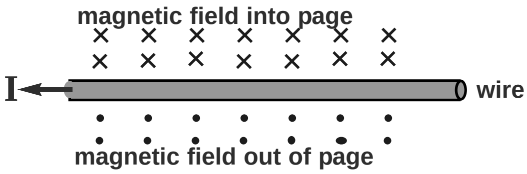


To more easily draw and understand diagrams you must also learn the "arrow" technique to represent currents or field-lines that are perpendicular to the page.

Imagine an arrow coming straight out of the page at you... all you see is its point (•). If an arrow is going down into the page, you only see its feathers (x).

Use the <u>R.H. Grip Rule</u> on these diagrams to get the idea.





Magnetic Field Strength "B"

The strength of the magnetic field (more correctly called the "magnetic flux density") around a straight wire carrying an electric current can be calculated as follows:

$$B = \frac{\mu_0 . I}{2.\pi.r}$$

B = strength of the magnetic field, teslas (T).
I = current in the wire, in amps (A).
r = radial distance from the wire to the point where the field is being measured, in metres.
μ_0 = a constant, (pron: "mu-naught") **called the "vacuum permeability".**
In vacuum (or air) its value = 1.26×10^{-6}.
(At this point, any discussion of the units of this constant would be a violation of the KISS Principle!)

The "Tesla" Unit

This unit is named in honour of <u>Nikola Tesla</u> (1856-1943) a Serbian immigrant to USA who contributed enormously to modern electrical technology of motors, generators and electrical supply grids. His name is also used by the world's largest manufacturer of electric cars, solar panels and high-tech lithium batteries.

Example Problem

A long, straight wire is carrying a current of 5.25A. What is the strength of the magnetic field around the wire at a point 1.00 cm from the wire?

Solution: $B = \mu_0 . I / 2.\pi.r$

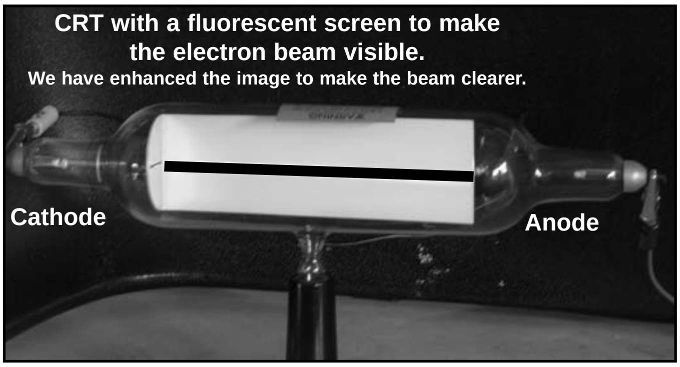
$= 1.26\times10^{-6} \times 5.25 / 2\times3.142\times0.01$

$= 1.05 \times 10^{-4}$ T

keep it simple science

Cathode Ray Tubes (CRT)

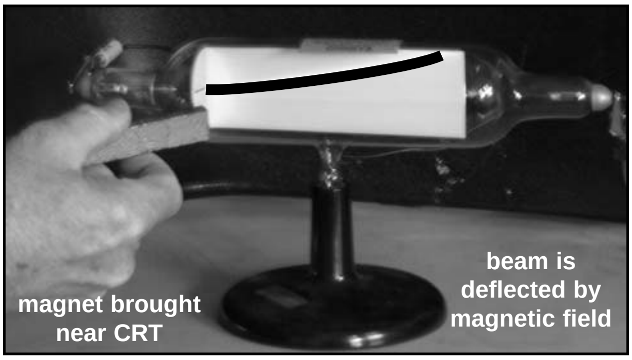
Cathode ray tubes were hi-tech scientific instruments from the mid-19th century and into the 20th. A simple CRT is a glass vacuum tube containing electrodes. When high-voltage electricity is applied to the electrodes, a beam of electrons accelerate from -ve (cathode) to +ve (anode) as shown in the photo at right. These beams were called "cathode rays" and to begin with, no-one knew what they were.



CRT's were instrumental in helping scientists to discover and understand the structure of atoms, electric & magnetic phenomena, x-rays and much more. Technologically, CRT's evolved into the earliest radio, television and radar devices. They were used to produce X-rays for medicine and they became the first electronic components leading to computers and finally to our modern electronic world.

Sadly, your syllabus no longer requires you to study this significant scientific history which made the modern world possible, but if you are lucky you may see CRT's in action to help you understand the next syllabus objective.

Force on a Moving Charge in a Magnetic Field



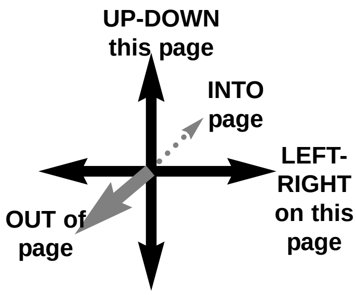
If a magnet is brought towards a CRT, the electron beam is deflected as in the photo at left.

Long-story cut short:
An electric charge experiences a force if it <u>moves</u> in a magnetic field. Basically this is because a moving charge creates its own magnetic field, as revised for electric currents on the previous page. Under certain circumstances, the magnetic field produced by the moving charge interacts with the external magnetic field to produce the force.

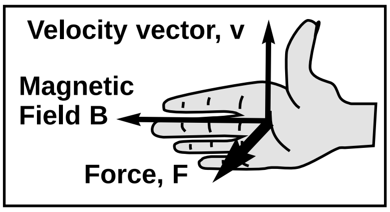
Direction of the Force

The interesting thing about this force is its direction.

The maximum force occurs if the velocity (vector) of the charge is at right angles to the magnetic field (vector) lines. The direction of the force (vector) is at right angles to both!



To help you figure out these directions use the "<u>Right-Hand Palm Rule</u>".



If your thumb points the direction of the velocity vector and your fingers point along the magnetic field lines, then the force will act on the perpendicular line out of your palm.

This applies only for a +ve charge. For negatives (such as electrons) the force comes from the back of the right hand, OR use your left hand palm.

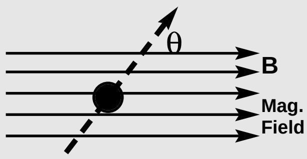
(In the photo above, you should be able to figure out that the magnet's SOUTH pole is approaching the CRT)

The size of the force can be calculated as follows:

$$F = q.v.B.\sin\theta$$

F = Force acting, in newtons (N).
q = Electric charge, in coulombs (C).
v = velocity of the charged particle, in ms^{-1}.
B= Magnetic Field strength, in Tesla (T).
θ = Angle between the velocity vector and magnetic field vector lines.

Since $\sin 90^o = 1$, and $\sin 0^o = 0$, then maximum force occurs when the charge moves at right angles to the field.



<u>Example Calculation</u>:
In the CRT above left, the cathode rays (electrons; q_e=-1.602x10^{-19}C) are moving at a velocity of 2.50x$10^6$$ms^{-1}$.
The magnet provides a field of 0.0235T.
Held as shown, the field lines are at an angle of 70^o to the beam. What force acts on each electron?

<u>Solution</u>:
$F = qvB\sin\theta = -1.602\times10^{-19}\times2.50\times10^{6}\times0.0235\times\sin70^o$
$= -8.84 \times 10^{-15}$ N.
(negative sign refers to direction being opposite to that of a +ve charge)

keep it simple science

Trajectory of a Moving Charge in a Magnetic Field

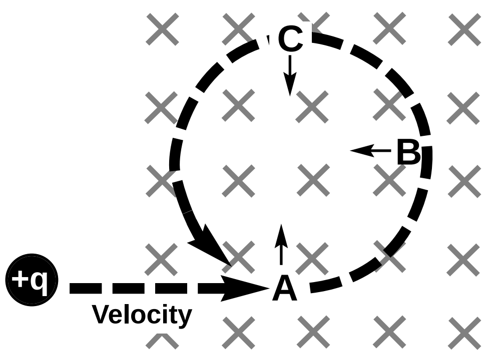
Imagine a positively (+ve) charged particle entering a uniform magnetic field with a velocity vector perpendicular to the field lines, it will experience a force at right angles to both vectors.

At point A in this diagram, the force vector is UP the page. Verify that with the Right Hand Palm Rule. (RHPR)
This force causes the particle to turn up the page.

At point B, its velocity is still perpendicular to the field lines, so you can determine that the force vector is directed across the page to the left. At point C, the force vector will be down the page and so on.

It is in Circular Motion!

Uniform magnetic field (B) into page



Here is another way to think about it:
Since the force vector is at right-angles to its velocity vector, the force cannot cause the particle to alter its speed; only its direction.

Since the force does not act along its path of motion, it can do no work on the particle and therefore, cannot change its kinetic energy.

These are all the characteristics of circular motion, so it follows that the force is acting as a centripital force.

Because it is a centripital force, it follows that:

Magnetic force = Centripital force

and so $$q.v.B = \frac{m.v^2}{r}$$

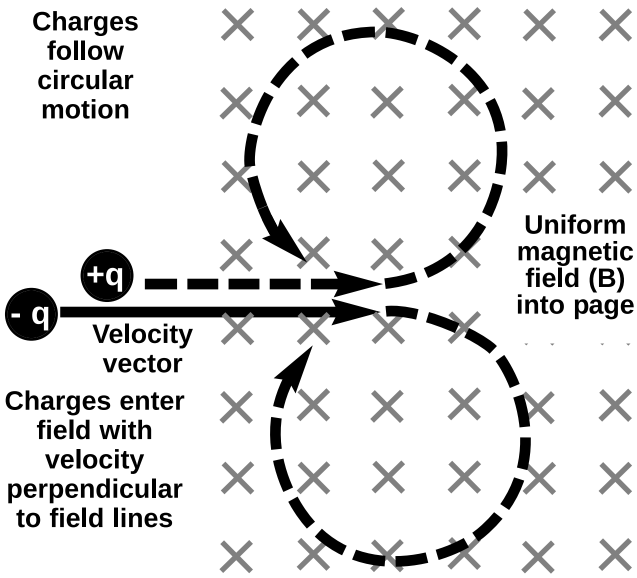
cancelling v's & re-arranging: $$r = \frac{m.v}{q.B}$$

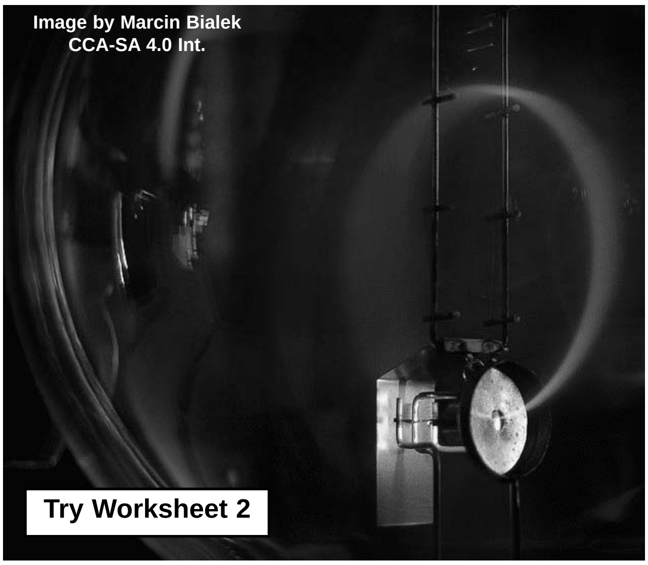
This allows you to see how the radius of the motion can be affected by particle mass, velocity & charge, and by the strength of the field. However, you are not required to go there... so we won't.

As you might figure out, a negative charge will do the same, but in the opposite direction.

The diagram below summarises the situation & the photo shows a beam of electrons in a very special CRT. A strong magnetic field is present, so the electrons are whizzing in a circle. Their faint glow is due to collisions with residual gas molecules in the vacuum flask.

Moving Charges in Magnetic Field





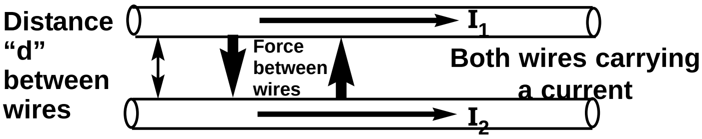
To sum up this section:
Electric charges moving in an electric field act rather like projectiles under gravity.
and
Electric charges moving in a magnetic field act rather like satellites under gravity.

keep it simple science

2. The Motor Effect

The Force Between Two Wires Carrying a Current

It was discovered in 1820 that a wire carrying an electric current produces a magnetic field. Almost immediately, Andre-Marie Ampere investigated the way that TWO wires, both carrying current, would exert a force on each other.



If the wires carry current in the SAME direction, the force ATTRACTS the wires.
If the currents flow in OPPOSITE directions, the force REPELS the wires.

Ampere found that the size of the force depends upon a number of factors:

- the amount of current in the wires
- the distance between the wires (separation)
- the length over which the wires run parallel

For his contribution, we name the unit of current after Ampere.

Mathematically,
$$\frac{F}{L} = \frac{\mu_0}{2\pi} \cdot \frac{I_1 . I_2}{d}$$

F = Force in newtons (N)
L = Length in metres (m)

F/L refers to the "force per unit of length"

μ_0 = "mu-naught" the "magnetic permeability constant". $\mu_0 = 4\pi \times 10^{-7}$ (data sheet)

So, $\mu_0 / 2\pi = 2.00 \times 10^{-7}$

I_1 & I_2 = the currents in the wires, in amps (A)
d = the separation distance, in metres (m)

The Ampere Unit

The relationship above is actually used to define the amp unit. "1 amp is the current in two long, parallel wires which are 1m apart in vacuum, which produce a force of 2×10^{-7} N per metre of length."

Note that there is a proposal to change this official SI definition by 2019-2020.

You'll notice that the force is very small in the example at right. In fact, this type of force is very weak and in general electrical wiring is totally insignificant.

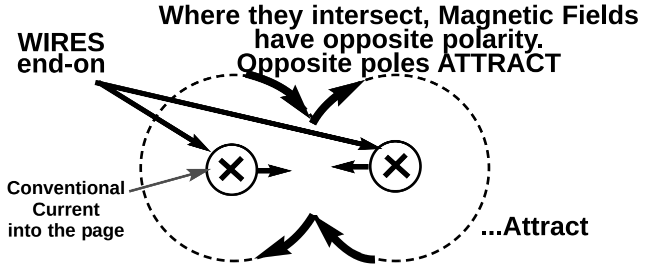
However, the point is that it shows that electrical currents create magnetic fields and forces, and that electrical currents can interact with magnetic fields and with other currents.

This is the basis of ELECTRIC MOTORS, GENERATORS and TRANSFORMERS... read on.

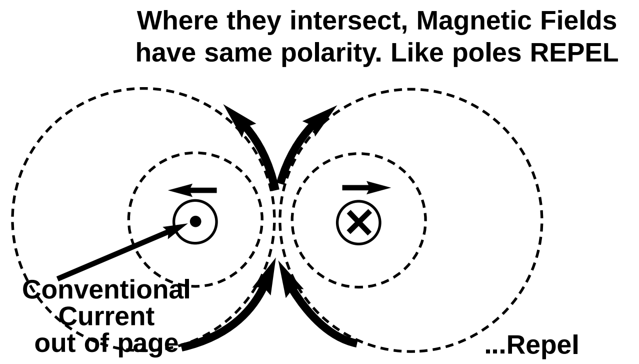
The explanation for the forces is quite simple...

If you look at the wires end-on, and use the "Right-Hand Grip Rule" to visualise their magnetic fields:

Currents in the Same Direction...



Currents in Opposite Directions...



Example Problem:
Two long, straight, parallel wires are carrying 5.60A and 12.3A in the same direction. The wires are 2.50cm apart.

a) Calculate the force per metre between them.
b) If the parallel section of the wires runs for 4.75m, find the total force acting in this section.

Solution:

a) $\frac{F}{L} = \frac{\mu_0}{2\pi} \cdot \frac{I_1 . I_2}{d} = 2.00 \times 10^{-7} \times 5.60 \times 12.3 / 0.025$

$= 5.51 \times 10^{-4}$ N/m, attraction.

i.e. Each 1 metre of parallel wires has a force of 0.000551N acting between the wires.

Note that the force is attracting the wires because the currents are in the same direction. If the currents flowed in the opposite directions, the same force would be repelling the wires.

b) $\frac{F}{L} = 5.51 \times 10^{-4}$ newtons per metre

So, $F = 5.51 \times 10^{-4} \times 4.75$
$= 2.62 \times 10^{-3}$ N attraction.

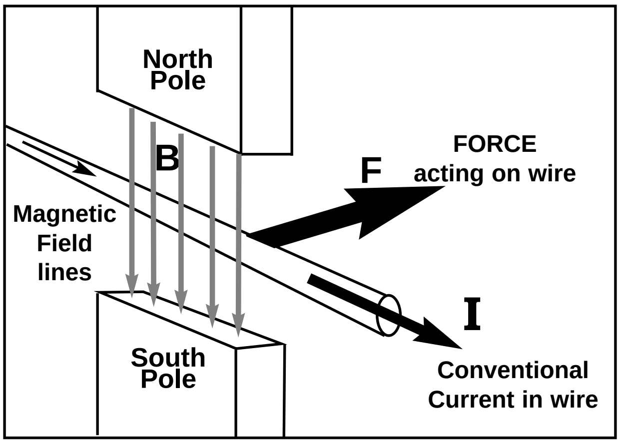
Try Worksheet 3

keep it simple science

The Motor Effect

Although the force between 2 wires carrying a current is rather weak, the effect can be much more powerful if more than one wire is involved, and if the magnetic fields involved are a lot stronger.

If, for example, a wire is carrying a current through a powerful magnetic field, the wire will experience a significant, noticeable force. This is called "The Motor Effect". This powers electric motors.

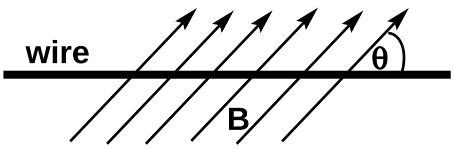


Factors Affecting the Magnitude of the Force

- The Strength of the Magnetic Field (B)
- The Current (I) carried in the wire
- The Length (L) of wire within the magnetic field
- The sine ratio of the angle (sinθ) between the wire and the magnetic field lines

$$F = B.I.L.\sin\theta$$

F = Force, in newtons (N)
B = Magnetic Field strength, in tesla (T)
I = Current, in amps (A)
L = Length of wire within the field, in metres (m)
θ = Angle between wire and field. See below



Measurement of Magnetic Field

Your are reminded that the "strength" of a magnetic field can be thought of as the "density" of the magnetic force lines passing through an area of space. The symbol used is "B".

The unit of measurement is the "tesla" (T), named after an engineer/inventor who made great contributions to the practical development of electricity generation.

Since the force is directly proportional to each of these factors, it follows that any increase in the
- magnetic field strength

or
- current

or
- length of wire within the field

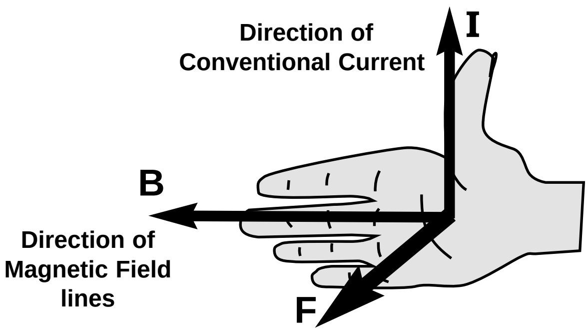
will increase the force, in proportion.

What about the angle?
You know that $\sin 0^o = 0$
and $\sin 90^o = 1$
Therefore, the maximum force on the wire occurs when the wire and the field lines are at right angles. If the wire is parallel to the field lines, $\theta = 0^o$ and so the force is zero.

Direction of the Force?

In the diagram at left, notice that the magnetic field lines, and the current direction, and the resulting force are all at right angles to each other.

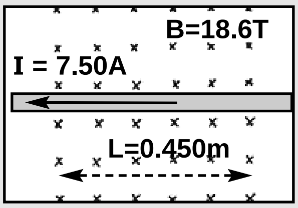
The simplest way to determine the direction of the force is "THE RIGHT-HAND PALM RULE".



Direction of Force.
In this diagram, the force is out of the page.

As before, if considering REAL CURRENTS, use the "backhand" or your left hand.

Example Problem:
A wire carrying 7.50A of current is within a magnetic field 0.450m wide, with a strength of 18.6T. The field is directed into the page as shown.



What force (including direction) acts on the wire?

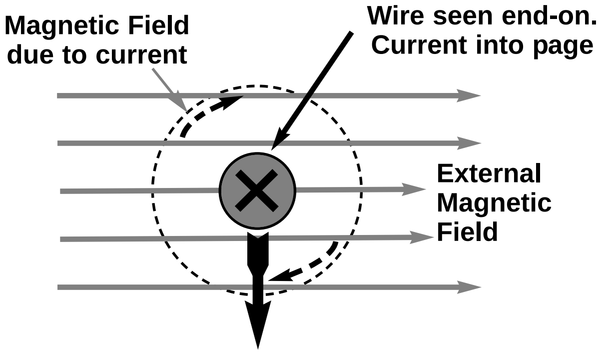
Solution: $F = B.I.L.\sin\theta$
$= 18.6 \times 7.50 \times 0.450 \times \sin 90^o$
$= 62.8N.$
The Right-Hand Palm Rule shows that the force is directed down the page.

Try Worksheet 4

keep it simple science®

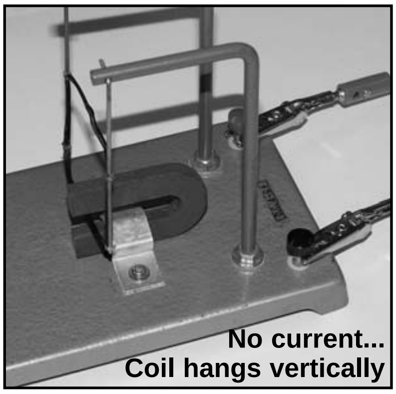
What Causes the Motor Effect?

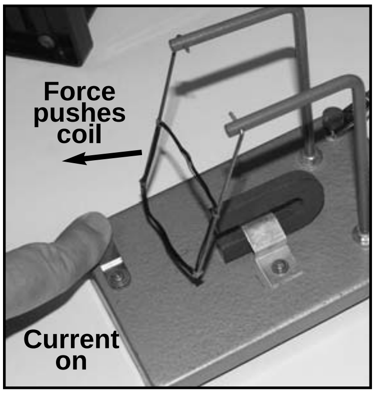
As you can probably figure out for yourself, the force on the wire is due to the external magnetic field interacting with the field produced by the current in the wire.



Force on wire due to interaction of magnetic fields

Verify the direction of the force using the RH Palm Rule.





Prac: Investigation of the Motor Effect

You will have done some experimental work in class to see the Motor Effect in action.

There are many possible ways to do this, but a simple example is shown in the photos at left.

The "external magnetic field" is provided by a horse-shoe magnet (U-shaped). This produces a magnetic field passing around the bottom wires of the rectangular coil.

Current passes through the rectangular coil of wire. Only the bottom, horizontal strands of wire are properly within the external field.

The wire is free to swing and deflects, as shown, when current flows.

Reversing either the current direction, or the polarity of the magnetic field, will reverse the force on the coil and the way it deflects.

A Reminder About Torque

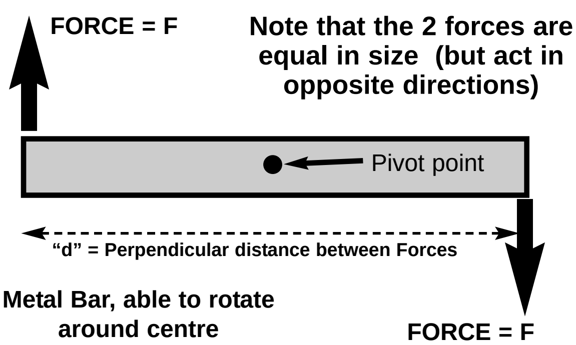
"Torque" was introduced briefly in Module 5. Here is a quick refresher:

Torque is a measure of the "turning moment" of a force, or more commonly a pair of forces, causing rotation as shown below. Mathematically,

$$\tau = F.d$$

τ = Torque, measured in newton-metres (N.m)
Note that the Greek letter "tau" is used for torque
F = Force, in newtons (N)
d = perpendicular distance between forces, in metres (m)

Note: the syllabus requires you know the definition of "torque", but not to solve problems with this particular equation.



Everyday examples of applying torque include:

- **pushing a door open on its hinges. If you push on the door at a point close to the hinges, you need much more force to get the same torque as pushing at the outside edge.**

- **winding the handle on a fishing reel, or winch. If the shaft of the handle is longer, you get more torque and the job is easier.**

The concept of torque is especially important with motors. We will come back to it later in this topic when electric motors are covered.

Is Torque the Same as "Work"?

The unit of torque is a newton-metre. This is the same unit as Work. (W = F.S) Work is equivalent to energy, so a newton-metre of work is equal to a joule of energy. So, is torque equal to energy?

NO! Torque is NOT the same as energy because the direction of motion (rotation) is NOT in the line of the forces.

(The energy of a motor can be found by multiplying the torque by the rotation rate, but we are not going there)

At this point we will diverge from the content sequence of the Syllabus. This bit should be covered later, but we think it makes more sense here.

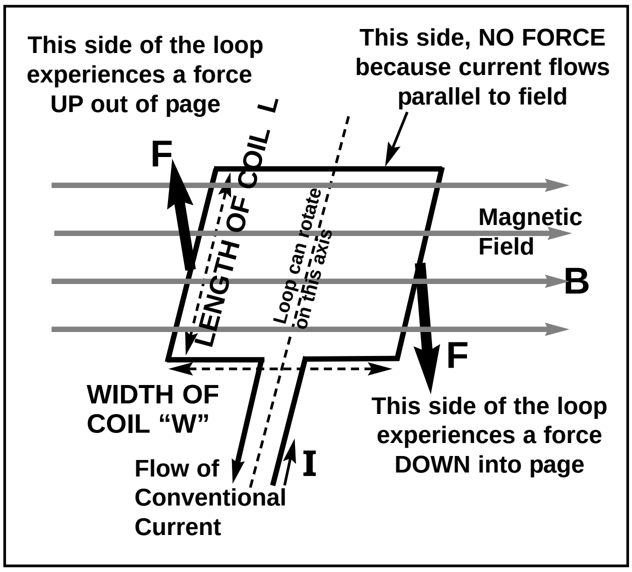
Torque on a Loop of Wire Carrying Current in a Magnetic Field

Instead of the simple deflection of a wire, what if we arrange for a loop of wire to rotate within the magnetic field? Now things become very useful!

The loop of wire below is carrying a current while in a magnetic field. If you consider the geometry shown in the diagram, you'll see that the sides of the coil, at left and at the right, will experience forces in opposite directions. (Use RH palm rule to verify directions)

If this loop of wire is able to rotate, the forces on each side will provide a torque and cause it to rotate about its central axis.

Notice that the other sides of the loop will NOT experience any force because the current flow is parallel to the field.



The force on each side is $F = B.I.L.\sin\theta$

(If the angle between the current and magnetic field is 90°, then $\sin\theta = 1$. We will assume that here.)

Remember that Torque = Force x distance between forces so the Torque on the loop is

$$\tau = B.I.L.W$$

However, the factor (LxW) = the AREA of the loop, so

$$\tau = B.I.A$$

This is the torque provided by just one wire in the loop. If the loop is a coil made up of "n" strands of wire, then

$$\tau = n.B.I.A$$

...continued above right

Finally, it can be shown that as the coil rotates, there are positions where the forces on the wires do NOT cause rotation, so the torque varies with the angle between the plane of the coil, and the field.

The angle preferred by the syllabus is "the angle between the magnetic field lines and the normal to the plane of the coil."

(Note that some sources & texts use a different angle)

The final formula is:

$$\tau = n.I.A.B.\sin\theta$$

τ = Torque on the coil, in newton-metres (N.m)
n = number of loops of wire in the coil
B = strength of the magnetic field, in tesla (T)
I = current flowing in wires, in amps (A)
A = Area of coil, in square metres (m^2)
θ = angle between mag.field & the normal to the plane of the loop.

Note that $\sin 0^o = 0$ and $\sin 90^o = 1$ so maximum torque occurs when the plane of the coil lies "flat" in the field, so the normal line is at 90^o to the mag. field.

Example Problem:

A rectangular coil (just like in the diagram at the left) made up of 50 loops of wire, is carrying a current of 5.65A through a magnetic field of 20.0T strength.
The dimensions of the coil are 4.50cm x 8.25cm.

What is the torque on the coil at the instant when the normal is at 60^o to the field lines?

Solution: $\tau = nIAB\sin\theta$

$\therefore \tau = 50 \times 5.65 \times (0.0450 \times 0.0825) \times 20.0 \times \sin 60$
$= 18.2$ N.m.

Try Worksheet 5

Notice that the dimensions of the coil were given in cm, but must be converted to metres; S.I. units must be used!

By now you will have realised where this is going... Electric Motors!
An electric motor is a coil (usually more than 1) which carries a current while surrounded by a magnetic field. The coil experiences torque, which causes it to rotate.
When attached to axles, gears, etc. the motor can do all sorts of useful work!

keep it simple science

Structure of a Simple DC Motor

Basically, an electric motor is nothing more than a coil of wire, built onto an axle so that it can rotate within a magnetic field.

When current is switched on in the coil, the magnetic forces create a torque which rotates the coil.

In small, simple motors (such as in a child's toy car) the magnetic field is provided by a permanent magnet. (As shown in the diagram) In most motors, the field is provided by an electromagnet.

The tricky bit is to supply electric current to a rotating coil, and to maintain a steady, continuous torque... read on...

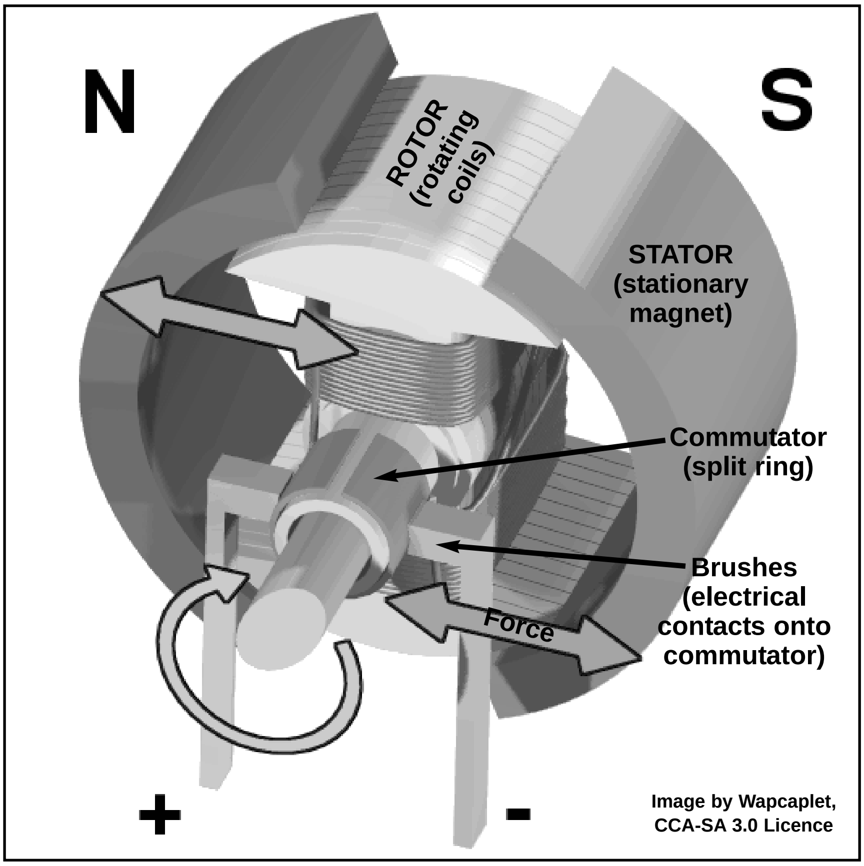
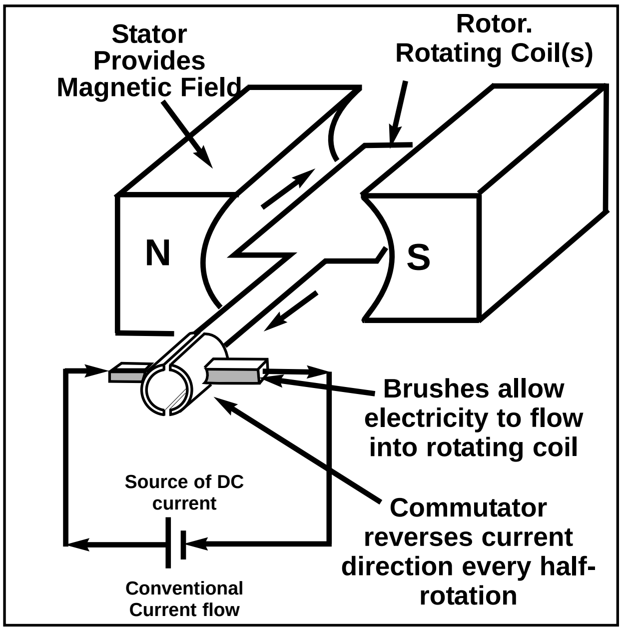


Image by Wapcaplet, CCA-SA 3.0 Licence

Main Features of a DC Motor

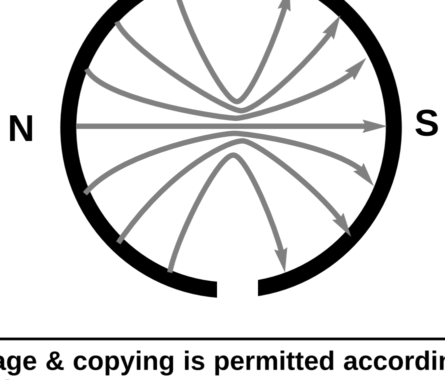


The Rotor **is the part that rotates. It is a coil of wire (or often several coils) mounted on an axle to allow rotation.**

The Stator **is the part that remains stationary. It may be a permanent magnet, or an electromagnet. Its purpose is to provide the magnetic field.**

Often, the magnetic poles are shaped in such a way to create a "Radial Magnetic Field"... one in which the lines of force are directed like the spokes of a bicycle wheel... radii of a circle. This means the plane of the coil is always "flat" in the field through most of its rotation. This means the normal line is at 90^o to the field and since $\sin 90^o = 1$, the result is maximum torque at (nearly) all positions.

Radial Magnetic Field



The Brushes **are fine, flexible metal wires, or (more commonly) a spring-loaded stick of graphite. The brushes maintain electrical contact onto the rotating metal ring.**

The Commutator **is a metal cylinder, split into 2 pieces. As it rotates, the direction of current in the coil is reversed every half-rotation. This way, the torque is always in the same rotational direction, even though the coil has turned over.**

keep it simple science ®

Other Applications of the Motor Effect

The Moving-Coil Loudspeaker

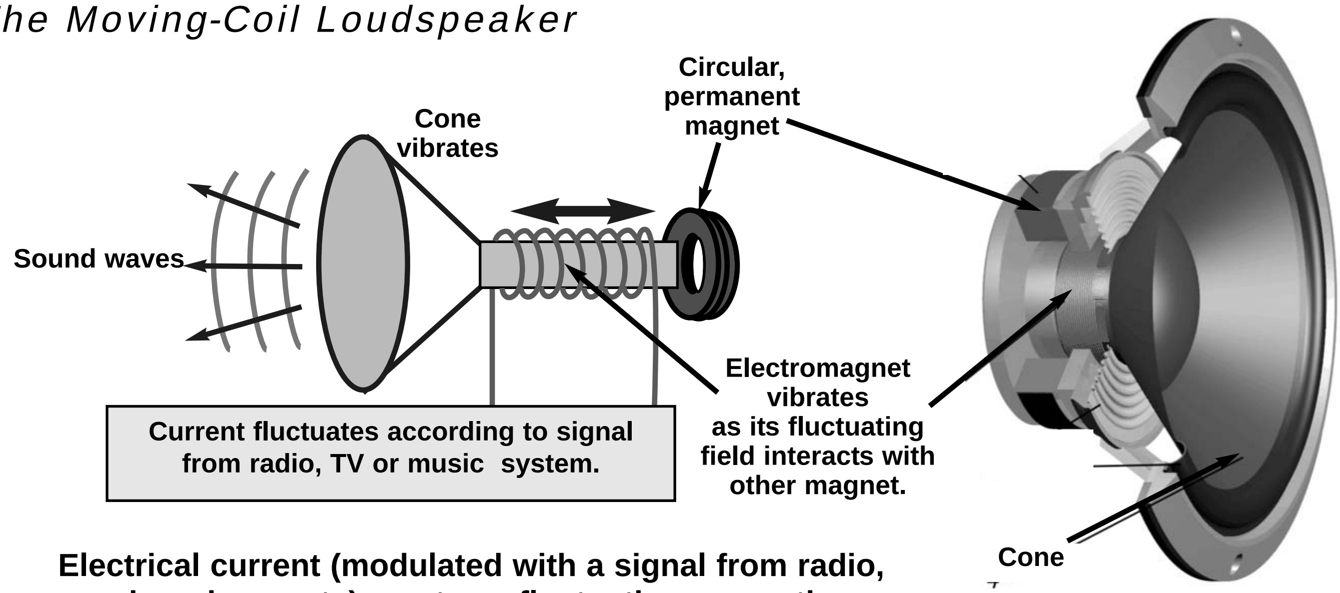
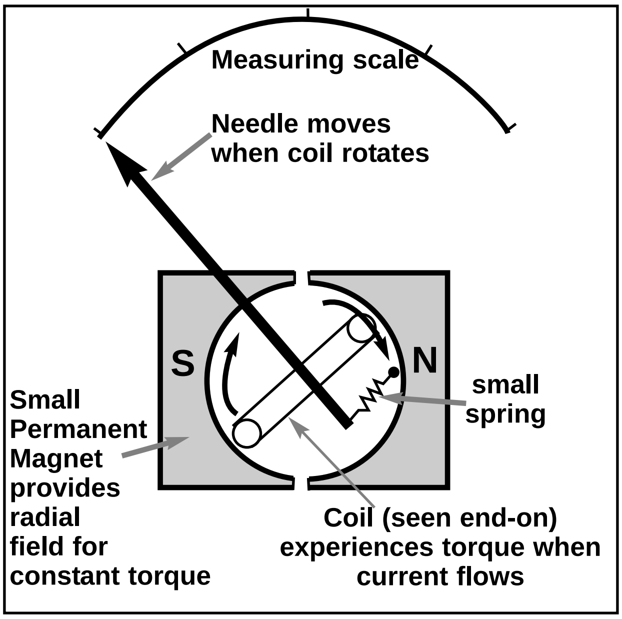


Image by Svyo, CCA-SA 3.0 Licence

Electrical current (modulated with a signal from radio, microphone, etc) creates a fluctuating magnetic field around a coil. This field interacts with a nearby magnet, and the coil vibrates rapidly back-and-forth. The attached speaker cone vibrates too, and sends compression waves (sound) into the air.

Try Worksheets 6 & 7



The Galvanometer

All electrical meters, ammeters and voltmeters, are based on a device called a "galvanometer", named in honour of Luigi Galvani, one of the pioneers of Electrical Science.

The galvanometer works because of the Motor Effect; the more current that flows through its coil, the greater the torque on the coil, and the greater the deflection of the meter needle, working against a small spring. The needle then points to a scale of measurements, which can be calibrated to read either current or voltage.

We come back to the Motor Effect again in a later section.

keep it simple science

3. Electromagnetic Induction

By now it must be obvious that electric and magnetic fields are intimately related... in fact they are manifestations of the same thing... "electromagnetism". You have seen that moving electric charges (currents) produce magnetic fields. It should be no surprise that the opposite is also true... moving magnetic fields produce electric currents.

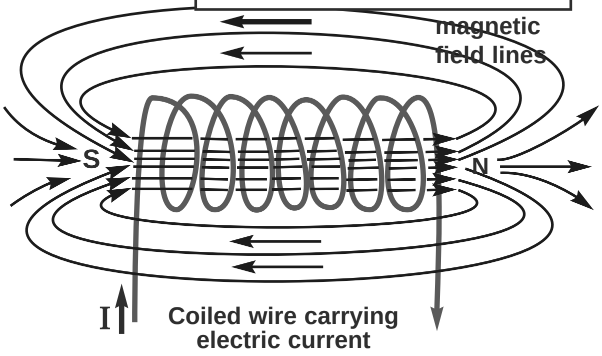
Once again, we begin this section with a quick reminder from Module 4:

Magnetic Field of a Solenoid

"Solenoid" is simply a fancy word for a cylindrical coil, or helix of wire which is carrying an electric current. Each loop of wire produces its own magnetic field, but all the adjacent fields interact to produce an intense, uniform field with parallel field lines inside the coil.

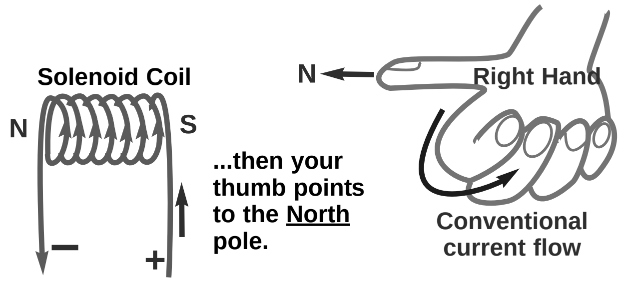
Outside, the field is weak & irregular, but the inside is where the action is!

Magnetic field of a Solenoid



Direction of the Field

If you curl your fingers in the same direction as the flow of conventional current in the coil...



Field Strength

The strength of the field inside a solenoid is given by:

$$B = \frac{\mu_0 . N . I}{L}$$

B = strength of the magnetic field, teslas (T).
N = number of turns of wire in the coil.
I = current in the wire, in amps (A).
L = length of the solenoid, in metres. (m)
μ_0 = "vacuum permeability" constant.
In vacuum (or air) its value = 1.26×10^{-6}.

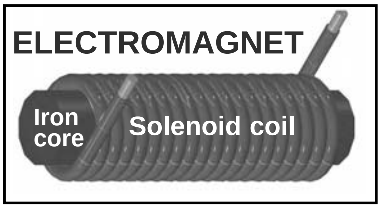
Example Problem

A long wire has been wound into a solenoid. It has 50 loops of wire and is 10cm long. It is carrying a current of 5.25A. What is the strength of the magnetic field inside the coil?

Solution: $B = \mu_0 . N . I / L$

$= 1.26 \times 10^{-6} \times 50 \times 5.25 / 0.10$

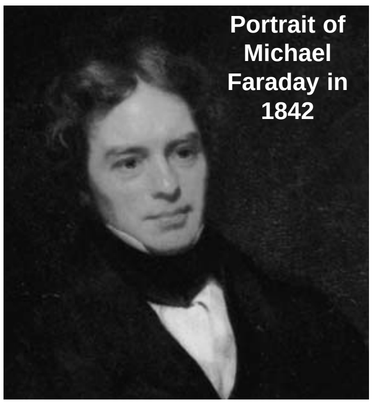
$= 3.31 \times 10^{-3}$ T



Solenoids & Electromagnets

Although the magnetic field of a solenoid is much more intense than the field around a straight wire, it is still not that impressive in terms of field strength. However, if a bar of soft iron is inserted inside the coil, the transformation is spectacular! The solenoid becomes an "electromagnet".

The field strength typically increases about 100 times compared to that of the same solenoid with an air-core. Mathematically, the reason for this is that the "permeability constant" involved is no longer that of air or vacuum, but the permeability of the iron core. Iron carries the magnetic field force vectors very well indeed and so has a much higher value.



Portrait of Michael Faraday in 1842

Electromagnetic Induction

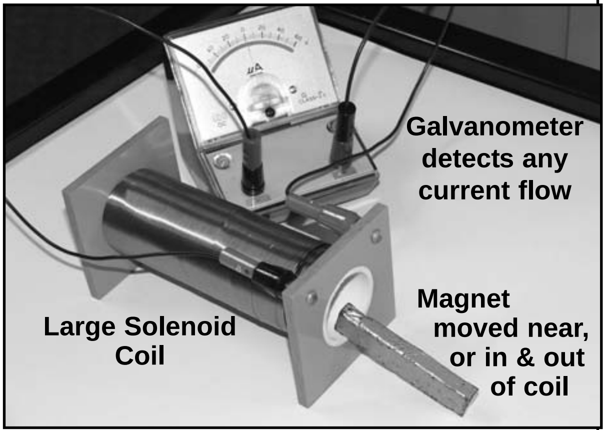
If electrical currents produce magnetic fields, and interact to produce forces and movement, shouldn't the opposite occur too? So went the argument among scientists about 170 years ago. Many experiments were carried out before Michael Faraday (English, 1791-1867) proved the idea correct.

Faraday discovered that if there is relative movement (or other changes) between a magnetic field and a conductor, then a current will be "induced" in the conductor. This is called "Electromagnetic Induction", and is the basis of electrical generators and all of our society's large-scale power production.

keep it simple science ®

A Simple Induction Experiment

You may have done a simple experiment to see electromagnetic induction first-hand.



When the magnet is moved near, or into the coil, the galvanometer needle registers a flow of current.

It doesn't matter whether the magnet moves, or the coil moves... as long as there is relative movement.

You may have investigated the factors which can effect the nature of the induced current...

- Using a stronger magnet produces more current.
- The closer the magnet is to the coil, more current.
- The faster the movement, the more current.

You may also find that...

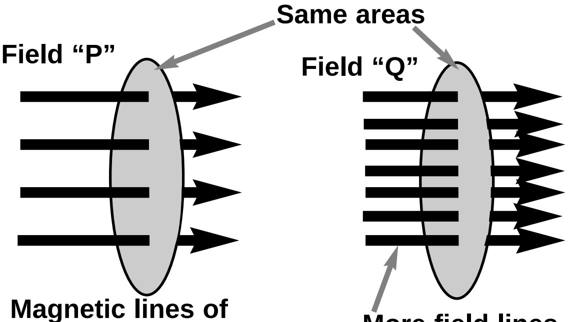
Reversing the direction of movement reverses the current flow. Reversing the polarity of the magnet also reverses the current flow.

Magnetic Flux & Flux Density

Magnetic Flux

To explain his discovery of induction, Faraday introduced the concept that a magnetic field is made up of a series of "lines of force". He showed that if a conductor moves so that it "cuts through" these field lines, then a current is induced to flow in the conductor.

He invented the idea of "magnetic flux" as a measure of how many field lines are cut by the moving conductor.



From this arises the idea of

Magnetic Flux Density

The "Magnetic Flux Density" is what we have been calling "Magnetic Field Strength". (symbol "B")

Magnetic Field Strength = Magnetic Flux Density

It is a measure of the intensity of a magnetic field, in terms of the number of force-field lines per unit of area.

Symbol used in equations = "B"
Unit of measurement = tesla (T)

The relationship between "flux" and "flux density" is summarised mathematically by:

$$\Phi = B.A.\cos\theta$$

Φ = (greek letter equivalent to "F") magnetic flux.
The unit of flux is called the "weber" (Wb)
B = "Magnetic field strength",
or more correcly "magnetic flux density".
The unit is the "tesla" (T). $1T = 1\ Wb/m^2$
A = area through which the magnetic flux occurs, in sq.metres (m^2)
θ = the angle between the magnetic field lines and the normal line to the area of the flux.
Note that when $\theta = 0^o$ $\cos\theta = 1$, so maximum flux occurs when the field is at right angles to the area. (so the normal is parallel to field, $\theta = 0^o$)

Faraday discovered that when there is a change in the magnetic flux surrounding (or passing through) a conductor, then an "electromotive force" (EMF) is induced within the conductor. EMF refers to "potential difference", or simply "voltage".

If the conductor is connected into an electric circuit then the voltage (EMF) created causes a current to flow through the circuit according to Ohm's Law.

What Can Cause a CHANGE in Flux?

- In the experiment described above, the changes which cause induction are mostly to do with relative movement between the conducting coil and the magnet. The faster the movement, the greater the flux change.

- A changing magnetic field can also produce a flux change. For example, if the current flow to an electromagnet is changed, the magnetic field changes. This can induce an EMF in a conductor. Even turning an electromagnet on and off causes flux change, as the magnetic field builds up or fades away. An electromagnet powered by AC electricity constantly reverses its field polarity. This is a very common reason for flux change.

keep it simple science®

Faraday's Law

Faraday was able to show that:

Size of the EMF α is proportional to **Rate of change of the FLUX in the conductor**

In its simplest form, Faraday's Law is

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

ε = (Greek "e") **induced EMF in volts (V)**
$\Delta\Phi$ **= change in magnetic flux, in webers (Wb)**
Δt **= time involved, in seconds(s)**

This is the voltage induced in a single conducting wire. If a coil containing "N" turns of wire is involved, then

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

and for reasons that will become clear later, we must add a negative sign to the whole mess.

So finally we get: $$\varepsilon = -\frac{N.\Delta\Phi}{\Delta t}$$

Example Problem

A rectangular coil of wire containing 50 loops, measures 8cm x 5cm. A magnetic field (from an electromagnet) with flux density of 5.5 x10^{-2} T passes through the coil at right angles. (So the "normal" angle is zero) **Suddenly, the electromagnet is turned off. The field drops to zero in 0.002 s.**
a) Find the area of the coil in m^2.
b) Calculate the initial magnetic flux in the coil.
c) Calculate the voltage induced in the coil when the electromagnet was turned off.

Solution: **a) Area = 0.08 x 0.05 = 4.0 x 10^{-3} m^2.**

b) $\Phi = B.A.\cos\theta$
$= 5.5\times10^{-2} \times 4.0\times10^{-3} \times \cos 0^o$
$= 2.2 \times 10^{-4}$ Wb

c) The change in flux $\Delta\Phi$ **= final flux - initial flux**
$= 0 - 2.2\times10^{-4}$

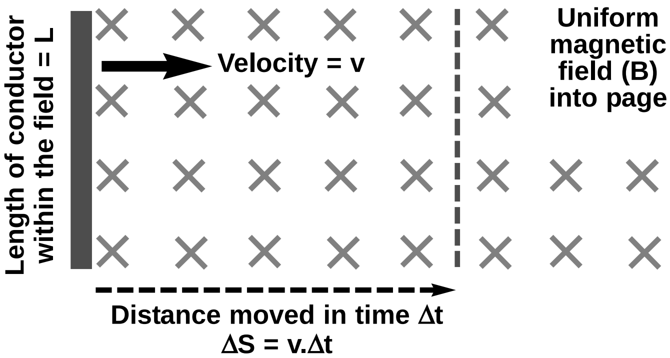
So, $\varepsilon = -\frac{N.\Delta\Phi}{\Delta t} = -50 \times -2.2\times10^{-4} / 0.002$
$= 5.5$ V

Try Worksheet 8

EMF Induced in a Conductor Moving Through a Magnetic Field

This scenario may help to get your head around induction of EMF, although it is unrealistic in the practical world of generators & transformers. These nearly always induce EMF by changing the magnetic fields, or by rotating the conductors... rarely by moving them in a straight line.

Imagine a rigid conductor which can move through a magnetic field (eg by running on rails). If it is pushed through the field it will cut through the magnetic field lines thus creating a flux change. This will induce an EMF in the conductor.



You should be able to see that the <u>area</u> of the field covered in time Δt is A = L.v.Δt. (think it through!)

Since the conductor is at right angles to the field, the "normal" to the plane of the area swept out $\theta = 0^o$
(So in the flux equation, cos 0^o = 1)

Since $\Phi = B.A.\cos\theta$

substituting A = L.v.Δt and cos0^o = 1, gives $\Phi = B.L.v.\Delta t$

Feeding this into Faraday's Law gives:

$$\varepsilon = -\frac{N.\Delta\Phi}{\Delta t} = -\frac{1.B.L.v.\cancel{\Delta t}}{\cancel{\Delta t}}$$

$$\varepsilon = -B.L.v$$

(This is NOT required by the syllabus, but might help understanding)

Example Problem

In the situation shown at left, the length of the conductor within the field, L = 30cm and its velocity is 15ms^{-1}. The field strength is B = 0.78 T.
a) Calculate the EMF induced in the conductor.
b) If it is connected into an electric circuit with total resistance of 6.0Ω, what current will flow?

Solution:
a) $\varepsilon = -B.L.v = -0.78 \times 0.30 \times 15 = -3.5$ V
(we can ignore the sign for now... it refers to direction only)

b) Ohm's Law: V= I.R,
So I = V / R = 3.5 / 6.0 = 0.58 A.

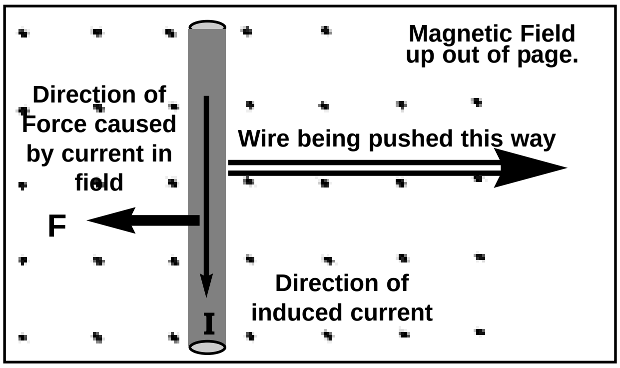
keep it simple science ®

Lenz's Law

It is Lenz's Law which requires the negative sign in Faraday's equation

Consider a conducting wire being pushed across a magnetic field. Because the wire is cutting the field lines, there will be an induced EMF, and (if there's a circuit available) current will flow..

BUT, when a current flows the Motor Effect will occur and create a force on the wire.
Which way will it push the wire?



Heinrich Lenz figured it all out 150 years ago. The induced current will create a magnetic field (and Motor Effect force) which will oppose the motion that produced it in the first place.

Lenz's Law

The direction of an induced EMF (and current) is such that it produces a magnetic field opposing the change that produced the EMF

Lenz's Law arises as a consequence of the principle that energy cannot be created from nothing... the "Law of Conservation of Energy".

Look at the diagram above. If the induced current flowed the other way, then the motor effect force would act to the right. This would accelerate the motion of the wire. Since it would move faster, it would cut more field lines (greater "flux change" Faraday would say) and thereby induce a greater EMF and greater current. This would produce more force and accelerate the wire even more... and so on. This would mean energy being created from nothing!

In the diagram above, the induced current must flow as shown, so that its own magnetic field opposes the motion of the wire, and so Conservation of Energy is not violated.

This is why:

• when you push a magnet into a coil, you may feel an opposing force... the current induced in the coil is creating a magnetic field which repels the one you're pushing.

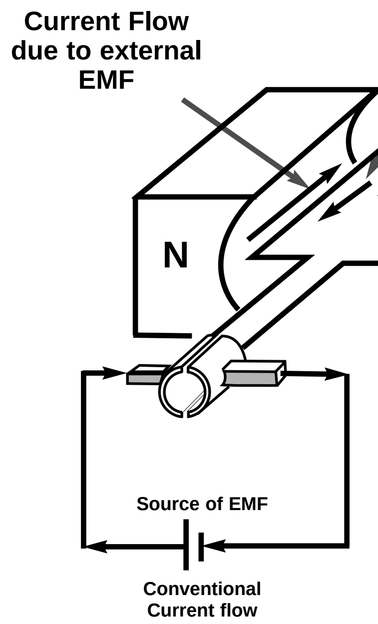
• When you wind the handle of a generator, the force required is much greater than expected... Lenz's Law opposes you!

Lenz's Law has a number of consequences...

Back EMF in a Motor

As dealt with earlier, an electric motor rotates due to the torque on the coil due to the applied current interacting with the magnetic field.

However, as the coil rotates through the magnetic field, induction also occurs, creating an induced EMF. Lenz's Law guarantees that the induced EMF will act against the supplied EMF.



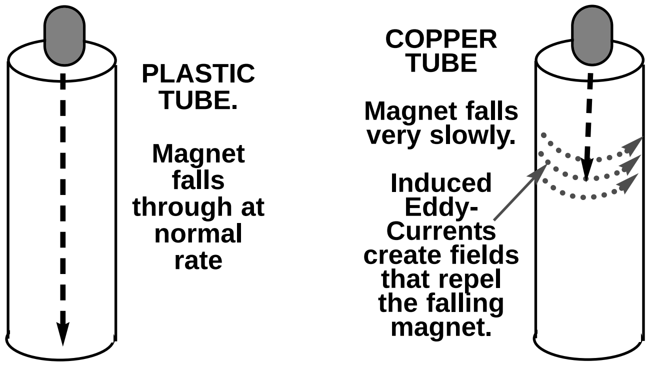
The final "net-EMF" driving current through the motor is the difference between the EMF supplied, and the "Back-EMF". More on this later.

Eddy Currents

Even when there is no designed electrical circuit present, whenever there is relative motion between a conductor and a magnetic field, an EMF is induced and currents will flow. In a flat sheet or tubes of metal the induced currents often flow in circles... these are called "Eddy Currents"

Lenz's Law guarantees that the eddy currents will create magnetic fields to oppose the motion that produced them.

Example: Get a small, but powerful "super-magnet" and drop it through a plastic tube. Then drop it through a copper, or aluminium tube.



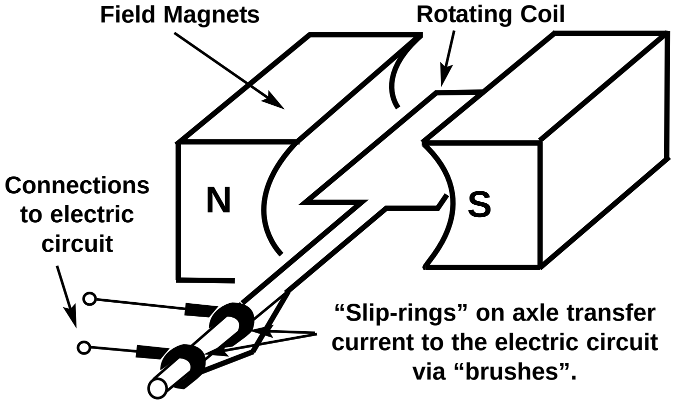
keep it simple science

Electrical Generators

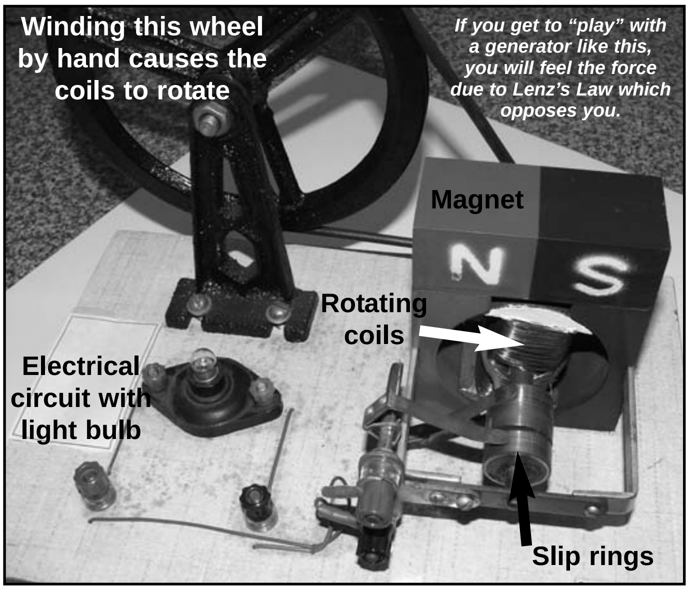
Structure of a Generator

A simple generator can be very similar to an electric motor. Both consist of one or more coils of wire which can rotate inside a magnetic field. The field can be provided by either permanent magnets, or electromagnets.

Both require "brushes" to maintain electrical contact with the rotating coil to pass current into the coil (motor) or carry induced current out of the coil (generator).



School Demonstration Generator



Motors & generators are functional opposites. Motors use electricity to produce movement in the coil. Generators use forced movement of the coil to produce electricity.

Practicalities

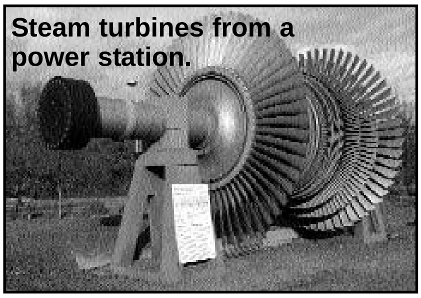
In reality, motors and generators are built very differently for practical reasons. For example, in power stations the generators are built to have the coils of wire stationary while the magnets do the rotating. This makes it simpler and more efficient to transfer the electricity to the power grid, without having massive currents sparking through the brushes.

What Makes the Generators Turn?

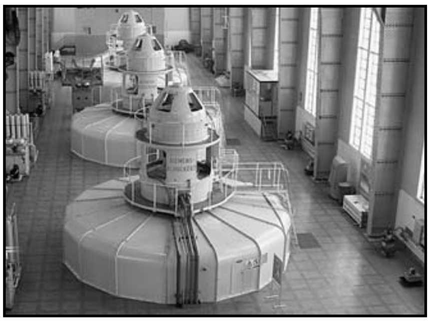
Usually, the answer to this question is... "TURBINES".

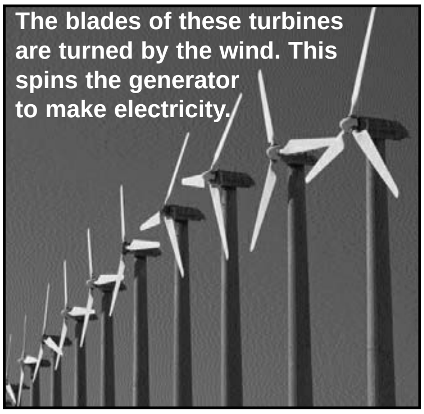
A turbine is a set of propeller-like blades on an axle. If a gas or liquid (e.g. water, steam, air) is forced to flow through the turbine, it spins. If connected to a generator, the rotor of the generator is forced to spin and electricity is produced.

In a "conventional" power station the turbines are driven by steam made by heating water. The heat comes from burning a fuel such as coal.



In a "Hydroelectric" power station the generators are turned by the flow of water. (Photo below) The turbines are below the floor, where high-pressure water flows in pipes from a high dam.



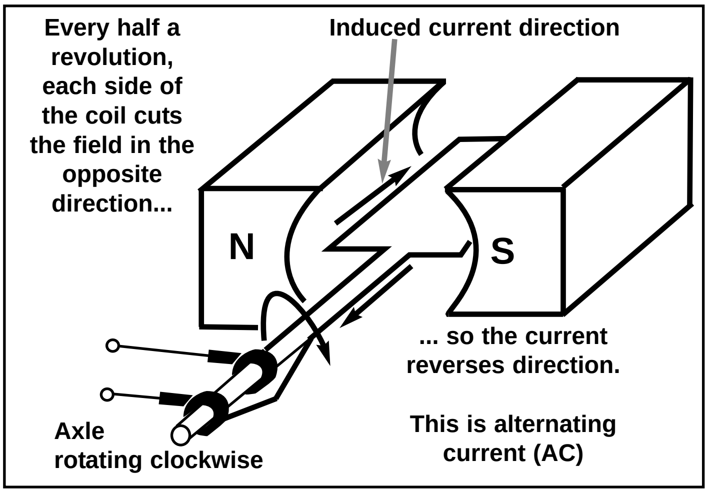


This geothermal power station (right) in NZ uses high pressure steam from volcanically heated water to spin the turbines & drive the generators.

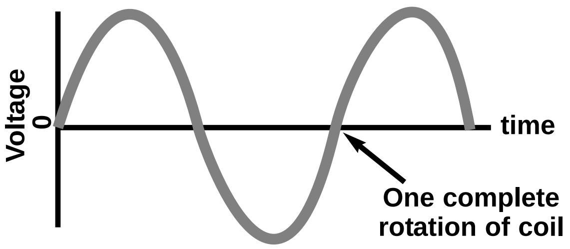
keep it simple science

AC and DC Generators

In a simple generator as described previously, the induced current will reverse direction every half revolution of the coil.

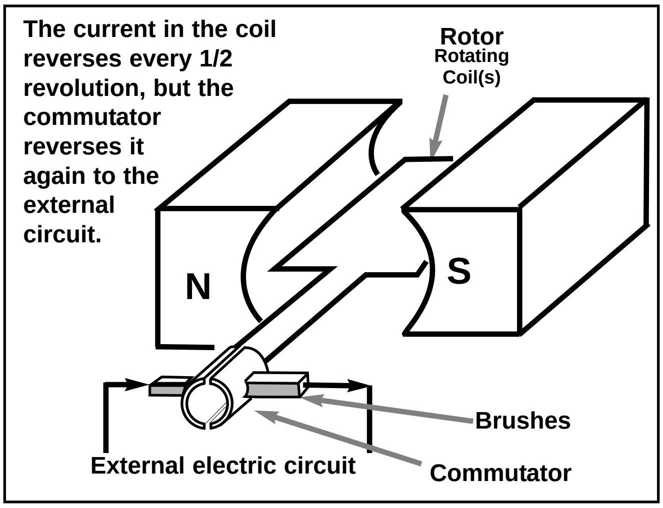


A graph of the EMF generated this way is shown.

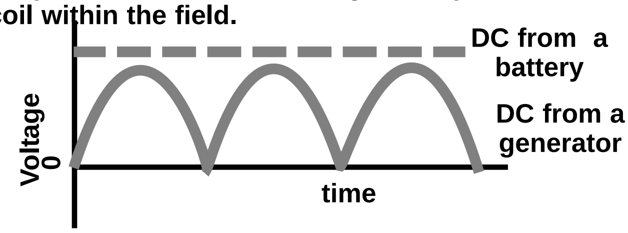


An AC generator has traditionally been called an "alternator".

It is also possible to make a generator which will produce direct current (DC) which flows in the same direction.



The electricity produced flows only in one direction, (DC) but fluctuates according to the position of the coil within the field.



A DC generator has traditionally been called a "dynamo".

Advantages & Disadvantages of AC & DC

The fact that our "mains" electricity supply is Alternating Current (AC) tells you that there must be advantages to generating electricity as AC, rather than DC.

One major advantage of AC has nothing to do with the generators, but relates to transmission of power and the ease of altering the voltage in a transformer.
This will be studied a little later.

In terms of the generators themselves, any advantages & disadvantages relate to their structure:

Disadvantage of a DC Generator

No matter how well it is made, the commutator is the weakness of a DC generator. Because it is a split-ring structure, the brushes must spark and wear out as the commutator revolves.

This is inefficient in terms of transferring electricity to the external circuit, and causes maintenance problems as the brushes wear out and need to be replaced.

Advantage of an AC Generator

Instead of a commutator, the AC generator has continuous "slip-rings" so there is less sparking and less wear on brushes.

Additionally, AC generators can be built with the massive, heavy coils stationary and the magnets doing the revolving on the inside. This simplifies the engineering and maintenance and eliminates entirely the use of slip-rings and brushes to carry the generated electricity.

Energy Losses in Power Lines

Our modern electricity system consists of a relatively small number of large power stations. The electricity needs to be distributed in power lines over hundreds of kilometers.

Try Worksheet 9

Although the wires (usually aluminium) are low resistance, over long distances there can still be significant energy losses due simply to the resistance causing heating in the wires.

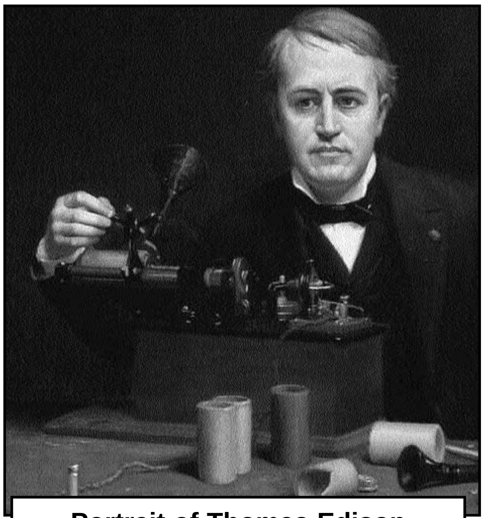
However, the energy loss due to resistance heating is greater at higher currents. So to minimise energy losses, electricity is carried at very high voltage and low current. Typically, long-distance power is distributed at 250,000 volts, but only tiny currents, such as 0.01 amp.

The fact that AC can be readily "stepped-up" to high voltage for transmission, then "stepped-down" for consumer use is a major advantage of AC electricity. The "step-up" & "step-down" is done by transformers.

keep it simple science®

The information on this page is NOT specified by the syllabus.
It is included for better understanding of how our modern world came about.

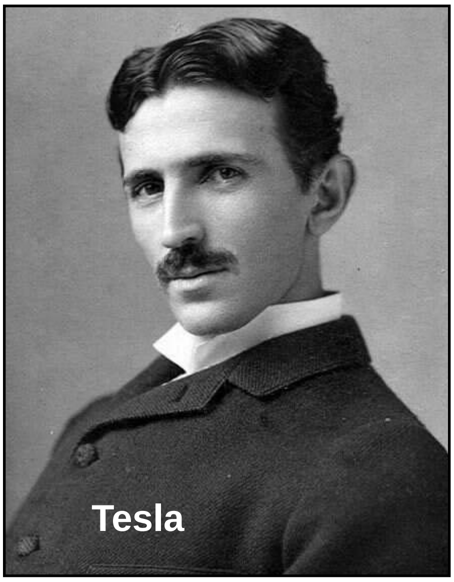
History... Edison v Westinghouse



Portrait of Thomas Edison (1847-1931) with his "phonograph", the first device for playing recorded music.

In the early days of electricity generation and usage, the famous American inventor, Thomas Edison, was pioneering electricity supply. He favoured the use of DC electricity and had set up hundreds of DC power stations around the New York area. His advantage was that he had invented the light bulb, and now stood to make a fortune selling both the bulbs and the electricity to power them.

Edison's first commercial light bulb, demonstrated in 1879.



His main competitor was the Westinghouse company, which set up an AC electricity system. They built a hydroelectric power station near Niagara Falls, taking advantage of the unlimited energy source of the fast flowing water from the "Great Lakes".

However, this also meant that they had to transmit the electricity over large distances to the cities where it would be used. This demanded that they generated AC.

In 1884, Nikola Tesla arrived in America from Serbia. He was an engineer and inventor and had developed new, improved versions of AC generators, motors and transformers. He got a job with the Edison company, but soon left and went to work for Westinghouse. Tesla sold his inventions to Westinghouse, which gave the company the technological advantages they needed to succeed.

Long distance transmission of AC electricity soon proved more economical that the multiple power stations and short-range Edison DC system. Also, Tesla's new electric motor, which ran only on AC, proved very economical and reliable for factories, elevators and a host of new consumer machines like vacuum cleaners and washing machines. The modern electrical world became established, and it was AC electricity that became the standard.

Nikola Tesla's contribution has been recognised by the naming of the unit of magnetic field strength (magnetic flux density) after him. His name is also used by the huge American company "*TESLA*" which makes high-tech batteries, solar panels, electric cars and is involved in space technology & future space tourism.

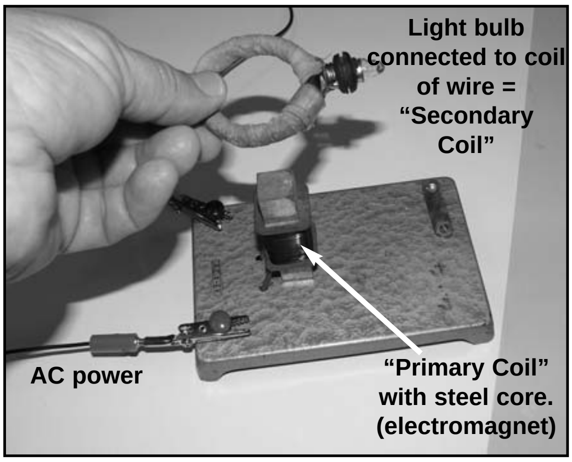
Transformers

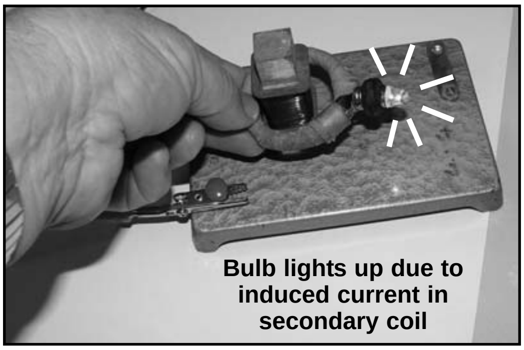
It has already been mentioned that the great advantage of using AC electricity is that it can be "stepped-up" to very high voltages for efficient distribution, then "stepped-down" again for convenient and safe usage by consumers.

It is this stepping-up & down of the voltages that is the purpose and function of a transformer.

Practical Investigation

There are many possible investigations you may have done in class to see the basic operation of a transformer. One simple example is shown.





Explanation

The AC supply to the primary coil (an electromagnet) produces a fluctuating magnetic field. The field lines keep building, collapsing and reversing direction.

This changing field constitutes a change of "magnetic flux" through the wires of the secondary coil, and so EMF is induced in it.

This causes current to flow, which lights the bulb.

<u>Note</u>:
This will NOT work with DC electricity from a battery. The key to the induction in the secondary coil is the fluctuating field caused by the AC supply.

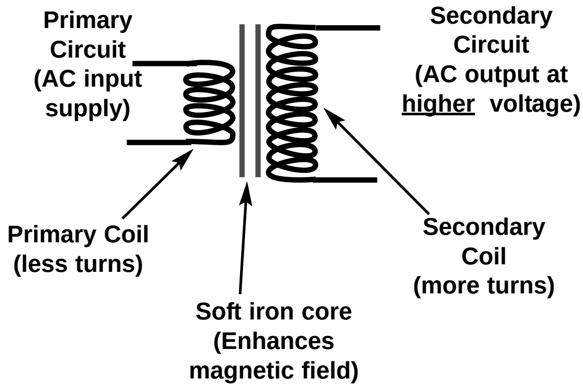
(You WILL get induction with "DC" from a school power pack because (typically) its low-quality "rectifier" unit fluctuates quite a lot.)

Step-Up, Step Down

Transformers work by inducing a new EMF and current in the "secondary coil". Whether the secondary voltage is higher or lower than the primary voltage, is simply a matter of the ratio between the number of "turns" of wire in each coil.

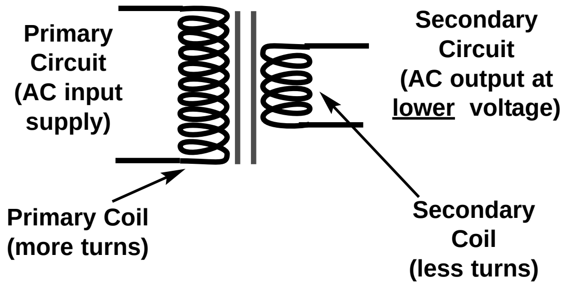
Faraday discovered that the size of the induced EMF is proportional to the number of turns of wire in the coil. In a transformer, if the number of turns in the secondary coil is greater than in the primary, then the induced EMF is higher too... the transformer "steps-up" the voltage.

Schematic Diagram of "STEP-UP" Transformer



In a "step-down" transformer, the opposite is true... the secondary coil has less turns than the primary, and the induced EMF is lower.

Schematic Diagram of "STEP-DOWN" Transformer



Current in Primary & Secondary Circuits

If you use a "step-up" transformer to get a higher voltage, does this mean you just got something for nothing?

No, of couse not! If the voltage goes up, the current goes down in the same proportion.
(Assuming perfect transformation of energy.)

As always, The Law of Conservation of Energy rules the Universe!

keep it simple science

The Transformer Equation

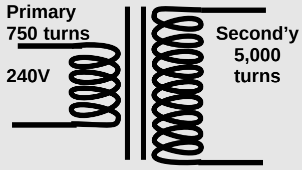
There is a simple relationship between the voltages and the number of turns of wire in the coils of a transformer.

$$\frac{V_p}{V_s} = \frac{n_p}{n_s}$$

V_p = Voltage in the primary coil.
V_s = Voltage in the secondary coil.

n_p = No. of turns of wire in the primary coil.
n_s = No. of turns of wire in the seconary coil.
(Assumes 100% efficiency in energy transfer)

Example Problem:
A transformer has 750 turns of wire in the primary, and 5,000 turns in the secondary coil.
Input voltage is 240V AC.
a) Find the output voltage.
b) Is this a "step-up" or "step-down" transformer?



Solution: a)

$$\frac{V_p}{V_s} = \frac{n_p}{n_s}$$

$240 / V_s = 750 / 5{,}000$

$\therefore V_s = 240 \times 5{,}000 / 750$

$= 1{,}600$ V.

b) Step-up transformer, since it has more turns in the secondary coil, AND the output voltage is higher than input.

Conservation of Energy in a Transformer

You will recall from a previous module that:

Electrical Power = Voltage x Current
$P = V.I$

and that Power is the the amount of Energy being transformed per second.

In a step-up transformer, the voltage increases, and the current decreases by the same factor, so that:

Primary coil Power = Secondary coil Power

$$V_pI_p = V_sI_s$$

Energy per second in Primary coil = Energy per second in Secondary coil

Therefore, the Law of Conservation of Energy is obeyed.

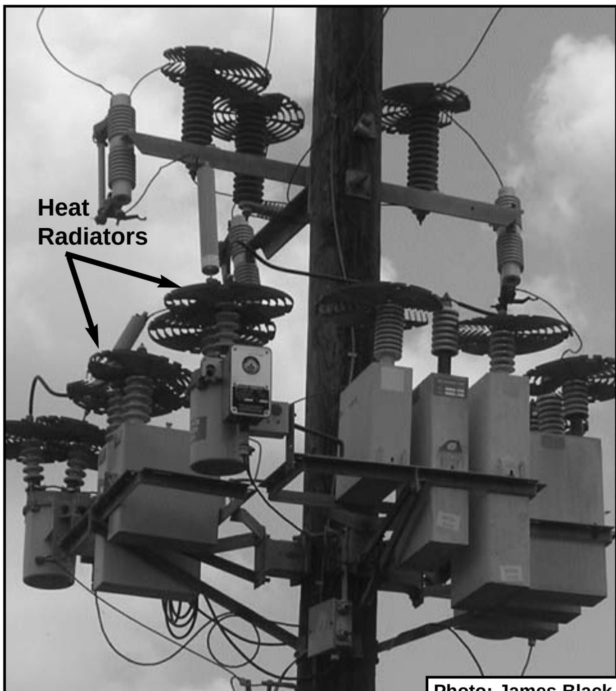


Photo: James Black

Energy Losses in Transformers

The descriptions above assume that a transformer works with 100% efficiency. This is often assumed for solving simple problems, but you need to be aware that, in the real world, nothing is perfect.

Real transformers are not perfect, and always lose some energy in the process of altering the voltage. The main loss of energy is by resistance heating, not only in the coils, but due to "Eddy Currents" induced in the iron core.

Once the transformer starts to heat up, the situation gets worse, because resistance in a metal increases with temperature.

A number of methods are used to minimise the energy losses:
- The iron core is not one large piece of iron, but is made of thin sheets laminated together, but insulated from each other. This way the eddy currents induced in the core are smaller, and cannot circulate very far.

- The coil wires are thicker on the higher current side of the transformer (depending whether step-up or step-down). Thicker wires have less resistance, so this minimises resistance heating in the coils.

- Transformers are designed to radiate heat away so they stay as cool as possible, to reduce resistance. Large transformers may have cooling oil circulating through a heat exchanger, rather like the radiator system of a car engine. In the photo above right, the transformers are equipped with small metal "radiators" to quickly lose heat to the air.

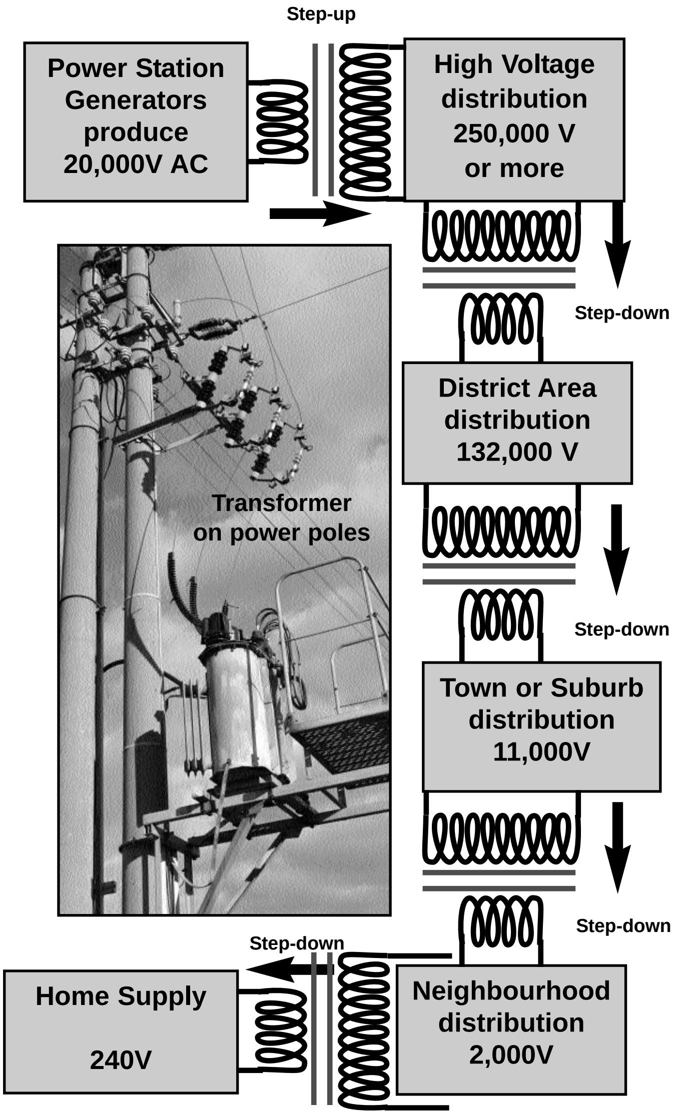
keep it simple science®

Importance of Transformers

From Power Station to Home...

Even though there may be some loss of energy in a transformer, it is still worth it. The advantage is the way AC can be stepped-up to very high voltages and efficiently distributed over long distances from large, economical power stations.

The typical chain of transformations is:



Transformers inside the Home

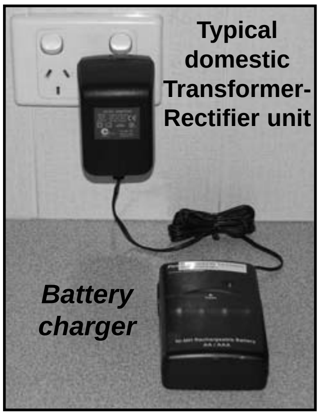
Even after all this transformation before the electricity gets into your home, it's still not finished.

Many appliances inside your home need a transformer because they need more, or less, voltage than the 240V supply.

<u>For example</u>:

Old-style TV picture-tubes need 1,500V to operate. Much of the weight of a TV set is the heavy <u>step-up transformer</u> inside.

(These sets are now obsolete and have been replaced by flat-screen technology.)



A lot of smaller devices not only run on low voltage, but often need DC instead of AC.

Their transformers are also "rectifiers" to produce direct current.

Many electronic devices need only low voltages, such as 12V or less. Smaller gadgets often have the necessary transformer in a "box" combined with the electric power plug.

Try Worksheets 10 & 11

keep it simple science

4. More Applications of the Motor Effect

Several of the syllabus items specified for this section were covered earlier. What is presented here is a rather haphazard collection of "left-overs".

Back-EMF in Electric Motors

Electric motors work because of the "Motor Effect". A coil of wire carrying current within an electric field experiences a torque which causes it to rotate.

As soon as the coil begins to move, induction occurs. The coil is a conductor which is moving within a magnetic field and so EMF is induced.

Lenz's Law demands that the induced EMF will create forces to oppose the motion which created it.

Therefore, a "back-EMF" is created in the coil. The actual voltage is the difference between the applied voltage & the back-EMF which opposes it.

The final voltage causes the final current flow, according to Ohm's Law & the resistance of the circuit.

Preventing Burn-Out on Start-Up

The coil(s) within the motor is designed to suit a particular operating voltage and final current. However, the operating voltage is lower than the external applied voltage because of the back-EMF.

This means that, when the motor is first turned on and has not yet come up to speed there is a danger of burning the motor out. Before the motor gets up to operating speed, there is less back-EMF being induced, so the start-up voltage may be excessive.

To protect against burn-out at start-up, many electric motors have a special, variable "protective resistor" circuit connected in series in their power supply.

When the motor is switched on, the added resistance limits the current flow to prevent burn-out in the coil(s). As the motor comes up to speed, an automatic mechanism reduces the extra resistance in the protective circuit.

Applications of Lenz's Law

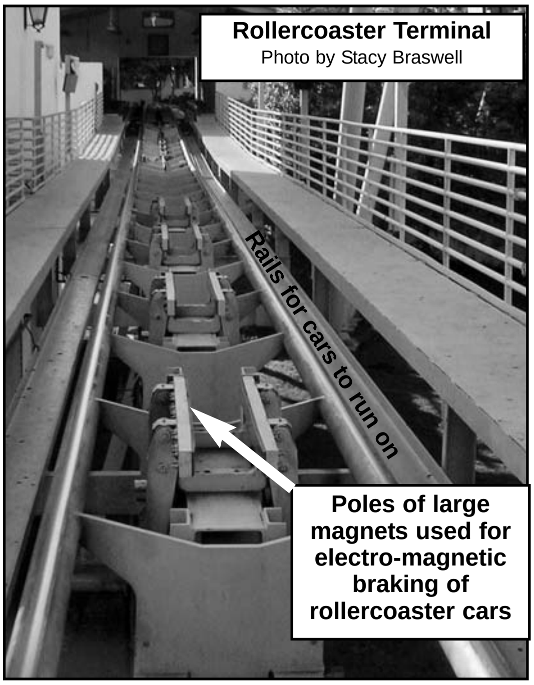
Electromagnetic Braking

In some amusement rides, the passenger seat or car is equipped with small, powerful magnets. At the end of the ride, there are sheets of copper which the magnets move past. (Or, vice-versa... the magnets are in the track and copper plate is onboard the car.)

Either way, eddy currents are induced in the copper sheets. These currents produce magnetic fields. These fields interact with the magnets to produce a force <u>opposing</u> the motion according to Lenz's Law. This smoothly slows the ride to a stop.

The beauty of this system is that:
- it requires no power input to operate. (except for electromagnets)
- it involves no contact surfaces or moving parts that can wear out.
- it is "fail-safe", so that in an emergency it will still work and safely stop the moving ride.

Some trains use electromagnets (can be turned on/off as needed) to induce eddy currents in the rails below the train. As always, Lenz's Law ensures that the induced currents create fields to oppose the motion, and acts as brakes.



Rollercoaster Terminal
Photo by Stacy Braswell

Induction Cooking

An "Induction Stove" has a flat ceramic (or glass) top with no visible heating elements.

Under the top are electromagnet coils. When switched on, these produce oscillating magnetic fields. If a metal saucepan is on top, eddy currents are induced in the pan, which gets hot due to the resistance of the metal to the eddy currents. This heat cooks the food in the pan.

Advantages

- Heat is produced directly in the saucepan, rather than a heating "element". This is much more efficient in energy terms, and thereby cheaper to operate.
- Only the cooking pan gets hot. The stove top only becomes warm by contact with the pan. Spilled foods do not burn onto the stove-top.
- The flat ceramic top is easy to clean.

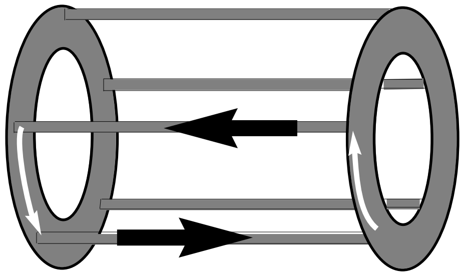
keep it simple science

The Induction Motor Principle

One hundred years ago, when Edison's DC system was "fighting it out" with Westinghouse's AC system, one of the factors that finally led to a victory for Westinghouse & AC was Tesla's Induction Motor.

The "induction motor" works on the same principle as the simple experiment shown at right.

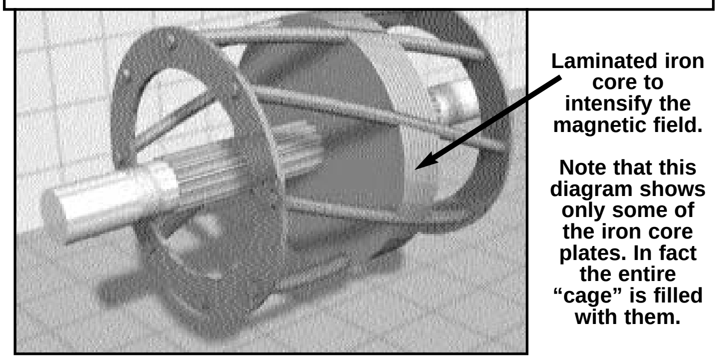
- **The Stator is a series of coils, fed with AC current in such a way that the magnetic fields "rotate" by a rippling on-and-off in sequence around the outside.**
- **The Rotor is mounted on an axle for rotation. It contains a laminated iron core to intensify magnetic fields. The main part, however, is a copper frame known as the "squirrel cage" because it resembles an exercise wheel for a caged pet.**



The moving magnetic fields produced by the stator coils induce "Eddy Currents" in the squirrel cage. These can circulate freely in the copper cage, and produce their own magnetic fields.

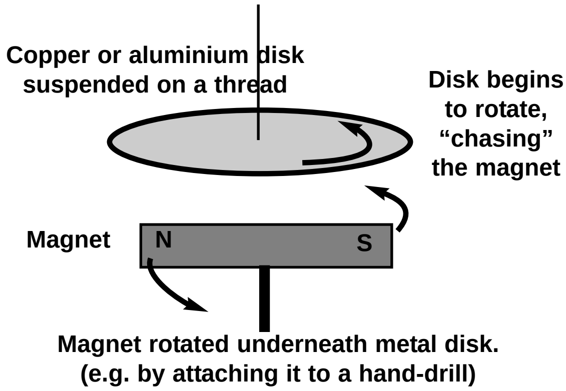
The squirrel cage fields interact with the rotating stator fields such that the rotor experiences torque, and rotates to "chase" the "rippling" stator fields.

Rotor from an induction motor showing the "squirrel cage"



Practical Investigation

You may have carried out an experiment similar to this:



Explanation

The moving magnet induces "eddy currents" in the metal disk. These in turn create their own magnetic fields. The magnetic fields interact with each other so that the disk experiences a torque, and begins to rotate, "chasing" the rotating magnet.

Features of the Induction Motor

- **No external current needs to be fed into the rotor, so there is no need for any slip-rings or commutator. This simplifies the motor, reduces maintenance, and makes it less likely that anything can wear out or need replacing.**

Therefore, the motor is reliable and low-maintenance.

- **The motor works only on AC, and rotates at a constant speed according to the frequency of the AC supply.**

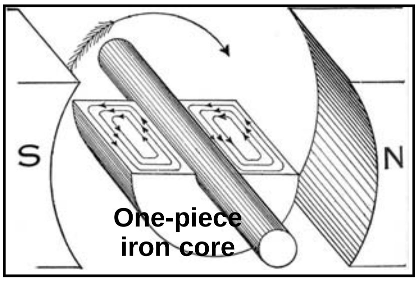
This can be a limitation, and means that gears or pulleys are needed to run machinery either faster or slower than the motor speed.

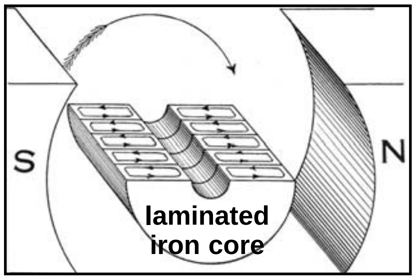
Apparently the simplicity and reliability advantages far outweigh the limitations, because it is estimated that about 95% of the billions of electric motors in the world are AC Induction types!

Why Have Laminations?

Inside the coils of most electromagnetic devices including motors, generators and transformers, there is a core of iron to intensify the magnetic field strength. This core of iron is usually laminated... made of many small sheets of iron rather than one larger piece. WHY?

It's all about Lenz's Law & eddy currents!





If the core was one large piece of iron, the induced eddy currents can grow larger. Resistance heating occurs, which wastes energy by converting it into heat & may threaten a melt-down of the device.

Thin, laminated iron pieces allow only smaller currents in each piece. Studies have shown that just 6 thin sheets (instead of the same amount in one piece) reduces energy losses by over 90%.