Electromagnetism

Ethan Chew M24304

Contents of this notes package:

Bridging the Gap

Electricity and magnetism are not two separate phenomena. Let's explore how these two fundamental properties of nature interact with each other!

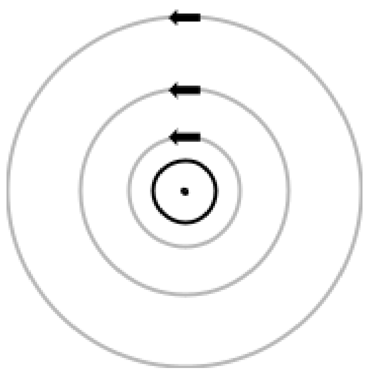
Recall your abbreviations: I - current, B - magnetic field.

Before we can visualise their interactions, we must first establish a way to express vectors in 3D space on our 2D paper. The following shows the notations of current / magnetic field vectors pointing in the third dimension:

Notation for **current** flow		Notation for **magnetic** field	
Current flowing **into** plane of paper	Current flowing **out** of plane of paper	Magnetic field going **into** plane of paper	Magnetic field going **out** of plane of paper
⊗	⊙	x x x x x x x x x x	• • • • • • • • • •

Think of it as an arrow. The back of an arrow is a cross, the tip of an arrow is a point.

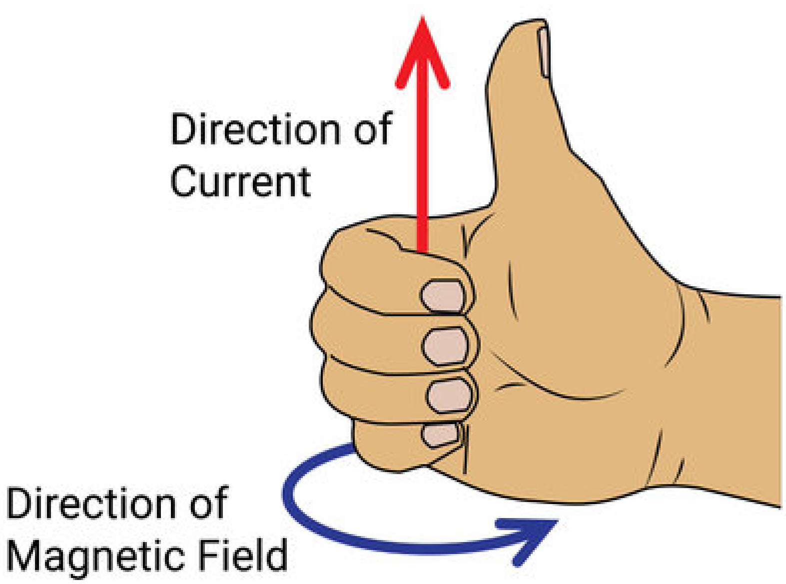
Now, consider the case where a **current** is flowing through a straight wire out of the page, like so:



The core concept of Electromagnetism is that a moving charge generates a magnetic field. The grey lines surrounding the current (going out of the page) is the magnetic field generated by said current. The magnetic field strength gets weaker the further we move from the wire (indicated by the **increasing space** between the concentric circles).

Now, you may realise I've indicated with an arrow the **direction** of the magnetic field. This is just a consequence of whether the current is flowing out of the page or into the page. The direction can be determined by the **Right-Hand Grip Rule:**

1. Stick your thumb out and curl your fingers towards your palm.
2. Your thumb corresponds to the current direction, and the curling of your fingers represents the direction of the magnetic field.

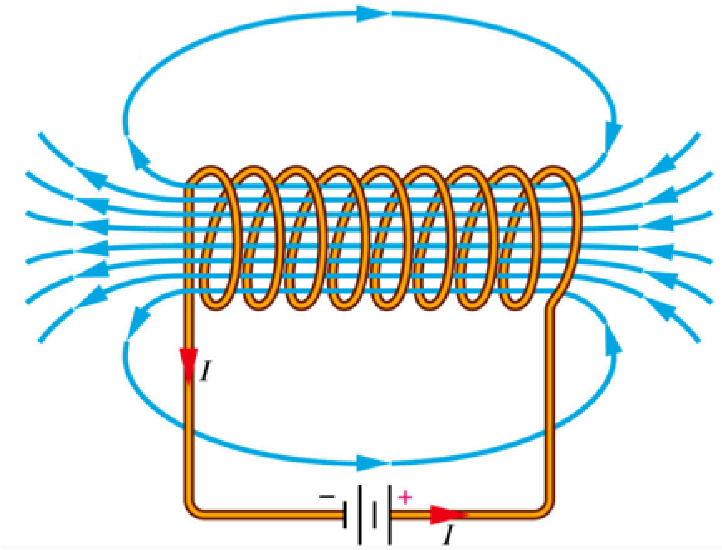


When compasses are placed around the vertical wire, their needles point **tangentially** to the magnetic field, with **North** pointing in the same direction as the indicated arrow.

Can you infer what the direction of the magnetic field is for a current going into the page?

Solenoids and Electromagnets

If a straight wire can generate a magnetic field, then a coil of wire (**solenoid**) can definitely also generate a magnetic field! However, the nature of this field is different.



Remember that direction of current is taken **conventionally**, i.e. the flow of positive charges from the positive terminal, through the entire circuit, and ending at the negative terminal.

Here, we may use the Right-Hand Grip Rule slightly differently:

1. Curl your fingers in the direction of the current looping in the coil.
2. Your thumb points in the direction in which the magnetic field leaves the loop, i.e. the **North pole**.

The solenoid has a uniform magnetic field within it, and a magnetic field pattern similar to that of a bar magnet outside of it. A **soft magnetic material (iron)** may be inserted within the solenoid to increase the strength of the magnetic field, as the magnetic domains of the material align. This brings us to electromagnets.

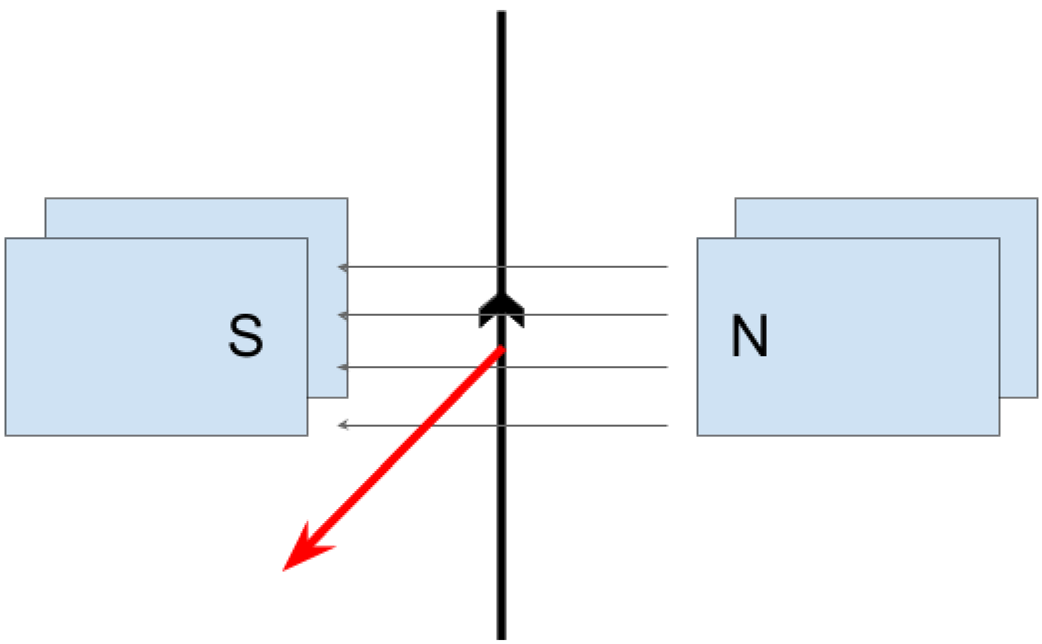
When solenoids and soft magnetic materials come together, we get electromagnets. In Electromagnetism, there are many different applications of electromagnets.

When answering application questions, take note of three things:

- The **nature** of how the electromagnet is magnetised - which direction is the current flowing?
- The **status** of the circuit - closed or open?
- The **effect** of the electromagnet - what does it control?

Electrical Energy to Kinetic Energy

When a current-carrying conductor interacts with an external magnetic field, a **magnetic force** is produced that acts on the conductor.

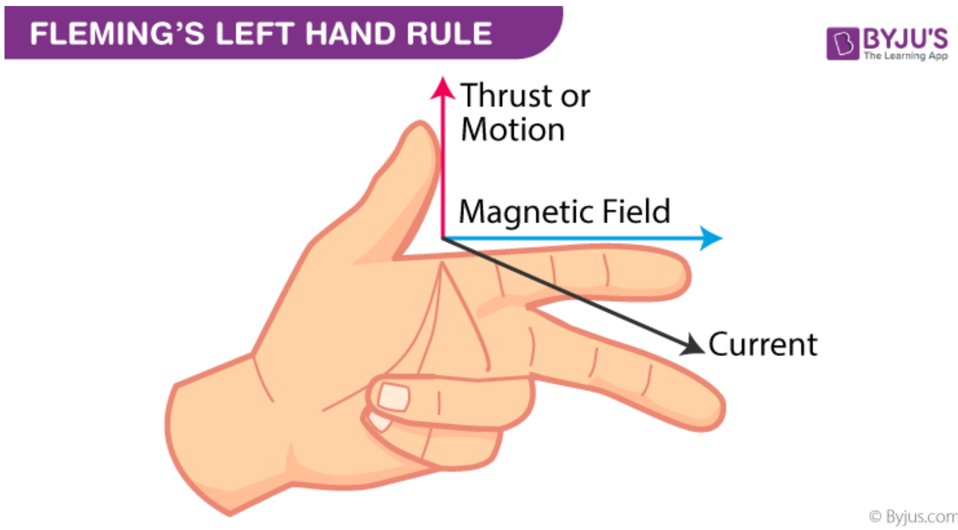


To find the direction of the magnetic force acting on this conductor, we apply **Fleming's Left-Hand Rule:**

1. Position your thumb and index finger at 90 degrees to each other, as if you are mimicking holding a gun.
2. Extend your middle finger out such that it is 90 degrees from your index finger.

3. Your thumb represents the **magnetic force**, your index finger represents the direction of the **magnetic field** (N to S) and your middle finger represents the direction of **conventional current** (positive to negative).

In the above example, the current points **up** and the magnetic field is **leftwards.** Hence, the magnetic force must be **out of the page**.
It helps to remember this as **FBI** - Force (F), Magnetic field (B), Current (I).



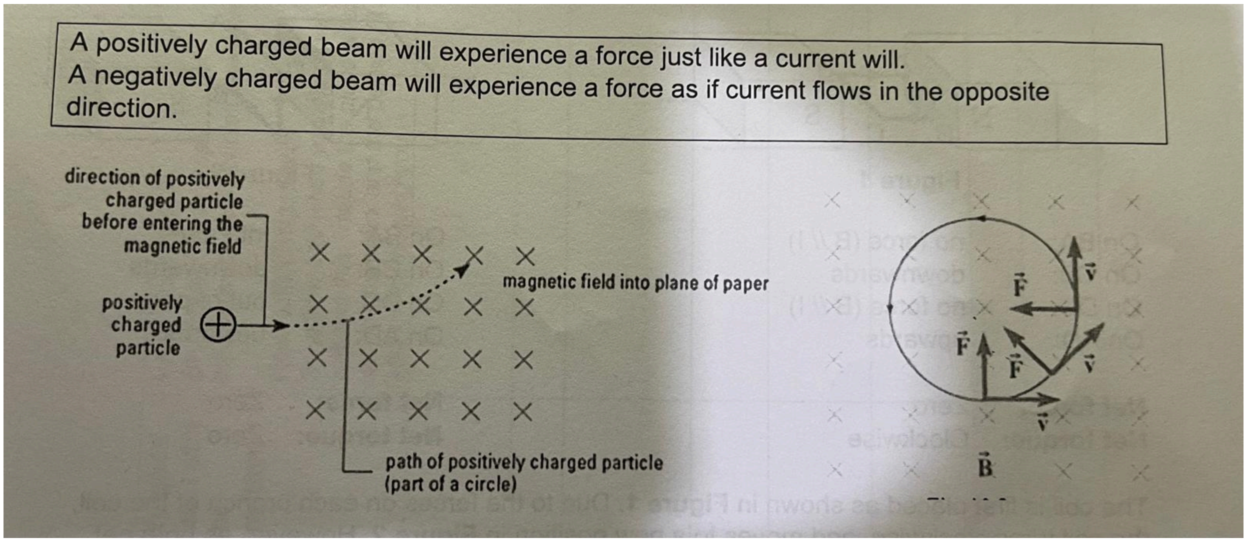
What happens when the magnetic field points rightwards?
What happens when the current points into the page?
What directions would the current and magnetic field point if the magnetic force was downwards?

NOTE: There is only a force if B and I are not parallel / antiparallel. If they are, F = 0.

Single Charge in Magnetic Field

We can also apply Fleming's Left Hand rule to single charges in a magnetic field.

If the velocity of the charge and magnetic field direction are perpendicular to each other, we can trace the path of the charge. As the **magnetic force** will also be perpendicular to the **velocity** of the charge, this results in the charge experiencing **uniform circular motion** (assuming the magnetic field can contain the entire motion).

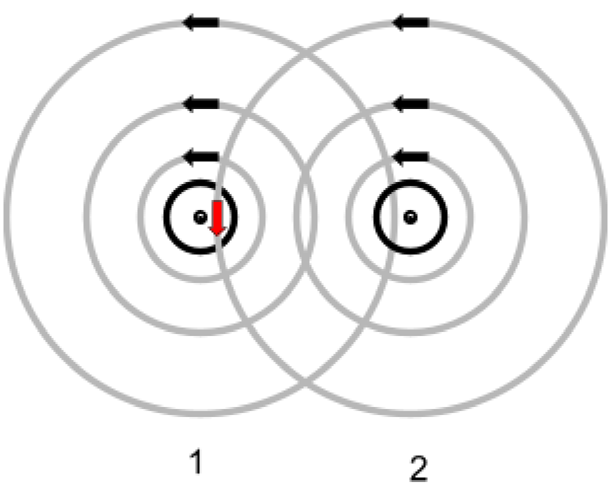


If there is not just one charge but a beam of charges of the same sign, we will observe the beam **deflecting** according to the circular path.

Observe the diagram above. The positive charge moves to the right, and the magnetic field goes into the page, resulting in a magnetic force upwards. If we replace this with a negative charge, what would happen to the direction of the magnetic force?

Interaction of Two Current-Carrying Conductors

Consider the scenario where two conductors are carrying current in the same direction. Each current can be affected by one or more surrounding magnetic fields, therefore resulting in a magnetic force acting on the conductor.



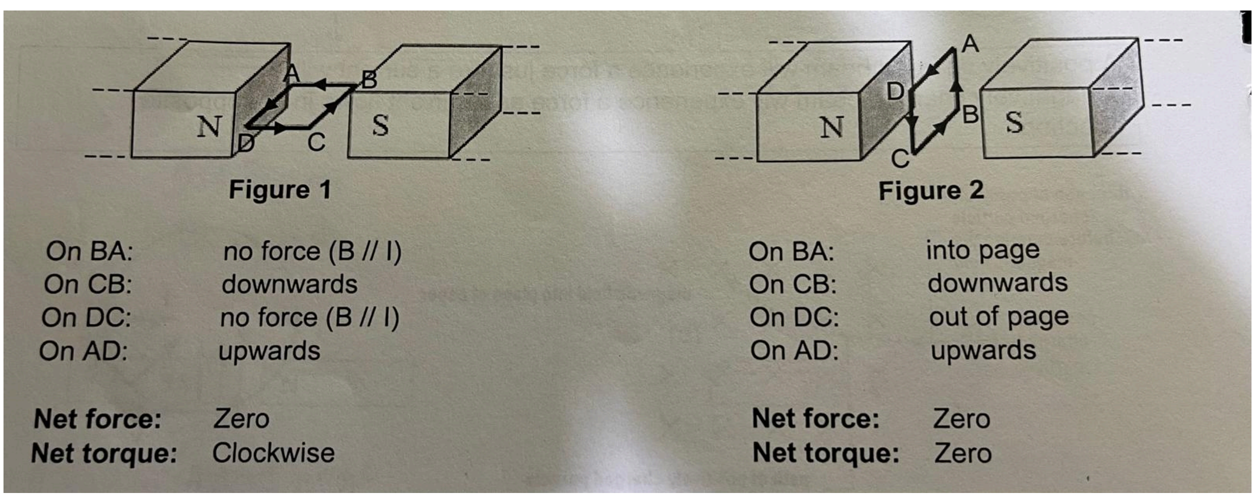
Note that because the magnetic field generated by each wire is **circular**, we take the tangent of the circle to be the direction of our magnetic field. In the above diagram, the direction of the magnetic field from wire 2 on wire 1 is **downwards** (red arrow).

Focusing on wire 1, we can now apply Fleming's Left Hand Rule to discover that the magnetic force on wire 1 is to the **right**. If we do the same with wire 2, we will find that wire 2 experiences a magnetic force to the **left**. Thus we can conclude that the two conductors will attract each other.

What if the conductors are carrying charges in opposite directions?

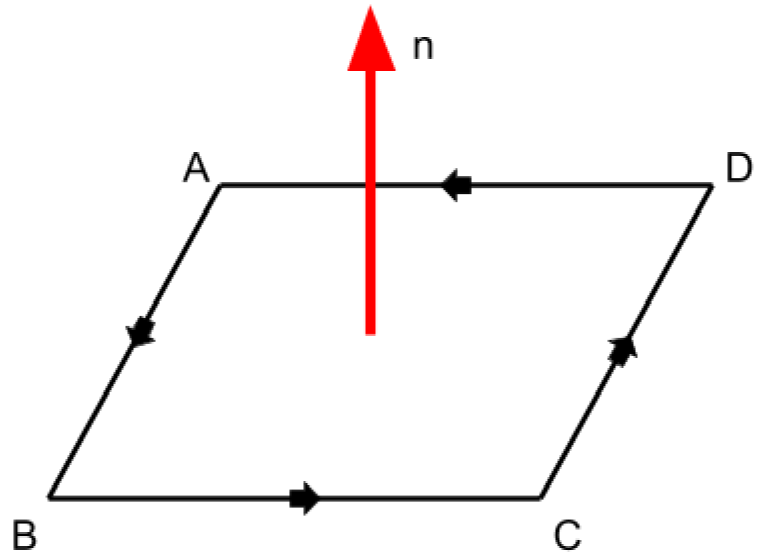
Torque on a Coil

A coil of wire within a uniform magnetic field may experience a net force or net torque due to the multiple directions in which the wires in the coil are oriented. For each segment of the coil, we can use Fleming's Left-Hand Rule to determine the magnetic force acting on it.

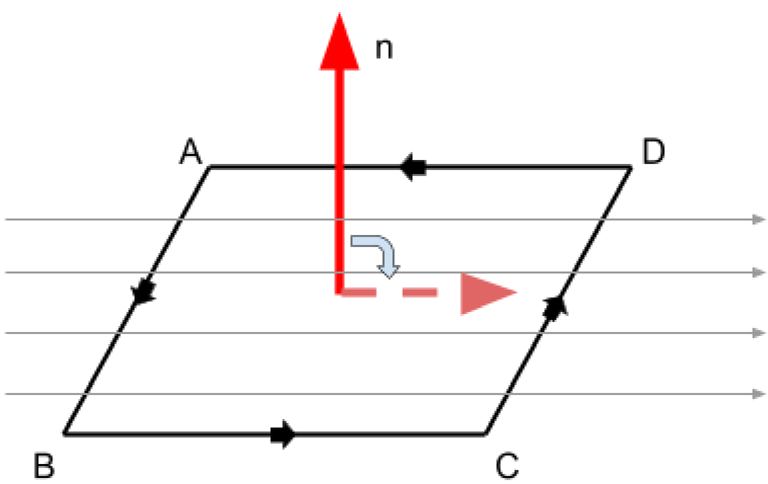


To check your answer, you may opt to **vectorise the loop current**.
What does this mean?

Using the **Right-Hand Grip Rule,** curl your fingers in the direction of the loop current. Your thumb represents the **vector** form (n) of the loop current.



This vector **n** will now rotate to be **parallel** (not anti-parallel!) to the magnetic field by the **smallest angle** it can. Assuming the magnetic field acts rightwards, this is what it will look like:

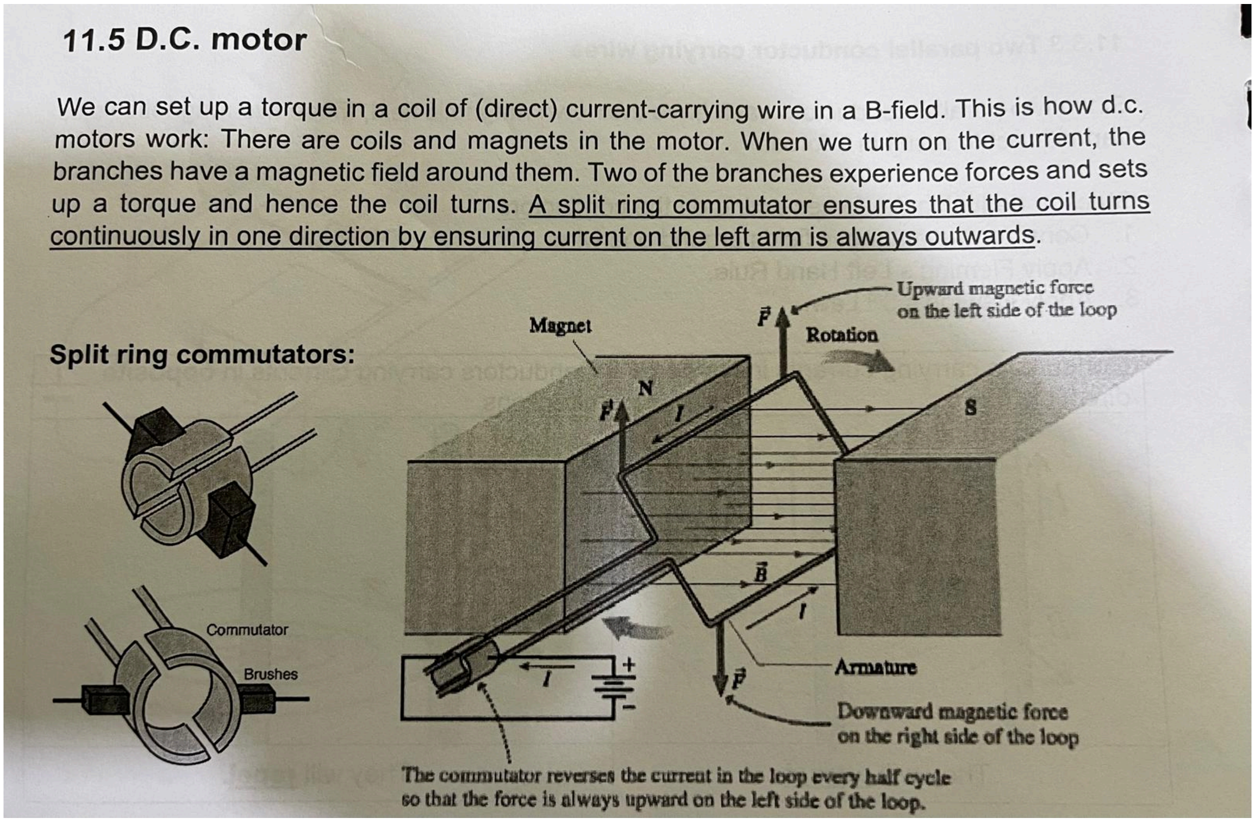


Don't forget the direction of the n-vector is bound to the coil. So, the coil will rotate as well.

NOTE: When asked to explain why the coil rotates in a certain manner, DO NOT use this method to explain it. You must cite Fleming's Left-Hand Rule.

D.C. Motor

We can exploit the free rotation of the coil in the presence of a magnetic field to create a motor.



11.5 D.C. motor

We can set up a torque in a coil of (direct) current-carrying wire in a B-field. This is how d.c. motors work: There are coils and magnets in the motor. When we turn on the current, the branches have a magnetic field around them. Two of the branches experience forces and sets up a torque and hence the coil turns. A split ring commutator ensures that the coil turns continuously in one direction by ensuring current on the left arm is always outwards.

Split ring commutators:

When the split-ring commutator is in contact with the brushes, current flows through the loop, creating a net torque clockwise.

When the split-ring commutator is **not** in contact with the brushes, no current flows through the loop, but there is still enough momentum to continue its rotation. Once it gets back in contact with the brushes again, the loop would have rotated 180 degrees and current flows through it as it would have when the loop was still rotated zero degrees, ensuring there is always a net clockwise torque.

What if the split ring commutator had no gaps? What if the split ring commutator had gaps that were too large?

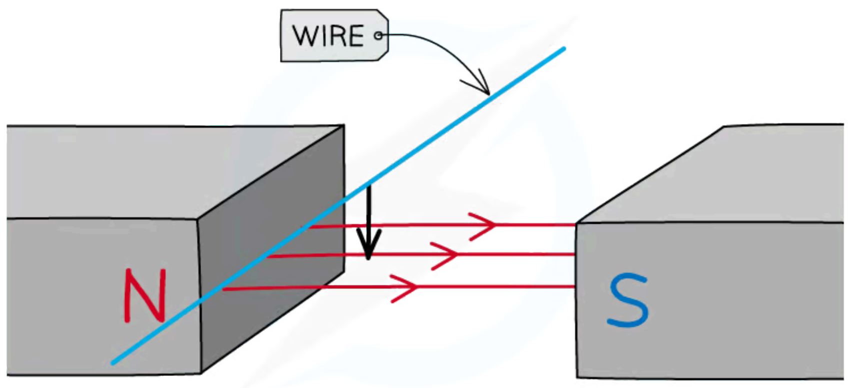
Electromagnetic Induction

When a current carrying conductor is in the presence of a magnetic field, we know that a magnetic force acts on said conductor.

But what if we purposefully move a conductor through a magnetic field? Well, it turns out that this in fact generates an **induced electromotive force** within the conductor. This phenomenon is known as electromagnetic induction.

Note: A conductor can take any shape or form - it doesn't have to be a wire. This may come out in the Physics exam so watch out!

Observations of Electromagnetic Induction

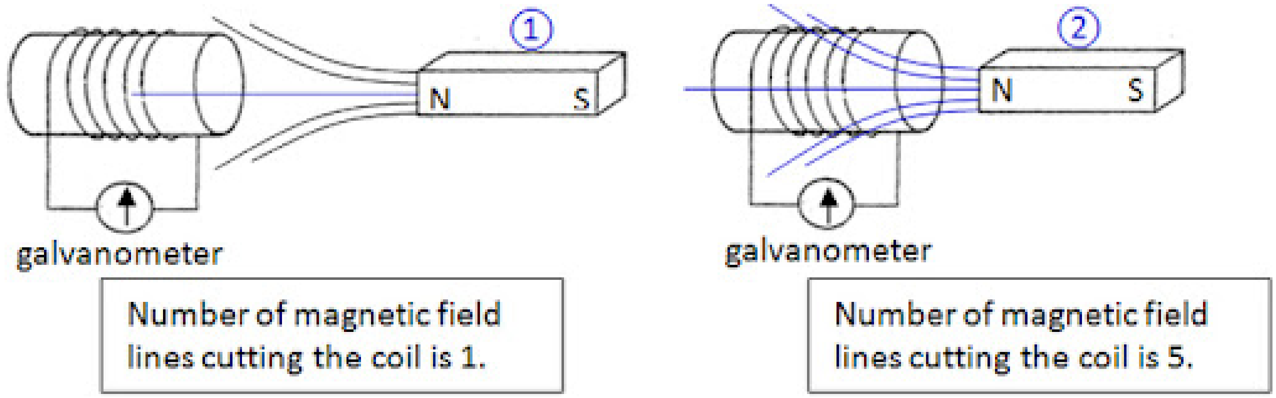


Consider the setup where a current-carrying wire is placed in a uniform magnetic field. If we imagine a positive charge within the wire being moved down, we can treat that as conventional current moving down. Applying Fleming's **Left-Hand Rule**, we can see that this would cause the positive charge to move out of the page. If the wire is not part of a closed circuit, this would result in a **potential difference** across the two ends of the wire, with positive charges accumulating out of the page and negative charges accumulating into the page. This movement is said to have **induced an EMF**.

If it is part of a closed circuit, there would also be an **induced current**.
What if the wire was moved up instead? What if the wire was moved parallel to the magnetic field? What if the wire was kept stationary?

From the above example we see that we require a movement perpendicular to the magnetic field to induce an EMF.

Now that we have gotten a basic idea of electromagnetic induction, let's turn our focus to Faraday's solenoid experiment.



Consider a magnet and a solenoid. We draw some arbitrary lines to indicate the magnetic field of the magnet (it is slightly inaccurate because two pairs of lines are quite close together). Initially, one of these arbitrary field lines is said to be **linking the coil**.

When the magnet is moved closer to the solenoid, more magnetic field lines link the coil. **The change in the number of field lines linking the coil is what induces an EMF in the coil** (and since it is a closed circuit, a current).

From the previous example, the following also applies that if the magnet is kept stationary in the solenoid, no EMF or current will be induced. We may now introduce some important terminology:

Magnetic flux - The number of magnetic field lines linking a cross-sectional area (of a coil). Denoted by Φ
Flux linkage - On a coil, the product of the magnetic flux and the number of turns of a coil. Denoted by $N\Phi$

In the context of PC3131, you need only know that you are strongly recommended to use the term "flux linkage" when the linked object in question is a **solenoid**. Else, "magnetic flux" is fine.

Laws of Electromagnetic Induction

From observing the results of Faraday's solenoid experiment we have stumbled upon **Faraday's Law**, which states that the EMF induced in a conductor is directly proportional to the rate of change of magnetic flux linkage.

To increase the rate of change of magnetic flux in the **wire cutting experiment**, we could:

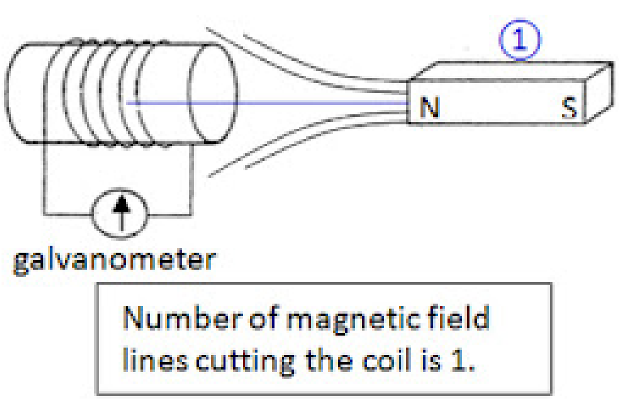
- Move the wire faster through the magnetic field
- Use stronger magnets which result in a stronger magnetic field (and hence would be represented with relatively more magnetic field lines)
- Increasing the length of the wire moving through the magnetic field / moving a coil of several turns through the magnetic field

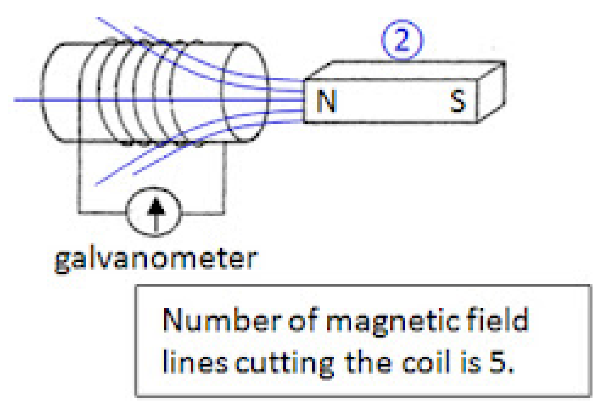
Note: The concept of the wire "cutting" through the field lines can be interpreted as a change in magnetic flux. Sounds weird, but just take it as it is.

To increase the rate of change of magnetic flux linkage in **Faraday's solenoid experiment**, we could:

- Increase the number of turns in the solenoid
- Use stronger magnets
- Move the magnet through the solenoid faster

Let's revisit the solenoid experiment again.

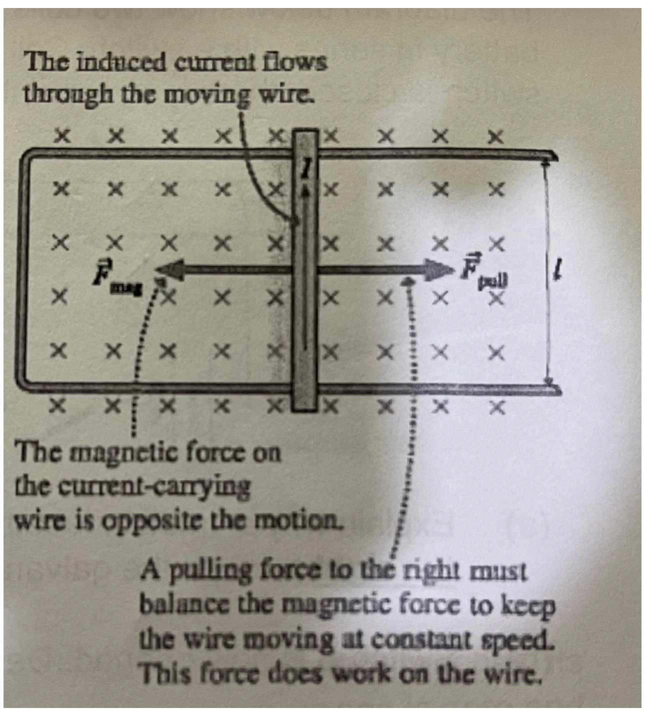




It just so happens that when the magnet is moved towards the solenoid, a current is induced in such a way that it generates a magnetic field that **opposes** the magnet's movement. In this case, it would mean that the solenoid has generated a North pole on its right. (How would the current be flowing in the coil then?)

We hence get **Lenz's Law**, which states that the direction of the induced current is such that its magnetic field will oppose the change that created it.

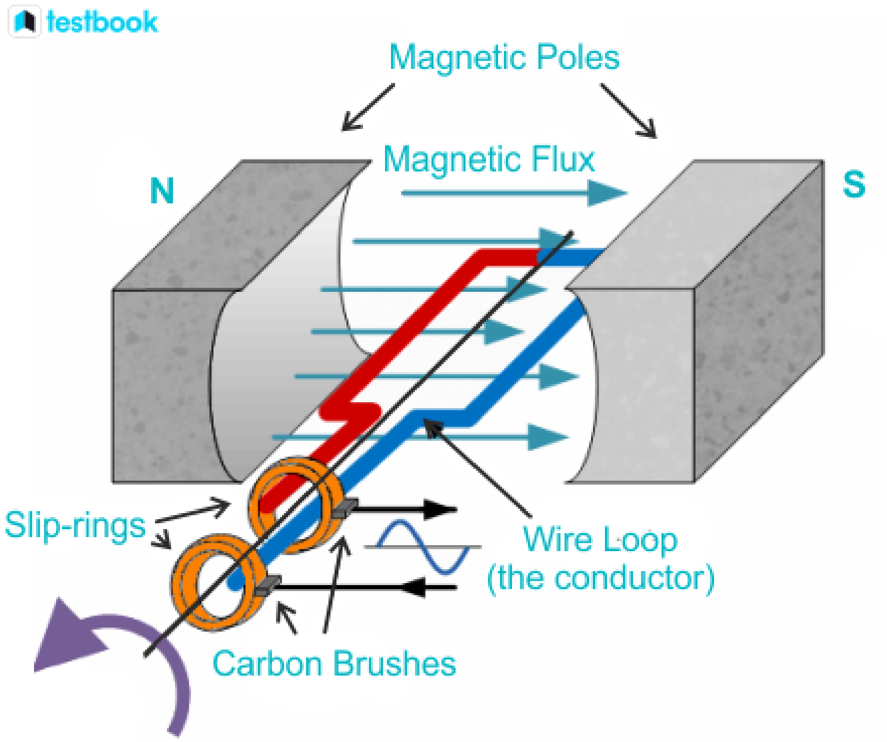
To help you justify this law, assume the direction of the current flows in a way that its magnetic field actually **increases** the change that created it. The magnetic field would get stronger, inducing a larger current, making the magnetic field even stronger, inducing an even larger current… it would be a never-ending positive feedback loop of energy creation, which would **violate the law of conservation of energy.** That should be a pretty solid argument :)



Force-Induced EMF

When we exert a pulling force on a slide wire on a U-shaped track as shown in the diagram below, there is an induced current upwards.
The magnetic field is into the page. If you attempt to justify this phenomenon with Fleming's Left-Hand Rule, plugging in the exerted force and magnetic field, you will find that you will get your middle finger to point the opposite way. **Hence, we will use Fleming's Right-Hand Rule for any cases where the current is induced by a force** (the shape of your hand is symmetrically similar to the case of the Left-Hand Rule).

A.C. Generator

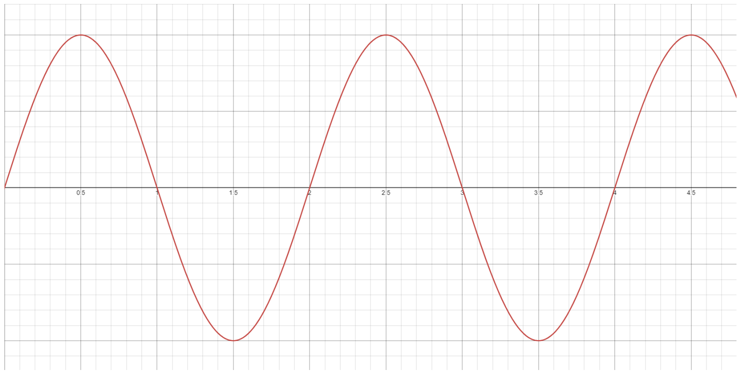


In this setup, a coil of wire rotates in the presence of a magnetic field. The rotation may be caused by a force, like a hand turning a wheel with a handle, or the rotation of a turbine caused by strong winds - **recall that the purpose of electromagnetic induction is for mechanical energy to be converted into electrical energy.** Notice that even though the area of the coil and the strength of the field remains constant, the magnetic flux changes.

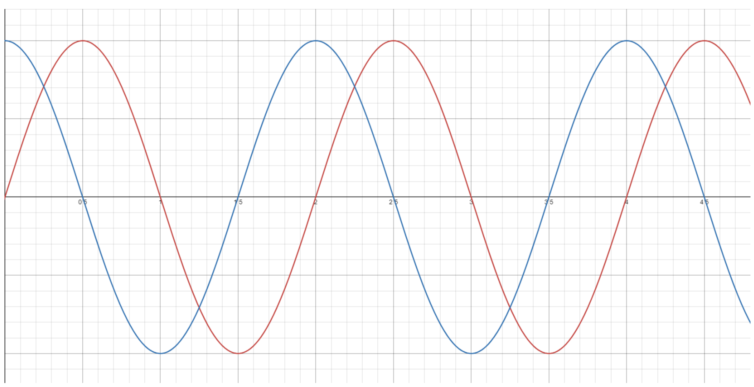
Note: Magnetic flux is actually more concretely defined to only consider the **perpendicular** component of the magnetic field lines to the cross-sectional area (or vice versa). That's why the magnetic flux can change purely by rotation of the coil!

When the current is induced, it is conducted to an external receiver by using **slip rings**. These ensure electrical contact at all times with the coil and carbon brushes which conduct the current to an external receiver.

If we take the initial state as shown in the diagram to be zero degrees of rotation, then at zero and 180 degrees of rotation, magnetic flux is zero. At 90 and 270 degrees of rotation, magnetic flux is at its maximum magnitude. The graph of magnetic flux against time can actually be modelled with a sinusoidal function like so:



Recall that the induced EMF is determined by the rate of change of the magnetic flux. Therefore, the graph of EMF against time is simply the **derivative** of this function:



Red is magnetic flux and blue is induced EMF.

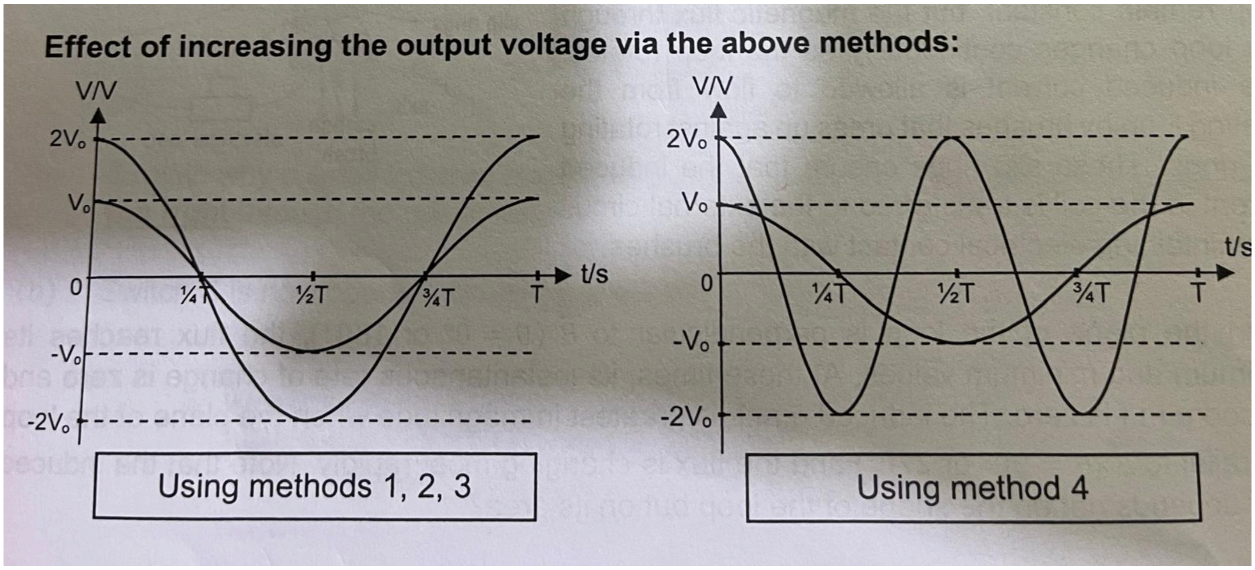
Note: The graph of EMF may be flipped across the x-axis as the exam will not specify from which reference point we calculate our EMF. Recall that $V_{AB} = -V_{BA}$. In actual fact, however, the equation of induced EMF is given by $\varepsilon = -\frac{d\phi}{dt}$.

In summary,

- When the magnetic flux is at its **maximum magnitude**, induced EMF is **zero**.
- When the magnetic flux is **zero**, induced EMF is at its **maximum magnitude**.
- You may say that the two sinusoids are out of phase by **90 degrees**

To increase the output voltage of the A.C. generator, we can do a few things, all of which increase the change of magnetic flux linkage:

1. Increasing the number of turns on the coil
2. Increasing the strength of the magnetic field
3. Inserting a soft iron core
4. Increasing the speed of rotation of the coil

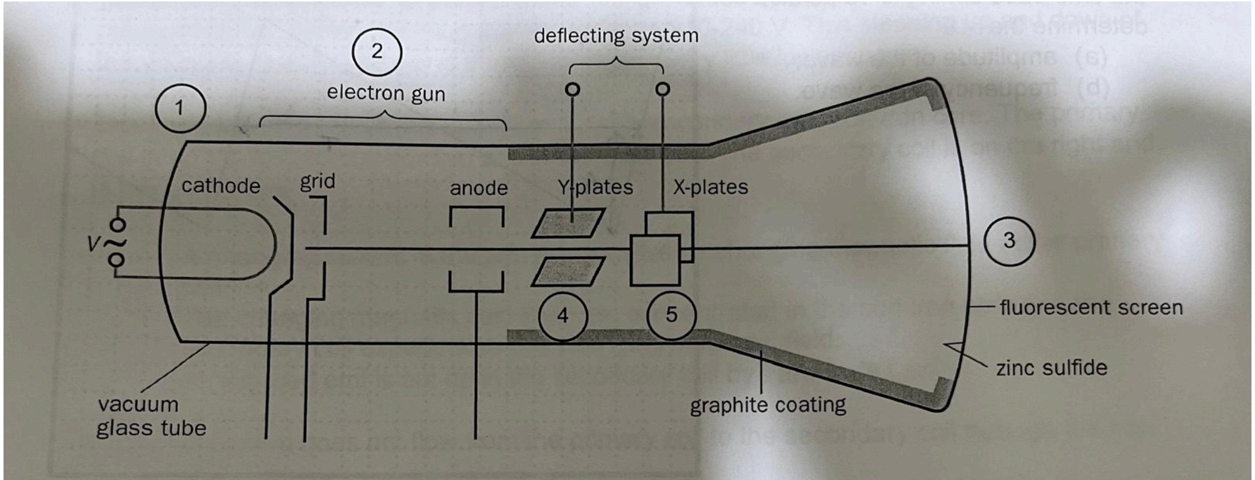


To double the output voltage, you need to double the relevant parameters as well. (e.g. use four loops of coil instead of two, using magnets twice as strong, doubling frequency of rotation). Only the soft iron core will not guarantee an exact doubling of output voltage.

Note: The graph of induced EMF is different when using method 4 as since the coil rotates faster, the period of the sinusoidal is shorter.

Cathode Ray Oscilloscope (CRO)

The cathode ray oscilloscope allows us to display voltages as points on a graph (over time).



Parts of the CRO:

1. The cathode-ray tube consists of a **vacuum tube** that holds an electron gun, a deflecting system and a fluorescent screen.
2. The **electron gun** emits a beam of electrons, which are produced by the cathode.
3. A bright spot is created when the electron beam strikes the **fluorescent screen** (coated with zinc sulfide).
4. Varying the voltage across the **Y-plates** changes the vertical deflection of the electron beam.
5. Varying the voltage across the **X-plates** changes the speed at which the electron beam sweeps horizontally across the fluorescent screen.

When a CRO graph is generated, the X axis denotes **time** and the Y axis denotes **voltage**.

The **time base** (allows voltage to be displayed over time) can be on or off.