

Copper and Electricity: Generation

(Electromagnetic Induction)

Below are different sections of this e-source, for quick navigation.

- Electricity from Movement
- What is Induction?
- Flux and Flux Density
- Questions

Electricity from Movement

What is a generator?

A wind turbine turns a generator to generate electricity. The wind makes it turn round. In turn, the turbine turns the generator; inside the generator is a coil of wire that is made to turn in a magnetic field. Making the coil turn produces a voltage in the coil. The voltage can drive a current along the cables of the national grid to light up our homes.

The generators in a power station are similar, but much bigger. They are capable of producing many megawatts of power.

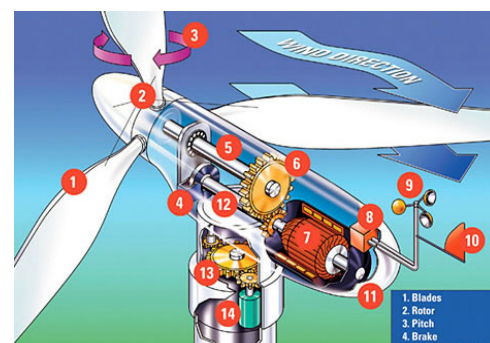
A generator is a bit like a motor in reverse. We put in movement and can take out an electric current.

This is an example of electromagnetic induction - a voltage is induced in the coil when it moves in a magnetic field.

Inside a generator

The inside of a simple generator is very similar to the inside of a simple electric motor. There is a coil that is free to rotate between two magnets. The magnets are linked by a steel former and the coil is connected to wires using brushes. However, instead of a commutator, the generator uses slip rings. So the contacts are not swapped over - each brush maintains contact with the one end of the coil all the way through the cycle.

A voltage is induced when the coil turns in the magnetic field. See the link to video on the right.



Components of a wind turbine.
(Courtesy of Alternative Energy News.)

Simple animation of
d.c. generation.
(Courtesy of Steven Carpenter.)



Notice:

- the position of the coil when the induced voltage reaches its maximum value.
- the change of direction of the current during a cycle.

What makes a generator work?

A generator generates a voltage. It will deliver a current when we connect it to a load (such as a light bulb). The current lights up the bulb. However, it also makes it harder to turn the generator.

We have to work harder to keep the generator turning once a current is being taken. The more current we take from the generator, the harder it is to turn it.

This makes sense: we don't get something for nothing. As soon as we get the generator to do work for us, we have to put more work into it. And the more work we get it to do, the more work we have to put in. If this weren't the case, we'd be getting something for nothing. And this would go against the ideas of the conservation of energy.

There is a good physical reason why it gets harder to turn the generator when it is delivering a current; it starts to behave like a motor. The current is flowing in the coils. Therefore there is a force on the coils – as though it were a motor. And this force will oppose the motion of the generator and make it harder to turn it. This is the physical origin of Lenz's law. The force on the induced current opposes the force you apply to make the current flow.

Work in, electricity out

When you pedal a bicycle, it's a bit harder when the dynamo is working to power the lights. It isn't simply that there is more friction. You have to do work to make the dynamo supply electricity to the lights. And the more current the lamp takes, the harder it is to pedal.

Whenever we take a current from a generator or dynamo, there has to be some mechanical driving force:

- A cyclist does work pedalling to turn the dynamo (using up the chemical energy from their food).
- The wind does work to turn the turbine; the wind slows down.
- Moving steam in a thermal power station turns the turbines which turn the generators (we have to burn more fuel to make more steam).

In each case, we don't get something for nothing. In order to deliver an electric current, we need to do mechanical work.



A bicycle dynamo generates a voltage to light a lamp. The bigger the current that it delivers, the harder it becomes to pedal.

What is induction?

Inducing a voltage

We can induce a voltage in a wire using a magnetic field. We need to make the wire move through the field. We call the voltage the induced EMF (electromotive force). The faster the conductor moves through the field, the bigger the induced EMF. This is Faraday's law.

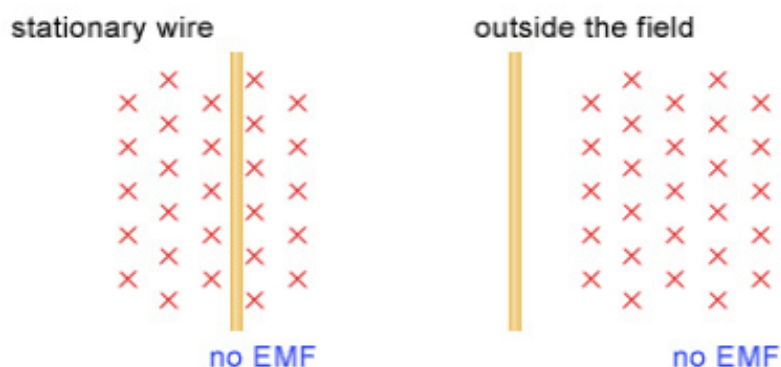
If we move the wire the other way, then the direction of the EMF will be reversed.

The EMF will drop to zero if the wire:

- stops moving or
- is outside the magnetic field.

The wire needs to be cutting through the lines of flux in order to induce an EMF.

[Click here to see an animation demonstrating this.](#)



We get the biggest induced voltage when these three quantities are at right angles to each other:

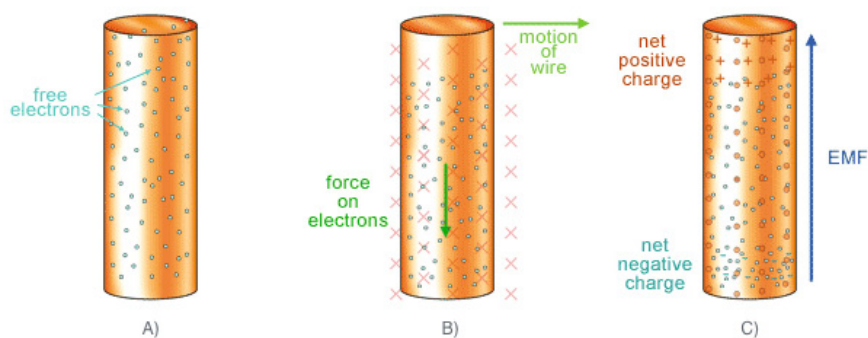
- the motion of the conductor.
- the magnetic field B .
- the wire (and hence induced EMF).

Why do we get a voltage?

Imagine some free electrons (or beam of electrons) being fired into the magnetic field. There will be a force on the electrons. The electrons have a negative charge. This means that, although the electrons are moving from left to right, they are like a current flowing from right to left.

We can use Fleming's Left Hand Motor Rule to find out the direction of the force. It is downwards. So the electrons are pushed downwards.

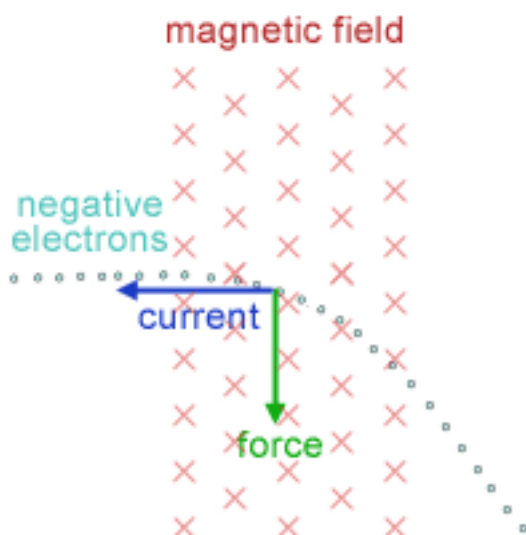
A piece of copper wire also contains free electrons (A). So when the wire moves into the field, the electrons are pushed downwards (B). This leaves behind a net positive charge at the top of the wire. Hence, the charge is separated in the wire setting up a voltage (C). The top has become more positive and the bottom has become more negative.



Which way is the force?

This EMF is like the EMF of a cell. It is available to drive a current around a circuit. If we attach a load to the wire, then a current will flow. We call this an induced current. However, as soon as we take a current from the wire, the wire will feel a force (a wire carrying a current in a magnetic field feels a force).

We can use Fleming's Left Hand Motor Rule to work out the direction of the force. In this case it is downwards.



In other words, the force will push against the motion of the wire. The wire will slow down. If we want to keep it moving, we'll have to push it.

If we take a bigger current from the wire, we'll have to push it harder. The bigger the current we get from the induced EMF, the more work we have to put in.

This makes sense: we don't get something for nothing. When we take a bigger current, we are getting the induced EMF to do more electrical work for us. Therefore, we have to put in more mechanical work. This is the conservation of energy.

Lenz's law

When we start taking a current from the induced voltage, there is a force on the wire. We have already seen that the force will tend to slow the wire down - or make it harder to keep it going. This is expressed in Lenz's law:

'The induced current flows in such a way as to oppose the motion that produced it.'

Lenz's law is based on the idea of the conservation of energy. If the induced current did not flow in this way, then we would be able to get something for nothing.

Induction in Coils

Inducing a current

Imagine a magnet near a coil of copper wire. The coil is connected to a sensitive ammeter. When the magnet is stationary, there is no current in the coil. However, if we move the magnet towards the coil, the ammeter flicks to the right. Now let's pull the magnet out. The coil flicks to the left.

This shows that we induced a current in the coil - but only whilst the magnet was moving. The direction of the current depended on the direction of the movement.

To get a lasting current from the coil, we have to keep pushing the magnet in and pulling it out. This will make the current go backwards and forwards. In other words, we have generated an alternating current.

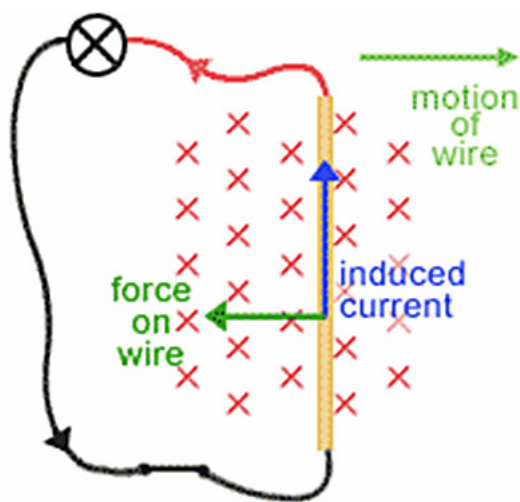
But how can we work out which way the current will flow? By using Lenz's law.

Lenz's law and coils

When we induce a current in the coil, it becomes an electromagnet. One end of the coil is a north pole and the other end is a south pole.

When the north pole of our magnet is moving towards the left hand end of the coil, the induced current flows anticlockwise (as we look at the left hand end). This makes the left hand end of the coil into a north pole. And this north pole tries to repel the incoming north pole of the magnet.

So the induced current opposes the motion that induced it (from Lenz's law).

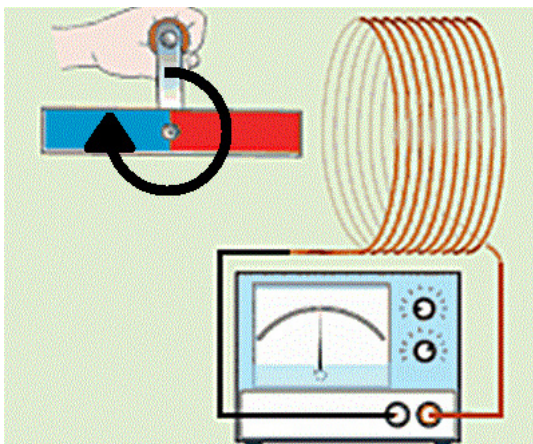


When we pull the magnet out, the left hand end of the coil becomes a south pole (to try and hold the magnet back). Therefore the induced current must be flowing clockwise.

Keeping the current going

We can mount the magnet on a crank shaft and turn the handle to make a simple generator.

As ever, we have to keep turning the magnet to overcome the opposing force produced by the induced current. I.e. we have to put mechanical work in to get electrical energy out.



Some generators use a magnet moving next to a coil. Others use a moving coil in a magnetic field. Although it is the coil that is moving, this works on the same principle - a magnetic field moving relative to a coil.

Moving coils revisited

We can now understand why we get an induced voltage in a moving coil. There are two ways of looking at it.

- the wires on the side of the coil are cutting through lines of magnetic flux
- the coil is being pushed towards a north pole and then towards a south pole and so on.

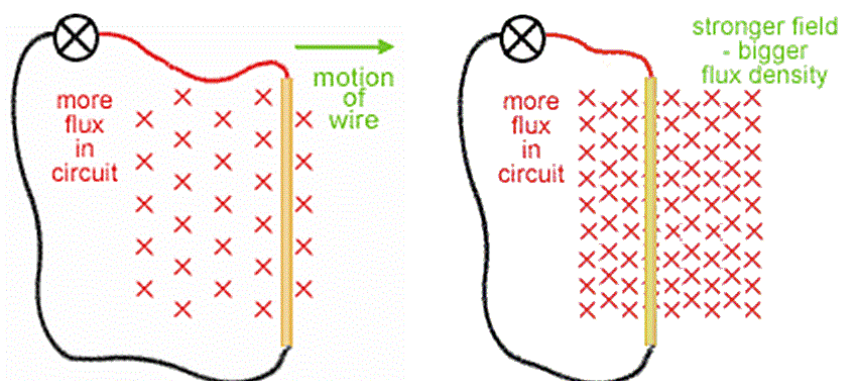
Flux and Flux Density

Inducing a current

We have seen that we can induce an EMF by changing the amount of magnetic field in a circuit. We can do this by moving a wire through a magnetic field or moving a magnet near to a coil. But what do we mean by amount of magnetic field?

Magnetic flux

Imagine a wire moving through a magnetic field. We represent the magnetic field with magnetic field lines. As the wire moves through the field, the wire cuts through the field lines. The number of field lines the wire cuts is called the magnetic flux. It is related to the area of magnetic field the wire crosses and the magnetic field strength (magnetic flux density).



We can increase the flux by moving a wire more quickly or increasing the magnetic field strength. This is like bringing a magnet closer to the coil in the earlier example.

So the flux in the circuit changes whether we:

- move the wire in a steady field, or
- change the field.

And in each case, we get an induced EMF.

Magnetic flux density

You can think of the flux as being represented by the number of field lines. We sometimes call them lines of magnetic flux. The closer together the lines of flux, the stronger the field. That is, the strength of the field is represented by the density of the lines of flux. We sometimes call the magnetic field strength B , the magnetic flux density. And we use this idea to define flux:

magnetic field strength = magnetic flux density = flux per unit area

$$B = \Phi / A$$

$$\Phi = BA$$

Faraday's law

We have seen that the faster we move a wire, the bigger the EMF we induce. In fact, we find that the EMF, \mathcal{E} , is proportional to the rate at which the flux changes. So, in a simple circuit:

$$\mathcal{E} \propto \frac{d\Phi}{dt}$$

This means that if we double the speed of the wire, the flux in the circuit increases at twice the rate. Therefore, the EMF is twice as big.

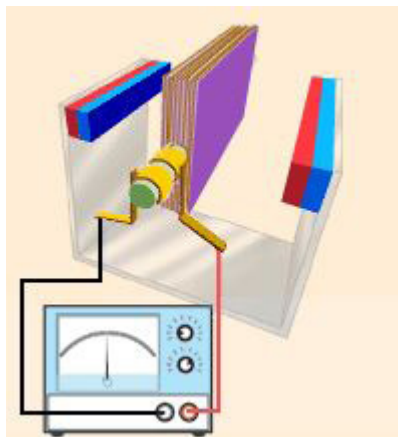
We can increase the total flux linking a circuit by using a coil rather than a single piece of wire. In which case, the EMF, \mathcal{E} , will increase in proportion with the number of coils, N . So we get an expression for Faraday's law:

$$\mathcal{E} = -N \frac{d\Phi}{dt}$$

Notice the minus sign in the equation. This is to indicate that the induced EMF opposes the change in flux that produced it.

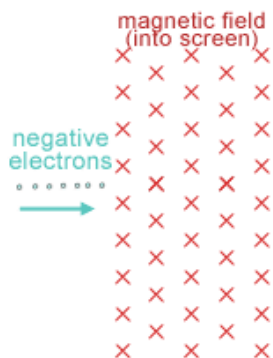
Questions

1. Look at the simple generator below.



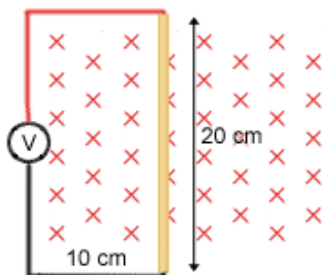
- Is the output voltage a.c. or d.c.?
- What is the effect on the voltage of reversing the direction in which the coil rotates?
- When the coil turns faster, two features of the output voltage change. What are they?
- When the output voltage is greatest, what is the position of the coil?
- When the output voltage is greatest, what is the direction of movement of the sides of the coil compared with the magnetic field?

2. In the figure below, the electrons are moving from left to right.



- Why is the current in the opposite direction to the electrons' movement?
- Explain why there is a force on a wire from which we take an induced current.
- The direction of the force opposes the motion that led to the induced current. Describe what would happen if this were not the case.
- Whose law is this?

3. Look at the circuit below. It shows a wire moving through a magnetic field. The wire is attached to a voltmeter. The magnetic flux density is 2 tesla and the wire is moving at 3 cm s^{-1} . The length of the wire is 20 cm. Imagine we start timing the moving wire when it is 10 cm into the field



- What is the area of magnetic field the wire has passed through?
- Calculate the magnetic flux the wire passes through?
- After 5 seconds, the wire will have moved through the field. How far will it have moved?
- By how much will the flux have increased in those 5 seconds?
- What is the EMF induced in the wire?

[Click here for answers](#)

Continue to Copper and Electricity: Transformers and the Grid

Return to Copper and Electricity: Electric Motors

Copper Development Association is a non-profit organisation that provides information on copper's properties and applications, its essentiality for health, quality of life and its role in technology. It supports education through a collection of resources spanning biology, chemistry and physics. These materials have been developed in conjunction with the Association for Science Education, and reviewed by teachers.

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