ELECTRICITY AND ELECTROMAGNETISM

PHYSICS

Level 2

NCEA | Walkthrough Guide
# Introduction

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## Key Terms
We’re about to go on a bit of a journey!

This journey has three main stops, and a whole bunch of twists and turns. The good news is, we’re taking all passengers! So, if you’re only just learning what this topic is about, or you’re a seasoned professional, we promise we’ve got something for you.

The reason we say this is a journey, is that electricity and magnetism (the two heroes in the title of this story) have more in common than we think. You may think of electricity as the force pumping through your lightbulbs, and magnetism as that handy tool holding your fridge shut, but it turns out, they have many things in common.

Magnets, like electricity, are powered by moving charges. Not quite sure what that means yet? Don’t worry! In this story, electricity and magnetism are our heroes, and moving charge is what makes them tick. As you read on in this guide, we’ll unpack what these terms mean - and introduce you to the wonderful world of electricity and magnetism!

What will you learn in this walkthrough guide?

I know I just told you that this standard has two main parts (electricity and magnetism), but NCEA really splits it into three. They are:

1. Static electricity
2. DC circuits
3. Magnetism

Static electricity is the prequel to our epic story (kind of like the hobbit). It is all about the non-moving charges that kick us into gear. Because of this, static electricity is all about ‘source charges’ -- a term you’ll be well familiar with by the end of this guide. This section also covers electric forces, electric fields and potential energy. All key parts of the story.
Once we have our non-moving charges sorted, we’ll get things moving. DC circuits involve moving charges. They are present in real life heroes like the lightbulb and the laptop this is being written on. To meet the DC circuit, we must be introduced to its super squad. There’s voltage, current and resistance -- and they all work together in different ways. In this section, we will also look at circuit diagrams, Ohm’s law and power.

Finally, we’ll introduce you to magnetism. Magnetism is all about magnetic fields. To really understand how magnetism works, we will look at the magnetic force on charged particles, the magnetic force on current-carrying wires and induced voltage.

A word on exam strategy.

Physics always has two parts:

1. Understanding the theory behind the concepts.
2. Understanding relationships to do some calculations.

Although you are given all the formulae on the resource sheet, you need to make sure you understand the meaning behind all of them, and can take the formula and describe the relationships between the different properties. If you can look at a formula and explain the underlying concepts you’ll know you have it sorted.

Here at StudyTime, we’re pretty much GCs (good citizens), so to help you out, we’ve made this guide in plain English as much as we can. We’ve also included a glossary for some of the key terms that you’ll need to master for your exam.

If learning key words first off scares you (or bores you), then focus on understanding the concepts the first time around, and then memorise the definitions.

In fact, in this guide, we focus on helping you to understand the concepts first. We use examples and analogies to help you understand Physics in a way that is fun, and makes sense in the real world.

However, the language we use isn’t always something you can directly write in your exam. When this is the case, we offer a more scientific definition or explanation (in a handy blue box) underneath. These boxes are trickier to understand on your first read through, but contain language you are allowed to write in your exam. Look out for them to make sure you stay on target!
STATIC ELECTRICITY

Let’s begin! The electricity part of this guide is broken into two components. The important thing to note about this section is that ‘static’ is just a fancy word for being ‘still’.

Because of this, the first thing to note about this section is that we will NOT be talking about circuits. Static electricity refers to electricity that does not run through a circuit. Instead, it travels in a different way, which we’ll unpack as we go on.

Static electricity is charge that is NOT pushed through a circuit. It’s the charge you get when you rub two balloons together.

Static electricity is all around us. Those annoying shocks you might have got as a kid going down the slide or the electricity causing your hair to stick up when you rub a balloon on it are all examples of static electricity at work. Intrigued? As you read on, we’ll explain exactly how to define static electricity and how it works its magic.

By the end of this section you should be able to:

- Talk about the forces that act on charged particle inside an electric field.
- Explain what determines the strength of the electric field, and what this strength means for any charged particles inside it.
- Draw a uniform electric field.
- Calculate the amount of potential energy stored by a charged particle at various locations in an electric field.

Electric Force

I think it’s about time we talked about charge

Let’s start by talking about mass. Mass is a concept you will have heard being thrown around in your everyday life. Mass is similar to weight, in that it describes how much
matter is in an object. For example, a bus has a large mass and a bike has a small one. We call ‘mass’ a property of an object. A property of a bus is that it has a relatively large mass compared to other transport options.

‘Charge’ is simply another property of an object. It describes how positive or negative an object is. In chemistry, you would have learnt that electrons have a negative charge, and protons have a positive charge.

In physics, we often refer to charge moving between objects, or around a circuit. In this context, when we refer to charge, we are referring to the movement of electrons. As electrons leave an object, the object it is leaving loses negative charge, and gains a more positive charge (due to a lack of negativity).

So, how do we summarise charge? It’s basically a cousin to mass that helps us describe stuff. It has the symbol \( q \). The more charge the stuff has, the more it will be pushed or pulled (i.e. forced around) by an electric field (which we will get to later on). In fact, you might not be surprised to know that magnetic fields care about charge too (which we will get to much, much later on).

Charge, \( q \), is a property of a particle or object that measures how much the object will interact with an electric and magnetic fields.
While mass is measured in kilograms (kg), charge is measured in coulombs (C). The more coulombs of charge there is on a particle or object, the more charged it is. The interesting thing about charge, is that, unlike mass, it can be a positive or negative value. A negative number of coulombs indicates a negatively charged object, whilst a positive number indicates a positively charged one.

**The best example of charged particles are electrons and protons**

In fact, the smallest amount of charge you’ll have to deal with is the charge on protons and electrons – except for things with no charge of course! Protons and electrons have the same amount of charge, but protons are positive and electrons are negative. The amount of charge found on protons and electrons is:

\[ q = \pm 1.602 \times 10^{-19} \text{ C.} \]

This is a very, very small number! Unfortunately, in level 2 physics, you need to get used to reading small numbers, which are assigned scientific notation.

If we were to write out the number above without scientific notation, it would look like: 0.0000000000000000001602. The ‘\( x\ 10^{-19}\) part of scientific notation tells us that the number we are looking at involves moving the decimal place 19 places to the left if we wanted to write the number out in full. (If the number was positive, we would move the decimal place to the right)

The smallness of this number tells us that the charge on a proton or electron is much less than one full coulomb.

\[ \begin{align*}
+ & \quad = + 1.06 \times 10^{-19} \quad \text{Coulombs} \\
- & \quad = - 1.06 \times 10^{-19} \quad \text{Coulombs} \\
+ + + & \quad = 3 \times ( +1.06 \times 10^{-19} ) \quad \text{Coulombs} \\
+ - & \quad = 0 \quad \text{Coulombs}
\end{align*} \]

**Introducing conductors and insulators**

Now that we’ve introduced our first character in this story, I’m going to tell you a bit of the backstory behind static electricity. Think of this as the history behind how static electricity got its powers. We’ll start off by discussing the difference between insulators and conductors.
Conductors are materials such as metals that carry moving charge easily. Think of them as a nice paved road for electrical charge - they simply glide along conductors to reach their destination. Because of their ease to travel through, conductors are used in wires, circuits, and other areas where moving charge is necessary.

Insulators do not carry charge as easily. Think of it as the charge equivalent of trying to walk through thick mud. Charge finds it very hard to travel through an insulator, and insulators are therefore used to coat electrical wires, so that the charge cannot escape through them.

A conductor is a material which is easily able to carry moving charge. An insulator is a material which is unable to easily carry moving charge.

How insulators and conductors relate to static electricity

Because insulators can’t carry electrical charge very well, when charges are passed to them, they tend to just build up. Think of this as a whole bunch of runners jogging down a smooth road (a conductor), and all of a sudden reaching a thick mud pond (our insulator). All of the joggers would slow right down, and we’d have a traffic jam at the mud.

So, insulators involve charges coming to a halt. We’ve already covered the idea that static electricity involves charges which aren’t moving. Therefore, it makes sense that insulators would be where we are most likely to locate static electricity. So, whenever you think static electricity - think insulators.

Back to static electricity

A long time ago, in a land far away, there was a child who went to the mall. At the mall, the child got a brand new haircut. Because he sat through his haircut so well, his mother gave him a balloon. Because they don’t carry electricity very well, the balloon and the boy’s hair are both referred to as ‘insulators’.

On the way home, the boy was checking out his new haircut, and ended up rubbing the balloon against it. As he did this, he noticed his hair begin to stick up on its end. Luckily, the boy was far too young to be studying NCEA physics, so laughed at what was happening, and didn’t have to question why.
Questioning why

Understanding what is going on when the boy’s hair sticks on end is a key part in understanding how static electricity works.
If you think back to level one chemistry, you’ll hopefully remember that everything in life is made up of atoms. Atoms are made up of neutrons (no charge), positively charged protons and negatively charged electrons.

Although protons are firmly locked away in atoms, electrons roam around the outside, and can move between objects.

When the balloon is rubbed against the boy’s hair, electrons are rubbed off his hair, and onto the balloon. The more the balloon is rubbed, the more electrons come off and stick to the balloon.

Because the balloon is an insulator, these electrons do not spread out or reach other parts of the balloon. Instead they build up on the surface.

Remember that electrons have a negative charge. This means that, as the electrons rub into the balloon, it gains more negative charges. Similarly, because the boy’s hair is losing electrons, it gains a positive charge.
This leaves us with a negatively charged balloon, and a positively charged hair cut. I guess we could call these opposites.

Now, a key thing to remember, is that opposites attract. This is another way of saying that positive and negative charges will always try to move towards each other.

Like charges have a force of repulsion between them, while unlike charges apply a force of attraction to each other.

In the context of the balloon, this means that, as the negatively charged balloon is pulled away from the boy, the positively charged hair will be attracted to it. This causes the hair to appear as though it is standing on end, as it moves in the direction of the balloon.

**What really causes this movement?**

When we have two charged objects (like the balloon and the hair), we will see them interact with each other (usually in the form of movement).

This movement can go two different ways:

1. The two objects are attracted to each other (like the balloon and the hair).
2. The two objects are repelled by each other.

Instead of saying all of that attraction/repulsion jazz, we make life easier by saying...
that there is an **electric force** acting on one object *due* to the other one (that word ‘due’ is important here).

So, in the case of our poor boy, there is an electric force acting on his hair due to the balloon.

To summarise, any time one charged object or particle causes another to move, we say there is an electric force acting.

Electric force, symbol $F$, is the force that causes the attraction or repulsion between two charged particles or objects.

**So, how big is this fancy electric force?**

When we start talking about forces, it’s handy to know how big they are. In the case of electric force on a charged object, it depends on two things: the amount of charge the object has ($q$) and the electric field (which we call $E$) that this particle experiences (we will talk about this next).

A bigger charge means a bigger electric force. A bigger electric field means a bigger force. So, the equation $F = Eq$ is used to find electric force.

**STOP AND CHECK:**

Turn your book over and see if you can remember:

- The two types of charged particles which make up an atom – which one is positively charged and which one is negatively charged?
- The symbol and unit for charge.
- The two things that the electric force depends on.
- Which of these situations count as static electricity? (a) current going through a light bulb, (b) thunderstorm, (c) the shock you felt when you got on the slide that one time as a kid.

Try to explain it in your own words.

**Electric Fields**

Now that we are a bit more comfortable with charge, static electricity and electric force, it’s time to dive into the concept of electric fields.

All we know so far is that electric fields help make the electric force - so we know that they must be important.
Let’s throw it back to our friend again, and think of his hair

Think of the balloon held above his head and his hair stretching up to reach it. Because it kickstarts this whole experiment, we call the negative charge in the balloon the ‘source charge’.

But what exactly is it the source of?

The negative charge that is now on the balloon generates an electric field in the space around the balloon. This is why they are called source charges. The more the balloon is rubbed against the hair the more charges are transferred, and the stronger the electric field around the balloon is.

You might be wondering why we didn’t say the positive charges in the hair were the source charges. Why choose the negative charges in the balloon? It actually depends on what you want to focus on! We wanted to focus on the way the hair is attracted to the balloon, and so the balloon must be the source.

A source charge is a charge that creates an electric field around it.

What is an electric field?

A field is defined as an area of space in which objects will be affected if they enter. When you spray a can of Lynx, you could say the area around the can where you can smell it is the ‘scent field’ of the can. This is because it is the area where you are affected by the smell.

In the exact same way, the electric field of a charged particle is the area of space where other charged particles are affected. In the balloon example, the negative charges on the balloon create an area of space where they affect (attract) the positive charge in the hair! You would have noticed that, at a certain point, the balloon becomes too far away to affect the hair. This happens when the negatively charged balloon is too far away to attract the hair towards it using its electric force.
An electric field is the region surrounding a charged particle or object where a force is exerted on another charged object.

**So how do we draw electric fields?**

Electric field diagrams give important information, such as how big the electric field is and how it affects other charges around it.

The first key to drawing electric fields is using lines to show the shape of the field. Most electric fields are uniform (and drawn using parallel straight lines), or radiate from a charge (and are drawn by a series of radiated lines).

The direction of an electric field is also super important. The direction tells us whether other charged particles will attract or repel, and therefore which direction they will move when they are affected by the electric field.

The direction of the electric field lines tells us the way that a *positive* charge would move if it was put into the field. Therefore, we draw the arrows pointing away from positively charged objects or particles (as positive charges repel other positive ones), and towards negatively charged ones (as negative charges attract positive ones). On the other hand, the *strength* of the electric field is indicated by how bunched up these lines are.

The first type of electric field you need to be able to draw, is one surrounding a single charge, or single object. If the charge is positive, the electric field will be made up of series of lines pointing away from the charge, and if it is negative, the lines will converge in towards it.
Lastly, electric fields have a strength assigned to them. The stronger the electric field, the greater its ability to affect particles of objects that travel into its range. The strength of an electric field is indicated by the symbol $E$, and it has units of NC$^{-1}$.

Electric field strength can be found by rearranging an equation we have already encountered. If we take our old friend $F = Eq$, we can rearrange to get:

$$E = \frac{F}{q}.$$

The unit of Electric Field strength can be found by considering the units for force and charge. We know that the unit for force is Newtons (N) and the unit for charge is coulombs (C). Putting these into our equation, we get:

$$\frac{N}{C},$$

which we can also write as NC$^{-1}$.

STOP AND CHECK:

Turn your book over and see if you can remember:

- What sources charges are. How do we choose what they are when we have two choices?
- How to draw electric field lines.
- How do you indicate the direction of an electric field? How do you indicate its strength?
- The symbol and units for electric field strength.
- If you put 1 electron and a clump of 2 protons (e.g. a helium nucleus) into the same electric field, which of these would describe the result?
  (a) they both move in the same direction, but the protons accelerate faster,
  (b) they move in opposite directions and accelerate equally,
  (c) opposite directions but protons accelerate faster or
  (d) they don’t move at all
Uniform Electric Fields

The term uniform simply means ‘the same’. That’s why, when you have a school uniform, all of your friends are wearing the same clothes.

Uniform electric fields are an early Christmas present from NZQA to you. Really.

In the context of electric fields, the term ‘uniform’ means that the field has the same strength \( E = F/q \) everywhere. This means that, no matter where the location of a charge within the field is -- or how close a charge is to either side the charge will be affected to the exact same degree as a charge located in any other place in the field.

**Because a uniform electric field is the same everywhere, it is super easy to draw**

A uniform electric field is made up of *straight* and *evenly* spaced lines. These lines run parallel to each other.

![Uniform Electric Field Diagram](image)

The best way to think about a uniform electric field, is to imagine two metal plates placed near each other so that they are parallel. One plate has a positive charge, while the other has the same amount of negative charge. These positive and negative charges on the plates are the source charges of the electric field between the metal plates!

This situation gives rise to a uniform electric field between the two plates. We know this field exists because we can imagine a positive charge being instantly attracted to the negative plate, and repelled by the positive plate. As the attraction increases, the repulsion decreases -- which is how we know the field is uniform!

Because any positive charge placed in the uniform field will move away from the positive plate and towards the negative plate, we draw the electric field arrows going from the positive to negative plate.

**So what’s the deal with voltage?**

Let’s link all this to a little word you’ve probably heard before: voltage. The two metal plates, one with positive charges and one with negative charges, make any charge between the plates move.
This means that the electric field between the plates is giving energy to the charge in between!

We use the word voltage whenever charges gain or lose energy. The most common place to use the word comes up in DC circuits, as we will see. But even the metal plates have a voltage across them.

If the energy change is positive (which really just means the charge gains energy when going across) then the voltage is positive. If the energy change in negative (the charge is losing energy - we will explain how this can happen later) then the voltage is negative. All this is captured by the formula;

\[ V = \frac{\Delta E}{q} \]

where \( \Delta E \) is the energy change (joules, J), \( q \) is the charge (coulombs, C) that experiences the energy change and \( V \) is the voltage (volts, V).

STOP AND CHECK:

Turn your book over and see if you can remember:

- What is uniform about uniform electric fields?
- The main situation where you expect to get a uniform electric field.
- How to draw a uniform electric field.

Try to explain it in your own words.

Electric Potential Energy

Before we jump into this topic, let‘s break down what the term ‘potential energy’ means. You will hopefully recognise it from thinking about gravitational potential energy.

Remember that gravitational potential energy is gained when an object is held above the ground. It has potential energy because it has the potential to gain kinetic energy from gravity - if you dropped it.
The same kind of thing happens within electric fields.

Imagine that you place a charge in a uniform electric field and hold it there. That charge really wants to move (in fact it will move once it’s let go). This must be because it has electric potential energy, which has the symbol $\Delta E_p$. Notice the Delta (use the symbol capital delta) in this formula. This is actually really helpful on two levels:

1. It reminds you that we’re talking about a change in energy (more on this later) and
2. It straight up distinguishes this $E$ from the electric field $E$!

Electric potential energy tells you how much a charge wants to move when it’s placed in an electric field.

How much it wants to move will depend on things like where it is positioned in the electric field and how big the field is.

**Let’s put this idea in the context of our parallel charged plates, since these are what exams love the most**

Remember, the electric field between the plates is uniform.

Imagine that you’re holding a negative charge (e.g. electron) right up against the negative plate. As soon as you let the charge go, it would move towards the positively charged plate. As this happened, we would say that the electric potential energy was being converted into kinetic energy. Kinetic energy is simply the name we give for energy of movement (in this case the movement from one side of the plates to the other).

![Image of charges and electric field](image-url)

If you’ve noticed anything about physics so far, it’s probably that, whenever we talk about concepts such as energy, we usually want to do a calculation.

The size of the electric potential energy on a charge in an electric field depends on a few things.

The first of these is where in the electric field the charge is placed.
What we’re asking about here, is the distance between where the charge starts and where it will finally end up once you’ve let it go.
In the case of a negative charge, this will be the distance between where it is let go from and the positive plate, check the previous diagram.

The amount of potential energy also depends on the electric field strength, $E$, because bigger fields obviously push and pull on charges more. The size of the charge $q$, that is doing the movement is also important, because bigger charges feel the electric field more!

All that being said, the potential energy of a charge ($q$) placed in an electric field ($E$) at a distance $d$ from the positive plate is:

$$\Delta E_p = Eqd$$

**Relating electric potential energy to kinetic energy and velocity**

Remember our old friend, the conservation of energy? This is a special rule that tells us that energy cannot be created or destroyed. This means that, if we ignore things such as friction (which we can conveniently do for this standard), we know that all of the electric potential energy is converted into kinetic energy.

With this in mind, once we calculate the electric potential energy using the above equation, we automatically have the kinetic energy of the charge when it hits the positive plate, $\Delta E_p = E_k$.

Once you have the kinetic energy, you can use the equation $E_k = \frac{1}{2}mv^2$ to rearrange to find the velocity of the particle when it hits the positive plate.
To do this, we first remove the fraction from the right hand side by multiplying both sides by two. This gives us:

\[ 2E_k = mv^2 \]

We then divide both sides by \( m \) and after that take the square root of both sides to get:

\[ \sqrt{2E_k} = \frac{v}{m} \]

When a charged particle is put inside an electric field \( E \) at a distance \( d \) from its final position (when let go), then the conservation of energy will tell us how fast it will be when it hits its final position (using \( E_k = \Delta E_p \)).

Relating electric potential energy to work

It’s all well and good when the electric field puts in the hard yards for us. But, what happens when we don’t want the charge to move in the direction that it does naturally? What happens if we want a negative charge to move towards the negative plate?

In this case, we are going against the electric force. In order to oppose the electric force, it makes sense that energy must be put in. In order to get a charged thing to the ‘unnatural plate’, energy must be given to the charge by someone or something on the outside (like your hand). Think about it like lifting something heavy -- when we lift something, we are acting against the force of gravity, so we need to put energy in.

In physics, we call putting energy in ‘work’. It basically means using energy to move an object or particle. As we put in work, the object travels further from the plate it naturally wants to move towards, creating more electric potential energy in the process.

Work \( (W; \text{ unit Joules}) \) is the amount of energy put in to move a charged particle towards a charge it would usually be repelled from. As the particle is moved further from the charges it is attracted to, electric potential \( (\Delta E_p) \) energy increases, because \( d \) is increasing.
Millikan’s oil drop experiment (our final boss)

NCEA is a fan of putting things in context, and Millikan’s oil drop experiment is a classic example of this. About one hundred years ago, Robert Andrews Millikan decided to try to measure the size of the charge on an electron.

He did this by placing a negatively charged oil drop between two charged plates held vertically apart. He then measured how strong he had to make the electric field to hold the oil droplet in place, and stop it falling due to gravity.

When the charged drop was still, it meant that the force supplied by gravity (pulling the oil drop down), was exactly equal to electric force (pulling the charge up). This made it appear as thought the oil droplet was ‘floating’ in mid air, and allowed Millikan to determine the charge of the electrons on the oil droplet.

You don’t need to understand the details of Millikan’s experiment in order to tackle questions on it in your exam. Instead, focus on understanding the different forces at play, the directions they work in, and how electric field strength can be altered. If you have forgotten any of these things, simply refer to the previous pages in this walkthrough guide.

In this way, understanding Millikan’s experiment is actually a great round-up of the static electricity section -- and a good way of reminding yourself of some of the key concepts we have talked about! If you can defeat Millikan, you can earn your badge as an official static electricity wizard.

Once you’ve got this down, we’ll move on to our next challenge: DC circuits.

STOP AND CHECK:

Turn your book over and see if you can remember:

☑️ Why does a particle want to move in an electric field?
☑️ The directions that a particle will move in an electric field.
☑️ What form of energy the electric potential energy is converted into.
Why the formula $E_k = \Delta E_p$ gives you the kinetic energy when the charge reaches its destination.

Why the top plate is positive in Milikan’s oil drop experiment.

Try to explain it in your own words.

Quick Questions

Consider the following diagram:

- Which plate - A or B - is positively-charged and which one is negative? Why?
- Is this electric field uniform? Explain your answer by referencing the properties of a uniform electric field.
- An electron is placed at plate B. Discuss what will happen to this electron in terms of forces acting on the electron, potential energy and kinetic energy.
- Calculate the maximum speed the electron will reach in this electric field, given that it has a mass of $9.11 \times 10^{-31}$ kg.
DC CIRCUITS

Ok, so, way back at the start of this guide, we mentioned that electricity is all about moving charges. We promise we didn’t lie!

In physics, DC stands for “Direct Current”. Basically, current refers to moving charges, and ‘direct’ tells us that this movement happens in one direction only.

So, the section on DC circuits is really about charges that move around a circuit (or loop) in one direction.

This is what’s in stock throughout this action-packed section:

- How to draw circuit diagrams to explain everything that’s going on in our circuits.
- A very special tool called Ohm’s Law, and what it says about voltage, current and resistance.
- Power! That is, power in an electrical circuit. We will be looking at power used by bulbs, and how it affects their brightness, as well as performing calculations to predict the activity of our electrical components.

All About Circuits

What is an electrical circuit?

Before we delve into the world of drawing and planning circuits, we should probably spend some time breaking down what they actually are.

We’ll think about the word first. In everyday language, the term ‘circuit’ usually refers to a circular path or track. This is important, as the key to a circle is that it connects back up with itself. Although electrical circuits can get quite complex, so often don’t resemble a simple circle, they do always connect back up with themselves.

An electrical circuit is therefore a collection of wires that might split up and do all sorts of complicated things, but in the end always reconnects with itself (to make a continuous path). Most importantly, electrons can travel through these wires and follow these paths.

Electrical circuits are pathways for electrons to travel through. If the circuit splits up at one point it must recombine later on.
Sometimes you will find ‘objects’ in between the wires, like in the diagram above.

As far as the electrons in the circuit care, these objects either

(a) take energy from the electrons or
(b) give energy to the electrons.

These objects are called **components**.

**The most important component in an electrical circuit is the power source**

A lot of different things can give power to an electrical circuit. A battery (like the ones in the remote) can do it, a power pack (like the one in your physics classroom) can also do it.

But when it comes to drawing electrical circuits, we use essentially one symbol to represent all of these. You can either choose to draw it in a simplified way or in a slightly more detailed way. Both mean exactly the same thing.

**How the power source provides electricity**

So, we’ve said that the power source provides electricity to the circuit, but how exactly does it do this?

To answer this question, let’s use some of the concepts we learnt about in the previous section. Wire is a conductor, which mean that charges can flow easily through it (you might know about this from chemistry: copper (for example) has delocalised electrons that aren’t stuck to any particular atoms). But those charges aren’t going anyway on their own: need a **kick** to move!
When a power source (such as a battery or power pack) is connected to the wires, it sends an electric field through the wire. This is just like the electric field between the two metal plates: it makes electrons inside move!

So, in a nutshell, the power source gives the electrons some energy (kinetic energy, in fact). Instead of talking about electric fields and so on, we can just talk about there being a voltage across the power source which gives the electrons energy when they pass through.

The power source (battery, power pack) provides a voltage to the circuit. This gives the electrons the energy to move.

Think back to the first section when we first started talking about voltage. The main idea there was that, if you know the energy of a charge is changing in any way whatsoever, then you should probably be thinking about voltage.

Well, we’ve been talking a lot about giving and taking energy from electrons recently. Batteries aren’t the only thing with voltages across them.

Resistors sap the energy from electrons and so have a voltage across them too! Just like in the Static Electricity section, batteries have a positive voltage and resistors must have a negative voltage.

When this happens, the electrons travel continuously around the circuit from the negative end of the power source- towards the positive end (the negative electrons are attracted to the positive side of the battery!). Every time they reach the power pack, they are given a new burst of energy, which allows them to travel around the circuit again. In this case, the electrons are travelling in an anti-clockwise direction in order to get to the positive side of the battery:
We give this group of moving charges a name, called the ‘current’. The current simply describes the amount of charge moving through the wires. The more charges there are moving in the wires, the greater the current is.

Current (symbol \( I \)) is the flow of electrons through a circuit, from the negative part of the battery to the positive part.

So our wires carry the current, and the power source gives the voltage. The power source and the wires are the most important parts of our circuit.

However, a circuit which is just made up of wires and a power source doesn’t do anything exciting.

A circuit really fulfills its purpose when other components are connected to it. It is these other components which carry out what the circuit is intended to do.

**Components and resistance**

So we know our power source is providing the voltage necessary for our current to travel around the circuit. But what use is this?

When the current reaches different stages in its journey, it is able to carry out different tasks. For example, when the electrons in the current reach a series of lightbulbs, they are able to donate some of their energy towards making the lightbulbs glow. After this, the (slightly tired) electrons continue their journey and travel back toward the power source, where they are given more energy to do it all over again.

This happens continuously, as long as the power source is turned on, and there are no breaks in the circuit. This means that the lightbulbs are supplied with a constant stream of energy from the power source, carried by the current. And so they shine constantly!
There are all sorts of components that can be connected to a circuit. An important thing they have in common is that they all have something called resistance.

Resistance makes it harder for the current to travel through the circuit. The best way of thinking about resistance is the crashing and bumping of electrons into atoms in the wire. Everything we put in a circuit is made of atoms, so everything has resistance. This crashing and bumping obviously saps energy from the electrons, which slows them down (and this is why resistance makes it harder for current to flow).

For example, lightbulbs have resistance because they take away energy from the current in order to make themselves glow (pretty selfish tbh).

Resistance (symbol $R$) is a measure of the opposition to the flow of electrical current.

Some components are literally called resistors, and are designed to serve the sole purpose of decreasing the energy of the electrons going around the circuit. This is often important in preventing power surges, or making sure the circuit is safe to handle.

Other components just have resistance because they have atoms (and aren’t specifically designed for this purpose). One example of this is wire. We usually ignore the resistance in wire since it’s usually kind of small anyway.

Now that we’ve covered a couple more components, let’s have a look at how we draw them all in a circuit:

Putting it all together:

Now that we’ve got the wires, the power source and some components under our belt, let’s look at what a circuit diagram looks like:
The important things to remember here are:

- Each component has wires coming both in and out of it (so that electrons can flow into and out of all of them).
- There are no gaps in the circuit (so that electrons can flow continuously and forever).

**Speaking of bringing it together:**

Besides learning how to draw electrical circuits, there was some pretty heavy terminology dropped in the last section.

To recap, these terms are all very important to understand for Level 2 physics:

- Voltage (supplied by the power source and gives electrons energy to move)
- Current (the movement of electrons through the circuit)
- Resistance (the opposition to electrons flowing in the circuit)

To bring them all together, let’s throw it back to revisit our friend from the mall. Before he got his haircut (and the balloon), our little friend was actually causing a lot of trouble for his mother.

You notice we haven’t given him a name yet. This was on purpose. We’re going to give our little buddy the rather romantic name ‘current’.

So, current is sitting in the mall foodcourt with his mother. He’s pretty tired, so his mother buys him a new McDonalds burger called the ‘Voltage burger’. Big mistake.

After he eats the Voltage burger, current starts running around the mall. As he runs around, he has to duck and weave between other unexpecting shoppers. These shoppers are all carrying bags labelled ‘resistance’.

All of the travelling through the resistance shoppers makes current tired again. Luckily, every time he passes the starting point on his journey, the over-enthusiastic McDonalds staff feed him another Voltage burger.
Current continues to travel around and around the mall, powered by voltage and opposed by resistance. The path he travels around the mall, is conveniently referred to by locals as ‘the circuit’.

Now, once we’ve got our head around the circuit, we can think a bit more about how to extend our analogy. A lot of this topic isn’t just about thinking about the circuit - but about what happens to it when things are added.

For example, what happens if current runs into a new mall with less shoppers? Let’s say that he still runs past McDonald’s and gets his voltage burger, just as before.

Now current bumps into less shoppers and loses less energy. So current has excess energy (some of his voltage burger is left uneaten)! So he can give some of the voltage burger to his friends and now they can run around the new mall with him.

STOP AND CHECK:

Turn your book over and see if you can remember:

- The symbols for the following components:
  - Voltage source - e.g. battery
  - Wire
  - Resistor
  - Light bulb
- How to define ‘current’, ‘resistance’ and ‘voltage.’
- An analogy you could use to explain the relationships between ‘current’, ‘resistance’ and ‘voltage.’

More Complex Circuits

Other important components

Now that we’ve got the basics covered, we can build some more components into our circuit.
Ammeters are important, as they measure how much current is travelling through a circuit. Similarly, voltmeters measure the amount of voltage.

An ammeter is a device that measures the current across a part of a circuit. A voltmeter is a device that measures the voltage across a component of a circuit.

Notice the use of the word ‘through’ for current and ‘across’ for voltage. Remember, voltage is about how much energy is gained or lost when electrons pass all the way through a component. So we use ‘across’ for voltage!

Variable resistors are special types of resistors that can be adjusted. This means that, they can change the amount of resistance within a circuit without having to add or remove any components.

Lastly, switches are super important. Remember how I said that, in order for circuits to do their job, they must not contain any breaks? Well, a switch can control whether a circuit is working or not, by creating a break which temporarily stops the flow of current. Switches are the reason why we can turn our televisions off when we’re not watching them.

Ammeters, voltmeters, variable resistors and switches are drawn in circuits using the following symbols:

What about conventional current?

Before we move into different types of circuits, we have to address one more concept. In class, you may have heard of something called ‘conventional current’.

*Conventional current* is an imagined current, where positive charges move through the circuit in the opposite direction to the actual flow of electrons. Conventional current is a historic mistake, made back when scientists didn’t realise that it was the electrons, not the protons, which made up moving charge in wires.

But, if you think about it, positive charges going one way and negative charges going the other are basically the same thing! So it doesn’t really matter if you use conventional current (positive charge) or actual current (negative charge).

Although we know now that it is electrons which move through the wires, you may sometimes hear of conventional current.
Just remember that conventional current always describes the opposite movement of charge to the one that is actually occurring.

Conventional Current Flow

Electron Flow

Positive Charge

Negative Charge

We can break circuits into two categories: series and parallel

The circuits we have been talking about so far are series circuits. Series circuits are our most simple form of circuit, and involve every component joined together with just one single bit of wire.

This means that there is only one pathway around the circuit -- so all of the current must take the exact same path back to the power source.

Series circuits are nice and simple, but they do have one large weakness. Because there is only one pathway through the circuit, if something goes wrong, or a break is caused in the circuit, all of the components fail to work.

Think of this as a road. Imagine that there were two different cities, and only one possible path to travel between them.

Now imagine a tree falls on the road, and cars are no longer able to travel along it. This causes all travel between the two cities to halt.
The same happens in the circuit. If a break is caused in a series circuit, all current through the circuit is halted, and all components will fail to work.

**Introducing parallel circuits**

Parallel circuits are what you get when the wires make ‘intersections’ or ‘junctions’.

A junction is where the current has multiple pathways to take in order to get back around to the power source.

We say that two components are in *parallel* if there is a *junction* between them - and current can therefore ‘choose’ which component it travels through.

Based on the diagram above it makes a bit of sense why we use the word ‘parallel’ to describe components separated by a junction.

In reality, just like the roading system, most circuits are made up of a combination of series and parallel routes. There are often intersections and different routes around the circuit, but a few main roads that all of the current travels down.
STOP AND CHECK:

Turn your book over and see if you can remember:

💡 The symbols for the following components:
  - Switch
  - Variable resistor
  - Ammeter
  - Voltmeter

💡 The difference between two components in series and two components in parallel to one another.

💡 Why it would be better to have a parallel circuit if there was a break somewhere.

Try to explain it in your own words.

**Ohm’s Law**

So, we’ve just blown your mind with a whole bunch of new terms, like ‘current’, ‘voltage’ and ‘resistance’.

Ohm’s law is a very special way of connecting these three terms together. It also gives Level 2 students a way of getting points in their exams.

Ohm’s law states that the current through a component is proportional to the voltage across it, and inversely proportional to its resistance.

Let’s get a little more technical and recap the crucial facts about current, resistance and voltage:

Current is measured using a unit called amps (A). This describes how much charge (the number of coulombs) is flowing through a point of a circuit during one second. If the ammeter measures a large current, then there is lots of charge moving through.
Let’s say that we measure the amount of charge moving through a point in a circuit for \( t \) seconds. If we think back to the previous section, we know that we can measure the amount of charge at a single point using the symbol \( q \). The amount of current (for which we use the symbol \( I \)) through that point is calculated using:

\[
I = \frac{q}{t}.
\]

**Bring your mind back to series circuits**

These circuits have no junctions... the current is the same everywhere. This is because the current can only travel down one route -- so it must stay constant!

But, when there are junctions, the current will split. This means that, some current will go down one path, and the rest will go down the alternate path.

In fact, more current will go down the arm with less resistance. This makes sense if you consider the concept of traffic. If there are multiple routes to the same destination, you are likely to travel down the one with the least resistance in the form of potholes, speed bumps and tricky corners.

So if you add another road with lots of speed bumps and tricky corners (more resistance) in parallel to a nice smooth road, most of the cars travel the smooth road to speed up the journey! This means that putting high-resistance branches in parallel will actually decrease the total resistance of a circuit!

The split in current is only ever equal if the values of resistance in both branches are equal. However the split occurs, the currents that goes into the junction equals the sum of the currents that come out of the junction.

![Diagram showing current splits in series and parallel circuits](image-url)
What happens to voltage in a series circuit?

In series circuits, the voltages across the components add to the voltage across the battery.

Voltage is the electrical potential energy each charge has. As the electrons flow around the circuit and reach a component, they give off a little bit of the energy given to them by the battery.

This means that, by the time they have travelled through every component, and are back at the power source, they have used up all the energy given to them from the power source (otherwise any extra energy would have come from nowhere!)

Because there is only one route around the circuit, every electron loses energy to every component.

\[ V_1 + V_2 + V_3 = V_5 \]

What happens to voltage in a parallel circuit?

In tricky parallel circuits, the voltages across the branches attached to the junction are equal.

Even when there are several resistors in one branch, the total voltage across one branch is equal to the total voltage across the other one.

This is because, in parallel circuits, the current splits and some electrons go down one branch and the others go down the other branch. This means that each component only saps energy (i.e. has a voltage) from the electrons travelling down its branch.

If you want to know why the voltage across branches is the same in parallel circuits, then think of it like this: Each branch is part of its own series circuit! So, in both branches, the voltages add up to \( V_s \).
What about resistance?

Resistance (measured in ohms, Ω) just tells us how much a component will restrict the current that goes through it. Resistance is really important because if it wasn’t a thing, current would flow super fast through circuits. This is what causes “short circuits” and is very unhealthy for electricians. Resistors (and other components) are able to resist current because the electrons in the current bounce off the atoms in the resistor, which reduces their energy.

In series circuits, the total resistance is the sum of the individual resistances. This is the easy version, with $R_T$ representing the total resistance of the circuit, and the other symbols (i.e. $R_1$) representing the resistance of each component:

$$R_T = R_1 + R_2 + \ldots$$

For parallel circuits, we have the harder version:

$$\frac{1}{R_T} = \frac{1}{R_1} + \frac{1}{R_2} + \ldots$$

Where $R_1$, $R_2$ and so on are the sub-total resistance values across each arm.

The reason the equation looks like this is that the more resistors there are in parallel to each other, the more branches there are in the circuit.

Thinking back to our analogy of the road before, this decrease in resistance is due to
there being more available routes for the current to travel around the circuit (even if they are high resistance routes).

$$\frac{1}{R_T} = \frac{1}{4} + \frac{1}{6} + \frac{1}{6}$$

$$\frac{1}{R_T} = \frac{7}{12}$$

$$R_T = 1.71 \, \Omega$$

Now that we’ve looked a bit more critically at current, voltage and resistance, let’s tie them all together using Ohm’s law.

Ohm’s law says that the voltage through a component is proportional to the current that flows through it. ‘Proportional’ simply means that if one thing doubles (for example), so does the other. Resistance is called the “proportionality factor”, as it defines how much current increases (or decreases) as voltage changes.

Ohm’s law can be used to calculate the resistance, current or voltage through a circuit or component when you know the other two factors. So:

$$V = IR.$$  

**Looks simple, but you should be careful when using Ohm’s law**

For example, to find the voltage of a battery in a circuit using Ohm’s law, you’d need to use the total current in the circuit and the overall resistance of the circuit.

In general, to find the voltage across a single component, you need to make sure you know what the current through it is, as well as what the resistance of that single component is.

**STOP AND CHECK:**

Turn your book over and see if you can remember:

- The definition, symbol for:
  - Current
  - Voltage
  - Resistance

- What happens to the current in a series circuit and in a parallel circuit.
- What happens to the voltage across components in series and in parallel.
Why the voltage across a battery is positive and why the voltage across resistors (including lamps) is negative.

Which formula for total resistance is used for resistors in series and for resistors in parallel.

Let’s say you have a parallel circuit and you wanted to calculate the voltage across the bottom branch. You know the total current and the current in the top branch, and you know the two resistances in the bottom branch. Can you do it?

Try to explain it in your own words.

Power in Electric Circuits

Now, power is probably a term you have heard in relation to electricity before. But what does it actually mean?

Power is just a technical way of saying ‘the amount of energy transferred per second’. In the case of electricity, this means the amount of electric energy transferred from the electrons to a component per second. Therefore, the higher the power of a lightbulb, the faster it is receiving electric energy from a circuit.

On a circuit level, imagine electrons flowing through a resistor. The resistor causes the energy of the electrons to decrease. Let’s say the energy decreases by $\Delta E$ ($\Delta$ because we’re talking about a change in energy, here). We’re also going to say that this energy change happens over $t$ seconds.

The power of the resistor is:

$$ P = \frac{\Delta E}{t} $$

But all circuit components have a certain amount of power, not just resistors. Batteries are a good example, but the energy change here is due to the battery giving the electrons energy.

Here’s an example of how to use this equation:

A 100W lightbulb is running in your house. You want to know how much energy it uses in 1 hour.

We like to have time in seconds, so let’s convert 1 hour into 3600 seconds.

So we know the power (P) and the time (t) but not the change in energy ($\Delta E$). We can work it out by rearranging the formula, substituting our values in and solving.
\[ \Delta E = P \times t = 100 \times 3600 = 360000\text{J} = 360\text{kJ} \]

So, there we go. This lightbulb uses 360kJ of energy per hour. That’s about half the energy in a can of Coke.

**What if we wanted to figure out the power in terms of voltage and current?**

The equation for this turns out to be:

\[ P = IV. \]

This is exactly the same as the first equation \((P = \Delta E/t)\), because:

\[ IV = \frac{q}{t} \times \frac{\Delta E}{q} = \frac{\Delta E}{t}. \]

Frankly, if that doesn’t blow your mind, I don’t know what will. So, if you can figure out the current through a component and the voltage across it, you can calculate the power of the component. If you don’t have the current (but do have the resistance), you can use Ohm’s law to substitute for it:

\[ P = IV = (\frac{V}{R})V = \frac{V^2}{R}. \]

If you don’t have the voltage (but do have the resistance), again you can use Ohm’s law to substitute:

\[ P = IV = I(IR) = I^2R. \]

**Please remember that these last two equations are not given to you on your formula sheet.**

Being able to figure them out is actually a pretty valuable skill. What we’ve been doing here is a little confusing, but it’s just squishing together different formulas from the formula sheet. Make sure you practice doing this!

**Another pretty important thing to remember - is that power is directly related to brightness.**

A lamp with a higher power converts more electric potential energy into light energy
every second that passes. So, a lamp with greater power will be brighter. In the same way, a hotter resistor will be more powerful.

This is because power measures the rate of energy conversion per second. A more powerful lightbulb is able to convert more energy, and therefore generates more brightness.

Low power  🟢 High power

Remember this, as NCEA will often try to trick you by asking questions about brightness - when they really want you to discuss power.

STOP AND CHECK:

Turn your book over and see if you can remember:

💡 The definition of power.
💡 The symbol and unit for power.
💡 Which lamp will be brighter: the one with bigger or smaller voltage across it, when they have the same resistance?

Try to explain it in your own words.

Quick Questions

Consider the following circuit diagram:

💡 What components are found in this circuit based on the symbols included?
💡 Explain what happens to the current and the voltage throughout this circuit.
💡 What will be the ammeter and voltmeter readings? Hint: You will need to do multiple Ohm’s Law calculations.
💡 Which bulb - A or B - will be brighter? Hint: How does brightness relate to power used?
MAGNETISM

Remember how, at the start of this guide, I mentioned that we had two heroes? Well, now that we’ve spent some time with electricity -- in both its static and DC forms -- it’s time to introduce you to our second hero: magnetism.

Here’s what we’ll be covering:

- Magnetic fields.
- The force exerted on charged particles and wires inside a magnetic field.
- Induced voltage

Magnetic Fields

We started off our discussion about electricity with a bit of an exploration of electric fields. It’s only right that we give magnetism the same introduction.

Now, instead of electric fields, we have magnetic fields

Just like charges producing electric fields around them, a magnet will generate a magnetic field in the space around it. This magnetic field defines the space in which other magnetic substances will be affected by it.

A magnetic field is a region surrounding a moving charge or magnetic substance which is able to cause an interaction with another magnetic substance or an electrically charged substance.

For example, a magnetic substance which comes within the field of another magnet will either be attracted or repelled, depending on the way the magnets are oriented.
Magnetic field notation

Just like electric fields, magnetic fields have a strength associated with them. The greater the magnetic field strength, the greater the force of attraction or repulsion on other magnets will be.

The strength of the magnetic field is given by the symbol $B$ (for no obvious reason) and is measured in teslas, $T$ (Tesla was the great scientist who introduced the world to another type of electricity, called AC electricity).

So, where do these magnetic fields come from?

We know that electric fields are created by charged particles or objects. But what creates a magnetic field? It turns out, magnetic fields are created by charge as well.

The difference is that magnetic fields are generated by moving charges inside the magnet. In fact, all moving charges will generate both an electric field and a magnetic field (while a stationary charge will only generate an electric field).

For example, if you took an electron and moved it around, it would create a very small magnetic field around it. The idea behind magnets is to get a large amount of these moving electrons, put them together, and create an object with a greater overall magnetic field. This is the magnetic field that makes compasses point north!

Now that we know that magnetic fields are generated by moving charges, or objects containing a lot of moving charges, let’s have a look at how to draw them.

Just like electric fields, we will use arrows to draw the field

Let’s start with a simple “bar” magnet. It has a north and a south end. The magnetic field lines curve around to get from north to south, in fact, magnetic field lines always go from North to South. (Think of this as similar to our rule about electric fields going from positive to negative).
Although this magnetic field looks pretty curved when we can see the entire magnet, if we zoom in enough on the curving magnetic field, it will eventually look straight.

In fact, the entire Earth is actually one huge curved magnetic field (that’s why we have North and South Poles). However, because the Earth is so large, we experience the magnetic field of the Earth as a uniform magnetic field. This is the magnetic field that makes compasses point north!

Sometimes, we don’t have the luxury of viewing a magnetic field from a side-on angle. Sometimes, you will have to think of magnetic fields from another angle -- where they are literally going into, or out of, the page.

When this is the case, we have two special drawing conventions:

- When it is drawn into the page, the symbol used for each line is a little cross (like the tail of an arrow).
- When it is drawn out of the page, the symbol for each line is a dot (like the head of an arrow coming toward you).

Now let’s talk about the magnetic field around a current-carrying wire

A current carrying wire is a wire in which electrical charge is moving through.

Now that we know that moving charges generate magnetic fields, it hopefully makes sense that an electric wire that’s carrying current, which is just another way of saying moving charges, will generate a magnetic field around it.
In fact, the magnetic field around a wire literally wraps around the wire itself. The direction of the magnetic field around a current-carrying wire can be found using just your right hand, which we call the right hand grip rule. If your thumb points in the direction of the current, and you curl your fingers around (in the normal way), then your curling fingers represent the magnetic field.

STOP AND CHECK:

Turn your book over and see if you can remember:

- The symbol and unit for magnetic field strength.
- How magnetic fields are generated.
- Which direction — north to south, or south to north — magnetic field lines travel from around a bar magnet.
- How magnetic field lines going into the page and magnetic field lines coming out of the page are drawn.
- How to determine the direction of the magnetic field around a current-carrying wire.
- For which of the following situations would you expect to measure a magnetic field?
  (a) around your phone
  (b) around the moon
  (c) around power lines and
  (d) at the LHC (Large Hadron Collider) near Geneva.

Try to explain it in your own words.

Force on a Charged Particle

So moving charges cause magnetic fields. But what if a moving charge goes into a magnetic field that is already there? Well, just like stationary charges experience electric forces, moving charges experience magnetic forces. If you want to calculate the size of the magnetic force, you have to use

\[ F = Bqv \]

where \( B \) is the magnetic field strength (in teslas, \( T \)), \( q \) is the charge on the particle (C) and \( v \) is its speed through the magnetic field (in m/s\(^{-1}\)).
Working out the direction of the force is a bit tricky. To do this, we can use a special rule.

**The right-hand slap rule for a charged particle moving in a magnetic field**

Your fingers represent the magnetic field lines
Your thumb represents the direction the particle moves through the field
Your palm is the direction of the magnetic force

This rule only applies if the particle has a positive charge, eg a proton or a positively-charged drop of oil. We will get to what to do if the particle is negatively charged in just a bit.

I like this rule because it’s easy to remember. You can imagine your fingers are magnetic field lines. You can pretend to slap the charged particle to show the magnetic force.

**Use left hand if the particle is negative**

The right-hand slap rule is for positive particles. If the particle is negative, you can use exactly the same rule but with your left hand.

Charged particles that move through magnetic fields experience a magnetic force. The size of the force is given by $F = Bqv$. The direction of the force is given by the right hand slap rule

**Force pushes particle in a curve**

The magnetic force pushes the particle at a right-angle to where it’s going (this is just the right hand slap rule in action). This force keeps changing as the particle changes direction. This means it makes the particle go in a curve.
If the field is big enough, it can make the particle go in circles.

### Examples

![Diagram showing magnetic force on a charged particle.](image)

### Important facts

- If the particle isn’t moving, there’s no force (because \( v = 0 \)).
- If the particle isn’t charged, there’s no force (because \( q = 0 \)).
- If the particle moves parallel (in the same direction) as the field, there’s no force.
- The particle has to cut through field lines. For the slap rule, this doesn’t happen when your thumb and fingers are pointing in the same direction.
- Negative particles get the opposite force from positive particles. You can see this by using your left hand for negative particles instead of your right hand for positive particles.

### STOP AND CHECK:

Turn your book over and see if you can remember:

- What the *magnetic force* acts on.
- What is the right-hand slap rule? What do your fingers, thumb and palm represent?
- What happens to a particle moving parallel to a magnetic field?

Try explain it in your own words.
Force on Current Carrying Wires

Here’s an equation:

\[ F = BIL \]

F is force (measured in Newtons, N), B is magnetic field strength (measured in Tesla, T), I is current (measured in Amperes, A) and L is length (measured in metres, m).

What do we do with this equation?

This equation is about current-carrying wires in a magnetic field. Since single charged particles moving through magnetic fields experience a force, it makes sense that a whole current (and the wire carrying it) would also experience a force! We can actually use the slap rules from the last section to understand this.

Current = moving electrons = moving negative charge

Remember, when a charged particle moves through a magnetic field, we can use the slap rules. If it’s positively charged, we use the right-hand slap rule. If it’s negatively charged, we use the left-hand slap rule (same as the right-hand slap rule but the force goes the opposite direction).

Electrons are negatively-charged particles. Current is just moving electrons. So the direction of the negatively-charged particles is the direction of the current. You can use that plus the direction of the magnetic field to work out the force on the electrons, and therefore the force on the whole wire.

Remember that the electrons in the current flow from the negative end of the battery to the positive end - often you’ll need to know that to work out the direction of the current.

There are a bunch of negatively-charged particles (electrons) moving through a
magnetic field. We can use the left-hand slap rule (because the charges are negative) to work out the direction of the force.

Look at the wire in the diagram above with the electrons moving up it. Left hand, fingers into the page, thumb pointing to the top of the page - your palm should be slapping to the right. That’s the direction of the force on all the electrons, so that’s the force on the wire too!

Let’s say the current is 5A, the length of the wire in the magnetic field is 50cm (0.5m) and the magnetic field strength is 0.0002T (they’re always really small). How big will the force be?

$$F = BIL = 0.0002 \times 5 \times 0.5 = 0.0005N$$

**Some things to note**

- Lots of questions will give you the resistance of the wire and make you work out the current using Ohm’s Law ($V=IR$).
- Lots of questions will give you the force and instead make you work out one of the other variables (B, I or L).
- The length is the length of current-carrying wire in the magnetic field. Any wire that is outside the magnetic field doesn’t count. Any wire that’s inside the field but doesn’t have current also doesn’t count.
- If the force makes the wire start moving through the field, this will have a secondary effect - induced voltage. Read about this in the next section. An important point is the induced voltage will oppose the current in the wire here, meaning it will also oppose the force.

**STOP AND CHECK:**

Turn your book over and see if you can remember:

- What do all the variables in $F=BI\ell$ mean?
- What part of the wire counts as the length?
- How do you work out the direction of the force?
- What will happen with induced voltage? Will it make a force too? What direction will that go in?

Try to explain it in your own words

**Induced Voltage**

Let’s take a slightly different look at the situation of a rod being pushed through a magnetic field.
As the rod is pushed through the field (by a person for example), the electrons are in motion through the field.

By now we should know that electrons in motion through a field will feel a magnetic force. This magnetic force moves electrons to one of the ends of the rod.

Now we have positive charge at one end (electrons from this end have moved away) and negative charge at the other (electrons have gathered here).

This should remind you of the two parallel metal plates (static electricity stuff)

There is a voltage between the two plates. In exactly the same way, there is also a voltage across the metal rod as it moves through the field.

The magnetic field “forces” this voltage to exist, so it is called induced voltage. Induced voltage is a voltage caused by movement of a conducting substance through a magnetic field.

An induced voltage occurs when a conductor is pushed through a magnetic field and the field creates a charge separation across the conductor.

![Diagram of charge separation and induced voltage](image)

The induced voltage depends on the speed that the rod moves through the field, the magnetic field strength and the length that electrons are actually moving.

\[ V = BvL. \]

If we attached a wire (and maybe some other circuit components like resistors and lamps), this voltage becomes a bit like a battery which causes a current to flow through the circuit.

If we knew the value of the induced voltage and the total resistance of the circuit, we could calculate the current that flows using Ohm’s law, \[ V = IR. \]
STOP AND CHECK:

Turn your book over and see if you can remember:

💡 How the induced voltage is generated inside a conductor when it is pushed through a magnetic field.

Try to explain it in your own words.

Quick Questions

💡 Using what you know about a current moving through an electric field, have a go at explaining how motor engines work. Simplify it down to a conductive rod moving around in a circle.

💡 Using what you know about voltage induction, have a go at explaining how wind turbines are used to generate electricity.
**KEY TERMS**

**Ammeter**
A device that measures the current through a part of a circuit, must be connected in series.

**Attraction and Repulsion**
Attraction occurs when two charged particles have opposite charges, they accelerate toward each other. Repulsion happens when two particles have the same charge, they accelerate away from each other.

**Bar Magnet:**
A rectangular piece of magnetic material.

**Charged Particle (sometimes just called a charge)**
A particle is a tiny object. A charged particle is a tiny object with a bit of charge on it. The most common of these are electrons (negatively charged) and protons (positively charged).

**Conventional Current**
Imaginary flow of positive charge in a circuit that moves in the opposite direction to the electrons (from positive terminal to negative terminal). A historic mistake that hasn’t gone away.

**Current Carrying Wire**
A wire that is part of a circuit so that electrons can flow through it. Since the electrons are moving, the current carrying wire will be affected by a magnetic field.

**Current**
The flow of electrons through the wire of a circuit.

**Electric Force**
The force of attraction or repulsion that a charge experiences due to a source charge.

**Induced Voltage**
The voltage that is “forced” in a metal wire as it is pushed through a magnetic field.

**Junction**
A split in the wires of a circuit.
**Magnetic Field**

The field a *moving charge* generates around it (magnets are made of special moving electrons). Magnetic fields affect nearby moving charges (and magnets!).

**Magnetic Force**

The force that a moving charge (magnet) experiences due to the magnetic field generated by another moving charge (magnet).

**Power**

How much electric potential energy a circuit component converts (e.g. into light or heat) every second.

**Resistance**

The degree to which an object resists current flowing through it.

**Right Hand Rule**

For finding direction of field around a current carrying wire: thumb represents current and curling fingers represent field. For finding direction of magnetic force on charged particle in field: pointer finger is velocity, middle finger is magnetic field and thumb is magnetic force.

**Series and Parallel**

Series means that components are connected by a single bit of wire. Parallel means that components are connected by a junction.

**Source Charge**

A charge that is “pinned down” and generates an electric field that interacts with another charge. A good example of source charges are the electrons found in parallel metal plates.

**Uniform Electric Field**

When the field lines are evenly spaced and the electric field strength (E) is the same everywhere. Happens between parallel charged metal plates.

**Voltage**

The amount of energy gained or lost by 1 coulomb of charge as it passes through a section of a circuit. Since charged parallel metal plates make charges placed in between them accelerate (i.e. *gain energy*), they have a voltage across them too.

**Voltmeter**

A device that measures the voltage across a part of a circuit, must be connected in parallel.