Preface

Hello! My name is Jamon, and I'm one of the people working with ATAR Notes to make incredible, accessible content to help students in Year 11 and Year 12.

I'm really excited to be able to share this set of notes for the new Physics course. Why? Because you are learning about some *cool* stuff. Crazy cool stuff! There are things in here I didn't see until my second year of university. The fact that you are being taught it earlier is an incredible thing.

In short, this course is going to equip you with an incredible set of tools and an amazing set of knowledge. It's a challenging course, no doubt, but incredibly rewarding.

So what are these notes? Well, this is meant to be a one-stop handy reference of all your content for Year 12 Physics, summarising everything you need to know for assessments and exams. They have just enough detail to revise concepts you've forgotten, or to read ahead a bit on the content, but not so much that it becomes way too overwhelming. When you are revising for exams, you need to revise quickly to keep yourself moving. Going through the whole textbook just isn't efficient, so these notes aim to be a way more effective study assistant!

My biggest piece of advice though is that revision is no substitute for **practice.** You absorb knowledge by using it and applying it to solve problems. So, have this book open while you are practising. Use it to jog your memory. The notes also have lots of examples at key points to guide you through some common question types.

Another thing I want to mention is that, way more than the old syllabus, this new course is heavily interlinked. Many dot points intersect with one another, even though it might be months before you cover a related one in class. These notes are structured according to the syllabus to make it easier for you, and I've done my best to explain topics in isolation before revisiting them later.

Best of luck for your studies – set your goals and work as hard as you can to achieve them!

— Jamon Windeyer

Part I

Module 5: Advanced Mechanics

Multiplying Vectors

Before we get into this course, we need to understand a little extra bit of mathematics. This doesn't appear as a stand alone item in the syllabus, but it is referenced frequently, and is a good thing to have some knowledge of if you want to study Engineering or Science at university.

In Year 11, you learned about the difference between scalars and vectors: **scalars** are mathematical quantities that only have a magnitude. **Vectors** have a magnitude *and* a direction. For example, temperature is a scalar, because you can't be 30 degrees Celsius *north*, or something. Velocity is a vector, because you can be travelling 100 kilometres an hour north, or west, or south-west... you get the idea!

In Year 11, you were also introduced to some basic mathematical operations with vectors: adding them, subtracting them, and so on. In Year 12, you need to be able to **multiply vectors.** To make things even better, unlike scalars, there are *two* ways to multiply vectors.

Before you panic, we won't be learning this new operation in great detail. Really, we'll just be learning the shortcut method for each, and skipping most of the heavy theory. You can definitely understand the rest of the course content without this, but it does come up quite often, so let's go through it together.

Let's say we have two vector quantities, magnitude A and B, and we want to multiply them. There are two ways to do it.

- **The dot/scalar product** of two vectors is just the product of the magnitudes of the vectors, with a cosine term added. Here, θ is just the angle between the vectors.

$$\mathrm{A} \cdot \mathrm{B} = \mathrm{A}_{||}\mathrm{B} = \mathrm{AB}\cos\theta$$

  As implied in the name, the result of this operation is a scalar, it has no direction. We don't use this very much in HSC Physics, if at all. We use the next one way more...
- **The cross/vector product** of two vectors is the product of the magnitudes of the vectors, but this time with a sine term added. Again, θ is just the angle between the vectors.

$$\mathrm{A}_{\perp}\mathrm{B} = \mathrm{AB}\sin\theta$$

  The result of this operation is a vector. The direction of the vector is perpendicular to both of the two vectors that we used in the operation. Since this is an operation that lets us get a new vector from two other vectors, it is used *far* more often in this course.

And that's it! Those two shortcuts and the notations above are all you need to know. I'll stress again that this is a simplified explanation of vector operations, but you don't need to be an expert in this to do well in HSC Physics. Really, if not for it appearing a couple of times in the syllabus, you wouldn't need to know it at all. I just want you to understand where a lot of the 'sine' and 'cosine' terms are coming from in the formulas we will be learning. You'll learn more at university if you need it!

Topic 1

Projectile Motion

SYLLABUS :
Inquiry question: How can models that are used to explain projectile motion be used to analyse and make predictions?

1.1 Projectiles and acceleration

SYLLABUS :
Analyse the motion of projectiles by resolving the motion into horizontal and vertical components.

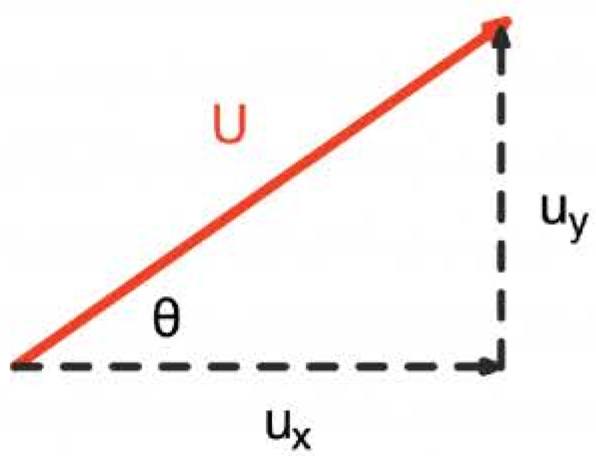
In this first section, we will be analysing the motion of *projectiles*. What exactly is a projectile? In our course, a projectile is an object launched with some **initial velocity** at some **initial angle,** that is **not acted on by any additional forces during its flight,** except gravity. In HSC Physics, we make two assumptions:

- The **vertical acceleration due to gravity is a constant,** $g = -9.8\text{ms}^{-2}$. In practical situations it might fluctuate depending on location and altitude, but we ignore that to keep things simple!
- The **effects of air resistance are negligible.** In practical scenarios, air resistance would apply a horizontal force/acceleration to a projectile. We ignore this to keep the maths easy!

We analyse the motion of projectiles by resolving their velocities into separate horizontal and vertical components, then analysing each of them separately. This is an exercise that you would have covered in Year 11, but let's quickly recap how it works!

We can consider the initial velocity of our projectile as a **vector,** with a magnitude equal to the initial speed of launch, and a direction the same as the direction of launch. To **resolve** the vector into horizontal and vertical components, we are effectively splitting this vector into two smaller vectors, one horizontal and one vertical. When you put these vectors together, you get back where you started.

Check out the example below to visualise what this means. Say we have an initial launch velocity of $U = 30$ metres per second, at an angle of $\theta = 30$ degrees to the horizontal. To split this into the horizontal component (u_x) and vertical component (u_y), we use some basic right-angled trigonometry.



$$\cos 30 = \frac{u_x}{30} \implies u_x = 30\cos 30 \approx 26\text{ ms}^{-1}$$
$$\sin 30 = \frac{u_y}{30} \implies u_y = 30\sin 30 = 15\text{ ms}^{-1}$$

What this means is that, at the moment of launch, our projectile is moving 15 metres per second vertically, and about 26 metres per second horizontally.

1.2 Horizontal and vertical direction and velocity

SYLLABUS :
Apply the modelling of projectile motion to quantitatively derive relationships between variables.

Once we're at this stage, we can analyse our horizontal and vertical components separately. It is vital to remember that **vertical and horizontal motion is independent.** This means that even if you add some horizontal velocity to one object compared to another, they'll behave identically in the vertical direction. For example, a bullet dropped from a height of 1 metre will hit the floor at the same time as another bullet shot horizontally from a gun at a height of 1 metre. The bullet being shot horizontally adds horizontal velocity, but does nothing to the vertical, so they'll hit the ground at the same time!

The horizontal direction is easier to analyse, because there is no acceleration in that direction, meaning that the velocity is constant. This means we can analyse the horizontal motion with two key results:

- $v_x = u_x$, the horizontal velocity is the same as the initial velocity at any given point in time (until the projectile lands)
- $s_x = u_x t$, the horizontal range is just the product of the initial velocity and the time of flight.

The vertical direction has acceleration, so the formulas are more complex:

- $v_y = u_y + a_y t$, the vertical velocity is affected by the vertical acceleration over time. This is of course g, which takes a *negative* value, because it is *downwards* acceleration!
- $s_y = u_y t + \frac{1}{2}a_y t^2$, the vertical position is affected by the initial vertical speed, and then the acceleration over time.
- We can combine the two results above to get another important formula, $v_y^2 = u_y^2 + 2a_y s_y$. This is useful if you want to know an object's vertical velocity at a specific *position* rather than a specific *time*.

KEY POINT :
These are all results that were first introduced in Year 11, so it could be worth brushing up on your preliminary content if you need to!

Let's have a look at how some of these formulas might be applied with an example.

Example 1.1

Find the maximum range of a projectile launched at 100 metres per second.

It doesn't seem like we are given much information here, but there's actually a very important key word: we want the **maximum** range. This happens when you launch the projectile at the optimum angle. **Maximum range occurs with a launch angle of 45 degrees.**

So we have a launch angle and velocity, and we can use these to calculate the initial horizontal and vertical velocity:

$$u_x = V\cos\theta = 100\cos 45 \approx 70.7\ \text{ms}^{-1}$$
$$u_y = V\sin\theta = 100\sin 45 \approx 70.7\ \text{ms}^{-1}$$

Now we want the range, which means we are analysing the point when the vertical displacement reaches zero for the second time (the first being the launch point). So, we use the vertical displacement formula:

$$\begin{aligned} s_y &= u_y t + \frac{1}{2}a_y t^2 \\ 0 &= 70.7t - 4.9t^2 \\ 70.7 &= 4.9t \quad (t \neq 0) \\ t &= \frac{70.7}{4.9} \\ &\approx 14.4\ \text{s} \end{aligned}$$

Notice that we excluded $t = 0$ early in the calculation, since we want the *end*, not the *start*. Now we know the projectile touches down again after 14.4 seconds, so we substitute that into the horizontal displacement formula for our answer:

$$s_x = u_x t = 70.7 \times 14.4 = 1018.08 \text{ ms}^{-1}$$

Key Point :
Just as important as using these results is having a bit of an intuitive idea of where they come from, and how the variables are related. For example, as you do more of these questions, you'll start to understand how the launch angle affects maximum range and maximum height, and how making an object faster affects how long it is in the air. Having this sort of intuitive understanding is best achieved through practice and observing lots of different scenarios, and this intuition can then eventually progress to hard quantitative statements like *the maximum range of a projectile is achieved at a launch angle of 45 degrees*. That's the sort of knowledge that will benefit you in tougher problems.

Let's do some derivation. We calculated the range in the previous example, but let's say we wanted to look at the maximum height of a projectile with a launch velocity V and launch angle θ. We know that at the maximum height, **vertical velocity is zero.** This is because when it gets to the peak of its motion, it has to stop and turn around. Let's set $v_y = 0$, and use the formula $v = u + at$:

$$\begin{aligned} v_y &= 0 \\ u_y + a_y t &= 0 \\ t &= \frac{-u_y}{a_y} \end{aligned}$$

Let's assume we are on our planet, meaning $a_y = -9.8$, and let's swap u_y for the expression we obtained in the previous section, $u_y = V \sin\theta$:

$$t = \frac{V \sin\theta}{9.8}$$

So this tells us *when* the maximum height occurs. Even here, we can make some intuitive statements. As the launch velocity or launch angle increases, the maximum height will occur at a later time.

What is the height itself? Let's use $v_y^2 = u_y^2 + 2a_y s_y$ for that (remembering that we know $v_y = 0$):

$$\begin{aligned} v_y^2 &= u_y^2 + 2a_y s_y \\ 0 &= u_y^2 + 2a_y s_y \\ s_y &= -\frac{u_y^2}{2a_y} \\ &= \frac{V^2 \sin^2\theta}{19.6} \end{aligned}$$

Again, at the end, we are assuming we are on Earth and using $u_y = V \sin\theta$. This is the maximum height reached! Just like before, we see that increasing V or θ will make the value higher. This should make intuitive sense – as we increase the launch angle, we are giving more of the initial velocity to the vertical component. This also means the projectile is in the air for longer, since time of flight is really just dependent on how much initial vertical velocity you have to overcome gravity. We can do a calculation for that too – we know that the peak of motion is at the halfway point of the motion, so if that happens at some time t_{max}, then $2t_{max}$ is where the motion will finish (unless the ground height changes). **Projectile motion is symmetrical!** These are the sorts of links you need to be making to really have a comprehensive understanding of projectile motion.

1.3 Practical applications

SYLLABUS :
Conduct a practical investigation to collect primary data in order to validate the relationships derived above.

There isn't much we can do in these notes to help you with practical investigations into projectile motion (*please*, do not throw this book at your mate and call it a projectile, that doesn't count!). Ensure that when you do these in class, you pay attention and actively try to understand what you observe! Some things you might try include:

- Rolling a projectile off a bench and trying to guess its landing location.
- Investigating how the angle of launch affects things like range, time of flight, and maximum height.
- Using a slow motion camera to observe the flight paths of various projectiles, to validate the independence of horizontal and vertical velocity.
- Simulations of all sorts of projectile motion scenarios.

Also ensure you can do things like suggest improvements to your experiments, spot sources of error, and identify dependent/independent/controlled variables. Practical tasks are still assessable in your exams, so don't neglect them!

SYLLABUS :
Solve problems, create models and make quantitative predictions by applying the equations of motion relationships for uniformly accelerated and constant rectilinear motion.

This dot point is essentially asking you to do one thing – **use your formulas!** You first learned them nearly a year ago and it is so important that you pick them back up and become an expert once again. We did an example earlier and have used the formulas in some derivations, but you should try to do more! Get your hands on problems from any source, and make sure you are ready for anything!

Topic 2

Circular Motion

SYLLABUS :
Inquiry question: Why do objects move in circles?

2.1 Uniform circular motion

SYLLABUS :
Conduct investigations to explain and evaluate key relationships for objects executing uniform circular motion.

The first thing to do is to actually *define* uniform circular motion. **Uniform circular motion** occurs when an object moves in a circle at a constant (uniform) speed – pretty simple right?

Why does this occur? We know that **acceleration** is defined as any **change in velocity** (meaning, any change in the speed ***or*** direction of movement of an object). Even though we have a uniform speed, we're changing direction all the time, so we definitely don't have a constant velocity – we're accelerating! This implies that there is some force causing the movement – for circular motion, we call this **centripetal force.** This force could come from a variety of sources: gravitational attraction (orbits), friction (a turning car), or tension (spinning something on a string), to name a few.

When we talk about uniform circular motion, we tend to talk about a few things: the **mass** of the object, the **speed** of its motion around the circle, and the **radius** of its motion. Changing any of these in isolation will change the centripetal force. For example, a larger mass will require more centripetal force. A smaller radius will also require more centripetal force (because of the smaller turning circle). A reduced velocity will reduce the required force, and so on!

You'll do practical investigations to investigate these sorts of relationships, and we'll analyse them mathematically very soon.

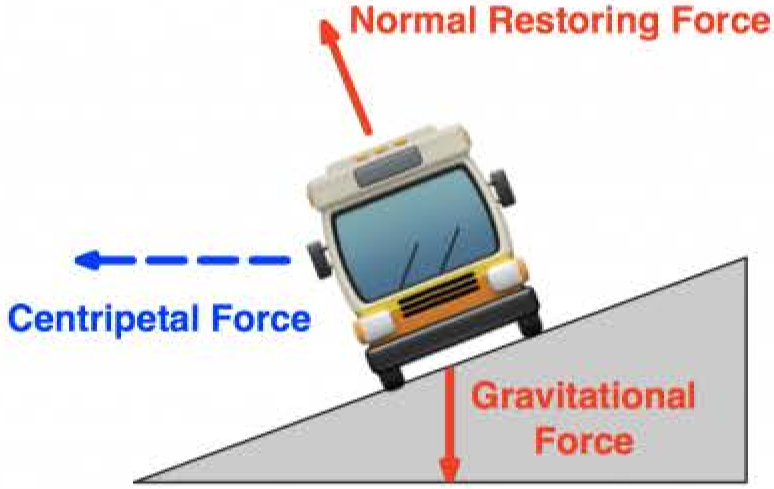
2.2 Centripetal forces

SYLLABUS :
Analyse the forces acting on an object executing uniform circular motion in a variety of situations.

As part of understanding uniform circular motion, we need to analyse the forces on objects executing this type of motion. Some scenarios you might investigate are:

- **A car moving around a bend:** this is probably the scenario we are most familiar with in everyday life – this is a classic example of uniform circular motion. Here, the centripetal force is provided by the friction between the tyres and the road. This is why they say you can't take turns too quickly, because your tyres can only provide so much friction! As we complete the turn, we feel a reaction force pushing us outward from the turn. Gravity is also acting in the vertical direction!
- **A mass on a string:** if we spin a mass attached to a string, the centripetal force is provided by the tension in the string (which is in turn caused by our spinning motions). Want to spin faster? That increase in velocity will require more force. Make the string longer, and that reduces the required force to keep the same speed.
- **Objects on banked tracks:** this one is actually a little more complicated. We've got gravity acting downwards, and then a restoring **normal force** acting perpendicular to the track. It is the vector sum of these forces that provides the centripetal force to keep the object in the circular path.

The diagram below shows these forces, from a point of view in front of the object as it is moving forward around the curve.



2.3 Quantitative predictions and formulas

SYLLABUS :
Solve problems, model and make quantitative predictions about objects executing uniform circular motion in a variety of situations.

We actually have quite a few formulas for analysing uniform circular motion. The most fundamental one is the relationship linking **centripetal force** F_c, to the **velocity** v and **mass** m of the object, and **radius** r of the motion:

$$F_c = \frac{mv^2}{r}$$

What about if we want the **centripetal acceleration** a_c rather than the force? We can easily use Newton's 2^{nd} Law to cancel out the mass in the result above, and obtain this new one:

$$a_c = \frac{v^2}{r}$$

Sometimes we might not be given the velocity directly, but we can find it, assuming we know the radius and the **period** of the motion T, the time taken to complete one circle of motion. With this knowledge, we know the speed is just distance over time – the distance is the circumference of the circle, and the time taken is the period. This gives:

$$v = \frac{2\pi r}{T}$$

We can also talk about **angular velocity,** which measures how quickly an object is rotating around the circle, rather than how fast it is moving along its edge. It's a rotational measure, not a linear measure. So whereas a linear velocity is a *distance over time*, angular velocity is an *angle over time*:

$$\omega = \frac{\Delta\theta}{\Delta t}$$

All of these together give us a fantastic suite of tools to analyse uniform circular motion.

Example 2.1

A 2 kg object is swung around in a circle on a 1.5 metre long rope. The tension force provided by the rope is 48 N. Calculate the linear and angular velocity of the object, as well as the time taken to spin the object 100 times (ignore any effects of gravity).

This is an example of uniform circular motion, with the centripetal force provided by the tension force in the rope. So, as with all numerical problems, the first step is to figure out what we are given. In this case, quite a bit: $r = 1.5$, $F_c = 48$, and $m = 2$. We can calculate the linear velocity using the centripetal force formula:

$$\begin{aligned} F_c &= \frac{mv^2}{r} \\ v^2 &= \frac{F_c r}{m} \\ v &= \sqrt{\frac{F_c r}{m}} \\ &= \sqrt{\frac{48 \times 1.5}{2}} \\ &= 6 \text{ ms}^{-1} \end{aligned}$$

We can link this with the radius to get the period, the time taken for a full revolution:

$$\begin{aligned} v &= \frac{2\pi r}{T} \\ T &= \frac{2\pi r}{v} \\ &= \frac{2\pi \times 1.5}{6} \\ &\approx 1.57 \text{ s} \end{aligned}$$

Since $T = 1.57$, the time taken for one hundred spins is one hundred times greater: 157 seconds! Finally, since we know that it takes 1.57 seconds to complete one revolution, and we know that one revolution is 360°, we can calculate the angular velocity:

$$\omega = \frac{\Delta\theta}{\Delta t} = \frac{360}{1.57} \approx 229.3^\circ/\text{s}$$

2.4 Energy and work

SYLLABUS :
Investigate the relationship between the total energy and work done on an object executing uniform circular motion.

We now need to analyse the energy of an object executing uniform circular motion. Energy in these situations is always a little bit tricky!

First, we know that the speed of an object executing this sort of motion is constant. The direction is always changing, but there is no change in speed. This means that the kinetic energy of the object, given by $E_k = \frac{1}{2}mv^2$, is a constant value.

If our object's kinetic energy isn't changing, this means we aren't actually doing any work on it as it moves through the motion! To do **work** you need to have an **energy change.** Since there is no energy change, there is no work done (remember that 'work,' in Physics, is just changing energy from one form to another).

But we have a force applied, and where there is a force there is work, right?

Well, almost. This is a case of us simplifying some more complex mathematics and definitions a bit. Basically, you only do work if you apply a force *in the direction of movement*. In this situation, the force is perpendicular to the motion of the object at all points. This means we aren't doing any work!

If you think carefully, this makes intuitive sense. In practical experiments on the ground it might not, because there are other forces at play – gravity or friction, for example. But get rid of those, and uniform circular motion requires no additional work at all. For example, once you get them into orbit, satellites essentially stay in orbit forever. You don't need to do any extra work – the orbital motion doesn't require any energy once it is there.

KEY POINT :
This is something that might be confusing at first, but you will get more comfortable with this idea when you start working through it. Until then, this is what you need to remember:

- The total energy of an object executing uniform circular motion is constant.
- This means there is no work done on that object!

2.5 Torque as rotational force

SYLLABUS :
Investigate the relationship between the rotation of mechanical systems and the applied torque.

Earlier we talked about **angular velocity,** where we looked at a change in angle over time rather than a change in distance or position over time. This would imply that there is angular acceleration, and by extension, some sort of **angular force.** This does in fact exist and it is the subject of this syllabus dot point.

Torque is defined as the **turning moment of a force.** This sounds complicated but it is quite simple; if a force is a push or a pull, then a torque is a twist. It is just rotational force.

Rotational force is intrinsically linked to our normal definition of force. This is because rotation is really just caused by linear forces anyway. The torque on an object is given by the vector cross product of the force applied, and the distance vector from the centre of rotation.

$$\tau = r_{\perp}F = rF\sin\theta$$

The angle in this formula can look a bit tricky, but it's just the angle between the radius (line from the centre of rotation) and the force applied. You get the most torque when you apply a perpendicular force!

Topic 3

Motion in Gravitational Fields

SYLLABUS :
Inquiry question: How does the force of gravity determine the motion of planets and satellites?

3.1 Gravitational fields and Newton's Law

SYLLABUS :
Apply Newton's Law of Universal Gravitation qualitatively and quantitatively.

Nothing like a section of the course on gravity to keep us grounded. *Right?*

Bad jokes aside, this section of the syllabus has us analysing gravitational fields and orbits. We should probably have at least an intuitive understanding of gravity, but here are a few points to get us rolling:

- A gravitational field surrounds any object with mass, and all gravitational fields are theoretically infinite in size. They are just really, really weak at significant distances. Technically, though, the Earth's gravitational field is exerting a force on every other planet in the universe (however tiny it may be).
- The strength of a gravitational field is dependent on the object creating that field. The heavier and denser the object, the stronger the field.
- To move *against* a gravitational field requires work to be done, and gives a form of potential energy to the object we are moving. We call this **gravitational potential energy**, and we'll learn a bit more about it later.

Newton's Law of Universal Gravitation allows us to determine the force of attraction between two bodies due to their gravitational fields. This force acts on both bodies with the same magnitude, with the direction being towards the other body. The force of attraction between two masses, M and m, separated by a distance of r metres, is:

$$F = \frac{GMm}{r^2}$$

Usually, M is something bigger like a planet, and m is something smaller like a satellite, but it really doesn't matter. In this formula, G is a fundamental constant called the **Universal Gravitational Constant**. It has a value of $6.67 \times 10^{-11} m^3 kg^{-1} s^{-2}$.

We can tie this formula to Newton's 2^{nd} Law, F = ma, to find the strength of a gravitational field at a specific distance. We define the strength of a field as the value of acceleration due to gravity at that point. By letting F = mg, where g is that acceleration due to gravity:

$$mg = \frac{GMm}{r^2}$$
$$g = \frac{GM}{r^2}$$

Using this method, we can determine the value of acceleration due to gravity on other planets!

Example 3.1
Calculate the value of acceleration due to gravity on the surface of Mercury, given that Mercury has a mass of 3.29×10^{23} *kg, and a radius of 2440 kilometres.*

For this, we just use the formula above, remembering to convert the radius into SI units!

$$g_m = \frac{GM}{r^2} = \frac{6.67 \times 10^{-11} \times 3.29 \times 10^{23}}{\left(2440 \times 10^3\right)^2} \approx 3.7ms^{-2}$$

You could be asked to find the strength of the field at any point in a field too, not just the surface. And Newton's Law of Universal Gravitation can be used in many ways. Essentially, as soon as you have two objects affected only by the gravity of the other, chances are that you will be using Newton's Law!

3.2 Orbital motion

SYLLABUS :
Investigate the orbital motion of planets and artificial satellites.

Of course, the type of motion we most frequently associate with gravitational forces is the orbits of planets and satellites. Let's review a few key points:

- **Orbital motion** is an example of uniform circular motion where the centripetal force is provided by gravitational force. That is, centripetal force and gravitational force are one and the same in this scenario.
- This implies that *more* gravitational force is required to keep a larger mass in orbit. This should make intuitive sense – you'll need a much stronger field to put something like our moon into orbit, compared to just a satellite. As the mass of the orbiting body increases, the amount of centripetal force required to keep the same orbit increases.
- This also implies that the value of acceleration due to gravity at some point in a field, is also the value of the centripetal acceleration at that point.
- Intuitively, you can think of an orbit like a body moving so fast around a planet, that the floor always falls away as fast as the object falls to the floor. That is, the curvature of the planet matches the curved path of the projectile.

We tend to classify and describe orbits in terms of three quantities.

- **Orbital radius:** the distance from the centre of the orbit to the object (r in both the Universal Law of Gravitation and centripetal force formula)
- **Orbital velocity:** the speed at which the object is moving in its orbit (v in the centripetal force formula)
- **Orbital period:** how long it takes to complete one complete orbit (T)

These quantities are all interrelated. For example, as orbital radius goes up, orbital period goes up as well (since you've got further to travel). Your orbital velocity will also be smaller in an orbit with a larger radius, and there is less centripetal acceleration too. This is a good point to note: you can only orbit at one certain velocity at a given altitude around a given planet/star. If you go any slower, you start to get pulled in and your orbital radius decreases. Faster, and you break your orbit and zoom off!

Perhaps the best way to get a handle on these concepts is to apply them to practical scenarios, which is what we are doing next.

SYLLABUS :
Predict quantitatively the orbital properties of planets and satellites in a variety of situations, and relate these to their uses.

Being able to put something into orbit is fundamental to our daily lives – communication satellites, navigation satellites, weather satellites... things we take for granted are totally reliant on chunks of metal whizzing around above our heads.

In general, the satellites in orbit around Earth fall into two distinct categories: **low Earth orbit satellites** and **geostationary orbit satellites**. The type of orbit a satellite is put into is based largely on what it will be used for.

- **Low Earth Orbits (LEOs):** are just what they sound like – orbits with a very small orbital radius. Specifically, we consider a satellite to be in a LEO if it has an orbital altitude of less than about 2,000 km (so, an orbital radius of about 8500 km if you include the radius of the Earth). Usually, they don't go lower than about 300 km, but even this is 20–30 times the cruising altitude of an international flight. LEOs have an orbital period of 1.5–2 hours, and satellites in these orbits are usually used for surveillance/monitoring, and some communications. They 'sweep' the Earth's surface very quickly, and it is far cheaper to put a satellite into a LEO compared to other orbits.
- **Middle Earth orbits:** are the orbits with a higher altitude than a low earth orbit, but not as high as a geostationary orbit (so 2,000–36,000 kilometres). These satellites are generally used for navigation and communication.

- **Geostationary orbits:** are orbits with a very specific orbital period of 24 hours. That is, these satellites take a day to orbit the earth, meaning they stay at the exact same point above the planet at any given time. Put them into orbit above Australia, and they'll stay there, constantly above Australia as the Earth spins – the orbit matches the Earth's rotation! The altitude for this sort of orbit is about 36,000 kilometres, and satellites in this orbit are usually used for communications and broadcasting, or any application where you always need to be above a specific point on the planet.

Getting satellites into these orbits is difficult, and the speeds involved are immense. Geostationary orbits are the slowest, but even they have satellites travelling at about 3 kilometres *a second.* In a low earth orbit, we're up to nearly 8 kilometres per second.

A natural question at this point might be, *where do all of these numbers come from?* How can we link these quantities of orbital velocity, radius and period together. For this, we turn to some extremely useful relationships!

3.3 Kepler's Laws

SYLLABUS :
Investigate Kepler's Laws of Planetary Motion.

Kepler's Laws of Planetary Motion have been around for centuries, and they are super powerful! We can break them down as follows:

- All orbiting bodies orbit in an **elliptical** fashion with the body being orbited at one focus of the ellipse. Already, this highlights a simplification – orbits *aren't* actually perfectly circular! They are close though, so we assume circular motion for simplicity.
- A line joining an orbiting body to the centre of its orbit will sweep out equal area in equal time. Again, this is more relevant and useful when we consider an elliptical orbit rather than a circular one. We don't worry much about these first two laws – the third one is the most important...
- The **ratio** of the **cube** of the **orbital radius** to the **square** of the **orbital period** is a **constant** for a given body being orbited.

Let's break this last one down. Mathematically, this is what it means:

$$\frac{r^3}{T^2} = K$$

We can actually derive the value of that constant K! To do this, start by equating centripetal and gravitational force (remember, in an orbit, they are the same):

$$F_g = F_c$$
$$\frac{GMm}{r^2} = \frac{mv^2}{r}$$
$$\frac{GM}{r} = v^2$$

Now, recall that v is the orbital velocity/speed. We can express this differently using the basic idea that **speed equals distance over time.** The distance travelled can be the circumference of the orbit, $2\pi r$, and the time taken can be the orbital period T. Substitute these in:

$$\frac{GM}{r} = \left(\frac{2\pi r}{T}\right)^2$$
$$\frac{GM}{r} = \frac{4\pi^2 r^2}{T^2}$$
$$\frac{r^3}{T^2} = \frac{GM}{4\pi^2}$$

Topic 3 – Motion in Gravitational Fields

That expression on the right contains only constants, so provided we are orbiting the same larger mass M, that is the value of our constant! Recall that this assumes a circular orbit – if we did things 100% properly then the law would be a little more complicated.

The implication of Kepler's 3rd law is that the **mass of an orbiting object is actually irrelevant** when determining its orbital path. Only the **mass of the central body is relevant!** This allows us to easily make comparisons between the orbits of objects.

Example 3.2

Two moons are found orbiting a small, distant planet. One is measured to have an orbital period of 20 hours, at an orbital radius of 1,000 km. The other orbits the planet in just 12 hours. What is its orbital radius?

Here, we have two objects orbiting the same planet. So, $\frac{GM}{4\pi^2}$ is the same for both orbits. We can compare them directly using Kepler's 3rd Law. Also, since this is a comparison of ratios, we *don't* need to convert to SI units! Of course, you can if you want to, and it is always good to do so unless you are super confident you don't need to! Here, we'll keep the units the same:

$$\frac{r_1^3}{T_1^2} = \frac{r_2^3}{T_2^2}$$

$$\frac{1000^3}{20^2} = \frac{r_2^3}{12^2}$$

$$r_2^3 = \frac{1000^3 \times 12^2}{20^2}$$

$$r_2 = \sqrt[3]{\frac{1000^3 \times 12^2}{20^2}}$$

$$\approx 711\text{km}$$

Since we didn't convert to SI units, our answer will match whatever our unit was to start with! We could use this information to find the mass of the planet, M, if we wanted to!

3.4 Gravitational potential energy

SYLLABUS :
Derive quantitatively and apply the concepts of gravitational force and gravitational potential energy in radial gravitational fields to a variety of situations.

To begin this dot point, let's define gravitational potential energy, or GPE. **GPE** is the **energy possessed by an object** when it is **raised against a gravitational field.** For example, let's say we lift an object from the ground to a height of 1 metre. We've done work to do that! That work converts our expended energy into GPE, which is stored 'in' the object as long as we hold it at the height of 1 metre. Once we let go, that energy converts back to kinetic energy as it falls!

The GPE of the object is equal to the **force applied, multiplied by the distance it is applied.** The force to lift an object is F = mg, so if we lift it a height Δh:

$$E_p = mg\Delta h$$

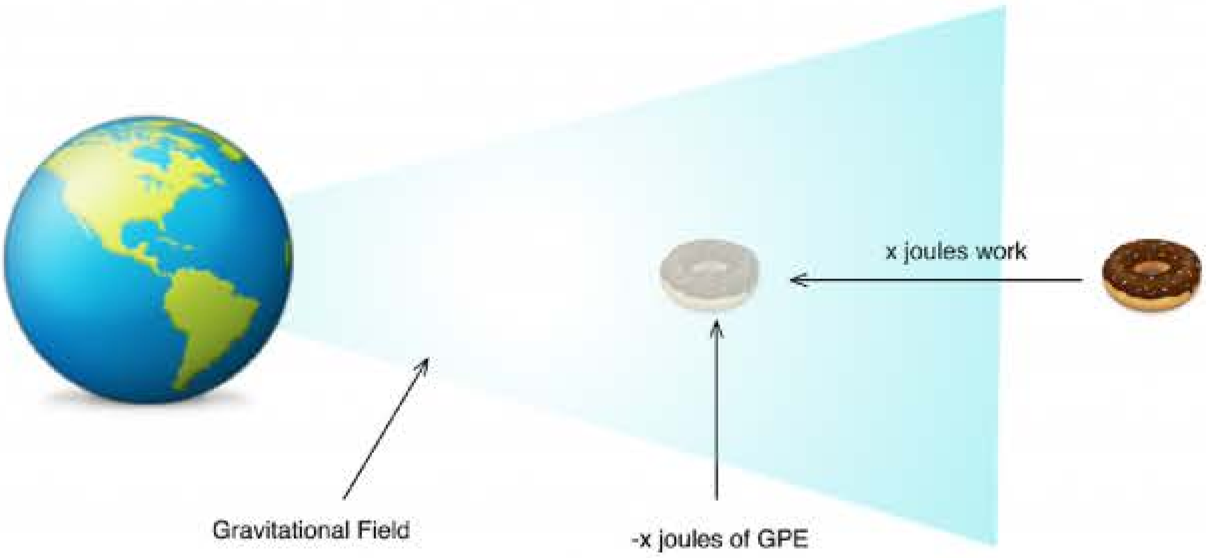
This is a formula we saw in the Year 11 course!

The same concept applies for objects in orbit, but there's a slight difference. When we are lifting objects off the ground, it makes sense to use the ground as a reference point, since we never go far from it. When we are orbiting, we are very far from it. Plus, planets have different radii and so the ground is at a different point in every field... we don't want to deal with that, so we set a new reference point, though the choice may seem a little bit unusual at first.

The **zero point for GPE** is defined to occur at a distance **infinitely far away!**

We do this for two reasons: one, it makes sense for an object infinitely far away to have zero GPE. Second, this point is somewhat independent of the thing we are orbiting (i.e. it doesn't matter where the 'ground' is). This has the consequence that GPE will *always* take a **negative value.** Think about it, GPE should increase as we get further from the centre of the field. But once we get infinity far away, we've increased to zero. This means GPE must be a negative quantity.

You can also think of GPE as the work done to bring an object from our zero point (infinitely far away) to some point in the field. Gravity might do, say, x joules of work to do this. But we would be doing negative work – gravity does the 'actual work' for us.



Mathematically, we can derive the GPE formula in a similar way. To do it 100% properly is beyond the scope of this course, but we can go through a slightly simplified process. Let's do the same thing we did previously: force multiplied by distance raised in the field. In orbital scenarios, the gravitational force is given by Newton's Law of Gravitation, and the distance from the centre of the field is the orbital radius. We'll also add the negative to match our definition above (that's the simplification):

$$E_p = -Fd = -\frac{GMm}{r^2} \times r = -\frac{GMm}{r}$$

Again, I promise there are mathematical reasons why that negative is there, but it is also what we need to match our definition! Now, what this expression allows us to do is calculate the **total** energy of an orbiting body – the sum of its **kinetic** and **potential** energies. Let's start with:

$$E = U + K = -\frac{GMm}{r} + \frac{1}{2}mv^2$$

What is v? It is the orbital velocity, which we can find another expression for. A little earlier we equated centripetal and gravitational force for an orbiting object, and we rearranged to get:

$$v^2 = \frac{GM}{r}$$

Aha! Let's substitute that into our formula instead of v^2:

$$\begin{aligned} E &= -\frac{GMm}{r} + \frac{1}{2}m\frac{GM}{r} \\ &= \frac{GMm}{2r} - \frac{GMm}{r} \\ &= -\frac{GMm}{2r} \end{aligned}$$

That last step might be a little unclear – we've got half of something (the two on the bottom of the first number cuts it in half), minus the same something. It's essentially $\frac{x}{2} - x$, which is $\frac{-x}{2}$. If you don't trust me, substitute in some easy numbers!

So this, to conclude, is a formula giving the total energy of an orbiting body. It will always be negative because there is always more negative potential energy than positive kinetic energy for an orbiting body. Let's do an example to see how this total energy changes in a change in orbit.

Example 3.3

A 2,500 kg satellite is orbiting the earth with an orbital radius of 6,500 km. It moves to an orbit with an orbital radius of 10,000 km. Find the energy required to perform this adjustment.

The energy required to perform the manoeuvre will be equal to the difference in energy before and after the change (i.e. **conservation of energy**). We have a formula for total energy, so:

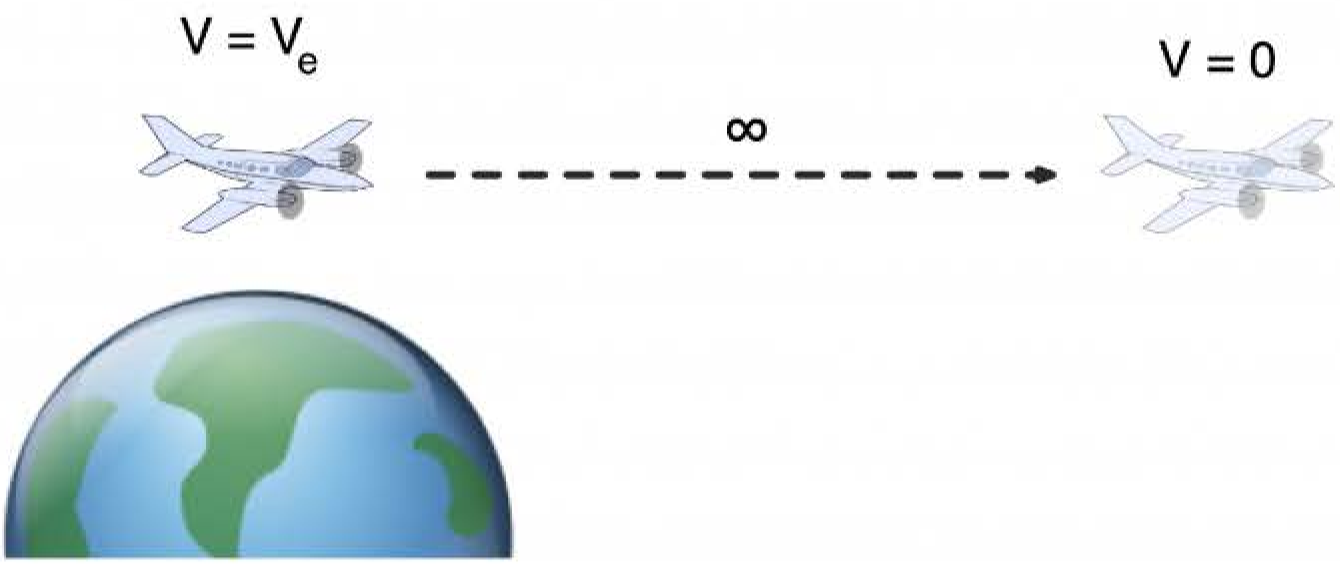
$$\begin{aligned}\Delta E &= E_f - E_i \\ &= -\frac{GMm}{2r_2} - \left(-\frac{GMm}{2r_1}\right) \\ &= 6.67 \times 10^{-11} \times 6 \times 10^{24} \times 2500 \times \left(-\frac{1}{2 \times 10000 \times 10^3} + \frac{1}{2 \times 6500 \times 10^3}\right) \\ &\approx 2.7 \times 10^{10}\ \mathrm{J}\end{aligned}$$

Notice that this is a positive quantity, even though the energy at each point individually is negative – we do work to make the total energy **less** negative.

3.5 Escape velocity

There's one more concept we can explore: **escape velocity.** Escape velocity is defined as the velocity you would need to travel at the surface of a planet (or at any other specific radial distance) **to escape the gravitational field of that planet.** Once you hit this velocity, that's it, you are gone, and you're never coming back!

We can derive this formula intuitively. Let's call the escape velocity v_e, and let's say we are at a distance r from the centre of a planet (for ease, let's just pretend it is the surface). Imagine we suddenly give an object of mass m escape velocity. This means that it will escape the gravitational field of the planet (which can have mass M) and eventually (after infinite time) end up an infinite distance away. At this point it will also have slowed to a stop. As it moves away, Earth's gravity gets weaker, but it is still there, gradually slowing it down. (Plus, it can't exactly get any further away than infinity, can it? So how could it still be moving? Mind blown!)



So, we have an initial state where the object is on the surface travelling at escape velocity. We have a final state, where the object is infinitely far away. Conservation of energy demands that the total energy of the object (kinetic plus potential) must be the same at the start and finish. Let's stick that into a formula: initial energy equals final energy:

$$K_i + U_i = K_f + U_f$$

However, from our earlier definition, we know that GPE = 0 at an infinite distance. So, $U_f = 0$. It also has zero velocity at this point, so, $K_f = 0$.

$$\begin{aligned} K_i + U_i &= 0 \\ K_i &= -U_i \\ \frac{1}{2}mv_e^2 &= \frac{GMm}{r} \\ v_e^2 &= \frac{2GM}{r} \\ v_e &= \sqrt{\frac{2GM}{r}} \end{aligned}$$

This is the value of escape velocity! Let's finish this module with an example.

Example 3.4

Calculate the escape velocity at the Earth's surface if the Earth's radius is taken to be 6,370 km.

Easy enough, just a quick calculation. Remember to convert to SI units!

$$\begin{aligned} v_e &= \sqrt{\frac{2GM}{r}} \\ &= \sqrt{\frac{2 \times 6.67 \times 10^{-11} \times 6 \times 10^{24}}{6370 \times 10^3}} \\ &\approx 11209\ \text{ms}^{-1} \\ &= 11.2\ \text{kms}^{-1} \end{aligned}$$

This is the speed an object would need to be travelling at the Earth's surface for us to let go and trust that it will leave our gravitational field without further acceleration (neglecting friction). A rocket accelerates upwards gradually, so the escape velocity doesn't work in the same way there. This would be the speed requirement for, say, a giant cannon to shoot something off the Earth in one push!

Part II

Module 6: Electromagnetism

Topic 1

Charged Particles, Conductors, and Electric and Magnetic Fields

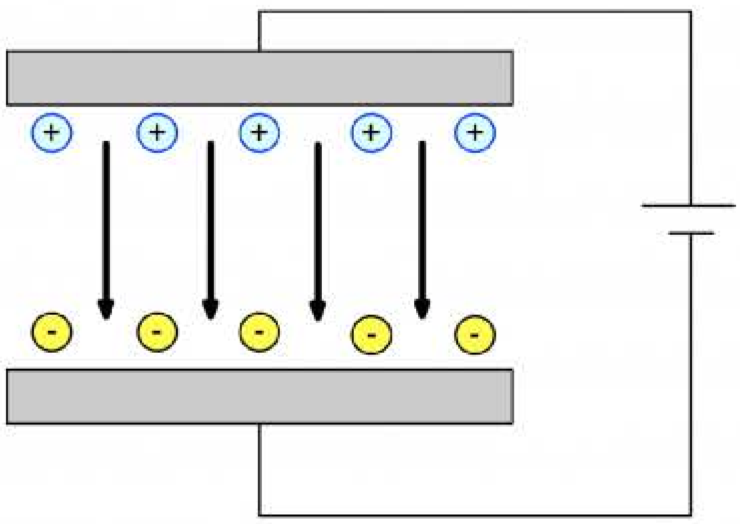
SYLLABUS :
Inquiry question: What happens to stationary and moving charged particles when they interact with an electric or magnetic field?

1.1 Charged particles and uniform electric fields

SYLLABUS :
Investigate and quantitatively derive and analyse the interaction between charged particles and uniform electric fields.

The first phenomenon we consider in this module is the interaction between charged particles, like positively charged protons or negatively charged electrons, and electric fields. For simplicity, we only consider *uniform* electric fields, meaning that the field is the same no matter how or where the particle moves. The simplest way to produce a uniform electric field is between two charged plates; this is what we will look at first.

Let's say we take two conductive plates a small distance apart, and apply a voltage between them (say, by connecting them to either side of a battery). This will cause an accumulation of charge on either plate. The plate connected to the positive end of the battery (more potential) will have an accumulation of positive charge, and the plate connected to the negative end of the battery (less potential) will have an accumulation of negative charge. This will result in an electric field between the plates, uniform in magnitude, directed from the positively charged plate to the negatively charged plate.



KEY POINT :
Remember, when we show a voltage source with two straight lines as I've done above, the longer line represents the positive voltage!

The size of the field is determined by the magnitude of the voltage across the plates, and the distance between them. We can approach simple problems with the formula below. This also introduces an alternative unit for electric fields besides Newtons per coulomb – we can also use **volts per metre.**

$$E = \frac{V}{d}$$

Example 1.1

Using two plates, we want to establish an electric field of 2000 *V/m using a 240 V voltage source. How close do the plates need to be?*

This is simple: just use the formula and rearrange:

$$\begin{aligned} E &= \frac{V}{d} \\ d &= \frac{V}{E} \\ &= \frac{240}{2000} \\ &= 0.12\text{m (12 centimetres)} \end{aligned}$$

This formula, $E = \frac{V}{d}$, should make sense since we know that the strength of an electric field is the *force* per unit charge, $E = \frac{F}{q}$, and that the definition of voltage is the *energy/work* per unit charge, $V = \frac{W}{q}$. And finally, we know we can relate energy/work to force using $W = Fd$. Putting all of that together:

$$E = \frac{F}{q} = \frac{W}{qd} = \frac{V}{d}$$

Let's now assume that we stick a charged particle in this uniform field. What happens? The particle will accelerate, as it is experiencing a force. We can determine the magnitude of this acceleration by combining our formula $F = Eq$, with Newton's 2nd Law, $F = ma$.

Example 1.2

An electron is placed into this 2000 *V/m electric field. What is the magnitude of its acceleration?*

By linking the two different formulas for force, we can calculate the acceleration of our electron. Keep in mind that, as usual, you'll always be given the mass and charge of an electron on your Data Sheet.

$$\begin{aligned} F = ma, F = Eq &\implies Eq = ma \\ \therefore a &= \frac{Eq}{m} \\ &= \frac{2000 \times 1.602 \times 10^{-19}}{9.109 \times 10^{-31}} \\ &= 3.5 \times 10^{14}\text{ms}^{-2} \end{aligned}$$

That's a *huge* acceleration! But we only get it for a split second, before the electron escapes the field and flows back into the circuit. In some scenarios, we might also want to calculate the work done on the charge by the electric field. We have lots of tools and results to do this:

- We can focus on the acceleration of the particle over a given time frame to determine a speed, and then find the kinetic energy of the particle using $K = \frac{1}{2}mv^2$. The energy of the particle will be equal to the work done on it by the field, assuming nothing else has impacted on its motion (remember conservation of energy!)
- We can calculate the work done as the charge moves from one point to another using a modified version of $W = Fd$. We know force is $F = Eq$, so, $W = Eqd$.
- We can use the definition of a volt, being **1 joule per coulomb,** $V = \frac{W}{q}$. Therefore the work done to move a charge from one plate to the other, given we know the voltage, is just $W = qV$.

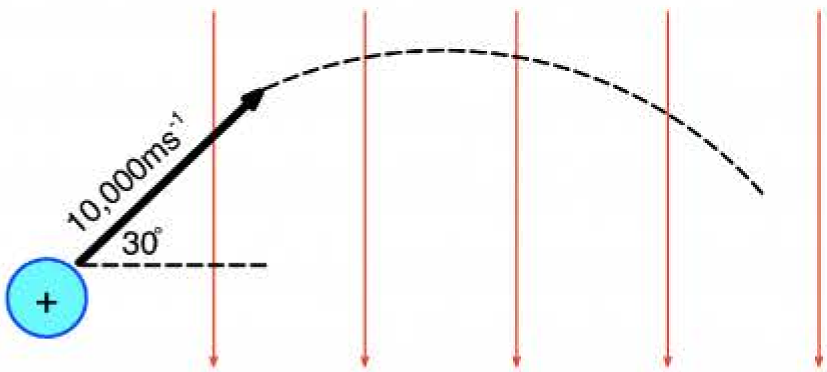
All of these are valid and all can be used to obtain the same result. Just ensure you understand the scenario you are analysing. For instance, you might not be analysing a particle moving from one plate to another; it might just be half that distance! Or, there might be other forces at play, which would mean you to need to calculate total kinetic energy. You have a toolbox – it is your job to pick the best tool at any given time, and to use it properly.

1.2 Particle trajectories

SYLLABUS :
Model qualitatively and quantitatively the trajectories of charged particles in electric fields and compare them with the trajectories of projectiles in a gravitational field.

When we have a charged particle in an electric field, it experiences a force. That is, we have an object released or thrown into an electric field, that then moves as a result only of its initial motion and the interaction with a single field. Sound familiar? It should; this is *exactly* the same as a projectile! Only now, instead of a force on the object from a gravitational field due to its mass, we have a force on the object from an electric field due to its charge. The origin of the force and acceleration is different, but the mathematics is the same, and the tricks are the same! It's still parabolic motion, so we can use all of our projectile motion formulas from the previous module in this scenario as well.

Example 1.3
A proton is projected into an electric field at a speed of 10,000 metres per second, at an angle of 30°. *The proton is found to experience an acceleration of 200,000* ms^{-2} *downwards in this field. Assuming gravitational effects are negligible, what is the horizontal range of the proton in this field?*



What we have here is essentially a projectile motion set-up. This is probably clear from the diagram. Only instead of gravity providing the downwards acceleration, it is an electric field. We use the same process to solve this as we would a projectile problem. First, let's divide the initial velocity into horizontal and vertical components.

$$u_x = 10000\cos 30 \approx 8660\ ms^{-1}$$
$$u_y = 10000\sin 30 = 5000\ ms^{-1}$$

Next, use this to calculate the time taken to reach the halfway point of motion. We know this happens when the vertical velocity is zero.

$$\begin{aligned} v_y &= u_y + a_y t \\ t &= \frac{v_y - u_y}{a_y} \\ &= \frac{-5000}{200000} \\ &= 0.025\ s \end{aligned}$$

This is the *halfway point*, so the complete arc of motion will take twice as long: 0.05 seconds. Note that you could also find this time of flight by solving a quadratic, $s = ut + \frac{1}{2}at^2$. Once we have this time, we can find the horizontal range easily:

$$r = u_x t = 8660 \times 0.05 = 433\ \text{metres}$$

So we can see that the processes involved in these sorts of problems are totally analogous to projectile motion problems, because it is still an object acted on by a single force once in flight! If you remember this parallel, questions involving trajectories of charged particles in electric fields should be a breeze!

1.3 Interactions of charged particles and uniform magnetic fields

SYLLABUS :
Analyse the interaction between charged particles and uniform magnetic fields.

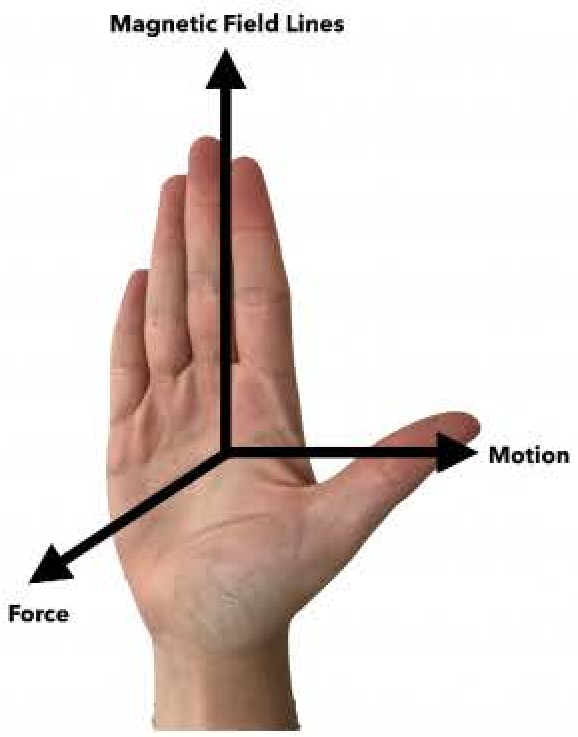
Electric fields are not the only thing that a charged particle will interact with – this module is called *Electro-MAGNETISM* after all. Charged particles will also interact with magnetic fields, because electrostatics and magnetism are two distinct (sort of) but heavily interrelated phenomena.

The key to a charged particle interacting with a magnetic field though, is that it **must be moving!** A stationary charge in a magnetic field will behave as if the magnetic field isn't there, and there would be no interaction whatsoever. As soon as the charge moves, it's a different story. This is because **all moving charges are surrounded by a magnetic field.** We alluded to this in Year 11 when we investigated the magnetic field around a current flowing through a conductor. This magnetic field is, in fact, the sum of billions of tiny magnetic fields that surround the electrons zooming through the conductor. A moving charge means there is a magnetic field, and this magnetic field will interact with other fields. This is why charged particles that are moving interact with magnetic fields.

What is the interaction? Basically, a moving charged particle will experience a force much in a magnetic field much like it would in an electric field. However, the **direction of this force** (and hence, **acceleration**) is **perpendicular** to the field, rather than parallel to it.

We have a really easy rule to determine the direction of force on a moving charge, called the **Right Hand Slap Rule.** Here's how we use it for a given scenario:

- Raise your right hand like you are about to give a high five, with your thumb fully stretched out to the side.
- Line your fingers (except your thumb) up with the direction of the magnetic field lines.
- Line your thumb up with the direction of motion of the particle. You shouldn't need to cross your thumb over your palm to do this, flip your hand over if you do!
- Wherever your palm is facing, that is the direction of the resulting force. You *slap* in the direction of the force!



This will give the direction of the force on a **positively charged** particle. If the particle is negatively charged, you can either:

- Use your left hand instead.
- Just swap the direction when you are done!

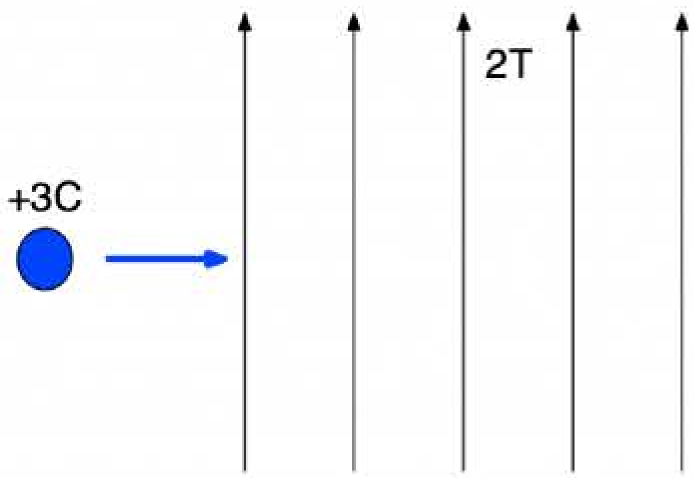
I personally recommend the latter, so you aren't ever confused about which hand to use – right is always right! How large is this force? We have a simple formula to find the magnitude. It is determined by the size of the field B, the charge of the particle q, the speed of motion v, and the angle between the field and the motion, θ.

$$F = qv_{\perp}B = Bqv\sin\theta$$

What you'll notice is that the force is largest when the field and motion are perfectly perpendicular, since $\sin 90 = 1$. As they become closer to parallel, the force reduces. This raises an important exception: if your charge is moving *along* the magnetic field lines, perfectly parallel to them, there won't be force, even though it is moving in the field.

Example 1.4

In the scenario below, the magnetic field has a magnitude of 2T, and the particle has a charge of +3C. What is the magnitude and direction of the force experienced if the particle is travelling at $10,000\text{ms}^{-1}$*?*



The magnitude of the force is the easy bit – just use the formula. The entry angle is 90°, the particle is moving perpendicular to the magnetic field:

$$\begin{aligned} F &= Bqv\sin\theta \\ &= 2\times 3\times 1.602\times 10^{-19}\times 10000\times \sin 90^\circ \\ &= 9.612\times 10^{-15}\text{N} \end{aligned}$$

The real purpose of the example though is to try that right hand slap rule. Your fingers line up with the magnetic field, so point up the page. Your thumb is the motion of the particle – it points to the right. This leaves your palm pointing towards you. Therefore, the force is **out of the page.** The particle is positively charged, so no swap is necessary at the end. Be sure to give a final answer with a direction:

$$\therefore F = 9.612\times 10^{-15}\text{N out of the page}$$

SYLLABUS :
Compare the interaction of charged particles moving in magnetic fields with other scenarios.

We've already compared the interaction of charged particles moving in magnetic fields with their interaction with electric fields. There are several key similarities and differences:

- Charged particles need to be in **motion** to interact with a **magnetic** field, where they interact with an electric field all the time.
- The **force** on a charged particle due to a **magnetic** field is **perpendicular** to the field, for an **electric** field it is **parallel.**
- Both electric and magnetic fields will apply a **force that varies in size** based on (at least) the **size of the field** and the **magnitude** of the charge.

However, charged particles moving in magnetic fields can be compared to many other sorts of motion, because the type of motion is quite typical: it is **uniform circular motion.** Think about it: we have an object that is moving, always experiencing a force perpendicular to its movement. That's the same thing that an object undergoing uniform circular motion will experience. This means you can think of the motion in a similar sense to other forms of uniform circular motion, like orbits. For an orbit, the gravitational force is always perpendicular to the orbital velocity. Here, the 'magnetic' force is always perpendicular to the motion of the particle. The net effect is essentially the same!

Topic 2

The Motor Effect

SYLLABUS :
Inquiry question: Under what circumstances is a force produced on a current-carrying conductor in a magnetic field?

2.1 Current-carrying conductors and uniform magnetic fields

SYLLABUS :
Investigate qualitatively and quantitatively the interaction between a current-carrying conductor and a uniform magnetic field.

We know from the previous section that a moving charge is surrounded by a magnetic field. By this logic, a current carrying wire is also surrounded by a magnetic field! Each of the tiny charges that make up the current is surrounded by its own field, and these superimpose to create a larger magnetic field around the current as it flows through the wire. The direction can be determined by the **Right Hand Grip Rule,** which is really easy to use.

- Raise your right hand in a thumbs up (go you for studying!)
- Align your thumb with the direction of *conventional* current flow (from positive to negative)
- In this position, your fingers should be wrapping around the wire/current. This represents the direction of the magnetic field.

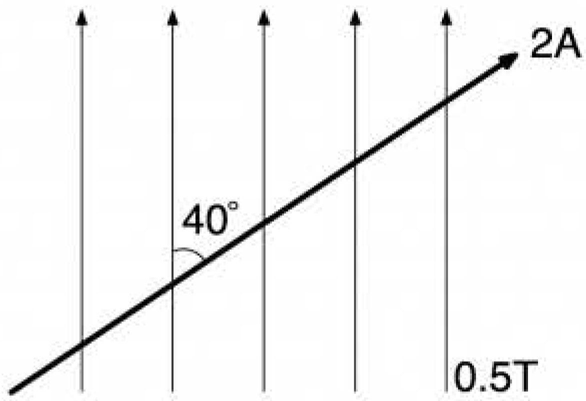
If we put a current carrying wire into an external magnetic field, the two fields (the external field and the field around the wire) will interact with each other. This will result in a force on the wire! The magnitude of this force is dependent on the size of the applied field B, the size of the current I, the length of the wire in the field L, and the angle between the current and the magnetic field lines, θ. The formula is:

$$F = LI_{\perp}B = BIL\sin\theta$$

The angle θ plays a large role in determining how large the force on the wire is. As soon as $\theta = 0^{\circ}$, this means $\sin\theta = 0$. No matter how large the field and current are, if the current is parallel to the field, you get no force! The maximum force is produced when the two are perpendicular (i.e. when $\theta = 90^{\circ}$). You'll likely do some experiments or simulations in class to see these forces in action and make these deductions for yourself.

The direction of the force can be determined with the right hand slap rule. It works almost the same as if we were determining the direction of the force on a single particle rather than a stream of them in a current. As usual, your fingers are the magnetic field lines, and you slap in the direction of the force. In our scenario, your thumb is the direction of **conventional current flow.**

Example 2.1
5 metres of wire carrying a current of 2 amperes is in a magnetic field of 0.5T as shown below. Find the magnitude and direction of the resulting force on the wire.



Again, the main purpose of the example is to practice the right hand slap rule, and to show how the angle plays in to things. It's bit easier to actually see, which is why diagrams are a great thing to draw if you aren't given one! We have our diagram, so we can jump into calculation:

$$\begin{aligned} F &= BIL \sin\theta \\ &= 0.5 \times 2 \times 5 \times \sin 40^\circ \\ &= 3.21394... \\ &\approx 3.2N \end{aligned}$$

Now for the direction: align your fingers with the magnetic field pointing up the page. The current is going up and to the right, so align your thumb with that. Your thumb should be shifted slightly towards your fingers, not quite flush with your index finger. This is another way to think about how force is affected by the angle – the further your thumb is from your index finger, the bigger the force. Once they are touching, the magnetic field and the current are parallel, which means no force. Either way, for us, the resultant force is out of the page.

$$\therefore F = 3.2N \text{ out of the page}$$

2.2 Parallel current-carrying wires

SYLLABUS :
Conduct a quantitative investigation to demonstrate the interaction between two parallel current carrying wires.

Many electronics applications require current carrying wires to be placed quite close to one another. And as we know, all currents are surrounded by magnetic fields. Can these magnetic fields interact and apply forces to the wires? Yes they can!

You'll do practical investigations in class to observe these forces, and we analyse them in detail in the next dot point. Qualitatively, the rule to remember is this: if we have **two wires** running **parallel** to each other, **both carrying a current,** they will **both experience a force.**

- If the currents are in the **same** direction (e.g. both going *up* the page), that force will be **attractive,** pulling the wires together.
- If the currents are in **opposite** directions, that force will be **repulsive,** pushing the wires apart.

We don't consider situations involving non-parallel wires in this course.

Syllabus :
Analyse the interaction between two parallel current-carrying wires and determine the relationship between the SI definition of an ampere and Newton's Third Law of Motion.

Now that we've observed the phenomena, we can analyse it. The force **per unit length** on wires in the above scenario (whether it is attractive or repulsive) is given by:

$$\frac{F}{l} = \frac{\mu_0}{2\pi}\frac{I_1 I_2}{r}$$

Here, F is the force and l is the length of the wires, carrying currents I_1 and I_2 at a distance r apart from one another. The symbol μ_0 represents a fundamental constant called the **permeability of free space/magnetic permeability constant** (something you may remember from Year 11), and takes a value of $4\pi \times 10^{-7} NA^{-2}$.

We can solve problems using this formula exactly as you'd expect, but we can also deduce something a little more interesting with this formula. We know that an **ampere,** the unit for current, is an SI unit. But where does the definition of an ampere come from? We know it is one coulomb per second, but we can't define it using the coulomb here. If we do things properly, the definition of a coulomb actually comes from the ampere first!

The answer actually comes from this formula. The SI definition of an ampere is:

The ampere is the amount of constant current which,
if maintained in two straight parallel wires one metre apart in vacuum,
would produce a force of 2×10^{-7} *Newtons between these wires.*

So, an ampere is the value of $I = I_1 = I_2$ above, assuming that $r = 1$ and $\frac{F}{l} = 2 \times 10^{-7}$. The answer is of course, 1 ampere, because... well, that's the point! This scenario of parallel wires also relates to Newton's 3rd Law. The wires are pulling or pushing on each other, and there are two forces, so it is an action/reaction pair just like the 3rd law predicts! Which is the action and which is the reaction? Doesn't really matter, the two forces exist together, one doesn't cause the other!

Topic 3

Electromagnetic Induction

SYLLABUS :
Inquiry question: How are electric and magnetic fields related?

3.1 Magnetic flux

SYLLABUS :
Describe how magnetic flux can change.

Let us recall our discussion about magnetic fields from the Year 11 Notes. The strength of a magnetic field is measured by its **magnetic flux density,** or how tightly packed the magnetic field is. This implies there is a separate quantity of magnetic flux, which we can think of as the magnetic field lines. So, magnetic flux is the magnetic field lines, and the magnetic flux density is how tightly packed those are. Which of these determines how 'strong' the field is?

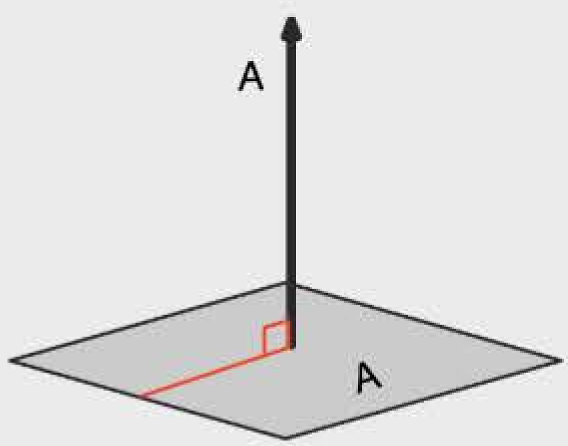
Mathematically, we can express magnetic flux density B, as a ratio of magnetic flux ϕ and area A. We can also include a cosine term to account for the angle between the field and our reference point.

$$B = \frac{\phi}{A} \implies \phi = B \cdot A = BA\cos\theta$$

In this section we will be talking about **changes** in magnetic flux. From this formula, it should be clear there are three ways to achieve such a change:

- Change the value of B (make the field stronger or weaker)
- Change the value of A (consider a larger or smaller area)
- Change the value of θ (change the angle you are making with the field)

KEY POINT :
The exact meaning of θ might be a tad confusing here – where's the second line to form the angle with the field? What we do here is this: take an arrow that is perpendicular to the area you are considering, like a flagpole stuck into the ground (or like the diagram below) – that is your reference. Formally, this is called an **area vector,** but we'll ignore the more rigorous mathematical definitions here. That's the second line you use for the angle with the field.



3.2 Faraday's Law and Lenz's Law

SYLLABUS :
Analyse qualitatively and quantitatively, with reference to energy transfers and transformations, examples of Faraday's Law and Lenz's Law.

Up to this point, we have learned that a current produces a magnetic field. Now, we work the other way, and explore how magnetic fields can cause electrical currents through **electromagnetic induction.**

- **Induction** occurs when a conductor is exposed to a changing magnetic field (more specifically, it must experience a **changing magnetic flux**).
- When this occurs, an electromotive force (or an **emf,** which is just a fancy way of saying voltage) is induced in the conductor. If a circuit is available, this will cause a current to flow.
- As this current flows it will set up its own magnetic field. The direction of current flow is *always* such that this new magnetic field **opposes** the changing field that created it in the first place. For example, if a current is induced by a field getting stronger in the north-to-south direction, this current will flow to create another field in the south-to-north direction.
- The **size** of the current is **proportional** to the rate of change of magnetic flux. If the change is greater, or happens more quickly, the current will be larger.

These ideas are encapsulated in two laws.

- **Faraday's Law:** induced emf is always proportional to the rate of change of magnetic flux.
- **Lenz's Law:** induced currents always flow in a direction such that the resultant magnetic field opposes the original field.

These laws manifest slightly differently in different scenarios. We'll consider a simple scenario, a coil with N turns exposed to a changing magnetic field. A change in magnetic flux $\Delta\Phi$ over time Δt, will induce an emf ϵ across the coil according to the following formula:

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

Example 3.1
A large, circular coil of wire with 100 turns has a cross sectional area of 1 square metre. A magnetic field is gradually switched on such that the magnetic flux density experienced by the coil rises uniformly from B = 0T *to* B = 2T *in 10 seconds. If the coil of wire has a resistance of* 10Ω*, calculate the current flowing in the coil during this 10 second interval.*

This is a longer, more complicated example, linking many different ideas we've covered so far. We need to calculate the rate of change of magnetic flux experienced by the coil. However, flux is different to **flux density.** So, we first need to figure out how the flux density change corresponds to a flux change. We'll use $\phi = BA$. Since no information is given on the angle/orientation of the field, we can assume the cosine term doesn't play a role (if you ever make an assumption like this, **state it** in your working!).

$$\Delta\phi = \Delta B \times A = 2 \times 1 = 2\text{Wb}$$

So, the change in flux is 2 Webers, and this happens over 10 seconds, therefore:

$$\frac{\Delta\phi}{\Delta t} = \frac{2}{10} = 0.2\text{Wb/s}$$

We can then use Faraday's Law to calculate the induced emf (or voltage) in the coil (the direction isn't important so we can ignore the negative):

$$\epsilon = N\frac{\Delta\phi}{\Delta t} = 100 \times 0.2 = 20\text{V}$$

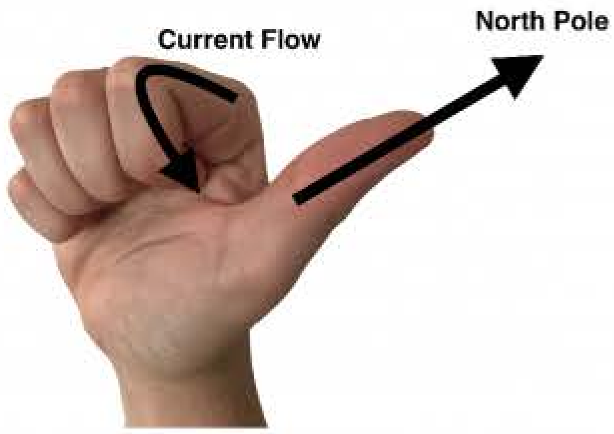
Then finish with Ohm's Law to find the current!

$$V = IR \implies I = \frac{V}{R} = \frac{20}{10} = 2\text{A}$$

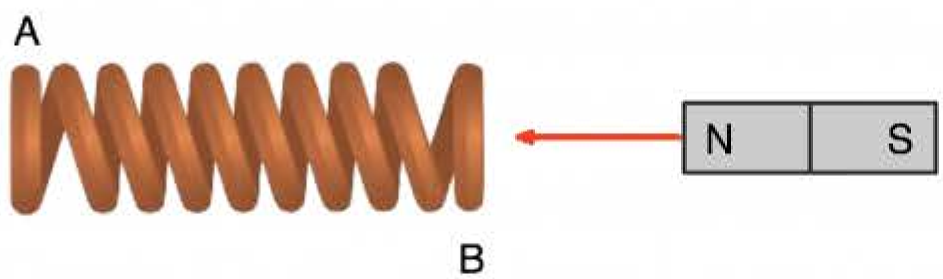
So where might this changing magnetic field come from? Well, let's say we have a coil of wire and a permanent magnet. We could *move* the magnet closer to the coil. In that action, we have increased the magnetic flux going through the coil (closer to the magnet). So, there's been a change in flux, and this causes a current to flow in the solenoid. Which way does it flow? We can figure this out as well.

The **right hand thumb/grip rule** for solenoids is what we'll use. It is slightly different to the one for magnetic fields around currents, but has similar mechanics.

- Hold up your right hand and form a first, with your thumb pointing up.
- Let your thumb point in the direction of the magnetic field you want to produce. In the case of a solenoid, point your thumb to the side of the coil you want the north pole to be on.
- In this position, your fingers are wrapping in the direction of the current required to produce that field.



So let's say we have the situation below: a coil of wire with a magnet moved towards it. We'll have an induced current – the change being caused by a north pole moving closer to the coil. The induced current will flow to *oppose* that change, that is Lenz's Law. Now, to oppose a north pole coming closer, what do you need? You need another north pole on that side of the coil, to repel the one coming closer. So, using the right hand grip rule, stick your thumb to the right. Your fingers should be wrapping in an anti-clockwise direction with respect to the magnet; the current is flowing from A to B. If we had an ammeter connected to the coil, we would actually detect this current, and it would be in the direction we've predicted (you might even do exactly this in class).



You don't even need to have a permanent magnet to do this – just use another coil as your magnet! Pass a direct current through the coil, and it will produce a magnetic field just like a bar magnet would. Bring that coil closer to another, and in that motion you'll see a current in the second coil. In fact, you don't even have to use coils – you can get the same effect in all sorts of ways. One of my favourites is taking a super long strand of wire, stretching it between two people, and spinning it like a skipping rope. If you connect each end to an ammeter, you detect a current. Why? The wire is actually experiencing a changing magnetic field, namely the *Earth's magnetic field*. As you spin it you are cutting through the Earth's magnetic field lines, so the wire experiences a change in flux and a current flows. It's tiny, but it is there if the wire is long enough. Cool, huh?

You should try to observe these effects in as many ways as possible, and make them reconcile with your understanding of Lenz's Law and Faraday's Law. For example, if you use a stronger magnetic field, you'd expect a larger induced current by Faraday's Law. Make sure you observe this and understand why situations are working the way they do. Verify that induced currents flow where you think they will flow based on Lenz's Law. For many, first hand observation is vital to really bring everything together.

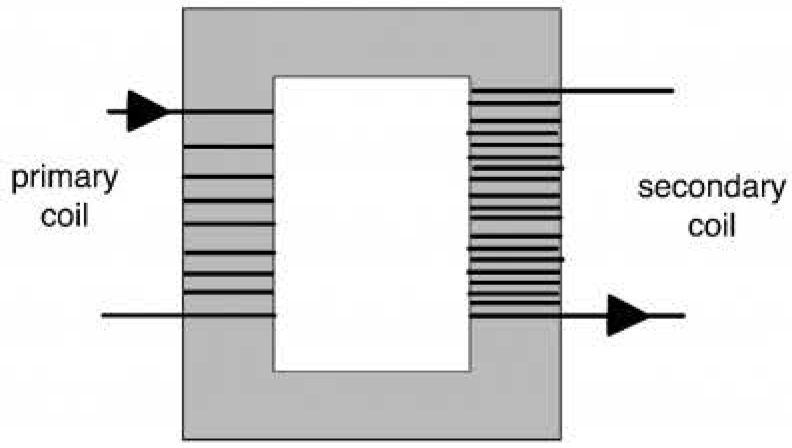
3.3 Ideal transformers

SYLLABUS :
Analyse quantitatively the operation of ideal transformers.

Electromagnetic induction allows us to do lots of incredibly useful things with our electrical circuits. Topping that list in terms of usefulness is the use of **transformers.** Transformers are devices which allow the **voltage** of an electrical signal to be **increased** (*stepped up*) or **decreased** (*stepped down*). We'll explore the ways in which these step-up and step-down transformers are used in later sections.

First, let's establish an intuitive understanding of how a transformer actually works:

- A transformer consists of three main parts:
  1. A **primary winding/coil** where the input signal goes in
  2. A **secondary winding/coil** where the output signal comes out
  3. An **iron core**
- The electrical signals used with a transformer **must be AC;** DC voltages will not work! As an AC electrical signal goes into the primary coil, the coil acts as an electromagnet switching on and off as the voltage oscillates. This creates an oscillating magnetic field.
- The iron core directs this magnetic field through the transformer and to the secondary coil. This is because iron is a highly permeable substance. Think of it like a conductor for magnetism! This makes a bit more sense if you're up to scratch with the Year 11 content.
- As the secondary coil is exposed to the oscillating, or *changing* magnetic field, a voltage is induced in this coil via electromagnetic induction. There is no electrical connection between the two coils. The electrical energy in the primary coil is converted to magnetic energy, directed through the core, then converted back into electrical energy at the other end.



The size of the voltage in the secondary coil of a transformer, as opposed to the primary coil, depends on the number of turns in each coil. The **ratio** of the primary to the secondary voltage is the same as the ratio of primary coil turns to secondary coil turns:

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

We can also use the conservation of energy to yield another result. We know that the input power to the transformer must be the same as the output power. We can't gain energy, after all. So, if power in equals power out, and P = VI, then we can equate VI for the primary and secondary coils:

$$V_p I_p = V_s I_s$$

It is important to note that these results are only true for **ideal** transformers. In reality, transformers aren't 100% efficient. There are losses, and later we will address the sources of those losses and how we seek to overcome them. For now, an example!

Example 3.2
A laptop charger label says it has an output voltage of 16.5 V and an output current of 4 A. If the input/supply voltage from the power point is 240 VAC, what is the current coming from the power point, assuming the transformer in the charger is ideal?

This is actually a pretty easy practical example. We know that the power in the primary/input coil is the same as the power in the output coil. We know that $V_s = 16.5V$, $I_s = 4A$, and $V_p = 240V$. So:

$$\begin{aligned} V_pI_p &= V_sI_s \\ \therefore I_p &= \frac{V_sI_s}{V_p} \\ &= \frac{16.5 \times 4}{240} \\ &= 0.275\text{ A } (275\text{ mA}) \end{aligned}$$

Example 3.3
You rip the transformer out of the charger from the above example, and you find that the primary coil has 960 turns. How many turns does the secondary coil have?

For this second example, we know $V_p = 240V$, $V_s = 16.5V$, and $N_p = 960$. Intuitively, since the voltage in the secondary coil is lower than the primary, we expect the number of turns to be lower in the secondary as well. Let's check!

$$\begin{aligned} \frac{V_p}{V_s} &= \frac{N_p}{N_s} \\ \therefore \frac{N_s}{N_p} &= \frac{V_s}{V_p} \\ N_s &= \frac{V_sN_p}{V_p} \\ &= \frac{16.5 \times 960}{240} \\ &= 66\text{ turns} \end{aligned}$$

3.4 Transformer efficiency

SYLLABUS :
Evaluate qualitatively the limitations of the ideal transformer model and the strategies used to improve transformer efficiency.

As aforementioned, these results assume that the transformer is *ideal*. They assume that every bit of electrical energy that goes in to the primary coil ends up in the secondary coil; that is, that the *conservation of energy* is observed. In reality, as with any energy transformation, we have losses. As the electrical energy is converted into magnetic energy and back again, energy is lost in various ways.

- Both the primary and secondary coils of the transformer have resistance, meaning they will heat up when a current flows through them. This is a source of power loss, with the power loss in each coil being given by $P = I^2R$, R being the resistance of the coil. We call this **copper loss.**
- In the process of generating a magnetic field, having this field directed through the core, and then having this induce another voltage, we have several losses in the core of the transformer. We call these **core losses**, and they include:
  - **Eddy currents:** these are small circular flows of current in the core of the transformer. They are caused by electromagnetic induction. We know a changing magnetic field induces a current in a conductor. Iron is a conductor! So, although we *want* all the currents to be induced in the secondary coil, we also get some flowing in the core itself. These are eddy currents, and they are a source of power loss.

- **Hysteresis:** no material is a perfect 'carrier' of magnetic fields. This causes energy loss since we don't get all of our magnetic flux density back out as magnetic intensity (that was intentionally vague; don't worry, this isn't something you actually need to understand).
- **Incomplete flux linkage:** although the core is designed to direct magnetic flux through to the secondary coil, some will still escape and go elsewhere. This is called leakage flux, and is another source of energy loss.

Of course, we want to reduce these losses as much as possible. Most transformers these days achieve efficiencies of around 99%, with the losses controlled in various ways:

- Eddy current losses can be reduced with **laminations,** which are thin layers of insulation placed through the core of a transformer. This reduces the area through which induced eddy currents can flow, drastically reducing their magnitude and thus reducing eddy current losses.
- Hysteresis and leakage flux losses can be reduced by using the right **material in the core** – one that is highly effective at carrying magnetic flux (**highly permeable**), and has a low resistance to changes in magnetic flux (**minimally coercive**).

The losses that do occur will be dissipated as heat in the coils and in the core. It is important for this heat to be carried away from the transformer to prevent it from overheating. This is usually done through natural/forced ventilation, an oil/water based cooling system, or a combination of both. Keeping a transformer cool is vital to achieving maximum efficiency and preventing malfunction.

3.5 Applications of transformers

SYLLABUS :
Analyse applications of step-up and step-down transformers.

We know there are two types of transformers: step-up and step-down. Both are found in our homes in order to adapt the supply voltage to different appliances. The voltage in regular powerpoints is 240 V. But if you plug that straight into a laptop, for example, it fries! The voltage must be transformed to something lower by the charger first, using a step-down transformer. The laptop itself might contain other step-down transformers too. For example, voltages that detect keystrokes won't need to be anywhere near as high as what is needed to light the screen. Equally, appliances might contain step-up transformers to get a higher voltage than 240 V.

Where transformers become pivotal though is in **power distribution.** As electrical energy is the main source of household energy, we need a way to effectively distribute it over large distances. This proves to be a problem. We know that losses occur according to $V = I^2R - R$, and though these might be quite small for cables/conductors, over distances of hundreds of kilometres, it adds up fast!

The solution is to make the voltage as high as possible (thus making current as low as possible). Say we wanted to transmit a megawatt of electrical power. We could do this with a voltage of 1000 V and a current of 1000 A. However, we'd get losses of $P_l = 1000^2R = 1000000R$, which even if R is small, is a huge loss! Chances are, over many kilometres, the resistance in the cable would cause all the power to be dissipated as heat. You'd get nothing useful at the other end.

Instead, we could use a step-up transformer and increase the voltage to 100000 V. This reduces the current to 10 A, reducing the losses to $P = 100R$. This is far more reasonable! Here we can see how basic circuit analysis is still applicable, even when figuring out something as important as how to get energy to every Australian household. This is the basis of high voltage electrical distribution. Electricity from the source is fed through a step-up transformer (or multiple) to increase the voltage, reduce the current and thus minimise losses. When you are distributing over long distances in Australia, voltages of hundreds of thousands of volts are typically used. This is then gradually reduced at substations. By the time it is in overhead powerlines, it is down closer to 50,000 V, and eventually reaching around 415 V at our power points. We keep it at high voltages for as long as possible to keep those losses minimal.

Topic 4

Applications of the Motor Effect

SYLLABUS :
Inquiry question: How has knowledge about the motor effect been applied to technological advances?

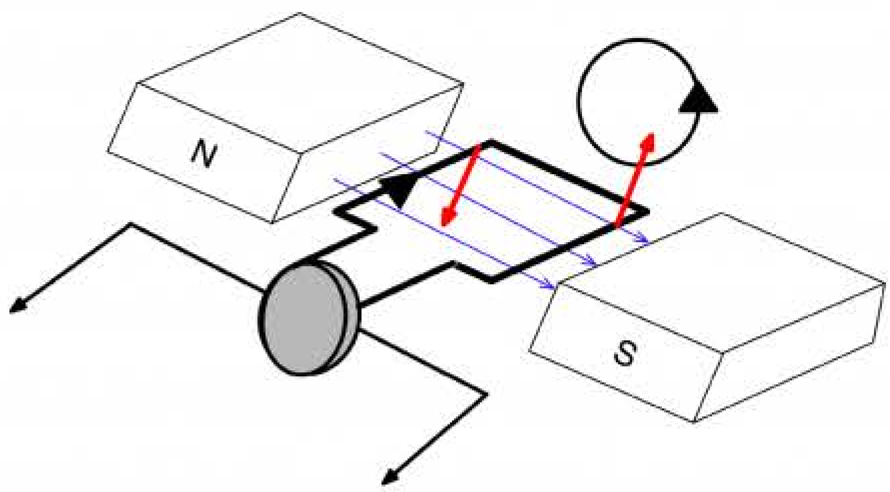
4.1 DC motors

SYLLABUS :
Investigate the operation of a simple DC motor.

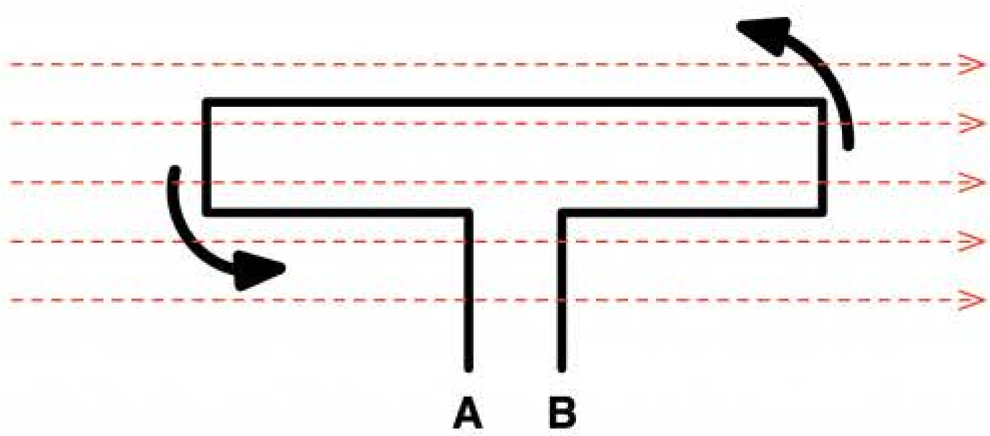
Earlier, we learned about the motor effect – the force experienced by a current carrying conductor in a magnetic field. Now, we see how this effect is applied in a basic DC motor.

A simple motor has two key parts:

- The **stator** provides a magnetic field, either via permanent magnets or electromagnets. We call it the stator because it is the stationary part of the motor!
- The **rotor** is where we feed the current. It consists of coils of wire that sit inside the magnetic field created by the stator. The coil spins due to the forces on the coil (themselves caused by the motor effect). We call it the rotor because it rotates!



Let's look at the forces at play on a coil in a simple motor. The diagram below shows the coil when it is 'flat,' parallel with the magnetic field, looking at it front on. Imagine there is a current flowing from A to B. If we apply the right hand slap rule we learned earlier to the left hand side, we end up with a force directed downwards (magnetic field to the right, current into the page, try it!). Apply it to the right hand side and we get a force directed upwards. Acting together, these forces work to spin the coil in the direction shown. More accurately, they produce a torque!



Topic 4 – Applications of the Motor Effect

If you were to swap the direction of current, so it is flowing from B to A, the direction of rotation would reverse. It is important to remember too that this is **conventional** current, not the flow of electrons!

The formula for the torque generated by a simple motor with a coil of n turns and an area of A, carrying a current I, inside a magnetic field B, is:

$$\tau = \text{nIA}_{\perp}\text{B} = \text{nIAB}\sin\theta$$

As is usual for a vector cross product, θ in this equation represents the angle between the two vectors, in this case the angle between A and B. Remember, the area vector A is taken to have a direction perpendicular to the area of the coil itself. This angle in the formula means that the torque provided by the motor is different as it rotates. When the coil is flat, you get the most torque, since $\theta = 90^\circ$. When the coil is oriented vertically with respect to the field (meaning A and B are parallel), you get no torque. This can be counteracted by using a *radial* magnetic field which maintains a constant magnitude of torque through the rotation.

Example 4.1

A motor consists of a square coil with 10cm sides and 1000 turns, sitting inside a magnetic field of 0.5T. What current is required to generate a maximum torque of 100Nm?

This is a case of simple rearrangement. Notice it says *maximum* torque, so we can ignore the $\sin\theta$ here. We want the value when $\theta = 90^\circ$, making $\sin\theta$ equal to its maximum value of 1.

First, find the area of the coil. It is a square coil with 10 cm sides, so:

$$\text{A} = 0.1 \times 0.1 = 0.01\text{cm}^2$$

We can now use this in our torque formula:

$$\begin{aligned} \tau &= \text{nIAB} \\ \text{I} &= \frac{\tau}{\text{nAB}} \\ &= \frac{100}{1000 \times 0.01 \times 0.5} \\ &= 20\text{A} \end{aligned}$$

Let's go back to this idea of torque varying with the angle with the field in a DC motor. We know that torque is maximised when the coil is flat, putting θ at 90°. When the coil is oriented vertically, so to speak, that torque drops to zero. The motor is spinning, so rotational inertia will carry it past that point. What happens then?

Well, if we think carefully, the forces actually start to slow down the motor. One side of the coil had an upwards force, one had a downwards force. After a half spin, those forces are now on opposite sides of the coil, effectively pulling it back where it has come from!

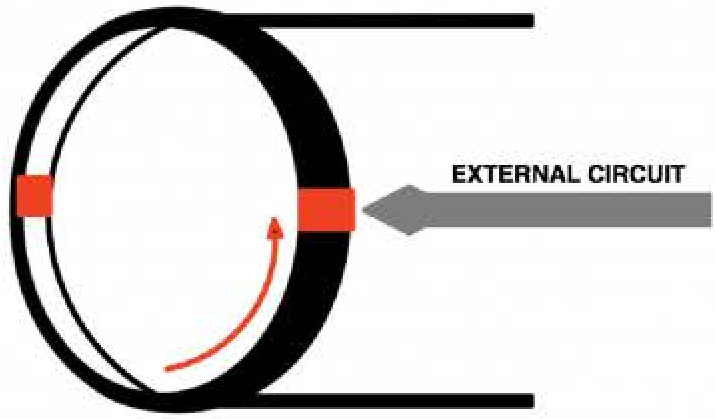
Key Point :
This is a *super* hard thing to visualise in any sort of two dimensional medium. This is an **investigate** dot point, which means you should hopefully get the chance to see a motor working to help make this click!

This is obviously not a good thing. We want the motor to keep spinning. One way to achieve this is by reversing the direction of the current every half spin, maintaining the direction of the forces with respect to the field. An AC motor does this by itself, but for a DC motor (where current is normally in a single direction) we achieve this with a **split ring commutator.**

A split ring commutator is the point where the current passes into the rotor. Carbon brushes slide along the commutator, which spins with the rotor. The commutator has small gaps on opposite sides. These gaps break contact with the external circuit every half spin, then as the motor keeps spinning, reconnect with the circuit on the opposite side. This swaps the direction of current flow!

You can sort of visualise how this works using the diagram below. The commutator itself is attached to the coil as it spins. The two shaded bits on the ring are the splits that don't contact with either side of the coil.

The connection from the external circuit rests on the ring as it spins, making contact via a sort of flexible contact called a **brush** (which really doesn't look like a brush). When that brush hits a split, the circuit is broken, before it is reformed in the reverse direction on the next half spin.



So this is how a motor works! But wait, haven't we been learning about induction? Are we just forgetting all that now? Not quite... induction also happens in motors. We've got a conductor (the coil, sometimes with a core similar to a transformer) rotating in a magnetic field. The conductor is experiencing a changing magnetic field. Thus, there will be an induced current!

Lenz's Law states that any induced currents must flow to oppose the change that created them. The supply current to the motor is what caused it to spin, and this is what causes the change in magnetic field. So, the induced current must flow in the opposite direction to that. It works 'backwards,' subtracting from the supply current. This is why we call it **back emf.**

What back emf means is that, as the motor spins, the current in the coil is actually equal to the supply current minus any opposing/back current:

$$I_{coil} = I_{supply} - I_{back}$$

I_{back} is larger when the motor is spinning faster. Faster rotation means a faster change in magnetic field, meaning a larger induced EMF. So, motors will have larger currents in their coils on start-up, which will then reduce as they start spinning and back emf starts to subtract from it. When you design a motor you need to keep this in mind. The coils should be able to handle this larger starting/inrush current, at least for a little while, as the motor starts spinning!

4.2 DC and AC generators

SYLLABUS :
Analyse the operation of simple DC and AC generators and AC induction motors.

Right, now that we've covered motors (at least the simple DC ones – we'll learn about AC induction motors soon), it's time to talk about generators!

We've hinted at how generators work in this module already – electromagnetic induction. As for the actual structure of a generator, it's the same as a motor!

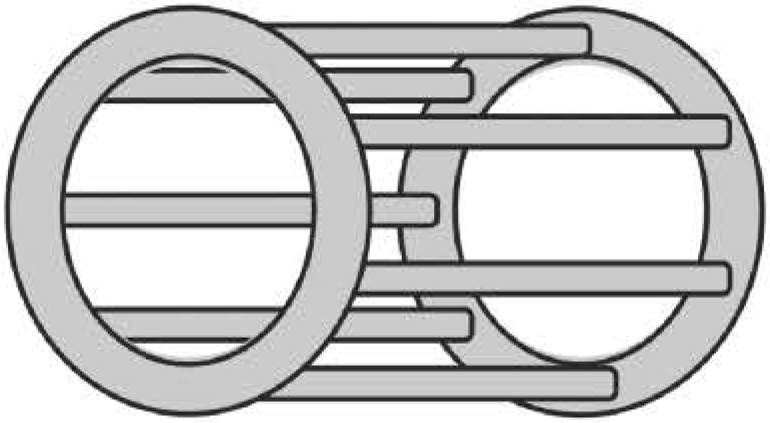
In a motor, we feed the coil a current to make it spin via the motor effect. In a generator, we spin the coil ourselves (using wind, or steam, or anything with kinetic energy) and induction generates the current in the coil for us to use. The stator provides the magnetic field, which you need for both applications. It has the same structure, but the opposite purpose! In a DC generator, the split ring commutator reverses the direction of output current every half turn, for the same reasons as we reverse the input in a DC motor. In an AC generator, we don't need to get rid of the reversing current direction, so we just connect the coil to the external load with brushes directly.

AC induction motors, however, work completely differently to regular motors.

As the name implies, induction is the key mechanism here. The basic principle is to expose the rotor of the motor to a changing magnetic field, and to let induction generate the current which eventually causes it to spin.

More specifically, a **rotating** magnetic field is used. This induces a current in the rotor and this causes it to spin. You can think of it in terms of Lenz's Law – the current wants to flow to oppose the change that created it. Since the change is a spinning magnetic field, the current will act to generate forces which get the rotor spinning *along with* the field. It wants to *chase it*, so to speak, because keeping up with the rotating field will minimise the change it experiences.

The key parts of a motor are still there. The stator consists of *pairs* of electromagnets (usually three pairs), which we switch on and off in sequence to create the rotating field. The rotor can consist of coils, but is also often what we call a **squirrel cage rotor** – conductive bars arranged in a shape similar to that shown on the right. Induction motors have an iron core similar to a transformer, to direct the flux through the rotor. The key difference is that in an induction motor, there is *no supply current to the rotor*. Induction generates the current for us.



4.3 Conservation of energy

SYLLABUS :
Relate Lenz's Law to the law of conservation of energy and apply the law of conservation of energy to DC motors and magnetic braking.

At its core, motors and generators act as energy conversion devices. Motors convert electrical energy to kinetic energy, generators do the opposite. All of these transformations are subject to the law of conservation of energy. If you want the energy out, you need to put the energy in, and then some, to compensate for losses.

Lenz's Law itself is an embodiment of the conservation of energy. It ensures that energy can't be broken. Let's explain that a bit: recall what we said earlier about back emf? The induced current flows *against* the supply current in a DC motor, because according to Lenz's Law, induced currents should always flow to oppose the change that created it.

Hypothetically, what if they didn't? What if the induced currents *supported* the change?

In our DC motor scenario, this means the induced current would flow in the same direction as the supply current, and the current in the coil would increase. But hold on, more current means more torque – which almost always means more rotational speed. But now the coil is spinning faster, which means the coil is exposed to a greater change in magnetic field. This means the induced current increases, increasing the current in the coil again, increasing the torque again, increasing the rotational speed again, increasing the change in magnetic field again! See where this is going?

The motor would spin out of control, getting faster and faster without any need for an input current. Without 'spending' any electrical energy, we get all of this kinetic energy out. And that would be nonsense! This shows us why Lenz's Law works the way it does – it ensures that energy isn't created from nothing.

So we're back to our actual DC motors that don't break laws of physics. Let's look at where energy is coming from and where it is going. The input is the electrical energy/power into the coil: $P = VI$. Much of that energy ends up as kinetic energy in the spinning rotor. However, as with anything, there are losses:

- The resistance of the wires will cause heat loss in the coil windings.
- Some of the kinetic energy of the rotor is put back into the induced back emf in the coil.
- There are also mechanical losses – friction, slip, and vibrations – which are sources of energy loss.

Overall, the aim is to minimise these losses to maximise the amount of useful kinetic energy produced by the motor!

Another process to which we can apply the conservation of energy to more easily understand it is **magnetic braking.** Magnetic braking works by applying a strong magnetic field to a conductive plate/surface on a moving object. The conductor experiences a changing magnetic field and this causes currents to be induced. These generate their own magnetic fields to oppose the motion, effectively *braking* the object.

This situation is a basic example of the conservation of energy. We want to reduce the kinetic energy of an object, so we take that energy and convert it into electrical energy in the form of induced currents. As a bonus, we can even use these induced currents to do other work. This is already done in some transport systems, including high-end electric cars! They use magnets to brake the vehicle, take the resulting induced currents and use them to charge the battery. Sweet!

At all times though, it is important to remember that we can never get out as much energy as we put in. Plus. generating the magnetic fields that brake the vehicle in the first place requires energy – you never get anything for free!

Part III

Module 7: The Nature of Light

Topic 1

Electromagnetic Spectrum

SYLLABUS :
Inquiry question: What is light?

1.1 Light as an electromagnetic wave

SYLLABUS :
Investigate Maxwell's contribution to the classical theory of electromagnetism.

As we learn about the concepts of electricity and magnetism, we always seem to be made aware that they are 'similar,' or 'connected.' We talk about them at the same time and with similar terminology. It was James Maxwell who first formulated a unified theory of **electromagnetism,** bringing together concepts that had until then been considered distinct, including the phenomena of light. This was a huge deal! Albert Einstein and Isaac Newton are known as being particularly influential in Physics, and Maxwell is right up there with them (in fact, Einstein's work stemmed straight from Maxwell).

Maxwell proposed a unified theory of electromagnetism in the 19th century, linking the ideas of electricity and magnetism with a series of twenty equations. These were later broken down to four key equations, **Maxwell's equations,** that encapsulate most of our modern understanding of electromagnetism. These laws, as you might imagine, are pretty complicated, but don't stress, we don't have to worry about them in this course.

Maxwell's work predicted the existence of **electromagnetic waves,** self propagating waves consisting of both electric and magnetic waves. Maxwell calculated the expected speed of these waves based on fundamental properties, including the permittivity and permeability of free space (ϵ_0 and μ_0, as you might remember from earlier topics). When he did this, he found it ***matched*** **the speed of light.**

Maxwell thus concluded that light was in fact an **electromagnetic wave.** Further, he supposed that light was just one example of an electromagnetic wave, one with a wavelength that the human eye could detect, and that others could (and should) exist! Of course, this prediction reigned true; it was proved in experiments by Heinrich Hertz in the late 19th century. We know now that there is a full spectrum of electromagnetic waves. Gamma waves, X-rays, microwaves and radio waves, to name a few.

There is lots to talk about here, and if you want to get more involved in the mathematics, you may like to research this further. Remember, always pick **valid** sources from reputable publishers, and ensure reliability by cross-referencing your information between sources!

SYLLABUS :
Describe the production and propagation of electromagnetic waves and relate these processes qualitatively to the predictions made by Maxwell's electromagnetic theory.

Let's delve into the idea of electromagnetic waves in a bit more depth. To produce an electromagnetic wave, we need an **oscillating charged particle.** The oscillation of the charge creates changing electric and magnetic fields, which then interact with each other to move through space. You can achieve an oscillating charge really easily with an AC power supply, as the constant reversal of polarity encourages charged particles to oscillate. This is exactly the method Hertz used to produce electromagnetic waves in his experiments. This aligns perfectly with Maxwell's predictions.

An electromagnetic wave consists of an oscillating electric and magnetic field at right angles to each other. Ignoring the complex mathematical reasoning behind it (based on Maxwell's equations), these fields will 'push' each other along through empty space at the speed of light. The frequency of the electromagnetic wave is the same as the frequency of its electric and magnetic components. This also aligns with Maxwell's predictions that changing electric fields could produce magnetic fields – a necessity for this type of wave to exist.

1.2 Measuring the speed of light

SYLLABUS :
Conduct investigations of historical and contemporary methods used to determine the speed of light and its current relationship to the measurement of time and distance.

There have been many attempts throughout history to measure the speed of light, using many different methods. Today, we can measure the speed with extreme accuracy, but earlier physicists did not have such tools.

- Galileo attempted to measure the speed of light by measuring a time difference between uncovering a lantern, and the perception of this event a great distance away. The time delay could be used to calculate the speed of the light travelling from the lantern to the observer. Galileo observed no delay (it would have been there, but it would have been microseconds, far too small for human perception).
- One of the more famous measurements was conducted by a Danish astronomer named Ole Romer. He used the orbits of Jupiter's moons, noticing that the moons would come into view at different times based on how far Jupiter was from Earth at that stage in our orbit. He deduced this was due to the time taken for the light to reach Earth, and that this changed based on distance. Using some clever calculations, he estimated the speed of light to be 220,000 kilometres per second (only a bit slower than the expected 300,000 kilometres per second).
- Later measurements attempted to use a grander scale for the measurements, using things like the position of the sun and the placement of shadows at different times to attempt an estimate. Some of these also got reasonably close!

Today, we've got lasers and other equally cool toys to measure the speed of light to a great degree of accuracy. We know it as 3×10^8 metres per second, it is actually just shy of that (2.9979×10^8, to five significant figures). So accurate is the measurement that we now use it to define other standard units of measure, including the metre and the second.

The metre is currently defined as the distance travelled by light in a vacuum over a period of 1/299792458 seconds. This sets the speed of light at exactly the measured value.

The definition of the second used above is based on the vibration of a caesium atom. There is a specific frequency of electromagnetic radiation (travelling at the speed of light) that causes a Caesium-133 atom to vibrate between two energy states. The second is defined as the time taken for precisely 9,192,631,770 cycles (or periods) of this specific radiation to occur. Super precise, right?

1.3 Spectra and spectroscopy

SYLLABUS :
Conduct an investigation to examine a variety of spectra produced by discharge tubes, reflected sunlight or incandescent filaments.

This is a practical dot point where you will observe and compare the spectra produced by various objects. What do we mean by *spectra*? Well, all objects emit radiation (we call this **black body radiation,** and we learn about it more later on in this module). The exact type and amount of radiation depends on the temperature of the object, and a *spectrum* is just a measure of how much radiation of each wavelength is radiated by an object. So this is what you'll be detecting and measuring using some sort of **spectrometer.**

KEY POINT :
As is usual, pay attention in your practical tasks – they are assessable content!

Safety warning: Notice that the syllabus says *reflected* sunlight. If you are using a spectroscope that you physically look through, don't look directly at the sun!

SYLLABUS :
Investigate how spectroscopy can be used to provide information about the identification of elements.

What you've done in the previous dot point is a sort of **spectroscopy,** observing how light interacts with matter to discern properties of that matter. For example, we can use the spectrum of an object to estimate its temperature. One of the most common uses of spectroscopy is to identify and characterise chemical elements. We know atoms consist of a nucleus surrounded by orbiting electrons (or if we don't, we'll learn about it in a later module!). These electrons can move from one energy level to another, and when they move to a lower energy level, they emit electromagnetic radiation. The specific frequency/wavelength of this radiation is characteristic of the element, so we can detect it and use that to identify which element we are looking at! This is, at the core of it, what a spectroscope allows us to do. A spectroscope/spectrometer **splits light into individual wavelengths and frequencies** so we can easily detect which ones are being emitted from an element. This is just brushing over the science of how spectroscopy works – you'll get a better understanding as you learn more of the course!

1.4 Spectral astronomy

SYLLABUS :
Investigate how the spectra of stars can provide information on those stars.

Spectroscopy also allows us to discern a lot of information about celestial bodies. The spectrum of a star consists of a curve of detected radiation that approximates a black-body radiation curve (we haven't studied this yet, but we're getting there!). It's not just a smooth curve though – we also have **spectral lines** which are specific frequencies where we get either much more radiation, or much less (we'll learn more about this a little later too – the syllabus jumps around a bit here).

Let's go through a few of the things we can ascertain by looking at the spectrum of a star:

- The **surface temperature** of a star is linked directly to the colour of the surface. When we look at the spectrum of a star, we can determine in which frequency range we are detecting the most radiation (this will correspond to the colour we see with our eyes). There will be one specific wavelength where we detect the most – this is called the **characteristic wavelength/frequency.** The surface temperature of the star is linked directly with this value of λ_{max} through a relationship called **Wiens' Law** that we'll learn about more properly a little later (and for stars it is an approximation anyway). In general though, hotter stars have more radiation in the blue end of the visible spectrum, while cooler stars have more radiation in the red end.
- The **rotational/translational motion** of a star will cause changes in its spectrum.
  - If the spectrum is uniformly red-shifted (that is, the frequencies involved are shifted slightly towards the red end of the electromagnetic spectrum, towards lower frequencies), this can be attributed to the star moving away from us. If the star is moving towards us, the spectrum will be blue-shifted. In both cases, the Doppler effect causes the shift, and we can calculate the translational motion from there.
  - Rotational motion is a little trickier, but it is the same basic idea. Think of a rotating star – with respect to the Earth, parts of it are moving away, parts are moving towards us, and some aren't moving at all. It depends on how we're looking at it. This will cause red shift of some of our detected radiation and blue shift in other parts, with the net effect being that the spectrum and spectral lines will *smear* or blur. It won't be as well defined as would normally be. We can (with clever maths) figure out how the star is rotating from that.
- The **chemical composition** of a star can be determined by where the spectral lines sit. Their location, as described above, can be combined with other data to determine the elements present in the atmosphere of a star.
- The **density** of a star can be determined by the width of its spectral lines. A higher density in the atmosphere of a star will widen the spectral lines.

Topic 2

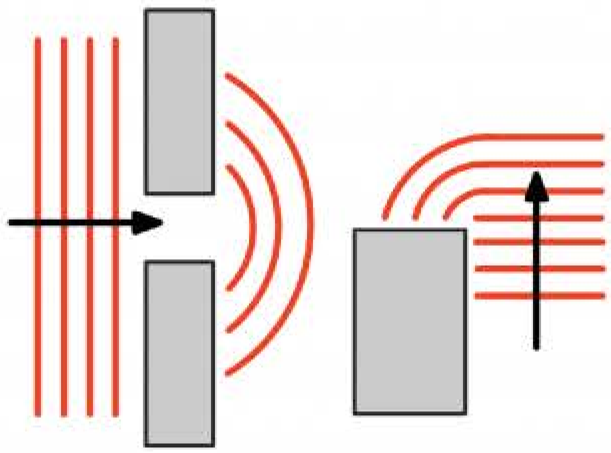
Light: Wave Model

SYLLABUS :
Inquiry question: What evidence supports the classical wave model of light and what predictions can be made using this model?

2.1 Diffraction and the wave model of light

SYLLABUS :
Conduct investigations to analyse qualitatively the diffraction of light.

In this section, we consider the first of the two models of light: the **wave model.** We have two models because there are certain properties of light that can only be easily explained by one or the other. **Diffraction** is one such property, explained fairly easily using the wave model, but with much more difficulty using the quantum model. Diffraction, in simple terms, is the bending of light (or any wave) around corners or in narrow passageways. The idea of diffraction is well represented by looking at what water waves do when they strike a corner – they bend around it! Water waves aren't actually waves in the proper sense, but this is a good way to picture what is actually happening.



You'll conduct experiments/perform simulations to observe this behaviour. What you'll discover in your experiments is that diffraction tends to happen more when the openings/obstacles involved in the experiment are of a similar scale to the wavelength of the wave. This is why we don't notice light bending in hallways and narrow corridors – the waves are still far too large for the effect of diffraction to make any sort of difference to observations. To meaningfully observe diffraction, you need extremely small gaps/slits.

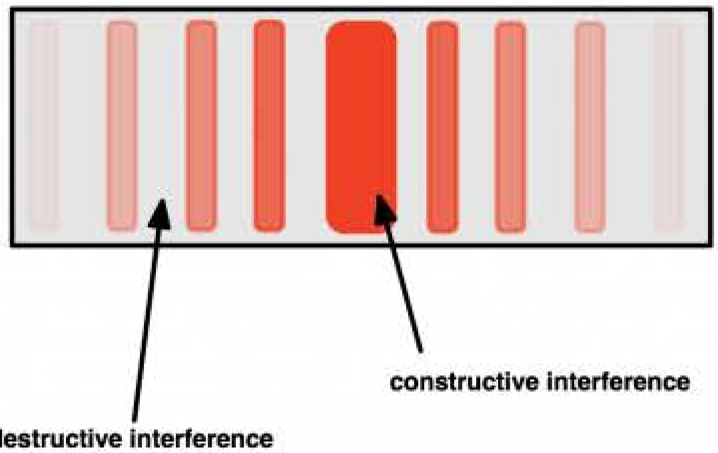
2.2 Young's double slit experiment

SYLLABUS :
Conduct investigations to analyse quantitatively the interference of light using double slit apparatus and diffraction gratings.

One of the key experiments you will do to observe diffraction will be the double slit experiment, also known as **Young's experiment** after the first to perform it, Thomas Young.

We know that when a wave passes through a narrow slit, it disperses/bends out from that slit on the other side. This is what we would observe in the experiments from the previous dot point. This experiment takes two of these slits close to one another and shines light through both. We shine this light onto a surface some distance away from the slits. When we do this, we observe an interference pattern of alternating light bands and dark bands. The two slits act as individual light sources, and the waves from each of them **superimpose** upon each other (which is just a fancy way of saying they overlap). In some places the light waves **constructively interfere** with each other, causing the brighter spots in the pattern. In other places, they **destructively interfere**, causing the darker spots. The interference happens because the waves have travelled a different distance from each slit to the surface, depending on which point you are looking at on the surface.

KEY POINT :
If you don't remember superposition of waves from Year 11, it's worth going back to your preliminary notes to make sure you understand this properly!



There is actually a formula that will tell us how far apart these light and dark bands (sometimes called **fringes**) will sit. You might even derive it in class, but we won't do that here as we'll just be *using* it:

$$d \sin\theta = m\lambda$$

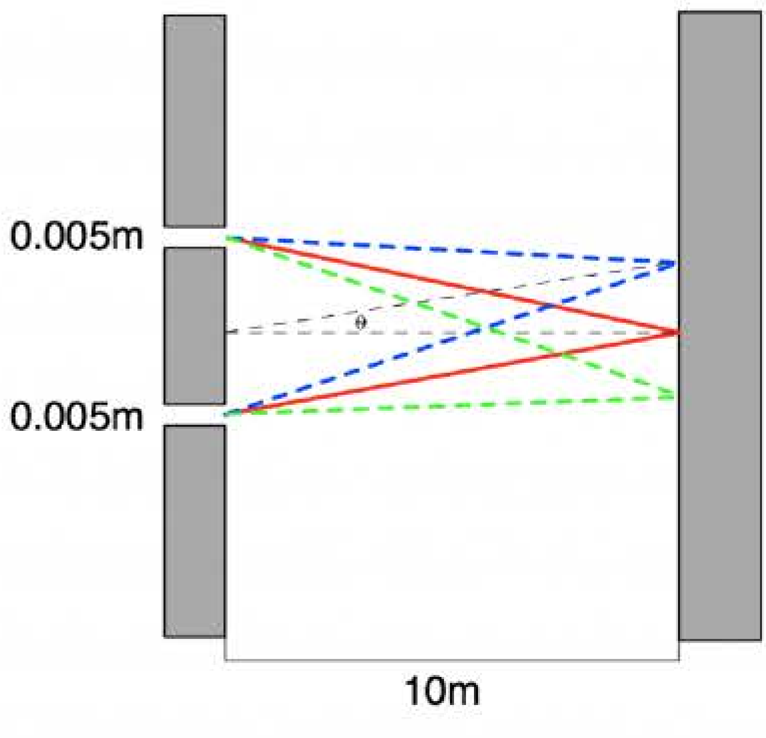
In this formula, d represents the distance between two slits, θ is the angle from the midline of the two slits to the point, λ is the wavelength of the wave, and m is any integer value: 0, 1, -1, 2, etc. This formula tells us all the points (and their corresponding angles, θ) that have **bright** spots, or points where the waves interfere constructively.

There is another formula for finding **dark spots** that is only slightly different:

$$d \sin\theta = \left(m + \frac{1}{2}\right)\lambda$$

Example 2.1
A double slit experiment is set up that uses light with a wavelength of 500 *nm, and two slits each with a width of half a centimetre. A wall is set up 10 metres behind the slits. How far from the centre bright spot do the two adjacent bright spots occur?*

For these sorts of questions, you *really* want to draw a diagram. Without one it is ridiculously difficult to figure out what is happening.



So, this diagram shows the path from each of the slits to the centre of the wall behind them. This represents the central bright spot at $\theta = 0$. On either side of this are another two bright spots, at some other angle θ to the centre line. We need this angle first, and we get it from the formula above. We know the slit width is d = 0.005m (half a centimetre), the wavelength of light is 500×10^{-9}m, and that we want the first bright spot. Therefore, we set m = 1 (or m = –1, which just gives us the one on the other side).

$$\begin{aligned} d \sin\theta &= m\lambda \\ \sin\theta &= \frac{m\lambda}{d} \\ &= \frac{1 \times 500 \times 10^{-9}}{0.005} \\ &= 0.0001 \\ \therefore \theta &\approx 0.006^\circ \end{aligned}$$

This is very close to the centre bright spot! Now, this is just a stepping stone – we actually want the **distance** from the centre spot, along the wall. For this, we need some trigonometry. Use the solid line that forms a triangle shown in the diagram. With $\theta = 0.006^\circ$, and a known adjacent of L = 10 m, we can use the tangent ratio to find our distance x:

$$\begin{aligned} \tan\theta &= \frac{x}{L} \\ x &= L \tan\theta \\ &= 10 \times \tan 0.006^\circ \\ &\approx 0.001\text{m (about a millimeter!)} \end{aligned}$$

The formula we ended up with there, $x = L \tan\theta$, will pop up a lot! There are also other ways to make similar approximations, but you should be able to do the full working, as above, too!

We can also do this experiment with a **diffraction grating,** which involves *many* slits, not just two! They will all be of the same width and be equally spaced. Amazingly, when we shine light through a diffraction grating, the bright spots and dark spots on the surface behind it occur in the exact same places as for a double slit! A diffraction grating just makes them far more pronounced (obviously bright, then obviously dark, with minimal transition). For this reason, you'll probably use a diffraction grating to observe the light/dark fringes in class. It's also why we use diffraction gratings in spectrometers, devices that analyse the spectrum of incoming waves.

2.3 Wave model vs. particle model

SYLLABUS :
Analyse the experimental evidence that supported the models of light that were proposed by Newton and Huygens.

In the 1700s, there were two models of light being proposed: a wave model, and a particle model. The wave model was proposed by Christiaan Huygens, while Isaac Newton supported a particle model. Each had different evidence to support their theory.

Newton was able to explain behaviours we typically associate with waves, like **reflection,** using a **particle model** (balls bounce off walls, right?). The fact that light appeared to travel in a straight line (evidenced by sharp shadows) was also explained more simply with the particle model. Effects of diffraction were not observable in everyday scenarios. The other big kicker for Newton's theory was the fact that light was able to travel through *nothing* – at this point, physicists thought waves needed a medium through which to travel. If there was no medium, it must be a particle!

Huygen relied on experimental observations of **refraction** in specific scenarios to back up his theory of the **wave model.** He also observed that when light hits a boundary, some of it is reflected and some is refracted. This matches the behaviour of mechanical waves meeting a boundary and cannot be explained well by Newton's particle model. Huygen also proposed an explanation for diffraction and other phenomena, called **Huygen's Principle.**

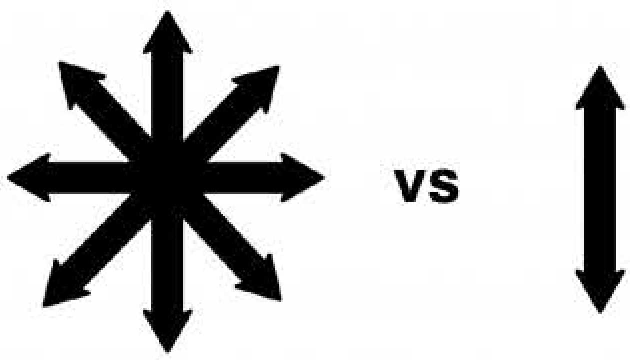
Eventually, it was the double slit experiment that (among others) led to Huygen's wave model being accepted over Newton's. As discussed above, the observations in the double slit experiment can be explained by the interference properties of waves. Light was also observed to slow down in denser mediums, contradicting Newton's prediction that it should speed up in denser mediums. Thus, the wave model became the accepted model of light (at least, until Einstein came along).

2.4 Polarisation

SYLLABUS :
Conduct investigations quantitatively using the relationship of Malus' Law for plane polarisation of light, to evaluate the significance of polarisation in developing a model for light.

The **polarisation** of waves (such as light) is a tricky little concept, so let's start there. Light is a **transverse wave,** with electric and magnetic fields each oscillating perpendicular to the direction of travel. Let's just focus on the electric field (as is convention when talking about polarisation). Even if we know that the electric field needs to be oscillating in a direction perpendicular to the direction of travel, this still leaves all sorts of directions to vibrate in. Imagine the light wave is coming towards you – the electric field could be oscillating up and down. Or left and right. Or diagonally up and to the right. Or, that same thing, but a little flatter. You get the idea.

Without any other sort of modification/interference, light is in an **unpolarised** form, which means the electric field can be oscillating in any direction perpendicular to the propagation of the light. Polarisation means taking this light and restricting the electric field to only oscillate in a single direction. You can see the difference in the diagram below. Such devices are called polarisers. There all sorts of methods to polarise light, but we don't learn about them in this course.



Unpolarised light (left) vs. polarised light (right)

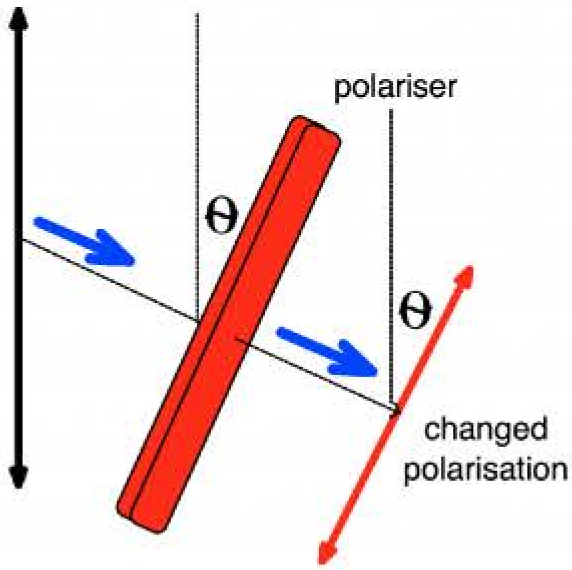
When you pass unpolarised light through a polariser, the intensity of that light decreases, since all the *parts* of the light beam that don't align with the polariser are reduced or removed. Specifically, the intensity is **halved,** so if we pass unpolarised light with an intensity of 100 W/m^2 through a polariser, we get 50 W/m^2 out the other side.

Topic 2 – Light: Wave Model

We can also use polarisers to take a beam of polarised light, and change the polarisation, aligning the electric field in a new direction. However, we also can't do this for free – we lose some of the intensity of the light in the process. We can analyse such situations using **Malus' Law:**

$$I = I_{max} \cos^2 \theta$$

Here, I is the intensity that we get coming out of the polariser, I_{max} is the original intensity going in, and θ is the angle between the direction of polarisation of the light, and the polariser.



You'll do some experiments with polarisation in class. Polarisation, and a proper explanation of the phenomenon, is a crucial aspect of a complete model of light. This is another part of the reason why the wave model of light came to be adopted over the particle model – Huygen was able to observe the polarisation of light, and this appeared more consistent with a wave model.

Example 2.2

Unpolarised light with intensity 64 W/m^2 *is passed through a pair of polarisers. The first is oriented vertically, the second is oriented at an angle of 45 degrees to the vertical. What is the intensity of the light after it passes through the pair of polarisers?*

So let's look at the initial intensity and call that I_0. After the first polariser, the intensity is halved, since it is initially unpolarised. So we'll let $I_1 = 32$ W/m^2, the intensity emerging from the first polariser. Then we use Malus' Law to calculate the final intensity I_2:

$$\begin{aligned} I_2 &= I_1 \cos^2 \theta \\ &= 32 \cos^2 45^\circ \\ &= 32 \times \frac{1}{2} \\ &= 16 \text{ W/m}^2 \end{aligned}$$

Topic 3

Light: Quantum Model

SYLLABUS :
Inquiry question: What evidence supports the particle model of light and what are the implications of this evidence for the development of the quantum model of light?

3.1 Black body radiation and the quantum model

SYLLABUS :
Analyse the experimental evidence gathered about black body radiation, including Wien's Law related to Planck's contribution to a changed model of light.

Right, you know all that stuff we talked through about light behaving like a wave? Forget about all that for a bit – we're about to step into the quantum realm!

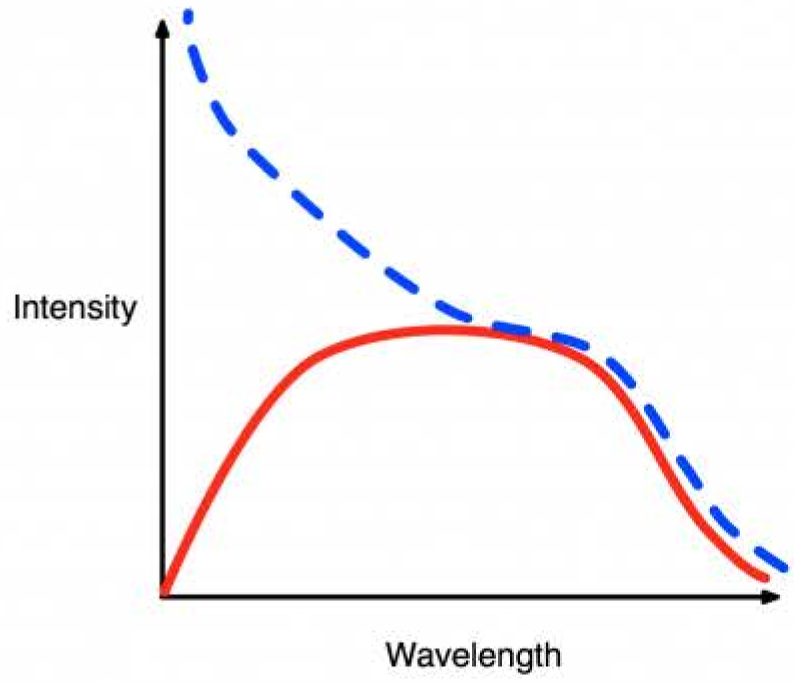
The first thing to discuss is **black body radiation.** This is the radiation emitted by things called **black bodies,** a theoretical object that reflects no light/radiation, only absorbs and then emits it. No actual black bodies actually exist, but we can talk about *approximate* black bodies that are really close. We can measure this as something called the **emissivity** of the object – perfect black bodies have an emissivity of 1.0. The emissivity of the sun is about 0.99, very close to perfect. Something like aluminium foil is a very poor approximation; it has an emissivity of about 0.05. Any object with a temperature above absolute zero emits this black body radiation, also called **thermal radiation.**

So we've got these things called black bodies, and they emit radiation that we call black body radiation. The amount and type of radiation emitted is dependent on temperature. This is something you probably know intuitively – hot objects glow, colder objects don't, and stars have different colours based on temperature. In the late 1800s/early 1900s, physicists were attempting to model and understand this radiation, and running into a fair bit of trouble.

Black bodies emit radiation across all frequencies – this had been documented in experiments with lamps and other approximate black bodies as early as the mid 1800s. The problem was that laws of physics at the time seemed to predict that the energy emitted by a black body should be greater at higher frequencies. The 'classical' theory, called **Rayleigh Jean's Law,** predicted that energy should vary based on the square of the frequency. This makes no sense for a couple of reasons, most obviously that it didn't match experimental observation! It was correct for lower frequency ranges, but as soon as we enter the ultraviolet range of the spectrum, it starts to deviate from experimentation. We call this failure the **ultraviolet catastrophe.**

The other issue was that the classical law violated the conservation of energy. Think about it: it would mean that all black bodies are emitting infinite energy. The approximate black body lighting your room right now would apparently be emitting a heap of gamma rays and have enough thermal radiation to power the planet! Yeah... no.

The issue is effectively visualised by black body radiation curves. These are graphs of how the intensity (roughly the same as energy) of radiation from a black body, on the vertical axis, is spread across different wavelengths (the horizontal axis). In the diagram below, the lower line represents experimental observation for a particular black body. Notice that there is a peak at one particular frequency/wavelength (we call this the **characteristic frequency/wavelength**), and the rest of the energy is distributed at lower levels around it. The upper, dotted line is the curve predicted by Rayleigh Jean's Law. At large wavelengths/low frequencies, the two are close. As wavelength decreases (so, frequency increases), the curve shoots upward. This is that extra energy we talked about, and it has no limit. As we move into considering higher frequencies, we get more and more energy. There's the problem.



Firstly, we need to figure out where that characteristic peak sits. A scientist named Wilhelm Wien managed to formulate a law that gives us where the peak wavelength sits for a black body at a particular temperature.

$$\lambda_{max} = \frac{b}{T}$$

The peak wavelength λ_{max}, is given as a ratio between the constant b and the temperature T is the temperature of the black body, measured in Kelvin. b is called **Wien's displacement constant,** taking a value of 2.898×10^{-3}.

KEY POINT :
As a side note: if you need to convert from degrees Kelvin to Celsius, just subtract 273.15 from your degrees Kelvin value!

Example 3.1
Given that our sun has a temperature of about 5780 Kelvin, what is the characteristic wavelength of the suns radiation?

This is an easy calculation. We will find that the characteristic wavelength of the sun is actually in the green portion of the visible spectrum (weird huh?) which just shows why these laws are only approximations for the super complex stuff happening in a star.

$$\lambda_{max} = \frac{2.898 \times 10^{-3}}{5778} = 502\text{nm}$$

Wien's work was a prelude to the work of Max Planck, who managed to solve the ultraviolet catastrophe and accurately model the black body radiation curve. He did this by making a strange assumption: that electromagnetic radiation could only be emitted in specific quantities, almost like little 'packets' which Planck called **quanta.** By doing this, the mathematics changed and matched experimentation. This was the first case of **quantum physics** explaining something that classical physics could not.

These little energy packets each had an energy proportional to the frequency of radiation emitted. The law is:

$$E_{quanta} = hf$$

The energy E is the product of the frequency f, and Planck's Constant, $h = 6.626 \times 10^{-34}$. What Planck was suggesting was that although the energy **per quanta** increased with frequency, this was balanced by the fact that there would be less quanta at higher frequencies. This idea allowed Planck to derive the mathematical law for black body curves, called **Planck's Law.** However, it was believed this was more of a mathematical trick than an actual explanation for what has happening – that acceptance would come later.

3.2 The photoelectric effect

SYLLABUS :
Investigate the evidence from photoelectric effect investigations that demonstrated inconsistency with the wave model for light.

If it was just black body radiation that couldn't be explained by classical physics, we might have assumed that it was just a limitation of our calculations or understanding, and that it could eventually be figured out. But other phenomena posed a problem for classical physics though too, particularly the **photoelectric effect.**

The photoelectric effect was first observed in experiments conducted by Hertz. Hertz was using transmitter and receiver coils to create sparks of electricity to transmit radio waves. He found that the sparking occurred more readily (that is, with lower voltages) if the coils were exposed to ultraviolet radiation. He never investigated the cause of the observation.

Further experimentation revealed the following about the photoelectric effect:

- Shining an **ultraviolet** or other high frequency light on a surface caused electrons to be emitted from that surface. With an external voltage applied, this could be directed through a circuit.
- A certain **frequency** of oncoming radiation needed to be reached before it occurred. No matter how much light was shone on a surface, electrons would never be emitted until a certain frequency was reached.
- Once the frequency was reached and/or exceeded, the amount of electrons released became dependent on the amount of light shone on the object. **More light, more electrons.** Increasing the frequency would have no effect on the number of electrons emitted, but would give each one more kinetic energy when it was.

These observations were totally inconsistent with a wave model of light. It just didn't make sense for the amount of electrons released to be somehow separate from the frequency of the light, even when it affected the amount of energy per electron.

3.3 The photon model of light

SYLLABUS :
Analyse the photoelectric effect as it occurs in metallic elements by applying the law of conservation of energy and the photon model of light.

Now it's finally time to introduce Einstein!

Einstein knew of Max Planck's analysis of black body radiation, and the idea of quantised energy, or *quanta*. He didn't believe it was a mathematical trick – he believed it could be the key to a new model of light, a quantum model, which could successfully explain things that classical physics could not.

Let's break down **Einstein's model:**

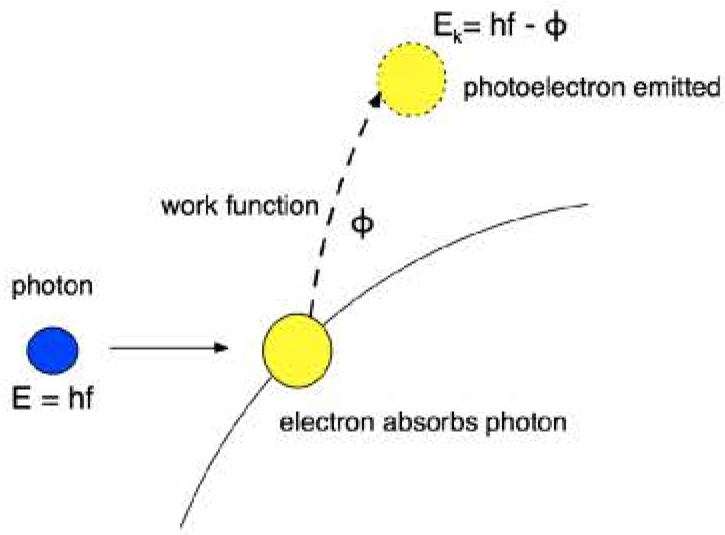
- Light can only exist in discrete quantities, little 'wave packets' which can be thought of as particles. Einstein called these **photons.**
- Each of these photons has an energy determined by the frequency of the light, $E = hf$, with the total energy given by the sum of the energy of all the photons.
- Each of these photons can interact with atoms in surfaces, either being absorbed or reflected. This is the **All or Nothing Principle** (i.e. you can't absorb or reflect half a photon – it is either reflected, or absorbed).
- Parallels can be drawn to the wave model. The amplitude of a light wave is analogous to the number of photons present in a beam of light. A higher amplitude means more photons, but each has the same energy. Increasing the frequency of the wave is what corresponds to more energy *per photon.*

The photon model can be applied to explain the photoelectric effect. Let's analyse what happens as a beam of light strikes a metallic surface.

Photons of light striking a surface may be reflected, or absorbed. Reflected photons will not contribute to the photoelectric effect, so let's focus on the absorbed ones. When a photon is absorbed by an atom in the substance onto which the light is shining, its energy is given to an electron in that atom. This is the conservation of energy. When a photon is absorbed, its energy cannot simply vanish – it has to go somewhere.

Now what does the electron do with this extra energy? We aren't chemists, so we don't need to analyse this bit in depth. Essentially though, the energy may allow the electron to move (or be *excited*) into a higher energy orbit. Other times (and this is what's most relevant for us), the electron can be ejected from the surface entirely. This is **photoelectric emission** – electrons being ejected from a surface without the need for a voltage or potential difference. Sometimes, we call the ejected electrons **photoelectrons.**

How much kinetic energy do these electrons have? Again, we apply the conservation of energy. They have used some energy to escape from the surface – we call this the **work function** of the material (i.e. the energy an electron is required to gain to escape the bonds of that material). We most commonly see the photoelectric effect in metals, because the work function is smaller than in other elements! So the energy of the electrons is the initial energy of the photon, minus this work function, commonly denoted as ϕ. In an equation: $E_K = hf - \phi$.



Example 3.2

A beam of light with a wavelength of 700 nm is shone onto an experimental metal. The speed of electrons ejected from this metal due to photoelectric emission is found to be $3 \times 10^5 ms^{-2}$*. What is the work function of the metal?*

This is actually a really difficult example, bringing together everything we've learned so far about the quantum/photon model of light.

First, we need to know the energy per photon of that light. Use Planck's energy equation, swapping f for $\frac{c}{\lambda}$ using the wave formula!

$$E = hf = \frac{hc}{\lambda} = \frac{6.626 \times 10^{-34} \times 3 \times 10^{8}}{700 \times 10^{-9}} \approx 2.84 \times 10^{-19} \text{ J}$$

So we know the energy per photon, now let's find the kinetic energy of those emitted electrons. The mass of an electron is a standard quantity, it appears on your data sheet!

$$K = \frac{1}{2}mv^2 = \frac{1}{2} \times 9.109 \times 10^{-31} \times \left(3 \times 10^5\right)^2 = 4.10 \times 10^{-20} \text{ J}$$

The work function is just the difference between these two quantities!

$$\phi = E - K = 2.43 \times 10^{-19} \text{J}$$

This is a tiny work function! And it would need to be, since 700 nm light is in the visible light range, far too low a frequency to overcome any realistic work function. In most cases, 700 nm light would not have enough energy per photon to cause photoelectric emission; the work function would be too large. You would know if this happened in a calculation like above, because your final answer would end up negative!

Topic 4

Light and Special Relativity

SYLLABUS :
Inquiry question: How does the behaviour of light affect concepts of time, space, and matter?

4.1 Einstein's Theory of Relativity

SYLLABUS :
Analyse and evaluate the evidence confirming or denying Einstein's two postulates.

Einstein is probably most famously known for his Special Theory of Relativity, which he proposed in 1905. It contained two key postulates:

1. All inertial frames of reference are equivalent.
2. The speed of light in a vacuum, c, is an absolute constant.

Let's briefly unpack these. First, what is a **frame of reference**? Put simply, it is a starting (or 'reference') point for measurements, or where you are measuring *from*. For example, when you measure the velocity of a car, you might measure its speed with respect to where you are standing, or you might measure it from another moving car travelling at a constant speed alongside it. The measurements will be different because the reference frames are different. This is sort of overlapping with the idea of relative velocity we covered in Year 11. Frames of reference can be **inertial,** or they can be **non-inertial.** Inertial reference frames are non-accelerating, meaning they are static or moving at a constant speed. Einstein's first postulate states that any and all of these reference frames are as equally valid as each other. So in the example above, even though the two answers are different, both reference frames are inertial. This means both answers are totally, 100% correct.

Non-inertial frames are ones that are accelerating. In these frames, the laws of physics don't behave the same as we would expect. Think of being in a car slamming on the brakes, and having all the loose items flying around. Imagine if that was *normal!*

The second postulate is the interesting one when you consider it carefully. We've just explored how different measurements (all correct) can be obtained for the same quantity from different inertial reference frames. Einstein's second postulate says that this doesn't apply for light – no matter how you measure it, it will always be the same value, about 3×10^8 metres per second. This has a variety of interesting consequences, which we will explore later.

Einstein's theory had no direct experimental support at the time. The **Michelson-Morley Experiment,** conducted in the late 19th century, attempted to measure changes in the speed of light based on different directions of travel. The experiment yielded a null result; no change could be detected. This seemed to lend credibility to Einstein's theory that the speed of light should be a constant, though some believed that the experiment was simply not sensitive enough.

SYLLABUS :
Investigate the evidence, from Einstein's thought experiments and subsequent experimental validation, for time dilation and length contraction and analyse quantitatively situations in which these are observed.

When seeking to find experimental proof for Einstein's theory, you need to look for evidence of the *consequences* of Einstein's postulates.There are two of note: length contraction and time dilation.

- **Length contraction:** is the phenomenon where an objects length while in motion, is measured to be shorter than its actual length. It *contracts*, along the direction of travel, but you only see it as an observer. If you were moving with the object, you wouldn't measure any difference. There needs to be a relative velocity between the observer and the object.
- **Time dilation:** is the phenomenon where time is measured to move more slowly in one reference frame compared to another. For example, if you put a clock on a rocket and observed while it travelled at extremely high speeds, you would see it slow down. Again, someone *on* the rocket would observe no change, this only happens due to relative velocity between reference frames.

It is important to note that we do not observe these effects in everyday life. This is simply because nothing moves quickly enough for the effects to be measurable. It's not like the clocks in our cars slow to a crawl while we are driving down the motorway. The effects are noticeable at **relativistic speeds** – speeds close to that of the speed of light. We've observed both in various scenarios using modern technology:

We have observed that fast-moving particles have longer lives than the same particles at rest. For example, we have observed elementary particles called muons at the Earth's surface, and found that they decay more quickly when at rest compared to when they are in motion. This is due to the effects of time dilation. When the muons are moving, we observe time passing for them more slowly.

Atomic clocks have been found to fall out of sync when one is accelerated to large speeds, while the other is kept at rest. When the clocks are brought together again, the clock in motion has fallen behind the other. The first experiment to test this was conducted in 1971 by Joseph Hafele and Richard Keating. They flew two clocks around the world and kept two at rest, and when they returned, they found time differences (albeit in nanoseconds).

Particle accelerators have provided further evidence for special relativity, one simple example of which is that they can't make any particle travel faster than the speed of light. Part of Einstein's theory was that the speed of light is a bit like a galactic speed limit – you can't go faster! Indeed, no matter how much energy particle accelerators give to these tiny little particles, they can't crack the speed of light. They can get close, within .00001% and perhaps closer, but they will never touch or exceed it!

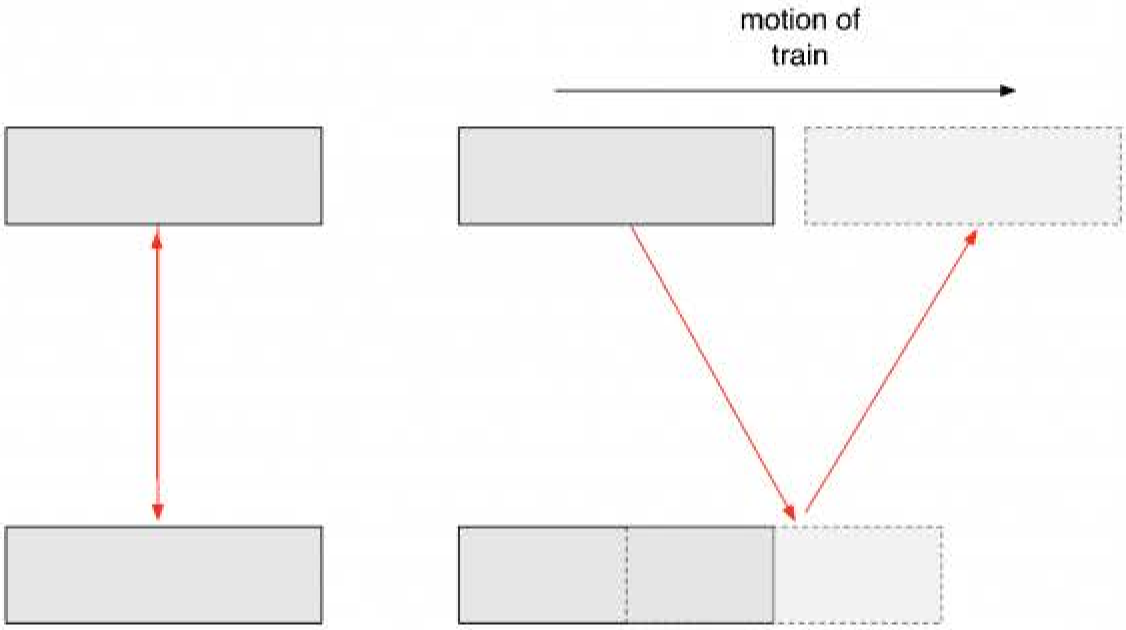
Cosmological studies have also provided evidence for special relativity. Classical physics predicts a shift in the wavelength of light from a moving body (say a star or a planet), called the **Doppler effect.** However, contemporary observations and measurements find that alone isn't quite enough to accurately explain the shifts. When you include the ideas of length contraction, it works! The blend of special relativity and the Doppler effect is usually called the **relativistic Doppler effect.**

Notice that all of these observations rely on sophisticated technology like super accurate atomic clocks, fancy telescopes, and particle accelerators? Einstein had none of these in 1905, so he relied purely on thought experiments and logical deduction. One of the most famous of these was the **train thought experiment.**

Imagine you are travelling on a train that is moving very close to the speed of light, say, 0.99c. Let's say you set up an apparatus which bounces a laser from the floor of the train, to the roof. This means, in your frame of reference, the laser travels from the floor to the roof, and back. Let's call that a distance of 2d, taking time T seconds.

Now, say you are standing outside the train, watching it go past, with the exact same thing happening. Only, what you see is different, because you see the laser moving at an angle due to the motion of the train. This means you measure the light travelling a further distance, call it 2D.

Remember, Einstein's theory says that both versions of you – the one on the train and the one outside – are totally correct. You are both in inertial reference frames, either at rest or moving at a constant velocity. He also says the speed of light is an absolute constant, the same for both versions of you. But how can the speed of light be the same, but the distances travelled be different? There is only one answer: the *time taken* must have changed. Specifically, the time measured from outside the train must be larger to compensate for the larger distance, without changing the speed. Thus, **time is measured to move more slowly from outside the train.**



From just these logical thought experiments, Einstein formulated detailed explanations and mathematical formulations for length contraction and time dilation. We will be using the following results to analyse situations involving these phenomena!

$$t_v = \frac{t_0}{\sqrt{1 - \frac{v^2}{c^2}}}$$

$$l_v = l_0\sqrt{1 - \frac{v^2}{c^2}}$$

These equations allow us to calculate how a 'rest' time or length value, t_0/l_0, for an object travelling at v metres per second, is measured by a stationary observer.

The reciprocated square root term, $\frac{1}{\sqrt{1-\frac{v^2}{c^2}}}$, is called the **Lorentz Factor,** and is always greater than 1.

This means t_v is always larger than t_0 (time dilates), and l_v is always smaller than l_0 (length contracts). Let's do an example to make some sense of the results!

Example 4.1

The time taken for a particle to decay at rest is measured to be 0.001 seconds. How long would the particle be measured to take to decay while travelling at half the speed of light?

Often, the hardest bit about these questions is deciding which is the relativistic quantity, and which is the rest quantity. Here, it is obvious: $t_0 = 0.001$, while t_v is what we are hunting for. $v = 0.5c$, so we can actually cancel out the c in the formula if we leave it in this form, so don't worry about evaluating it!

$$\begin{aligned} t_v &= \frac{t_0}{\sqrt{1 - \frac{v^2}{c^2}}} \\ &= \frac{0.001}{\sqrt{1 - \frac{0.5^2c^2}{c^2}}} \\ &= \frac{0.001}{\sqrt{1 - 0.5^2}} \\ &= \frac{0.001}{\sqrt{0.75}} \\ &= 0.00115\text{s} \end{aligned}$$

Even at half the speed of light, the difference is tiny, but it *is* measured to have a longer life span. In other words, we (as the external observer) measure the time to be moving more slowly.

Example 4.2
A train zooms past a platform travelling at 0.99c. *A passenger on the train looks outside as it passes the platform and measures the platforms length to be just 1 metre. Another observer is on the platform. How long would they say the platform is?*

Here, we are given the value affected by length contraction: $l_v = 1$. In this case, we want l_0, so we'll need to rearrange:

$$\begin{aligned} l_v &= l_0\sqrt{1-\frac{v^2}{c^2}} \\ l_0 &= \frac{l_v}{\sqrt{1-\frac{v^2}{c^2}}} \\ &= \frac{1}{\sqrt{1-0.99^2}} \\ &\approx 7.09 \text{ m} \end{aligned}$$

4.2 Relativistic mass and momentum

SYLLABUS :
Describe the consequences and applications of relativistic momentum.

So far we've looked at two quantities which become relative as a consequence of special relativity: Length, and time. There is another: *mass*! The phenomena in question is called **mass dilation,** and describes how objects are measured to have larger masses while in motion compared to when at rest. Of course the amount of matter in the object doesn't actually change; it's more about how it behaves. For this reason we have a new term for the *apparent* mass of an object based on the effects of special relativity: **relativistic mass.**

The relativistic mass of an object is given by the result below, where m_0 is its rest mass (you'll notice similarities with the time dilation result – the Lorentz Factor is back!). It's important to note that this is a bit of a mathematical construct. Relativistic mass by itself doesn't mean much, since we can't really take this speeding object and stick it on a scale.

$$m_v = \frac{m_0}{\sqrt{1-\frac{v^2}{c^2}}}$$

Of more interest to us in most cases isn't the mass of the object, but the **momentum** of the object in motion. Normally, momentum is given by $\rho = mv$. Substituting this formula for relativistic mass for m, and we get a formula for **relativistic momentum.** It looks really similar to equations on from the previous dot point, and mechanically, it works almost exactly the same way.

$$\rho_v = \frac{m_0 v}{\sqrt{1-\frac{v^2}{c^2}}}$$

Relativistic momentum means pretty much exactly the same thing as the classical idea of momentum. You can still think of it as linked to how much impact an object can cause in a collision. It still obeys the conservation of momentum. There is just one hidden little consequence in the result.

In the classical formula for momentum, $\rho = mv$, there is no intrinsic limit to how high the momentum of an object can go. Even restricting v to be less than the speed of light, as long as you can get a heavier object, you can get more momentum.

In our version though, mass is linked to velocity. As you get faster, you get *heavier*, so to speak. So, it actually requires more energy and more force to accelerate the object, the faster it goes. Mathematically speaking, ρ_v approaches infinity as v gets closer and closer to c, the speed of light.

Since momentum is approaching infinity, you need more and more energy to speed up. So it becomes like this self-perpetuating speed limit. You can't exceed the speed of light, because the corresponding increase relativistic momentum with speed will always make it too hard to do so!

This might sound a bit weird at first, but we can see this limit in practice in particle accelerators, and it is a vital consideration for space travel. We can only move through space so fast, and the faster we want to go, the harder we need to work to get to that speed in terms of the energy required. These phenomena are some of the key restrictions placed on modern space travel.

4.3 Converting mass to energy

SYLLABUS :
Use Einstein's mass/energy equivalence relationship to calculate the energy released by processes in which mass is converted to energy.

We finish this section of the course with perhaps the most famous equation ever derived: $E = mc^2$.

So, what the heck does this mean? Well, Einstein's theory had one more hidden consequence: the equivalence of mass and energy. Essentially, mass and energy are not separate things; they are two forms of the same thing, and you can convert between them... sort of. It's much easier to get energy out of mass than to go back the other way. We get energy from mass in all sorts of situations – in combustion engines, nuclear reactors, and many more. It's how the sun produces its energy too!

The famous formula states that the amount of energy E in a mass of m kilograms is just the product of the mass with the speed of light squared (c^2). In other words, there is a *heap* of energy in a tiny little bit of mass. We'll be using this formula a lot in the next module, but here's a quick example for now!

Example 4.3
A new energy production technique can convert mass from household waste to energy with 1% efficiency. Australia's average annual energy requirement is about 10,000kWh per person. How many kilograms of waste would need to be 'burned' to meet this requirement?

First, let's convert that energy requirement to joules. A kWh is a kilowatt hour, the energy used by a 1kW device in one hour. 1kW is 1000 joules per second, so:

$$1 \text{ kWh} = 1000 \text{ Joules Per Second} \times 60 \text{ Seconds} \times 60 \text{ Minutes} = 3.6 \times 10^6 \text{ J}$$
$$\therefore 10,000 \text{ kWh} = 3.6 \times 10^{10} \text{ J}$$

So, how much mass would we need to produce this much energy? Well, $E = mc^2$, but our technique is only 1% efficient. So, here, $E = 0.01mc^2$. Therefore:

$$\begin{aligned} E &= 0.01mc^2 \\ m &= \frac{100E}{c^2} \\ &= \frac{3.6 \times 10^{12}}{9 \times 10^{16}} \\ &= 4 \times 10^{-5} \end{aligned}$$

Therefore, we'd only need to burn less than tenth of a gram of waste to cover one person's annual energy usage. Crazy! Of course, getting energy from mass isn't easy, but we'll go through some ways we can do it in this next module.

Part IV

Module 8: From the Universe to the Atom

Topic 1

Origins of the Elements

SYLLABUS :
Inquiry question: What evidence is there for the origins of the elements?

1.1 The Big Bang

SYLLABUS :
Investigate the processes that led to the transformation of radiation into matter that followed the 'Big Bang.'

You've almost certainly heard the story before – but here's the abridged version. Once, there was nothing. Actually, you can't say there *was* nothing because it wasn't in the past – time didn't exist. Nor did space. Just, nothing. Then, BANG! A Big Bang. And suddenly there was something from nothing!

We don't need a detailed, comprehensive understanding of what the Big Bang was (indeed, the story I told above would upset many a physicist), and we definitely don't need to even attempt to understand *why* it occurred. What this dot point requires of us is to understand what happened in the moments immediately following the Big Bang. You could write a textbook on even just this topic alone, so let's just go through a few of the more important points.

Nearly 14 billion years ago the Big Bang released an incomprehensible amount of energy. The universe in its initial form was just pure **radiation.** It was too hot for anything to actually *exist*, so to speak. However, the universe was *expanding*, growing in size extremely rapidly. What happened as the universe expanded was that things started to cool down. As this happened, the radiation began to 'condense' and managed to form matter. Huge amounts of energy/radiation were turned into tiny specks of matter (according to $E = mc^2$). This transition only caused things to expand faster as matter suddenly started appearing everywhere, which cooled things down more, which formed more matter, which... you get the point. We have a name for this period of rapid cooling and expansion: **inflation.**

So radiation was turning into matter, but it was also turning into something called **anti-matter.** What the heck is that? Again, you could write a textbook about this, but essentially anti-matter is exactly what it sounds like: the opposite of matter. It's the opposite because it has the opposite *electrical charge*. For instance, one example of a particle of matter is an electron, negatively charged. Its antimatter/anti-particle equivalent, the positron, is positively charged, but weighs the same and is essentially identical in every other way.

Anti-matter isn't just a science fiction thing or something that no longer exists. We can and have produced and detected the stuff. We are constantly learning more and more about it, but what we know for sure is that matter and anti-matter don't play nice! If they touch, they go boom, and they are both converted right back into energy. This process is called **annihilation,** and it happened a heap in the earliest stages of the universe. Eventually, things settled down and we ended up with more matter than could be annihilated by the anti-matter (for reasons that aren't worth discussing here).

This is an *investigate* dot point, so you should do some wider reading to supplement your knowledge... and because this stuff is crazy cool to read about!

1.2 Hubble's Law

SYLLABUS :
Investigate the evidence that led to the discovery of the expansion of the Universe by Hubble.

Edwin Hubble contributed hugely to our understanding of the universe. It was Hubble, for example, who first concluded that our universe extended beyond our own galaxy. What we seek to understand here is his discovery that our universe was expanding, and the evidence that lead to it.

Hubble's observations came primarily from the largest telescope at the time, the Hooker telescope in California. Hubble sought to measure the Doppler shift of galaxies; that is, how the wavelength of light is shifted/altered due to motion relative to the Earth. Hubble took long exposures and compared the spectra he obtained with known references, using this to calculate the velocity of each galaxy. Hubble found that most galaxies exhibited **redshift,** a shift in the spectra towards the red end of the visible spectrum. This means that the galaxy must be moving *away* from the Earth. Not only this, but Hubble found that the galaxies were moving more quickly at further distances. That is, the further away a galaxy was, the faster it was moving away from us. This has become known as **Hubble's Law.**

These observations are evidence of an expanding universe. If everything is getting further away, then it makes sense to say that the universe as a whole must be expanding. Hubble even performed calculations to give some of the first estimates of the age of the universe, based on how quickly it was expanding.

1.3 Nuclear reactions of stars

SYLLABUS :
Analyse and apply Einstein's description of the equivalence of energy and mass and relate this to the nuclear reactions that occur in stars.

We discussed Einstein's description of energy/mass equivalence in the previous module. To refresh, we know that energy and mass are related by the formula $E = mc^2$ where c is the speed of light. This suggests we can get a heap of energy from just a little bit of mass. One of the ways we can achieve that is through nuclear reactions. This is the source of the energy radiating from stars, specifically, **nuclear fusion.** We'll learn more about how this works further on in this module.

Take our sun, which has a mass of about 2 million million million million million kilograms (or 2×10^{30}, but I feel like it is more fun to write it out!). If you were to convert all of that to energy, you'd get 1.8×10^{47} joules of energy (which the internet tells me is 180 *quattuordecillion* joules). Essentially, this is why stars are able to 'burn' for so long – the nuclear reactions in the star use just a little bit of mass to produce a huge amount of energy. Specifically, stars fuse smaller elements into bigger, heavier ones, producing energy in the process (feel free to flick ahead to page 73 to the section on nuclear fusion if you want to understand this now!). The exact nature of the reaction depends on how big the stars are, but this idea of $E = mc^2$ is the basis for all of them.

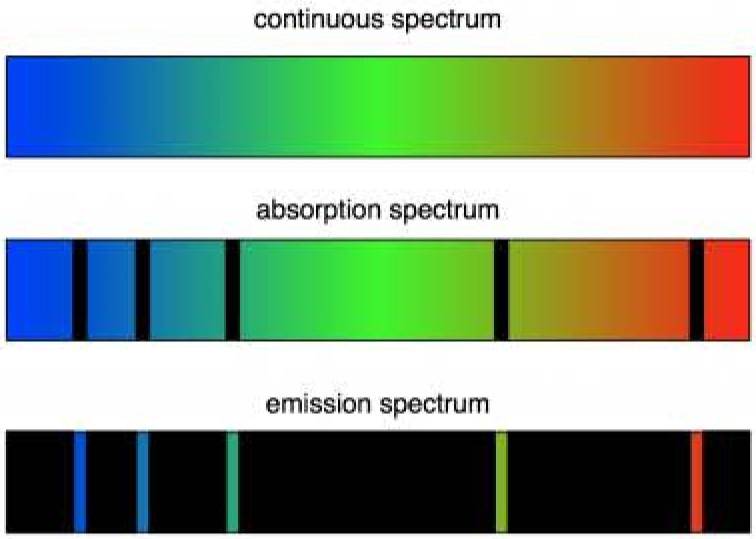
1.4 Emission and absorption spectra

SYLLABUS :
Account for the production of emission and absorption spectra and compare these with a continuous black body spectrum.

When we look at a stellar spectrum (which we've done before, and will do again soon) what we are essentially looking at is a black body spectrum. This is different than what we call a **emission and absorption spectra.** Now, when we have photons interacting with electrons in atoms, very specific frequencies are involved.

An electron might absorb a photon to move to a higher energy level, but it will only absorb photons of light with exactly the right amount of energy needed to do this (meaning, exactly the right frequency, since $E = hf$). What this means is that when you shine light through a chamber full of, say, a gas, you'll have specific frequencies absorbed. At the other end, you'll see dark spots in your spectrum where this has happened. This is an **absorption spectrum.**

Equally, an electron might give off a photon to move down to a lower energy level. Again, the frequency of this emitted photon depends on how much energy is lost by the electron (because of the conservation of energy). So, if we have light being emitted from an object (say, because it is has been heated up), we'll have bright spots corresponding to the photons emitted by the electrons as they go from one energy level from another. This is an **emission** spectrum.

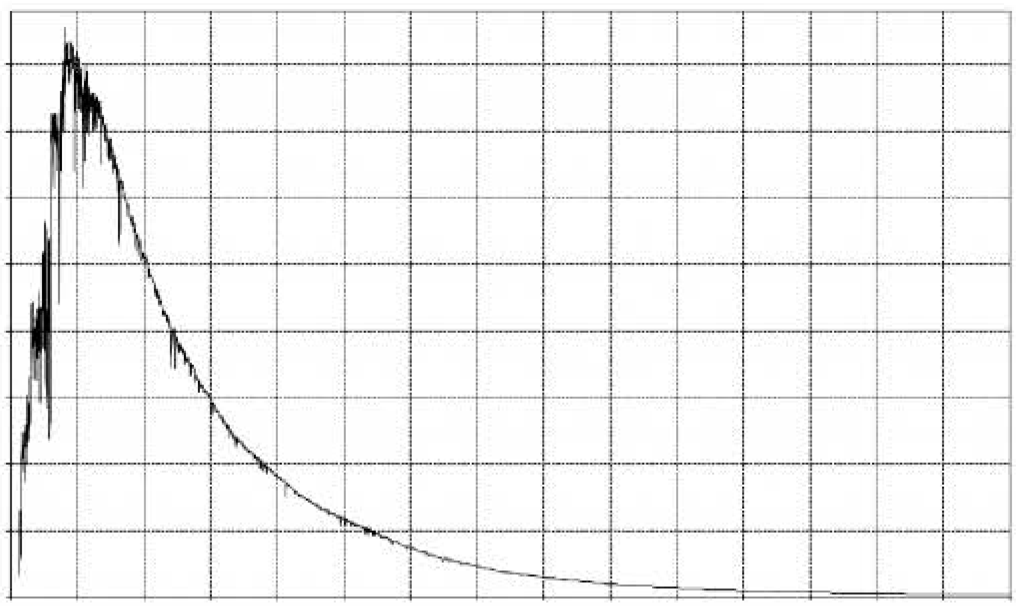


1.5 Stellar spectra

SYLLABUS :
Investigate the key features of stellar spectra and describe how these are used to classify stars.

When you have an absorption or emission spectrum of a single element, the spectra are discrete. You get a lines at specific frequencies and nothing anywhere else. We call them **spectral lines.** This is different from a black body radiation curve, which is continuous. For stars, we actually have a bit of both: a continuous spectrum with lots of dips corresponding to absorption frequencies. As radiation is emitted from the star itself, some frequencies are absorbed by elements in the atmosphere of that star. These are the locations of the spectral (absorption) lines. As we've alluded to, the location of these spectral lines can tell us a lot about a star, and it will also help us classify them into groups.

This is what the spectrum of a star might look like – all those little bumps are what we are looking at. Yep, this is complex, but don't worry; we are only skimming the surface.



Stellar classification involves grouping stars based on specific spectral characteristics. A variety of systems exist and have been used, but today we most commonly use a combination of the **Harvard Spectral** and **Morgan-Keenan** classification systems.

The Harvard Spectral system has seven classes, each represented by letters: **O, B, A, F, G, K, M**.

Key Point :
You should come up with a mnemonic to remember these! One I hear a lot is:

__O__h, __B__e __A__ __F__ine __G__irl/Guy, __K__iss __M__e!

Each of these letters represents a spectral type, based on the location of the spectral lines for that star. The location of these lines is dependent on a variety of things, including temperature. Here is a table, summarising their characteristics from hottest to coldest:

Spectral Types			
Type	**Temperature**	**Colour**	**Spectral Lines**
O	28,000K +	Violet	Few, only type with lines corresponding to ionised helium
B	10,000K – 28,000K	Blue	Medium Balmer series lines, neutral hydrogen lines
A	7,500K – 10,000K	Blue	Strong lines (including strongest Balmer series lines)
F	6,000K – 7,500K	Blue/White	Weaker Balmer lines, neutral metal lines
G	5,000K – 6,000K	White/Yellow	Even weaker Balmer lines, ionised calcium lines
K	3,500K – 5,000K	Orange/Red	Most prominent neutral metal lines
M	Up to 3,500K	Red	Strong neutral metal lines

We will learn about the Balmer series on page 67, which will make this table make more sense!

The specifics of the right-hand column in this table aren't that important – what *is* important is that as temperature changes, the spectral lines appearing in the spectrum of a star are different. This is due to the different temperatures involved (it's not like the stars are made of vastly different elements). All stars contain a heap of helium, for example. It's just that the helium lines only appear in the hottest, O-class stars.

Each of these types is further divided into ten subclasses, 0–9, based on the strength/intensity of the absorption lines. It's essentially just a way of being a tad more specific. You stick this number on the end of a letter, and you have the classification: For example, our sun is a G2 star.

The Morgan-Keenan scheme classes stars based on their **luminosity,** a measure of how much energy they emit in a given time across the entire electromagnetic spectrum (or in a finite range, depending on the definition). This is something that the original scheme could not distinguish, making it hard to tell the difference between stars at different stage of their life cycles.

So, to the letter and the number from the Harvard scheme, we also add a Roman numeral – a luminosity class:

Luminosity Class	
Class	**Type of Star**
I	Supergiants (this can be divided subcategories as well)
II	Bright Giants
III	Normal Giants
IV	Sub-Giants
V	Main Sequence Dwarf Stars
VI	Sub-Dwarfs
D	White Dwarfs

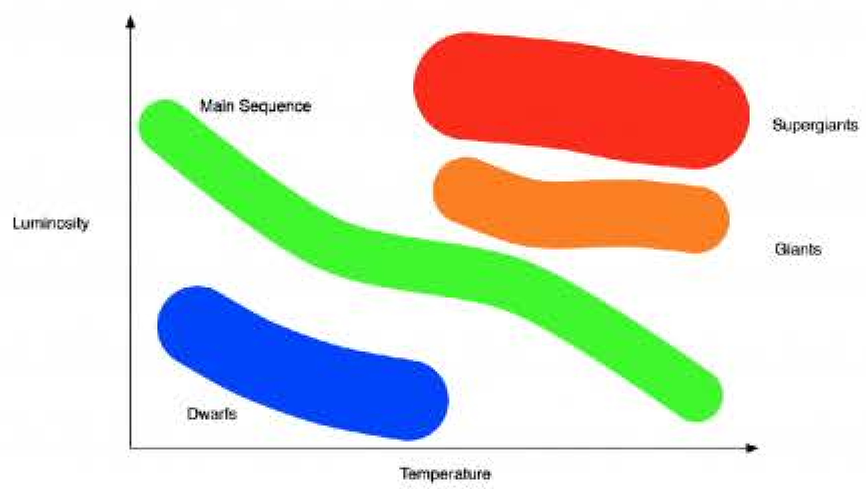
Let's go through these a little bit:

- **Main sequence stars** are the most common, since this is where a star spends the majority of its life. Stars of this luminosity class are burning hydrogen into helium in their cores.
- **Giants and supergiants** come to be when stars run out of hydrogen and start to burn more helium, and heavier elements. They have a high luminosity, but are cooler, meaning they are also *huge* (which makes sense, given their name).
- **Dwarfs** are the end point for small-to-medium size stars. When the fuel runs out, they collapse into a dwarf star, which glows with leftover thermal energy. Depending on the size of the star, it might become a giant first, or it might go straight to a dwarf star.

1.6 Hertzsprung-Russell diagram

SYLLABUS :
Investigate the Hertzsprung-Russell diagram and how it can be used to determine characteristics of stars.

That last dot point was quite intense – there is lot to remember! Thankfully, we have a tool to make all of this easier to visualise: **the Hertzsprung-Russel diagram.** This is a diagram of a star's temperature on the horizontal axis (represented by their spectral class according to the Harvard scheme) and their luminosity on the vertical axis. You'll study proper versions of this diagram, but it's good to start with just a blurry, intuitive understanding of the different sectors, as shown below:



Many of the characteristics of a star can be determined purely by their location on this diagram. The main sequence stars run down the middle, from the top left to the bottom right. Above this are the giants and supergiants, with the dwarfs found below it.

1.7 Nucleosynthesis

SYLLABUS :
Investigate the types of nucleosynthesis reactions involved in Main Sequence and Post-Main Sequence stars.

To finish this section, we need to take a more in-depth look at the sorts of reactions that are taking place in stars at various stages of their life. These are **nucleosynthesis** reactions, meaning they result in the creation of new elements.

As aforementioned, main-sequence stars tend to get most of their energy by converting hydrogen into helium. There are two possible reactions that can achieve this:

- **Proton-proton chain reactions** are more common in stars up to around the size of our sun. It happens in (roughly) the following way:
  1. Two protons (hydrogen nuclei) join together to form a deuterium nucleus, a hydrogen isotope with one proton and one neutron. This releases a positron and a neutrino, but they don't play into this reaction.
  2. Another proton is added to this nucleus to form a helium-3 isotope containing two protons and a neutron (this releases gamma radiation).
  3. Two of these helium-3 isotopes combine to form helium-4, with two protons and two neutrons. The two spare protons in this reaction are released to continue the process.
- **Carbon-nitrogen-oxygen (CNO) reactions** are more common in larger main sequence stars. These are also more complex, requiring other elements to be present. One way for this reaction to occur is:
  1. A carbon-12 isotope combines with hydrogen to form nitrogen-13, releasing a gamma ray.
  2. Nitrogen-13 is unstable, and decays to carbon-13, releasing a positron.
  3. Carbon-13 combines with hydrogen again, this time forming nitrogen-14, which is stable.
  4. Nitrogen-14 combines with hydrogen to become oxygen-15.
  5. Oxygen-15 decays to nitrogen-15, releasing a positron.
  6. Nitrogen-15 combines with hydrogen one last time, producing helium (finally!) and carbon-12, which is where the process started.

  The reaction can occur in other ways, always involving carbon, nitrogen, and oxygen. The result is always a helium nucleus and other by-products, including gamma radiation.

When these reactions can no longer take place, new types of reactions will begin. This brings the star into the giant/supergiant stage of its life cycle. When this happens, the star will start fusing helium into carbon, via a process called the **triple-alpha process.** This essentially involves combining two helium nuclei (alpha particles, the alternative name when talking about nuclear reactions, that will explained later!) into beryllium, then adding a third helium nucleus to produce carbon-12. If the star is large and hot enough, this can keep going, with the carbon being fused into even heavier elements.

Topic 2

Structure of the Atom

Syllabus :
Inquiry question: How is it known that atoms are made up of protons, neutrons, and electrons?

2.1 Properties of electrons

Syllabus :
Investigate, assess, and model the experimental evidence supporting the existence and properties of the electron.

Most of us have at least an intuitive understanding of the structure of the atom. At the centre there is a **nucleus,** which contains positively charged protons, and neutrons (which have no charge). Orbiting this nucleus in various layers (or shells) are **electrons,** which are tiny negatively charged particles that are much smaller than protons or neutrons. The electron specifically first came to be understood through experiments with **cathode rays** in the 19th century.

'Cathode rays' was the name given to a glow that appeared between two charged electrodes in a low pressure, evacuated glass chamber. If the voltage between the plates was high enough, and the gas pressure low enough, a glow could be seen between the plates. This glow would change based on the pressure of the gas. Of course we now know what was causing this glow: the movement of electrons jumping from the negatively charged plate to the positively charged plate. At the time though, it was the subject of much debate!

- Experiments with the 'beam' found that it was attracted to a positively charged metal plate. This indicated that the cathode rays were likely negatively charged (as we now know electrons to be).
- Experiments also indicated that the cathode rays carried energy, and even possessed momentum.
- The issue was that the cathode rays exhibited behaviour similar to light waves. They moved in straight lines and thus cast shadows, and they could induce fluorescence in some instances.

The definitive 'proof' came from an experiment by J.J Thomson in the late 19th century. Thomson found that the cathode rays could be deflected by magnetic fields, as well as electric fields. He was able to use this property to measure the charge/mass ratio of an electron, by balancing the effects of opposing electric and magnetic fields on the electron. Mathematically (using some results from earlier study):

$$F_E = F_B$$
$$Eq = Bqv$$
$$v = \frac{E}{B}$$

With a known velocity, Thomson then observed the centripetal motion of the cathode rays under the influence of a magnetic field alone. By measuring the radius and using the formula for centripetal force, the charge/mass ratio could be obtained:

$$F_B = F_C Bqv = \frac{mv^2}{r}$$
$$\frac{q}{m} = \frac{v}{rB}$$
$$\frac{q}{m} = \frac{E}{rB^2}$$

All of that mathematical stuff aside though, Thomson's experiment proved that the cathode rays did in fact consist of individual particles, with a large charge/mass ratio. He deduced that these particles were much smaller than the smallest atom (hydrogen), and thus, proposed that there were in fact *subatomic* particles. The first subatomic particle, the electron, had been discovered!

The charge/mass ratio of the electron was measured more accurately in the 20^{th} century, in a pretty brilliant experiment by Robert Millikan, outlined below:

- First, a mist of oil droplets was analysed to determine the droplets' mass and radius, as well as the size of the gravitational force on the droplets.
- Next, metal plates were used to apply an electric force on the oil, directed upwards. It was adjusted until the oil droplets were suspended in mid air, indicating that the electrical force and the gravitational force were equal in magnitude.
- Now knowing the size of the electrical force, and that $F = Eq$, the charge q on each droplet could be obtained.
- This experiment was repeated *many* times, and of course, the value of q changed every time. You can't keep an oil droplet the same size in every trial. However, it was found that in every experiment, the value of q was an integer multiple of a specific value (about 1.6×10^{-19}). The amount of charge could only, apparently, be a multiple of that number. Millikan deduced that this must have been the charge on an electron, and indeed, it is extremely close to the now accepted value of 1.602×10^{-19} coulombs.

2.2 Nuclear model of the atom

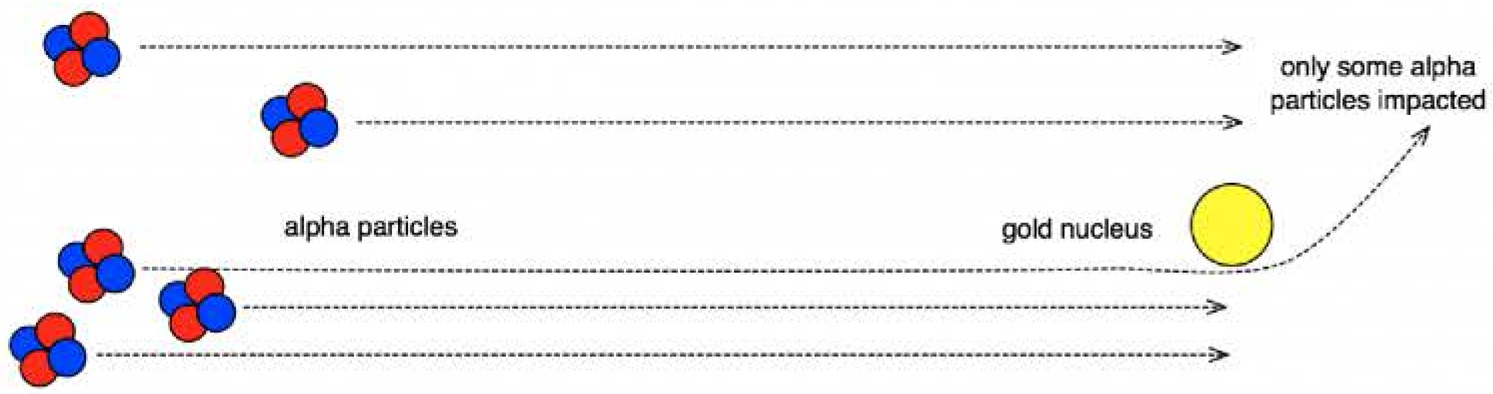
SYLLABUS :
Investigate, assess and model the experimental evidence supporting the nuclear model of the atom.

To understand some of the material here, you might need to know a bit about the types of nuclear radiation! We do this properly later in the module, but for now, here are some brief definitions:

- **Alpha particles:** are particles consisting of two protons and two neutrons. These are not very penetrative as their mass is relatively large.
- **Beta particles:** consist of an electron/positron (a particle with the same mass of an electron, but positively charged). These are more penetrative than alpha particles, but can still be stopped relatively easily.
- **Gamma rays:** are high-frequency forms of electromagnetic radiation that are extremely penetrative!

We know about all of these compositions now, but while the atomic model was being developed, these were known more by their effects and characteristics.

Various significant experiments provided evidence in favour of our current understanding of the atom. The atomic nucleus itself was first discovered in the Geiger-Marsden experiment in the early 20^{th} century. The experiment involved projecting a beam of alpha particles at a thin strip of gold foil. The beam of alpha particles would be scattered by the foil, and by analysing this pattern, the structure of an atom could be inferred. Most of the alpha particles were observed to pass straight through the foil, with a small number largely affected and deviating significantly from their original path. This suggested that the atom was mostly empty space, with a large charge concentration at the centre. This supported the nuclear model! It also rejected a model proposed by Thomson, a sort of 'pudding' model where the positive and negative charges were distributed evenly through the atom.



The director of this experiment, another scientist by the name of Ernest Rutherford, used these results to formulate the now accepted model of the atom: a concentration of positive charges at the centre, with orbiting electrons. However, the neutron still hasn't entered the picture!

As Rutherford developed his model, he started to believe that there was more in the nucleus than just positively charged protons. The mass of the nucleus appeared to be more than what would be consistent with its charge, assuming there were only protons in there. Rutherford believed that either:

- There were additional negative charges, cancelling out the positive charge of some protons.
- There were additional particles in the nucleus without any charge.

James Chadwick performed experiments in the early 20th century to try and detect a neutrally charged particle in the nucleus. These experiments were quite complicated, and relied on lots of earlier theories. Essentially though, they involved the study of a particular type of radiation that was emitted when alpha particles were directed towards certain elements, such as beryllium. This radiation was thought to be gamma radiation, since it wasn't affected by electric fields, but it was far more penetrative than even gamma radiation should have been, and affected things in a way inconsistent with just electromagnetic waves.

Chadwick managed to prove that it was in fact a new type of radiation, consisting of a neutrally charged particle *ever* so slightly larger than a proton. The nuclear model of the atom as we now know it was essentially complete!

Topic 3

Quantum Mechanical Nature of the Atom

SYLLABUS :
Inquiry question: How is it known that classical physics cannot explain the properties of the atom?

3.1 Atomic model limitations

SYLLABUS :
Assess the limitations of the Rutherford and Bohr atomic models.

Niels Bohr would expand/elaborate on Rutherford's atomic model in the early 20^{th} century, specifying that electrons could only move around the nucleus in certain orbits, at certain distances from the centre. Each of these orbits had an associated energy, and by absorbing or releasing electromagnetic radiation, an electron could jump to a 'lower' or 'higher' orbit. Lower orbits are associated with lower energies, and higher orbits are associated with higher energies.

However, there are limitations to this model.

For one thing, an electron orbiting around a nucleus is accelerating (centripetal acceleration). An accelerating electron should radiate electromagnetic energy, thus causing the electron to shift into lower orbits and eventually crash into the nucleus. This definitely makes no sense, and Bohr's model pretty much refuted this by saying, "yeah, nah." Okay, maybe it was more scientific than that... but the assumptions made to avoid it were dubious!

Bohr's model also has issues correctly explaining the emission spectra of certain elements. Now we've discussed emission spectra before but let's cover it again specifically for this context. The **emission spectrum** of an element is the spectrum of radiation emitted by that element as it loses energy, caused by electrons making transitions between energy levels. This means that as an electron transitions from a higher energy state to a lower energy state (high orbit to low orbit), it will emit a photon of electromagnetic radiation. The energy of the photon is the same as the difference in energy between the two states, and this will correspond to a certain frequency according to $E = hf$. Detect how much of each frequency you get, and that's an emission spectrum, which gives a good indication of the sorts of transitions happening as an atom changes state.

emission spectrum

The above diagram shows a typical spectrum. The lines represent places on the electromagnetic spectrum where more radiation was detected, representing a more common energy transition.

Specifically, Bohr's model isn't compatible with the emission spectra of larger elements. It couldn't predict where the spectral lines would sit, and it couldn't explain why some had greater intensities than others (i.e. why were certain energy transitions more common?). There were other, more subtle, issues as well.

Finally, Bohr's model appeared to violate an emerging principle called the **Heisenberg Uncertainty Principle.** This principle dictated that you could not know both the position and momentum of a particle to absolute precision. There was always an *uncertainty* no matter how much you measured. Get more accurate with position, and you *must* get less accurate with momentum. This wasn't a restriction of technology, but an actual law of physics! The problem was that Bohr's model relied on knowing both of these things to absolute precision to calculate the energy levels of electrons.

3.2 Line emission spectra

SYLLABUS :
Investigate the line emission spectra to examine the Balmer series in hydrogen.

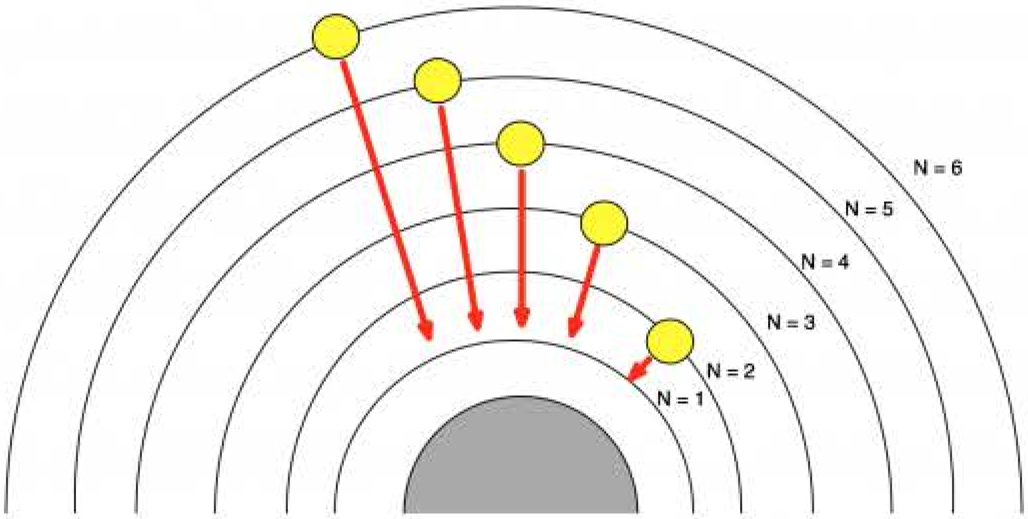
There's quite a bit of chemistry coming up here, but don't worry, this *is* still Physics!

Bohr formulated his atomic model to explain the spectral emission patterns of hydrogen, and this dot point is about doing a bit of that ourselves. The spectrum of hydrogen is divided into various 'series,' each of which is given a name. The series that falls in the visible part of the electromagnetic spectrum is called the **Balmer series.** You may even try to detect these spectral lines using a hydrogen discharge tube in class.

The Balmer series is produced when electrons fall from higher orbital positions into the second orbital position above the nucleus (so, from n = 3, n = 4, n = 5, n = 6, and so on, down to n = 2). In doing so, photons of radiation are released. Some of these are in the visible spectrum:

- The n = 3 $\longrightarrow$ 2 transition releases a photon with a wavelength of 656 nm, in the red part of the visible spectrum.
- The n = 4 $\longrightarrow$ 2 transition releases a photon with a wavelength of 486 nm, in the light blue part of the spectrum.
- The n = 5 $\longrightarrow$ 2 transition releases a photon with a wavelength of 434 nm, in the dark blue part of the spectrum.
- The n = 6 $\longrightarrow$ 2 transition releases a photon with a wavelength of 410 nm, in the violet/purple part of the spectrum.

The rest of these are in the ultraviolet region of the spectrum (although some may be visible to the naked eye). Notice that as the transition gets larger, the wavelength gets smaller. This is what we expect, as more energy means more frequency according to E = hf, and more frequency means a smaller wavelength. Note that n is the **principal quantum number,** which in Bohr's model just represents the orbital position/energy level above the nucleus, with n = 1 being the closest.



SYLLABUS :
Relate qualitatively and quantitatively the quantised energy levels of the hydrogen atom and the law of conservation of energy to the line emission spectrum of hydrogen.

Let's get mathematical with some of these ideas.

We know the formula E = hf. We can easily use the wave formula for electromagnetic waves, $c = f\lambda$, to obtain a new version of Planck's formula involving wavelength instead of frequency. This tends to be more useful, since we designate spectral lines using their wavelength:

$$E = \frac{hc}{\lambda}$$

Now we can finally, after alluding to it earlier, introduce the formula for the differences between energy levels in the Bohr Model. The **Rydberg Formula** relates the difference in energy between an initial energy level n_i, and a final energy level n_f, to the wavelength of the emitted photon.

$$\frac{1}{\lambda} = R_H \left(\frac{1}{n_f^2} - \frac{1}{n_i^2} \right)$$

In this formula, R_H (or just R) is the **Rydberg Constant**, which takes a value of 1.097×10^7 for hydrogen. Note that the right hand side will be negative if the energy transition goes *up* to a higher state, which signifies that a proton needs to be absorbed. We don't usually apply the formula in this way, however.

Example 3.1
Prove that the wavelength of light associated with an $n = 3$ *to* $n = 2$ *energy level transition in Hydrogen is 656nm, and thus, find the energy difference between these two states.*

So, to find the wavelength, we just use the Rydberg Formula:

$$\begin{aligned} \frac{1}{\lambda} &= R \left(\frac{1}{n_f^2} - \frac{1}{n_i^2} \right) \\ &= 1.097 \times 10^7 \times \left(\frac{1}{2^2} - \frac{1}{3^2} \right) \\ &\approx 1523611.11 \\ \therefore \lambda &= 0.656 \times 10^{-6} = 656 \text{ nm} \end{aligned}$$

This matches! Say we detect this wavelength, we can find the energy difference between the two states. We know this because the conservation of energy states that any energy difference in a transition must *go* somewhere. In our case, it's in the emitted photon. So we just work backwards!

$$E = \frac{hc}{\lambda} = \frac{6.626 \times 10^{-34} \times 3 \times 10^8}{656 \times 10^{-9}} \approx 3 \times 10^{-19} \text{ J}$$

3.3 De Broglie waves

SYLLABUS :
Investigate de Broglie's matter waves.

Bohr's model had the limitations we discussed above because it was a *half* quantum model. It tried to integrate Planck's ideas into a fundamentally classical model of the item. While this was able to explain certain things, it didn't work perfectly. To be completely correct in all scenarios, we needed a fully quantum model.

Enter Louis De Broglie. Einstein had proposed that light could be considered to behave as a particle, the photon. Therefore it wasn't totally absurd to assume that a particle could exhibit wave behaviours. This was De Broglie's proposal: that **particles could also have wave-like properties.**

He used Planck's formula for the energy in a quanta of energy, $E = hf$. He also used the formula for the momentum of a photon. Now, this might seem a bit strange, given that photons have no mass. But you can still find the momentum of a photon by taking its energy and dividing it by the speed (a formula which comes from other parts of Einstein's special theory of relativity):

$$\rho = \frac{E}{c} = \frac{hf}{c}$$

However, $\frac{f}{c} = \frac{1}{\lambda}$, so we finally end up with:

$$\rho = \frac{h}{\lambda}$$
$$\lambda = \frac{h}{\rho}$$

This gives the wavelength of what is called the **de Broglie wave** or **matter wave** for a particle with a certain momentum (the wave equivalent of that particle). It might sound like crazy science fiction, but this is an experimentally confirmed aspect of quantum physics!

Electrons as individual particles have been observed to demonstrate effects of diffraction, just like waves of light. That is, electrons have been seen to *interfere* with themselves, just like waves do. This has been seen in several experiments occurring in the late 20th century, such as the Davisson-Germer experiment. In this experiment, electrons were fired at a target, and the scattering patterns are consistent with diffraction patterns for light in similar situations.

3.4 Schrodinger's cat

SYLLABUS :
Analyse the contribution of Schrodinger to the current model of the atom.

Matter waves allowed physicists to finally develop a fully quantum mechanical model of the atom. This was done by Erwin Schrodinger, who you might know colloquially as the physicist behind the 'Schrodinger's cat' idea. We'll get to that soon.

Schrodinger proposed an equation that modelled how a matter wave evolved over time. This is a *nasty* equation – if you happen to be reading this on October 31st, here's a good way to get scared on Halloween. One way of writing the equation for some situations is shown below:

$$\frac{-h^2}{8m\pi^2}\frac{d^2\Psi}{dx^2} + U\Psi = E\Psi$$

Thankfully, we will never touch this equation in HSC Physics! We only need to know the implications intuitively.

What Schrodinger's equation does is predict the behaviour of a quantum mechanical system, sort of like how you can use Newton's Laws to calculate the motion of an object in classical physics. However, it does this using *likelihoods*, or probabilities that certain particles will occupy certain positions at certain times, based on their matter wave functions. This is where the idea of the cat comes in.

For those unfamiliar, the **Schrodinger's cat thought experiment** goes something like this. You stick a cat in a box with an unstable nuclear sample. If this sample decays, it will release a poison that will kill the cat. If it doesn't, the cat will be fine. However, until you open the box, there is no way of knowing whether the cat is alive or dead. You can only look at it in terms of probability, based on the probability of the nuclear sample decaying or not decaying. This is sort of the idea of Schrodinger's equation – you look at systems in terms of the probabilities of certain events. Once you actually measure or observe the system, you force it to make a choice (alive or dead cat). Until then, the cat is (sort of) both alive **and** dead.

Let's bring this full circle and apply this idea to the atom. What Schrodinger did was take Bohr's model and merge it with his idea of probabilistic matter waves. We don't define specific positions/orbits/energy levels, instead we define *probabilities* that electrons will occupy these spaces. You can think of this as sort of like a nucleus surrounded by a cloud of electrons, with dense patches where the electrons are most likely to be found. These 'hotspots' coincide with the precise energy levels that were predicted by Bohr, but, electrons can (with a lower probability) be found outside these spaces!

To keep you on track with timing, these developments on matter waves and how they apply to the atom actually took place **before** the discovery of the neutron. Matter waves and Schrodinger were the 1920s, and neutrons were the 1930s.

Topic 4

Properties of the Nucleus

SYLLABUS :
Inquiry question: How can the energy of the atomic nucleus be harnessed?

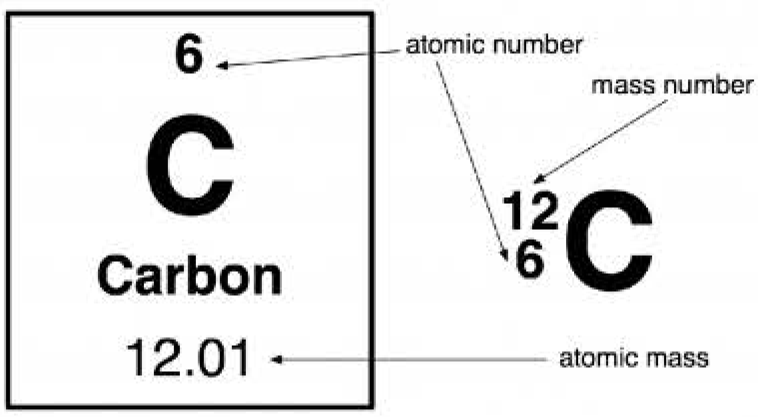
4.1 Parts of the nucleus

SYLLABUS :
Analyse the spontaneous decay of unstable nuclei, and the properties of the alpha, beta, and gamma radiation emitted.

Let's now delve into the properties of the nucleus, and specifically how it applies to nuclear physics. What we'll start with is a more complete explanation of how certain nuclei decay and the certain types of radiation emitted when we do. We touched on it earlier in the module, but now we'll do it properly. Before we do, some quick definitions from earlier study to help us follow along:

- The **atomic number** of an element is the number of protons in the nucleus of that element. An element is defined by the number of protons in its nucleus. That is, if a gold atom loses a proton, it is no longer gold.
- The **mass number** of an atom is the combined number of protons and neutrons in the nucleus of that atom. This is different for different isotopes of the element (see below). You can calculate the number of neutrons in a nucleus by subtracting the atomic number from the mass number.
- The **atomic mass** of an atom as you see on periodic tables is just a measure of the average mass of an isotope of a given element, given the abundance of that element. You don't need to worry about this much in this course!
- An **isotope** is just a variant of a particular element with a different mass number. So, all the isotopes of say, carbon, have six protons in their nucleus, otherwise they wouldn't be carbon. But they will have a different number of neutrons in their nucleus. For example, carbon-14 has a mass number of 14, meaning there are eight neutrons in the nucleus. Carbon-13 only has seven neutrons, and so on.

This diagram shows how these quantities appear in entries in the periodic table, and in the common notation of atomic isotopes (in this case, a carbon-12 isotope). It is important to note as well that unless otherwise indicated, we assume an atom is neutrally charged, which means that there are always as many electrons as protons.



Nuclei are considered to be **unstable** where there isn't enough binding energy/force to hold all of the neutrons and protons in the nucleus together. This simply means there is an excess of either protons or neutrons, and all radioactive decay is just various ways of getting back to a stable number of protons and neutrons in the nucleus. We don't really need to understand *how* the radiation is ejected so to speak, just that it is, and what it is.

- **Alpha decay:** occurs when a particle consisting of two protons and two neutrons is ejected from the nucleus. An alpha particle is actually exactly identical to a helium nucleus. When alpha decay occurs, the original element decaying will change. Its atomic number will drop by two, and its mass number will drop by four.
- **Beta decay:** can happen in two ways:
  - **Beta-plus decay:** occurs when a proton transforms into a neutron, releasing a positron in the process. Remember, a positron is just an electron with positive charge (i.e. the anti-matter equivalent). The atomic number of the original element will decrease by 1, but its mass number will be the same.
  - **Beta-minus decay:** occurs when a neutron transforms into a proton, releasing an electron in the process. The atomic number will increase by 1, but the mass number will stay the same.

  These decays should make sense since for a proton to go neutral, its positive charge must *go* somewhere, hence the positron. For a neutron to go positive there must be some negative charge to cancel it, hence the electron.

  Note that in these forms of decay you also get things called neutrinos and anti-neutrinos, but these aren't important.
- **Gamma decay:** in any situation where a nucleus has excess energy (perhaps from other forms of decay), it can release this energy in the form of a gamma ray. This is just electromagnetic radiation, with energy equal to that lost by the nucleus.

These types of radiation are listed in ascending order of penetrative power: alpha particles won't go very far at all, even in air. Beta particles can be absorbed by a thin layer of metal. Gamma radiation, though, will travel through thin layers of metal – usually, you use a chunky layer of lead to block them.

4.2 Half-life model of radioactive decay

SYLLABUS :
Examine the model of half-life in radioactive decay and make quantitative predictions about the activity or amount of a radioactive sample.

Radioactive decay is quantum mechanical, which implies that we can never say for sure when, or even if, an unstable nuclei will decay. However, we can guess what is *likely* based on the usual behaviour of that element in the past.

We tend to analyse radioactive decay in terms of the **half-life** model. The half-life of a radioactive isotope is the average time taken for half of the material to decay. It could actually be more or less, but we look at averages for the purposes of calculation. We use two results: the first links the number of particles N_t after time t has passed, given an initial quantity of N_0, to a decay constant λ.

$$N_t = N_0 e^{-\lambda t}$$

Be careful: λ is not wavelength here! It is a decay constant. This is a number between 0 and 1 that tells us how quickly the isotope is going to decay.

The second formula allows us to link this decay constant to a half-life $t_{\frac{1}{2}}$:

$$\lambda = \frac{\ln 2}{t_{\frac{1}{2}}}$$

We don't need to understand the mathematical basis behind these results; we just need to use the formula! One thing you might not have seen before is the ln function – this will be on your calculator in the functions section, probably near your sin/cos/tan buttons! The e button will likely be the same as your π button.

Topic 4 – Properties of the Nucleus

Example 4.1

An unknown isotope is found to have a half life of 24 hours. Calculate the decay constant for this isotope, and hence, estimate what percentage of an initial sample would remain after thirty days.

For this example, we first use the second formula, slightly rearranged:

$$\lambda = \frac{\ln 2}{t_{\frac{1}{2}}} = 0.02888$$

Notice that we didn't convert to SI units! This is one of the few situations where you can keep non-SI units, so long as you use them consistently in the problem. So, for this next part of the problem, we need to use hours as our unit for time. We want the percentage remaining after thirty days, so $t = 30 \times 24 = 720$ hours. We're looking for the percentage of the sample remaining, so, $\frac{N_t}{N_0}$:

$$\begin{aligned} N_t &= N_0 e^{-\lambda t} \\ \frac{N_t}{N_0} &= e^{-\lambda t} \\ &= e^{-0.02888 \times 720} \\ &\approx 9.3 \times 10^{-10} \end{aligned}$$

This is approximately 0.000000093%, so basically nothing! The maths tells us that it will never fully disappear, but realistically, the isotope has pretty much decayed.

4.3 Nuclear fission

Syllabus :
Model and explain the process of nuclear fission, including the concepts of controlled and uncontrolled chain reactions, and account for the release of energy in the process.

Nuclear fission is one of those buzzwords that appears a lot in popular culture; people use it without really knowing what it is. Let's fix that!

Fission is really just a fancy word for *split* – **nuclear fission** means the **splitting of unstable nuclei.** We already know that a nucleus with too many protons/neutrons is unstable and will tend to decay. So if we take an atom with a large nucleus, such as uranium, and add a neutron, we are going to make that atom far more likely to decay. In a fission reactor, low energy (slow-moving) neutrons are added to a heavy isotope like uranium-235, creating the extremely unstable uranium-236. The neutrons are slow-moving to make them more likely to be captured by the uranium. This uranium-236 will quickly split into two smaller nuclei of different elements – this is nuclear fission.

However, the total mass of the fission products is *less* than the original mass of the uranium atom. The conservation of energy/mass should apply, so where did the mass go? The difference is released as a huge amount of energy from the reaction – many, many, many, many times more energy than was injected into the system by the original neutron. The reaction will also release loose neutrons that can cause nuclear fission in other uranium atoms, perpetuating the reaction.

Nuclear fission reactions can either be **controlled** or **non-controlled.** Non-controlled reactions can happen very quickly if you think about it. Say you start with a single neutron, causing nuclear fission in a single atom of uranium. Depending on specifics, this might release three additional neutrons. Each of these induces another fission reaction, releasing nine neutrons in total. Then 27. Then 81. It skyrockets *very* quickly, and if uncontrolled, leads to an explosive release of energy – in other words, a nuclear bomb!.

This is obviously not very useful (well, depending on your definition... but let's be nice, reasonable people and say we don't want to create a nuclear bomb). We want to harness the energy, which means controlling the reaction such that we don't get too much at once.

We do this by removing neutrons from the reaction, ensuring that only a single neutron from each fission event is allowed to start another reaction. One fission reaction might produce three neutrons. This means two are absorbed/removed, and the third is allowed to be recaptured for another reaction. The number of neutrons in the system monitored *very* closely to make sure things don't get out of hand. This is a controlled reaction. Note that fission can also occur spontaneously in certain elements. That is, you don't necessarily need to add a neutron to a nucleus to get fission. It's just much, much rarer.

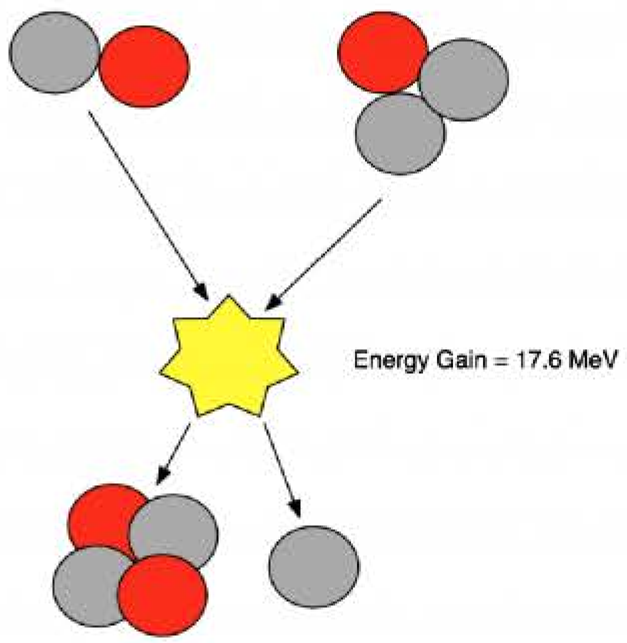
4.4 Nuclear fusion

SYLLABUS :
Account for the release of energy in the process of nuclear fusion.

Nuclear fusion is any sort of reaction in which we bring two lighter atoms together to form a heavier atom. In certain atoms, the force that binds protons together in the nucleus (called the **strong nuclear force,** because it is very strong!) is strong enough to pull nuclei together, even though the protons in those individual nuclei will repel each other. Nuclear fusion is absolutely pivotal to our existence. It is how our sun produces energy – fusing hydrogen nuclei into helium nuclei.

So let's say we fuse two nuclei together. This will produce one new nucleus, and perhaps some extra particles (neutrons or alpha particles, say, depending on the reaction). However, the total mass you are left with is *less* than what you started with! That mass has been converted into energy, according to $E = mc^2$. This energy is mostly kinetic energy gained by the products of the reaction, but it could also take the form of electromagnetic radiation. Either way, we've created energy by losing some mass!

As a specific example, a common nuclear fusion reaction involves the fusion of two hydrogen isotopes: deuterium and tritium. Deuterium is a hydrogen atom with two neutrons in the nucleus, while tritium has three. Fusing these two particles will produce a helium nucleus, and an extra neutron. However, both the helium nucleus and the neutron will have more kinetic energy than they started with! This energy comes from the mass of the neutrons and protons, which is *ever* so slightly reduced when they join together to form the nucleus. This is a concept called **mass defect,** which we'll explain in a bit. Even this slight reduction results in a heap of energy ($E = mc^2$)!



It's important to keep in mind that the a nuclear fusion reaction is not easy to produce – you need super high temperatures, which means getting these nuclei moving extremely quickly. However, if you are fusing elements that are very light, you'll get more energy *out* of the reaction than what you used to produce it. This is why you get **net energy gain** from nuclear fusion! There's a lot of research going on at the moment trying to make this process more efficient and more viable as a consumer-grade energy source.

4.5 Conservation of mass-energy in nuclear reactions

SYLLABUS :
Analyse relationships that represent conservation of mass-energy in spontaneous and artificial nuclear transmutations, including alpha decay, beta decay, nuclear fission and nuclear fusion.

As you might be able to tell from reading this section, explaining these sorts of nuclear reactions can be really tricky using just words. So, we need to be able to read and interpret relationships that demonstrate these reactions occurring, and verify that they adhere to the conservation of mass-energy. Basically, we can't have an electron appear out of nowhere.

It's probably best to see an example of how this could be done, then break it down. Earlier in this module we talked about the triple alpha process; here's how we could notate the combination of two alpha particles to form beryllium in that process:

$$^{4}_{2}\mathrm{He} + ^{4}_{2}\mathrm{He} \rightarrow ^{8}_{4}\mathrm{Be} \quad (-0.0092\mathrm{MeV})$$

First, what does the $^{4}_{2}\mathrm{He}$ mean? This is a common way of expressing isotopes in nuclear reactions. The top number represents the mass number of the isotope (how many protons *and* neutrons in the nucleus), and the bottom number represents the atomic number (number of protons). The letters are the element we are talking about. So $^{4}_{2}\mathrm{He}$ is a helium isotope with 2 protons and 2 neutrons (adding to four). This is why we call it helium-4, to match with that top number.

Then we have an arrow; that represents the reaction taking place, and after the reaction we are left with $^{8}_{4}\mathrm{Be}$, a berrylium-8 isotope. The term in the brackets represents the energy associated with the reaction. A negative value means the reaction *requires* energy, a positive value means it *releases* energy.

Here's another example; this one describes a nuclear fission reaction:

$$^{235}_{92}\mathrm{U} + \mathrm{n} \rightarrow ^{236}_{92}\mathrm{U} \rightarrow ^{89}_{36}\mathrm{Kr} + ^{144}_{56}\mathrm{Ba} + 3\mathrm{n} + 2\gamma \quad (+177\mathrm{MeV})$$

Bear with me, I know it looks scary. Let's break it down. A uranium-235 isotope, $^{235}_{92}\mathrm{U}$, captures a neutron, and it becomes uranium-236. This is highly unstable, and so quickly undergoes nuclear fission into krypton and barium. This also releases three neutrons (3n), and two gamma ray photons (2γ). These gamma ray photons have no mass, so they are carrying the surplus energy, 177MeV.

The conventions used in these sorts of notations can vary depending on where you seem them written. Sometimes, you don't have to worry about the energy at all and can just look at the particles with mass. Sometimes you notate a neutron as $^{1}_{0}\mathrm{n}$ instead of just n. All will be similar, and you should easily be able tell what is happening even with some slight differences in notation.

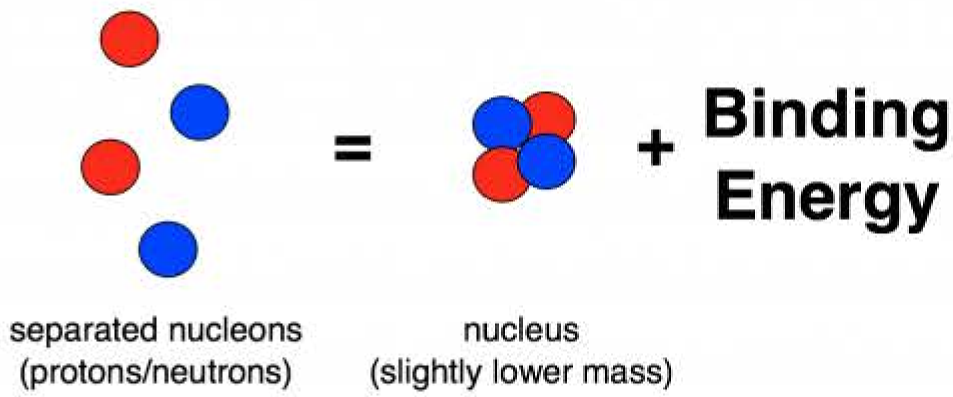
SYLLABUS :
Predict quantitatively the energy released in nuclear decays or transmutations, including nuclear fission and nuclear fusion.

To complete this part of the module, we need to actually quantify some of the energy released in these reactions. We'll do this using, primarily, $E = mc^2$ and the conservation of energy. However, there is one final idea we need to become familiar with first.

We know the mass of the neutrons and protons that make up the nucleus of an atom. However, what we find is that the mass of a nucleus is *less* than the sum of the mass of its parts. For example, a helium-4 nucleus of two protons and two neutrons weighs less than those two protons and two neutrons do separately. This difference is called the **mass defect** of a nucleus – the thing we mentioned earlier that allows us to benefit from nuclear fusion.

To understand where this comes from, consider a nucleus made up of some number of protons and neutrons. Let's say we want to break it apart into its individual pieces, which we *can* do! All we need to do is overcome the strong nuclear force holding all of those protons and neutrons together (we learn a bit more about this force in the next section of the module). This requires energy, an amount equal to the energy keeping the nucleus together. We call this the **binding energy** of the nucleus.

So let's say we are able to provide this necessary energy and successfully break our nucleus into protons and neutrons. The conservation of energy demands that **the energy in the system must be constant.** This means that we can't just put energy in to break up the atom and have it disappear. It needs to have gone somewhere. Where it appears is in each individual proton and neutron, and their mass when separated increases just a little bit. This is the mass defect.



In other words, the binding energy (ΔE) of the nucleus is linked to the mass defect (Δm) of the nucleus by Einstein's equation:

$$\Delta E = (\Delta m)\, c^2$$

Example 4.2

Helium-4 contains two protons and two neutrons, and has an atomic mass of 6.645×10^{-27} *kg. Find the mass defect and binding energy (in electron-volts) of this nucleus.*

So, for this example, we can first calculate the mass of the two protons and neutrons making up the nucleus. The values of these masses are on your data sheet. We'll call this mass m, and the mass of the nucleus M:

$$m = 2\left(1.673 \times 10^{-27}\right) + 2\left(1.675 \times 10^{-27}\right) \approx 6.696 \times 10^{-27}\text{kg}$$

We can now find the difference between this and the mass of the nucleus, the mass defect:

$$\Delta m = M - m = (6.696 - 6.645) \times 10^{-27} \approx 0.051 \times 10\text{–}27\text{kg}$$

Thus, the binding energy must be:

$$\Delta E = (\Delta m)\, c^2 = \left(0.051 \times 10^{-27}\right) \times \left(3 \times 10^{8}\right)^2 = 4.59 \times 10^{-12}\ \text{J}$$

To convert to electron-volts, use the conversion on your reference sheet ($1\text{eV} = 1.602 \times 10^{-19}$J), and you'll get about 28.6MeV. This is huge – millions of times greater than the energy you need to remove an electron from an orbit around a nucleus, which makes sense because helium-4 is a stable isotope, so ripping it apart is not easy.

We can apply similar mathematics to nuclear reactions, to determine the energy released. We'll do one example here, and make sure you do lots of practice with a variety of different types of reactions! Thankfully, the steps are almost always identical to those here.

Example 4.3

Consider the following fission reaction:

$$^{235}_{92}U + ^{1}_{0}n \rightarrow ^{93}_{37}Rb + ^{141}_{55}Cs + 2\,^{1}_{0}n$$

The mass of the reactants and products are given below:

- $^{235}_{92}U = 390.173 \times 10^{-27}$ *kg*
- $^{1}_{0}n = 1.675 \times 10^{-27}$ *kg*
- $^{93}_{37}Rb = 154.248 \times 10^{-27}$ *kg*
- $^{141}_{55}Cs = 233.927 \times 10^{-27}$ *kg*

Find the energy released in the reaction.

This is another example of a nuclear fission reaction involving uranium-235. As usual, we add a neutron, creating uranium-236, and this quickly decays. In this case, we get rubidium and caesium, as well as an extra two neutrons. To calculate the energy released, we need to calculate the difference in mass before and after the reaction: the mass defect. Add up the masses on the left hand side, you'll get this for the initial mass:

$$m_i = 391.848 \times 10^{-27} \text{ kg}$$

And do the same on the right hand side for the final mass:

$$m_f = 391.525 \times 10^{-27} \text{ kg}$$

The difference between these is the mass defect, and this will tell us how much energy is released in the reaction.

$$\begin{aligned} \Delta m = m_f - m_i &= 0.323 \times 10^{-27} \\ \therefore \Delta E &= \left(\Delta mc^2\right) \\ &= \left(0.323 \times 10^{-27}\right) \times \left(3 \times 10^8\right)^2 \\ &= 2.9 \times 10^{-11} \text{J} \\ &= 181 \text{MeV} \end{aligned}$$

Topic 5

Deep inside the Atom

SYLLABUS :
Inquiry question: How is it known that human understanding of matter is still incomplete?

5.1 Evidence for other subatomic particles

SYLLABUS :
Analyse the evidence that suggests that protons and neutrons are not fundamental particles, and the existence of subatomic particles other than protons, neutrons and electrons.

The idea of atoms usually gets floated to students in late primary school or early high school, and protons/neutrons/electrons are usually introduced at a similar time. This might lead you to believe that protons and neutrons are as small as it gets; the individual bits of Lego, so to speak. In reality, even protons and neutrons are made up of other, even tinier bits of Lego!

The evidence that even protons and neutrons are made up of even smaller bits of stuff comes mostly from particle accelerators. To break it down into the simplest possible terms: if something was as small as you could get, you couldn't break it. Fair enough right? Well, we've broken neutrons and protons, and seen the trails of the debris in our particle accelerators. Since we can break it, it must be made of stuff. This is kind of like throwing Lego at a wall: if you've got multiple Lego bricks stuck together, you can break them apart if you throw them hard enough. But an individual Lego brick can't be broken so easily. You *could* do it, but breaking a piece of Lego just means breaking plastic. Breaking a fundamental particle means breaking *physics* itself... which is a *little* tougher!

In a similar train of thought, if protons and neutrons are made of stuff (which we'll explore in detail soon), that implies we could put that stuff together in a different way to make new stuff. And indeed, we can! We've spotted others in particle accelerators. Most are super unstable and exist for super brief periods of time under super specific conditions, but they are there. What we've come to realise is that what we see the most is just the most stable arrangements of fundamental particles; there are many, many more.

5.2 The Standard Model of Matter

SYLLABUS :
Investigate the Standard Model of matter.

So, let's dive in to the **Standard Model of Matter**. Proposed in the 1970s, this model predicts the existence of fundamental particles and how they interact. Before we start, a quick warning: we'll only cover the basics of this model because it's a *super* complicated branch of physics. But even these basics are pretty mind blowing!

The Standard Model consists of seventeen fundamental particles. These can be divided into two groups: **fermions** and **bosons.**

Fermions are the most alike to our Lego pieces analogy – they are the actual building blocks of matter. There are twelve different types of fermions, divided into two groups of six.

- The first group of fermions are the ones that must bind together, and these are called **quarks.**
  - They cannot be found by themselves, they always exist in pairs (called **mesons**) or triplets (called **baryons**). Collectively, we call these arrangements **hadrons.**
  - There are six types of quarks: up, down, charm, strange, top, and bottom. Weird names, right?
  - We get different hadrons by arranging the quarks into different groups. The most stable are the subatomic particles we already know. A proton is a baryon consisting of two up quarks, and a down quark. A neutron consists of two down quarks, and an up quark.
  - Quarks have a mass much smaller than a proton, and carry *fractions* of the elementary charge (the charge on an electron/proton). This makes sense, and when you stick them together, you get back to the elementary charge.
- The second group of six fermions are those which can exist independently, called **leptons.**
  - These particles are (mostly) smaller than hadrons. The **electron** is the one we are most familiar with. We mentioned **muons** earlier in these notes, and the **tau/tauon** (which is actually really big, bigger than a proton).
  - Each of these has a 'partner' – the electron has the **electron-neutrino**, the muon has the **muon-neutrino**, and the tau has the **tau-neutrino**. This makes up the six leptons in total.
  - These neutrinos are the smallest of the fundamental particles, and they are all neutrally charged. Hence the name – **neu** (neutral) **trino.**

So these are the fermions, the building blocks of matter. Let's move on to the **bosons.** Bosons are *carriers*, so to speak. They are the particles which actually interact with fermions to dictate their interaction with forces of nature. That is, we have a particle that actually dictates and 'carries' the electromagnetic force (which, as we know, is the photon). We have another which carries/mediates the strong nuclear force that binds neutrons/protons together in a nucleus. There's even one that dictates *mass*. Let's delve into these.

There are four fundamental forces of physics, and each has an associated boson (sort of).

- The **photon**, as mentioned, is the boson for the electromagnetic force.
- The **gluon** is the boson for the strong nuclear force. This is what binds quarks together to form neutrons and protons, and what keeps a nucleus full of positively charged protons from flying apart.
- The **W Boson and Z Boson** dictate the weak nuclear force, which is responsible for some of the nuclear phenomena we've discussed in this section (for example, beta decay).
- Gravity is the missing one. The standard model doesn't include/allow for gravity, and trying to get gravity to work with the Standard Model is one of the big remaining mysteries in physics. If there was, hypothetically, a boson for gravity, it might be called a graviton. But we don't know yet, and we certainly haven't ever spotted a graviton, but maybe physicists will discover this soon!

Each of these four bosons (not including the theoretical graviton) is a **vector** boson, in that it imparts a fundamental force with a direction and magnitude, a vector. There is one more boson – the **Higgs Boson.** You might have heard of this one, since it was only discovered in 2012 at CERN. The Higgs Boson is responsible for giving particles their mass, and mass is a scalar, so the Higgs is a **scalar** boson.

So that's the Standard Model! I would *strongly* recommend you copy this information onto some flash cards or a poster, or however you think best to get all of these new terms and groupings into your head. Again, you only need to know these basics for HSC Physics; we've ignored all the complex stuff that you might study if you pursue this at a tertiary level. For now, impress your friends with lots of big words to try and make them stick in your memory!

5.3 Particle accelerators

SYLLABUS :
Investigate the operation and role of particle accelerators in obtaining evidence that tests and/or validates aspects of theories, including the Standard Model of matter.

Pretty much all the information I'm able to share with you in this section is thanks largely to the experiments and results that come from particle accelerators. So, it seems fitting to end the module with a bit of a run down on what these are, how they work, and the sort of role they play in physics.

Particle accelerators have been around since the 20^{th} century, constantly improving since that time. The most famous is, of course, the **Large Hadron Collider** (LHC) in Switzerland, which has been operated by CERN since 2008. The operation of the LHC is much the same as other, less powerful accelerators. Powerful electric fields are used to accelerate charged particles from rest (in the LHC, protons are the particle being accelerated). Magnetic fields are used to direct and focus these particles into beams, which end up travelling *extremely* close to the speed of light. They are directed around a huge vacuum contained within a thick pipe, to ensure they don't collide with any gas particles along the way (some are straight lines, some are circular). When everything is ready, we take two of these 'proton' beams and direct them at each other.

See, physics can be cool!

As the protons collide, particle detectors pick up the remnants of the impact and use the trails to extrapolate the properties of what caused them. In this way, we can 'detect' new particles. It isn't that we physically see them, but we see their presence in the aftermath of the collision.

These sorts of accelerators are vital in providing evidence to prove these emerging theories of physics. As we seek a way to unite gravity with quantum physics and resolve other gaps in our knowledge, we need information about how physics works in the harshest of circumstances. What we see in daily life is just how everything settles – we want to see how stuff works in much more interesting scenarios. Accelerators provide us with the sorts of conditions that would have been around when our universe began, allowing us to see how things work at the most fundamental level!

Part V

Exam and Revision Tips

Section 1

General Advice

Scaling of HSC Physics

Some of the most common questions asked about HSC Physics concern scaling and alignment. What is the Band 6 cut-off? How does my HSC mark translate into an ATAR? These sorts of questions shouldn't take up too much of your time; you should focus on performing to your absolute best in the subject! That said, I do think it is important to understand how these sort of things work. There are two types of scaling/alignment that take place for HSC exams:

1. Alignment of your exam marks to Band cut-offs
2. Scaling of your HSC Mark (as it appears on your actual HSC) to contribute to your ATAR aggregate

Alignment is the process where, put simply, NESA decides 'how well' a Band 6 student would have performed on the exam, 'how well' a Band 5 student would have performed, and so on, and adjusts everyone accordingly. The alignment of your exam marks is fairly tricky to have real data for, especially since we've moved to a new syllabus now! Over time, we'll start to get a fairly good picture of how exam marks will be aligning. In the past, marks in the 80's and 90's aligned have up to the 90's. Even marks in the 50's have been aligned to the 70's before.

Scaling is handled by UAC, and again, isn't something we can predict with much accuracy! With lots of new courses kicking in, it is hard to say how students will be performing across the board, which makes it near impossible to have a solid idea of how high or low scaled marks are going to be.

The purpose of this section of the book isn't to delve into these things in depth – there are other resources for that. NESA and UAC document these processes very thoroughly; I also recommend you give this summary a read: http://atarnotes.com/how-does-scaling-work/

Why then, is this section in the book? Well, everyone asks about this sort of stuff, and there are always loads of questions about how it all works. And here's the answer to all of those questions: **it doesn't matter!** The moderation, the scaling, the alignment – it might be worth knowing about, but it's *never* worth stressing about! You've picked Physics because you get at least some enjoyment out of knowing how the world works (hopefully, at least). Let that interest and your own hard work fuel your results, and just let all the background stuff happen as it will. Hard work speaks for itself!

Exam Tips

Physics exams can be really tricky. They are a mix of conceptual explanations and calculations, so you can't rely on just effective use of jargon or being good with numbers. Physics exams very much reward the all-rounders, so here are my tips for smashing those questions in the exam room!

Using the space

The Physics exam is completed in an answer booklet that has spaces for your answers. Use those spaces as your guide! The key to doing well in Physics is knowing when you need the detail, and when you don't, thus maximising your efficiency. In most exams, that relies on knowing your verbs (which you should definitely know as well). You will be told how much detail you need, because they give you the space! Always try to fill the space, and just as importantly, don't waste time going excessively outside the space!

Multiple-choice

I've heard many opinions on whether multiple-choice questions should be done first, or last, or somewhere in between. My personal opinion is that you should get it done *first*. Why? Because it jogs your memory, eases you into the paper, and gets you warmed up. I'm a big believer in **momentum** in exams; if you do well in the easier questions and come into the hard ones feeling confident, you'll do better. This is why I suggest to use the multiple-choice questions as a warm up; get them out of the way first, unless you are seriously struggling to get the exam done in time and would rather leave them until the end.

Reading time

Your brain is good at working on things subconsciously. Of course, this isn't as quick or effective as actively focusing on something, but it does run background processes. That's why you may experience that 'light-bulb' moment about something you forgot a week ago (or as you're walking out of the exam room!) – your brain is still thinking about the problem it had faced.

Physics is very similar. You should use reading time to expose your brain to the sorts of questions that are coming. Map out a plan for responses in your head. Read the complicated questions a few times. Scan the multiple-choice section. Look through the whole paper before doing any specific reading of harder questions, or answering multiple-choice questions.

Leave tough questions for last

Doing well in the HSC is not just about knowing your stuff. It's also about mark maximisation, and doing what you can to squeeze all the marks out of your paper. This involves things like answering all questions, checking for silly mistakes, and leaving tough questions for last.

There are certain Physics questions that will always be tough. Projectile questions, the big 6-markers on Einstein and Planck, BCS theory... all that sort of stuff. I always left those questions for last. Why? To take the pressure off! I'm a big believer in getting the easy marks first. So, go through the paper and do the questions you are confident about first. Only then should you go back and tackle the harder stuff. That way, most of your paper will be done, so there's less time pressure, and it means you can focus your efforts exclusively on getting the last of those elusive marks, confident in the fact that everything else is complete.

Walk in confident

Most years, Physics is near the end of the exam timetable. By that point, you will have had other exams, and hopefully they went well! However, that isn't always the case, and as a result you might not be the most confident on exam day. Whatever the case, you must walk in confident!

This does wonders for your exam technique. I used to literally strut into my exam rooms. I probably looked like an absolute moron, but I was using physical confidence to develop mental confidence. Confident movements correspond to a confident psyche. It's psychological trickery at its finest!

Even if you don't believe that, seriously, be confident. Going in scared or worried does you no favours, so just trust in your work, and trust in your abilities! Believing you can do it is half the battle!

Section 2

Common mistakes in Physics Exams

Physics is a really easy subject to make a mistake in. There are lots of little details to account for, and lots of different ways to reach solutions. All of this equates to lots of ways to lose marks. The key to avoiding these mistakes is being aware of where they can happen, because once you know where they are, they become much easier to spot and even easier to avoid.

Not converting to SI units

I start with this because no matter how many times I told myself to do it, no matter how many times I forgot, I almost always did it again, only spotting my mistake in the few minutes at the end of an exam. For every mathematical question, be sure to convert all your units to SI units before you use them. Make it part of your process!

Right hand rule errors

You've got quite a few different versions of the right hand slap and grip rules to use in the electromagnetism module. It's really important not to get these mixed up, and to fully understand exactly what information each version of the rule requires (and what it gives you). A few tips here:

- Don't muck around with using your left hand for the rules as a shortcut in certain scenarios. If you're like me, you'll want a single process that will work every time. So, always use the right hand rule, then make the direction swap at the end (say, for finding the force on a negatively charged particle instead of a positively charged one).
- Whenever you use the rule, make a little mark on the page and come back and use the rule again a few minutes before the end of the exam. It's really easy to accidentally stick your thumb in the wrong direction when you are under pressure. Just a quick double check could save you a mark, or more!
- You can always sort of tell which aspect of a scenario needs to be assigned to which part of a rule with a bit of common sense. For example, the right hand slap rule for the force on a current carrying wire. Your **thumb** (singular) is the current, because there is a **current** (singular). Your **fingers** (plural) are the magnetic field, because there are field **lines** (plural). The right hand grip rule for the magnetic field generated by a coil, and your **thumb** (singular) is the north pole because there is **one** north pole generated (singular). Your **fingers** (plural) are the current because the current is wrapping around **multiple** times (plural). These kinds of hints can help you remember how the rules work.

Direction and units

Make sure to include both when required! Not including units in any question with a quantitative answer will automatically cost a mark, and the same is true for not including a direction with a vector quantity. This includes but is not limited to: forces, acceleration, current, magnetic fields, etc. It might seem a tad harsh, but this is about preparing you for practical calculations. If an engineer opens up a spreadsheet full of calculation results and doesn't know whether the result is in watts or kilowatts, that's a big problem. This is a super easy thing to check at the end of an exam too! It only takes 60 seconds to sweep through the paper, look for numerical answers, and make sure you've got units and (where needed) direction.

Not using the formula sheet

I asked a friend of mine, who also did really well in HSC Physics, what his number one tip was. I was expecting something insightful and provocative. I got this: *"the formula sheet is really useful since it has the formulas on it."*

This may seem really stupid, but you'd be surprised how many students forget that they have the formula sheet at the back of the exam. They rip it off, get busy working, and then forget all about it under pressure. Obviously, you would be better off knowing the formulas off by heart anyway, it saves you time and will generally mean you know the content more effectively. However, the formula sheet can be useful: don't forget it is there.

Furthermore, make sure you know your way around the sheet! If you are going to use it, you don't want to be wasting time trying to find the result you need. Thankfully, the new formula sheet for the new syllabus is nicely organised under headings. This said, using the formula sheet in your practice sessions could save you precious seconds when you are using it in the real exam.

Skipping practical skills

There is *guaranteed* to be at least one question in your HSC exam relating to some sort of practical skill. Even though these skills aren't listed as syllabus dot points in the actual content, they are absolutely still assessable. This includes things like graphing, sources of error in experiments, assessing the effectiveness of experimental set-ups/methods, identifying/mitigating risks, and more. It's so easy for this stuff to take a back seat, given the huge amount of content in the Physics course. Don't let that happen! Practice this stuff, know this stuff, and be prepared for exams to assign a decent chunk of your marks to this stuff!

Errors with vectors

We learn about vectors properly in Year 11, and though they are sort of neglected in Year 12, you still need to be able to work with them in HSC examinations. The most simple example would just be knowing that the acceleration due to gravity on earth is $9.8ms^{-2}$ *downwards.* You need to account for that, usually by setting $g = -9.8$. This seems easy, but the amount of times I see students mess this up (or make other, really similar mistakes with one-dimensional vector problems) is insane.

Always consider the direction of your quantities **throughout** the problem, not just at the end. Be well-rehearsed in handling vectors with trigonometry, resolving vectors into horizontal and vertical components, and using Pythagoras' theorem. The mathematics itself isn't that difficult, but it's so often neglected. Make sure you make it part of your exam revision.

Forgetting physics terminology

Terminology is absolutely everything in science. Not using the right jargon is a huge mistake in Physics, and one you should avoid at all costs. It is probably the biggest difference between a Band 6 student and the rest of the cohort.

Consider the two mini-responses below to this (reasonably straightforward) question: **Explain two sources of power loss in a transformer and how they are mitigated.**

SAMPLE :

Response A: One way energy is lost in a transformer is through the currents that flow in the core. These cause energy to be lost as the transformer gets hotter. This can be fixed by cutting the core into smaller sections to stop the currents flowing. Energy is also lost due to the magnetic field from the input coil not properly flowing through to the secondary coil. To fix this you need to use a better material in the core, such as iron, to make sure the most field gets around to the secondary coil.

SAMPLE :

Response B: One source of power loss in transformers is eddy currents, which are small circular flows of current induced in the core by changing magnetic field from the primary coil. The size of the eddy currents can be reduced through laminations, which are thin layers of insulation that restrict the space available for these currents to flow. Power loss also occurs due to flux leakage between the coils, meaning not all the magnetic flux reaches the secondary coil. The material used in the core is the determining factor, and should be as permeable as possible (e.g. iron) to facilitate effective flux linkage.

Despite being similar length, it is clear which of these is more effective. Notice also that some Year 11 terminology shows up in the second answer; don't forget all of that work from last year! Using the proper terminology allows more information to be expressed more succinctly, and enables you to properly understand any question that is thrown at you. This is super important in every part of the exam.

Section 3

Strategies for Mathematical Questions

The maths questions in Physics can either be a bit of a gift and give you some easy marks, or (and this is far more common), they can be downright brutal. Handling these questions is tough because the only way to prepare for them is to **practise, practise, practise!**

However, if you go into the exam with a method, you'll have a better chance of getting marks out of these questions. Even if it isn't all of them!

Write out all the information you have (in SI units)

The first step is to write all the information that you have been given out at the top of your working space, giving yourself a bank of data to use. Use this moment to convert to SI units. Always do it at the start, so you don't ever have to worry about doing it later. Routines are efficient like that.

Apply mandatory steps

There are certain question types that almost always require the same first steps. For projectile motion, it is resolving any velocities into their horizontal and vertical components. For special relativity questions, it will be figuring out which data value corresponds to the relativistic value, and which is normal. If you *have* to do something, because you've done it every time before, then that is a good place to start.

Find your formula

Using all the information you have, you will now need to select a formula. Now, using your data bank at the top of the page, you are searching for a formula where you have **every value except one.** You need a formula with a single unknown. Once you have it, you solve it. This could lead to the answer, or it could get you one step closer to another formula which now only has one unknown. It depends on the question. But either way, your answer will almost always just come from substituting information into the correct formula.

Consider significant figures and units

Since we converted to SI units at the start, there will be no converting to be done here unless specifically asked to do so in the question (they might want the answer in days, for example). However, make sure you put units in your answer when required, including direction! This also includes using the scientific prefixes, so saying MW instead of $\times 10^6$ W.

The other thing to keep in mind is significant figures. If the question doesn't specify, it is up to you to decide how many significant figures you need to give. The rule of thumb for this is to give the number of significant figures that equates to the least number of significant figures you've been given elsewhere. So if your values in the question had no less than 3 sig figs, that's how many you give! It's an easy rule, but it guarantees that you won't have accidentally cut off too many decimal places.

"Is this reasonable?"

Once you've completed a numerical problem and gotten your answer, it helps to step back a bit and ask, "does this make sense?" Would you expect it, or does it seem out of place? For example, if you get the speed of a marathon runner to be faster than the speed of sound, chances are you have made an error somewhere. Equally, if you've got a planet in orbit at about 1 metre per second, that could be a problem. Any time you exceed the speed of light, that's *definitely* a problem.

Physics questions are designed to be as realistic as possible, so your answers should be as well. If they aren't, then it is worth looking for an error. It might be a power-of-ten error (for example, you got 12.6 when the answer was actually 1260). Maybe you entered something into your calculator incorrectly. Either way, looking for a reasonable answer is a great way to catch errors at the last moment.

Section 4

How to Study for Physics

Studying Physics is an uphill battle, lets be honest. Some of the topics are just tough to understand, let alone remember in an exam scenario. There are three main ways I recommend studying for Physics.

Past papers

The absolute best way to study for Physics is past papers. Practice makes perfect after all, and that is all the more important for a skill-based subject like this. Practice not only locks in the concepts quickly, but allows you to hone your exam technique and time management skills, both of which are crucial for mark maximisation.

If time is short, there is a way to make sure you get the most out of your past papers. Find a past paper and sit yourself down with a highlighter. Put 10 minutes on the clock and do a scan of the paper (probably focusing more on the short response sections). As you read each question, picture how you would approach answering it. For maths questions, do you know which formula to use? For explanations, do you understand the situation in front of you? Do you know what to include in your answer?

If you see a question and it is confusing to you, highlight it. You might highlight half a dozen questions in a paper, or maybe nearly all of it! Either way, that's awesome, you've just highlighted questions to do as an exercise. You've removed the easy stuff, now you've only got the things that will actually benefit and challenge you. It's a more efficient way to do past papers, and although doing the whole paper is still a great idea, this method is more time efficient.

Study notes

Most Physics students will have a set of study notes (although if you have these, maybe you won't need your own!). Writing those notes is an excellent learning tool, and actually allows you to practice the filtering process. Picking useful information that you need and disregarding unnecessary stuff is a great skill. However, writing study notes is not a substitute for practice. In the period immediately before exams, writing study notes is not such a good idea, since that time is much better spent practising!

When you do write notes (or flash cards, or posters, etc.) they should focus on one thing: **terminology.** Terminology is so crucial, as I've mentioned a heaps of times already. Bring terminology to the forefront of your material and effective understanding is sure to follow. The glossary at the back of this book is a good place to start!

Brainstorms

Remembering something when you have a specific trigger is fairly easy (with practice). Ask a question, give the answer. For example, what is an alpha particle? Give the answer.

However, what is much more difficult is being able to recall the information when given a broader question, like: *'Describe the three different types of radiation.'* This involves not only knowing the answer, but when it is necessary to give that answer. A lot trickier. This study technique is perfect for handling that.

Pick a syllabus area, or even a specific syllabus dot point, at random. Once you've picked, brainstorm absolutely everything you can about that topic. Once you're done, compare it to your notes. Did you miss anything? Pay close attention to the things you missed and be sure to brush up on those areas.

These are the three methods I used most when studying for Physics. Of course, there are a heap of other awesome methods. HSC Physics is all about remembering your jargon (see, I said it again; that's how important this is!), so maybe you could design worksheets with missing words for yourself. Teaching others is another fantastic way to lock the content in. Add any techniques you have developed yourself, and you'll have a varied list to mix up your study routine!

Section 5

Glossary

absorption spectrum: the spectrum of electromagnetic radiation transmitted through a material, with dark spots corresponding to the absorption of specific frequencies of radiation

acceleration: rate of change of velocity over time

all or nothing principle: photons can either be completely absorbed by an electron, or not at all; they cannot be partially absorbed

alpha particle: a helium-4 nucleus, two protons, and two neutrons, emitted from a nucleus undergoing alpha-decay

ampere: the SI unit for electrical current, corresponding to one coulomb of charge per second

angular velocity: rate of change of angle over time

annhilation: the process by which a particle and an anti-particle meet and vanish, releasing energy in the process

atomic number: the number of protons in the nucleus of a given element

back emf: the emf induced in electric motors in the opposite direction to the supply emf

Balmer series: the spectral emission lines in hydrogen which correspond to electron transitions from higher energy levels to the energy level n = 2

baryon: a subatomic particle consisting of three quarks

beta particle: an electron (beta-minus) or positron (beta-plus) emitted by a nucleus undergoing beta-decay

binding energy: the energy holding a nucleus together

black body: a theoretical object that is a perfect absorber/emitter of radiation (no radiation reflects off its surface)

black body radiation: also called thermal radiation, electromagnetic radiation emitted by all objects with a temperature above absolute zero

boson: a 'carrier' particle, a particle which carries energy/mediates interaction with fundamental forces

brush: a device which conducts electrical current between moving and stationary parts

carbon-nitrogen-oxygen chain reaction: a fusion reaction by which four protons eventually fuse to produce Helium-4, positrons and electron-neutrinos.

cathode ray: a beam of electrons that travels from the cathode to the anode inside a cathode ray tube

centripetal force: a force acting perpendicular to the direction of travel of an object to maintain circular motion

characteristic wavelength/frequency: the wavelength/frequency at which the most radiation is emitted for a particular object

classical physics: the frame of physical thought that existed before the introduction of quantum physics and special relativity in the 20^{th} century

controlled variable: a variable that is unchanged during an experiment

conservation of energy: energy cannot be created or destroyed, only converted into different forms

conventional current: positive to negative, opposite to the direction of electron flow

current: flow of electrical charge

dependent variable: the variable that is measured in an experiment

diffraction: the bending of light around corners or through small gaps

Doppler effect: increases/decreases in the frequency of a wave due to the relative motion of the source and the observer

eddy currents: induced, circular flows of current in conductors without any set path for current to flow

electromagnetic induction: the generation of an electromotive force (voltage) in a conductor exposed to changing magnetic flux

electron: subatomic particle orbiting the nucleus in an atom

emission spectrum: the spectrum of electromagnetic radiation emitted from a material, with bright spots corresponding to the emission of specific frequencies of radiation

emissivity: a measure of the effectiveness of a body at emitting thermal radiation (emissivity of 1 is a black body; emissivity of 0 is a white body)

energy: capacity to do work

escape velocity: the velocity that must be attained to completely escape the gravitational field of a planet at a specific distance from the centre of the field

Faraday's Law: the size of an induced emf is proportional to the rate of change of magnetic flux

fermion: one of the two types of elementary particles in the Standard Model, the other being the boson

field: an area of influence

flux linkage: in the context of transformers, the degree to which magnetic flux is completely transmitted from the primary coil to the secondary coil

force: an interaction which changes the motion of an object, a push/pull/twist

frame of reference: a starting/zero point for measurements

friction: a force resisting the relative motion of physical objects

gamma ray: electromagnetic radiation of high frequency, a type of radiation emitted from decaying nuclei

Geiger-Marsden experiment: an experiment where alpha particles were shone through gold foil, the results of which lead to the development of the Rutherford atomic model

geostationary orbit: an orbit with orbital radius of about 36,000 km from the centre of the earth, giving an orbital period of 24 hours

gluon: the boson carrying the strong nuclear force

gravitational potential energy: the potential energy possessed by an object due to its position in a gravitational field (taken to be a negative quantity)

gravity: the attractive force experienced between all objects with mass

hadron: a particle made from quarks

half-life: the time taken for half of a given amount of radioactive material to decay

Heisenberg Uncertainty Principle: the principle whereby the uncertainty in measurement of a pair of properties of a particle (such as momentum and position) must be greater than a fixed limit

Hertzsprung Russel diagram: a diagram of luminosity versus temperature allowing which assists with stellar classification

Higgs Boson: the boson associated with the mass of fermions

Hubble's Law: the recession velocity of celestial bodies is proportional to the distance of that body from the earth

hypothesis: the expected outcome/observation of an experiment, to be confirmed in the experiment itself

independent variable: the variable which is changed in an experiment

induction motor: a motor where the current in the rotor is generated through electromagnetic induction caused by a rotating magnetic field

inflationary period: the period immediately after the Big Bang characterised by rapid expansion and cooling of the universe

interference: the superposition of waves, either constructively or destructively, to form a wave of greater/lesser magnitude

inertial frame of reference: a reference frame that is not accelerating

isotope: atoms of the same element but with different numbers of neutrons

kinetic energy: the energy possessed by an object due to its motion

laminations: insulating layers in an iron core designed to reduce the prevalence of eddy currents without affecting the magnetic properties of the material

leakage flux: in the context of a transformer, magnetic flux which does not link to the secondary coil

length contraction: a decrease in length along the direction of motion for objects with relative motion to the observer, most noticeable at relativistic speeds

Lenz's Law: an induced emf will always form in a direction such that it opposes the change that created it

lepton: the fermions that are not composed of quarks, consisting of the electron, muon and tau particles, and their respective neutrinos

low-earth orbit: an orbit around earth with an altitude of less than 2,000 kilometres

magnetic braking: also called inductive braking, where the opposing force is generated by the interaction between a magnetic field and induced currents

magnetic flux density: the measure of magnetic field strength, corresponding to the amount of magnetic flux per unit area

mass: the amount of matter present in an object

mass defect: the difference between the mass of a nucleus and the total mass of the protons and neutrons which make up that nucleus

mass number: the number of protons and neutrons in the nucleus of an atom

matter waves: a wave associated with the existence of a particle with mass, much like the photon is the particle associated with electromagnetic waves

Maxwell's equations: four equations which dictate the interaction of electric and magnetic fields with charged/magnetised objects

meson: a hadron consisting of two quarks

Michelson-Morley experiment: an experiment attempting to detect the medium through which electromagnetic waves travel (returned a null result)

motor: a device which converts electrical energy into kinetic energy via the motor effect

motor effect: the force experienced by a current carrying conductor inside a magnetic field

neutron: a baryon of neutral charge with mass slightly greater than a proton

Newton's Law of Universal Gravitation: the law governing the gravitational attraction between two objects with mass

non-inertial frame of reference: an accelerating reference frame

normal force: the supporting force exerted on an object due its contact with another object (for example, the force the floor exerts on you when you stand on it)

nuclear fission: nuclear reactions where a nucleus splits into smaller parts

nuclear fusion: nuclear reactions where two or more nuclei come together to form larger nuclei

nucleosynthesis reactions: nuclear reactions where new elements are created

nucleus: the region of protons/neutrons found at the centre of an atom

orbital period: the time taken for an object to complete a single orbit around a planet/star

orbital radius: the distance between an orbiting object and the centre of the gravitational field

orbital velocity: the velocity of the orbiting object (perpendicular to the direction of the gravitational force)

particle accelerator: an apparatus that uses electric and magnetic fields to accelerate atomic and sub-atomic particles to extremely high speeds

period: the time taken for an object to complete a single revolution in uniform circular motion

permeability: the measure of an objects susceptibility to magnetisation and magnetic fields

photoelectric effect: the emission of photoelectrons from metallic surfaces when light of a high enough frequency is shone on that surface

photoelectron: electrons emitted from a surface via the photoelectric effect

photon: the boson associated with electromagnetic energy

polarisation: the process whereby the direction of oscillation of a transverse wave is restricted or specified

primary coil: in the context of transformers, the coil where the AC voltage is applied to generate the changing magnetic field

projectile: an object moving only under the influence of gravity

proton: a positively charged baryon found in the nucleus of atoms

proton-proton chain reaction: a fusion reaction whereby four protons eventually combine to form Helium 4, positrons and electron-neutrinos

quanta: an 'energy packet'

quarks: the building blocks of hadrons, of which there are six types: up, down, charm, strange, top, and bottom

Rayleigh Jean's Law: the classical law governing the intensity of radiation at a given frequency for a black body

refraction: the bending of a wave as it passes through the interface between two mediums

relativistic Doppler effect: the Doppler effect with the effects of special relativity incorporated

relativistic momentum: the momentum of an object, accounting for its relativistic mass

reliability: a measure of experimental effectiveness, the extent to which repeated measurement yields a similar or identical result

resistance: the extent to which a medium opposes the flow of electrical charge

rotor: the rotating part of a motor

secondary coil: in the context of transformers, the coil where an emf is induced by the changing magnetic field, which is then fed to an external circuit

scalar: a quantity with magnitude only (e.g. energy)

solenoid: a wire wrapped into a circular coil or helix

spectral lines: a dark or bright line resulting from the emission or absorption of a specific frequency of radiation, used to characterise elements in spectroscopy

spectroscopy: characterising matter by observing how it interacts with electromagnetic radiation

split ring commutator: the device which maintains a constant direction of torque in a DC motor by reversing the direction of current flow through the coil every half turn

squirrel cage rotor: the rotor in an induction motor where currents are induced to allow the motor to run

stator: the stationary part of a motor

stellar classification: the classification of stars according to their temperature, luminosity, and other spectral characteristics

time dilation: the observed difference in elapsed time between two observers due to their relative velocity, most noticeable at relativistic speeds

torque: rotational force

transformer: a device which allows the voltage/current of an electrical signal to be increased/decreased using the principles of electromagnetic induction

transverse wave: a wave where the oscillations occur at right angles to the direction of movement (propagation)

triple alpha process: a set of reactions where three helium nuclei are converted into carbon

ultraviolet catastrophe: the discrepancy between predictions of classical physics and experimental observations of black body radiation curves

uniform circular motion: circular motion at a constant speed

validity: a measure of experimental effectiveness, the extent to which an experiment tests what is being intended by controlling all other variables appropriately

vector: a quantity with both direction and magnitude (e.g. force)

velocity: rate of change of position over time

voltage: an electromotive force resulting from differences in electric potential between two points

W-Boson/Z-Boson: the bosons associated with the weak nuclear force

Wien's Law: the characteristic wavelength of a black body is inversely proportional to temperature

work: an energy conversion or transfer

work function: the energy required for a photon to free an electron from an atom, causing it to be emitted as a photoelectron

Young's experiment: the double-slit experiment which demonstrated the interference of light and thus contributed to acceptance of the wave model

As a final tip, feel free to jump onto atarnotes.com! I'm always hanging around the Physics forums answering questions on the site, and it's a great place to get some extra help for any of your subjects. Free downloadable notes, Q&As, guides – all for free!

Besides that, best of luck for your HSC! I genuinely hope you smash your exams and achieve all your goals!