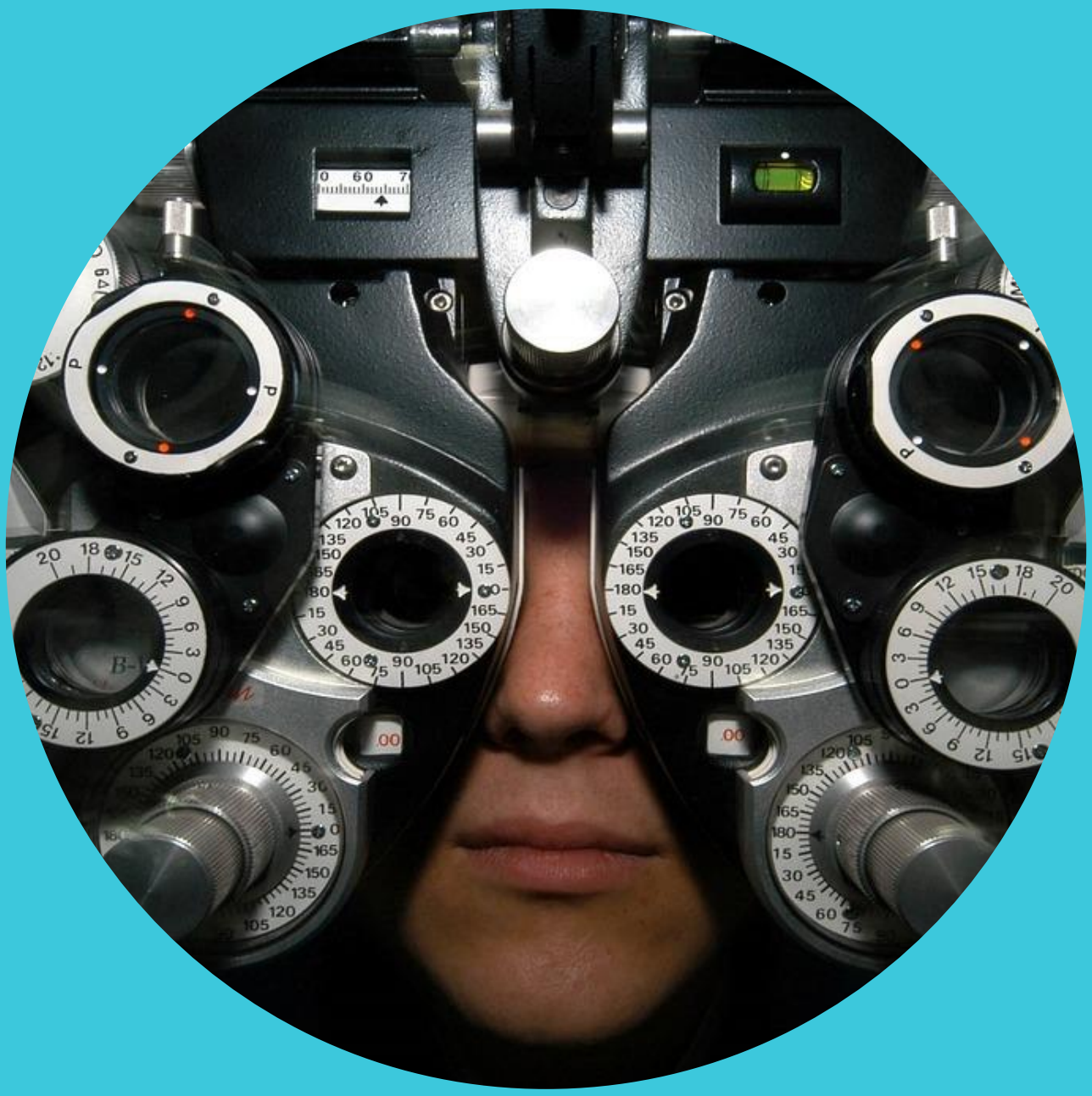
Researchers in Schools



Beyond X-ray Vision!

How scientists see more than Superman

Pupil Name

Coursebook Designed by **Dr A Freeman**

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Uni Pathways launch event

Welcome to Uni Pathways! We are delighted to be able to launch the Uni Pathways programme with you. We hope that you are ready to embark on your Uni Pathways journey and that you enjoy the video.
You will be asked to pause the video at times to complete some work in this workbook, so make sure you have a pen / pencil to hand when you start the video.

By the end of the video, you will have

- Learnt about what studying at university means
- Learnt about some of the skills that you will develop during Uni Pathways
- Heard from pupils who have participated in Uni Pathways or The Scholars Programme (which is the same programme!)
- Heard from current university students talking about what life is like at university

If you are in school your teacher will play the video. If you are at home and logged in to a session with your teacher, your teacher will play the video and show it to you. If you are participating independently your teacher will email you the link to the video or the video file. There are opportunities for you to answer some questions, and you will be told when to pause the video to answer them.

Introduction to Uni Pathways

1. Write down what you think a supra-activity is

_____
_____
_____

2. Independent learning is

_____
_____
_____

3. Write down in your own words what resilience means, and come up with a different example to the one mentioned in the PowerPoint.

_____
_____
_____
_____

4. Why do you think analysis and evaluation skills are useful in your academic career?

_____
_____
_____
_____
_____

5. Why do you think analysis and evaluation skills are useful in life in general?

_____
_____
_____
_____
_____

6. What are the different types of learning that university students do?

Pupils' experience of Uni Pathways

You will now watch some pupils talk about their experience of learning a PhD topic and producing a final assignment. Some may refer to The Scholars Programme rather than Uni Pathways. As you heard in the introduction PowerPoint, The Scholars Programme is a very similar programme to Uni Pathways. Listen carefully and then respond to the questions below. Be prepared to share some of your responses with your peers.

1. How did the pupils describe talking about writing a long essay for their final assignment?

2. Write down something that one of the pupils mentioned was particularly interesting in their course.

3. What were some challenges that the pupils met?

Virtual campus tours

You will now go on a virtual tour of some universities! Once you have seen some of the university campuses, respond to the questions below.
Note down something that you liked out of any of the campus tours you saw. It may be a particular building, space, city etc.

1. Were there any similarities between the different university campuses? If so, what are the similarities?

2. If you had to pick one of those universities to go and visit in person, which one would it be and why?

3. Note down some of the societies that you could join at different universities

Meet university students!

You are about to virtually meet or hear from some current university students.
If you are virtually meeting them, think about what questions you would like to ask the students, share your questions with a partner and note those questions down in the space below.

If you are not meeting them but watching some videos that they have made, use the space below to note down what else you would like to find out about university. You can then ask your teacher during Uni Pathways tutorials!

Reflection

Congratulations on completing the launch of the Uni Pathways programme. Before you go, take some time to reflect on what you have learnt by answering the following questions:

1. Are there any aspects of university style learning that you would look forward to? If so, what are they?

2. What challenges do you think students face when learning at university? How would you try to overcome these challenges?

3. What skills do you hope to develop during your Uni Pathways course?

4. What part of Uni Pathways seems the most challenging for you?

5. What are you most looking forward to about Uni Pathways?

Timetable and Assignment Submission

Timetable – Tutorials

Tutorial	Date	Time	Location
1			
2			
3			
4			
5			
6 (Feedback)			
7 (Feedback)			

Timetable – Homework Assignments

Homework Assignment	Description	Due Date
Tutorial 1	Baseline assignment	
Tutorial 2	'X-rays from electrons'	
Tutorial 3	'Synchrotrons'	
Tutorial 4	'Applications of synchrotron research'	
Tutorial 5	Final assignment	

Assignment Submission – Lateness and Plagiarism

Lateness	
Submission after midnight on 9th August	10 marks deducted
Plagiarism	
Some plagiarism	10 marks deducted
Moderate plagiarism	20 marks deducted
Extreme plagiarism	Automatic fail

Course Rationale

Why is your phone better than the one you had two years ago? How are scientists finding new treatments in the fight against Covid-19? We will look at what tools drive these advances and consider if there is a limit beyond which we can't make things any better.

Our advances would not be possible without the means to look deeply into materials, to understand how the very atoms are interacting. To get this deeper view of tiny things, we need to enlist the help of huge and incredibly powerful machines: particle accelerators. These allow us to use particles and x-rays to see things our eyes cannot.

In this Uni Pathways course, you will learn about how scientists harness these techniques, how we interpret and make sense of information, and why these methods drive the progress for new materials. Alongside this, it should give you the opportunity to problem-solve as a scientist would when designing an experiment.

Superman can use his x-ray vision to see through walls, but this doesn't scratch the surface compared to what scientists can do with x-rays!

Uni Pathways Mark Scheme 2020 – science-based assignments

	Subject Knowledge	Critical Thinking	Written Communication
1st	The work shows a depth of knowledge and understanding of key concepts and scientific methods, through engaging with relevant sources. Knowledge is used to build and support highly effective scientific arguments and explanations.	Analyses key scientific evidence, arguments, and reasoning. Interprets meaning and makes connections. Identifies and critically evaluates key scientific arguments and evidence, deciding on their credibility, strength, and relative significance, drawing convincing conclusions.	The work has a coherent flow and is well structured. The writing style is appropriate; scientific language and key scientific terms are used accurately and effectively to support the arguments and explanations made. There are no, or very few, errors in spelling or grammar. Consistent referencing, appropriate paragraphing and use of correctly labelled tables and graphs matching the style taught in the course.
2:1	The work shows an understanding of key concepts and scientific methods, drawing on relevant sources. Knowledge is used to build and support effective scientific arguments and explanations.	Analyses relevant scientific evidence, arguments, and reasoning. Identifies and critically evaluates relevant scientific arguments and evidence, deciding on their credibility and strength, drawing reasonable conclusions. Shows some understanding of the relative value of evidence and arguments.	The work is well-structured. The writing style is appropriate; scientific language and key terms are used correctly. There are few errors in spelling or grammar. Mostly consistent referencing and use of tables and figures; matching the style taught in the course.
2:2	The work shows an understanding of key concepts and scientific methods, with no major misconceptions. Beginning to apply this knowledge to build and support effective scientific arguments and explanations.	Identifies and uses basic scientific evidence, arguments, and reasoning. Showing some understanding of the quality of scientific arguments and evidence. Not yet showing understanding of the relative value of evidence and arguments.	The work has some structure. The writing style can sometimes be informal; occasionally scientific language and key terms are not used when it would be appropriate to do so. There are some errors in grammar and spelling do not get in the way of communicating the content. Referencing has some consistency; matching the style taught in the course Limited use of tables and graphs.
3rd	Shows a developing understanding of key concepts and scientific methods, with some misconceptions.	Beginning to analyse scientific evidence, arguments, and reasoning.	The grammar, spelling, style, and structure of the work need improving in order

	Does not yet apply this knowledge to build and support scientific arguments and explanations.	Describes evidence and arguments, while not yet evaluating them.	to communicate ideas to the reader. Scientific language, key terms and references are not always used correctly. Limited, or no use of tables and graphs.

Baseline Assignment (essay based): Pupil Feedback Report

Name of Pupil	
Name of School	
Name of RIS teacher	
Title of Assignment	

How your assignment is graded:

Grade	Marks	What this means
1st	70+	Performing to an excellent standard at A-level
2:1	60-69	Performing to a good standard at A-level
2:2	50-59	Performing to an excellent standard at GCSE
3rd	40-49	Performing to a good standard at GCSE
Working towards a pass	0-39	Performing below a good standard at GCSE
Did not submit	DNS	No assignment received by The Brilliant Club

Lateness	
Any lateness	10 marks deducted
Plagiarism	
Some plagiarism	10 marks deducted
Moderate plagiarism	20 marks deducted
Extreme plagiarism	Automatic fail

Marks

OVERALL MARK / 100		FINAL MARK / 100 (including any deductions)	
DEDUCTED MARKS		FINAL GRADE	

If marks have been deducted (e.g. late submission, plagiarism) the teacher should give an explanation in this section:

Mark Breakdown and Feedback

Subject knowledge	
	mark
Critical thinking	
	mark
Written communication	
	mark

Final Assignment (essay based): Pupil Feedback Report

Name of Pupil	
Name of School	
Name of RIS teacher	
Title of Assignment	

How your assignment is graded:

Grade	Marks	What this means
1st	70+	Performing to an excellent standard at A-level
2:1	60-69	Performing to a good standard at A-level
2:2	50-59	Performing to an excellent standard at GCSE
3rd	40-49	Performing to a good standard at GCSE
Working towards a pass	0-39	Performing below a good standard at GCSE
Did not submit	DNS	No assignment received by The Brilliant Club

Lateness	
Any lateness	10 marks deducted
Plagiarism	
Some plagiarism	10 marks deducted
Moderate plagiarism	20 marks deducted
Extreme plagiarism	Automatic fail

Marks

OVERALL MARK / 100		FINAL MARK / 100 (including any deductions)	
DEDUCTED MARKS		FINAL GRADE	

If marks have been deducted (e.g. late submission, plagiarism) the teacher should give an explanation in this section:

Mark Breakdown and Feedback

Subject knowledge	
	mark
Critical thinking	
	mark
Written communication	
	mark

Subject Vocabulary

Word	Definition	In a sentence
X-ray	Light which has a very high energy. X-rays are often used in medical imaging or treatment. Sometimes the image produced is simply called an x-ray.	
Radiation	Energy that is travelling, emitted as particles or waves. It can mean light, or particles coming from a radioactive material.	
Spectrum	A continuous range of a measurable property. The electromagnetic spectrum includes visible light, radio waves and x-rays	
Frequency	The number of waves produced each second. The unit of frequency is hertz (Hz).	
Wavelength	The distance over which a wave repeats itself.	
Oscillation	A repetitive movement between two states or positions. In mechanical systems this is called a vibration.	
Crystal	A special type of solid material in which the building blocks (atoms or molecules) are arranged in a very ordered fashion – like soldiers lining up for a parade. This alignment gives crystals very useful properties.	
Synchrotron	A particle accelerator in which particles are accelerated into a loop by magnets.	
Particle	An object of matter too small to see by the human eye. There are many different sizes and types of particles.	
Probe	To probe is to measure something. This can be done using a physical tool (poking something with a stick) or by measuring it in other ways.	
Technique	A refined experiment method used to obtain a certain type of information.	
Pharmaceuticals	Medication which is used to diagnose or treat or prevent disease.	

Knowledge Organiser

Atoms

All things are made up of atoms – a dense positively charged nucleus surrounded by a cloud of negatively charged electrons.

Transparency

X-rays can travel through certain materials, like our skin and muscle tissue, but are stopped by **denser** materials, like bone and metal. When radiation is stopped by matter, the energy is absorbed by the **electrons**. If no absorption happens, the radiation can usually pass straight through.

Particle accelerators

Colliders like the LHC at CERN) and **synchrotrons** (like Diamond Light Source at RAL) are examples particle accelerators.

Experiment types

The three main categories of experiment which you can do at synchrotrons are:

- Imaging
- Diffraction
- Spectroscopy

Light waves

Visible light and **x-rays** are types of radiation within the electromagnetic (EM) spectrum. Other types of non-visible light are part of the EM spectrum, including radio waves, microwaves, infra-red, ultraviolet, and gamma rays.

All these types of EM radiation travel at the same speed. The speed of light is approximately 300 000 000 metres per second (186 000 miles per second)!

Electrons and fields

Electrons are accelerated by electric fields.
Electrons moving through a magnetic field follow a curved path.

Research areas which make use of synchrotrons

- Chemistry
- Earth Science
- Engineering
- Environmental Sciences
- Life Sciences
- Physics and Material Science
- Cultural Heritage
- Other applications

Tutorial 1 – Waves of pure energy

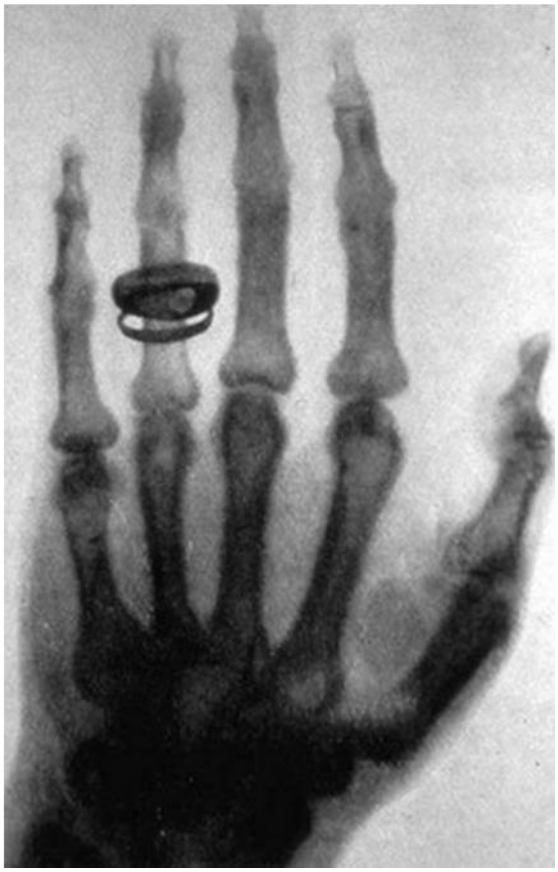
What is the Purpose of Tutorial 1?

- Explain what x-rays are.
- Introduce the electromagnetic spectrum.
- Show how frequency and wavelength of light are related using an equation.

Activity 1 – The 'Unknown' Rays

Write the answers to these questions in the box below.

1) What are these images showing?
2) Can you see any metal objects? If so, what are they?
3) Are the details of the image clearer on the left image or the right image?



Who discovered x-rays? How were they awarded for this discovery?

The picture below is a security x-ray image of a bag taken at an airport. Can you spot the following items? Circle and annotate them on the image if you can.

- AA batteries
- Zips
- Drinks bottles
- A camera with a big lens
- The outline of the bag itself

Can you identify any other shapes?
Why do you think different objects show as different colours?

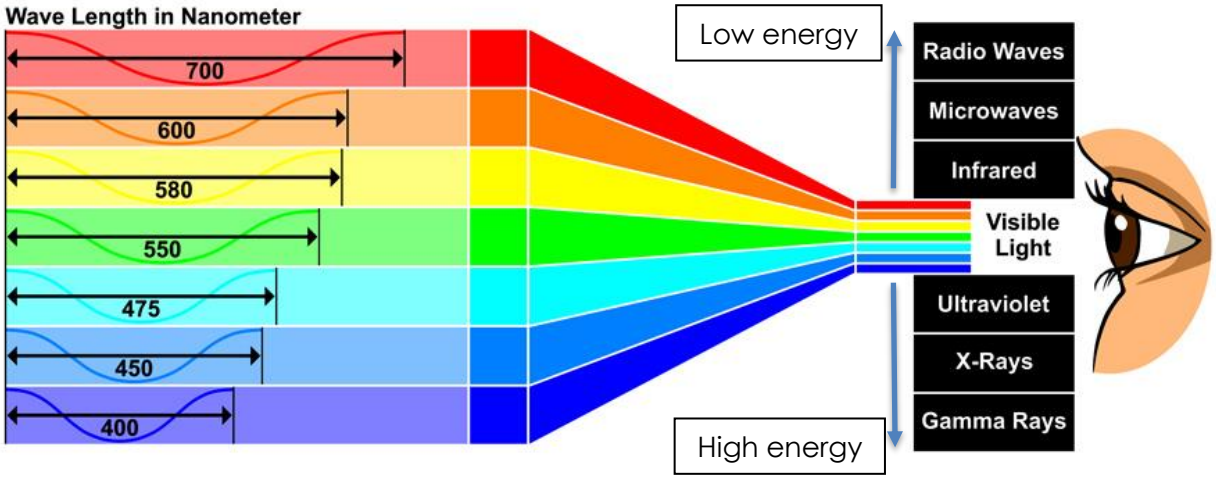
State at least 2 types of things that x-rays can pass through.
State at least 2 types of things that can stop x-rays.

Share your answers with the group.

Activity 2 – The EM spectrum

Besides x-rays and visible light, there are other types of radiation in the electromagnetic (EM) spectrum which you may know.

The diagram below shows how the colours of the rainbow (visible light) compare to the other parts of the electromagnetic spectrum.



In the table below, match the type of radiation with its description. Two of them have been linked to their descriptions as examples for you.

Type of radiation		Description
Radio waves		Useful for heating food
Microwaves		Can be harmful to human skin. Used for detecting forged bank notes
Infra-red		Used for taking medical images of our bones
Visible light		Very high energy waves, used for sterilizing food and medical equipment.
Ultra-violet		Used to transmit signals over long distances (for TV and radio)
X-rays		Can be used to radiate heat. Used in night-vision cameras.
Gamma rays		The small section of the EM spectrum we can see

Write down your ideas on these questions:

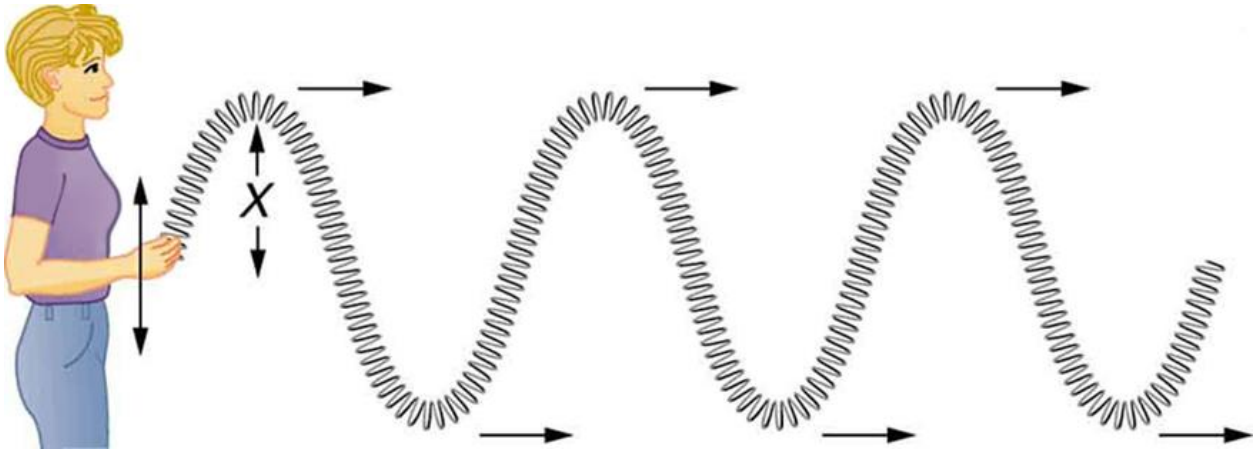
- What happens to an x-ray if it is absorbed?
- Where does the light energy go (what does it change into)?

Activity 3 – Wavelength and frequency

Light waves are an example of **transverse waves**. They vibrate at right angles to the direction of travel.

If someone was to stretch out a 'slinky' spring and shake one end up and down, waves would travel along the length of the spring.

(a)



Draw a representation of a transverse wave.
(b) Label on your sketch its direction of travel,
(c) Draw a line between two points on the wave

The distance between these two points is the **wavelength**!

In the example of the slinky spring above, if the person shakes the end of the spring up and down faster, they put in more energy into the waves and more waves are created per second. The number of waves per second is called the **frequency**.

Extension – Light speed

The speed (or velocity) of a wave is related to both its wavelength and frequency.

The speed of light is 299,792,458 m/s, fast enough to go around the world seven and a half times in one second!

The equation below relates three key properties of light:

speed of light = wavelength × frequency

In symbols this is written: $c = \lambda f$

See Appendix 2 for more about Equations, Units and Standard Form.

Performing a calculation:

1) For x-rays with a frequency of ***f* = 1 x 10^{18} Hz**, what is the wavelength? Use the box below for your working and answer. (Take the speed of light c = 300 000 000 m/s, alternatively written in standard form as 3.0 x 10^{8} m/s).

If your answer is in metres, please also state your answer in nanometres (nm, equal to 10^{-9} m) or picometres (pm, equal to 10^{-12} m).

2) A typical human hair has a width of 0.075mm. How many wavelengths of this light would be able to fit across the width of a single hair strand?

Tutorial glossary

Use this space to write down any new words you have learned today

Word	Definition	In a sentence
EM Spectrum		

Homework 1: Baseline Assignment

Write 450-550 words on the topic of "**Light Waves**".

Use your tutorial notes to help you. You can also do some of your own independent research on the topic.
To help you plan and structure your report, following these guidelines can help:

- Describe the different parts of the electromagnetic spectrum.
- Explain what is meant by 'wavelength' and 'frequency' of a wave.
- Describe what different types of light can be useful for. Explain why some can be dangerous.
- State who won the first ever Nobel Prize for Physics. What did they discover?
- How could you explain to someone that there is more to light than what we see with our eyes? Remember to link to examples of different types of light (EM radiation) and their uses.
- Find some unusual or surprising applications of EM radiation.

Success criteria

- Use correct spelling, punctuation, and grammar.
- If you include any equations or numerical quantities, use correct scientific and mathematical notation, units, and symbols.
- Include information you find from other resources.
- The essay should be between 450 and 550 words in length.

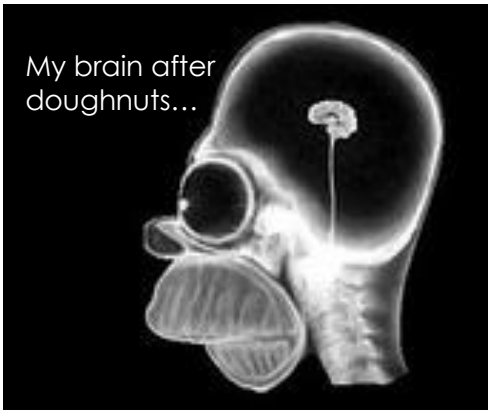
Further reading/viewing:

-
- 'How x-rays see through your skin TED-Ed' [4 minute video cartoon] https://www.youtube.com/watch?v=gsV7SJDDCY4

Tutorial 2 – Making X-rays with Tubes and Doughnuts

What is the Purpose of Tutorial 2?

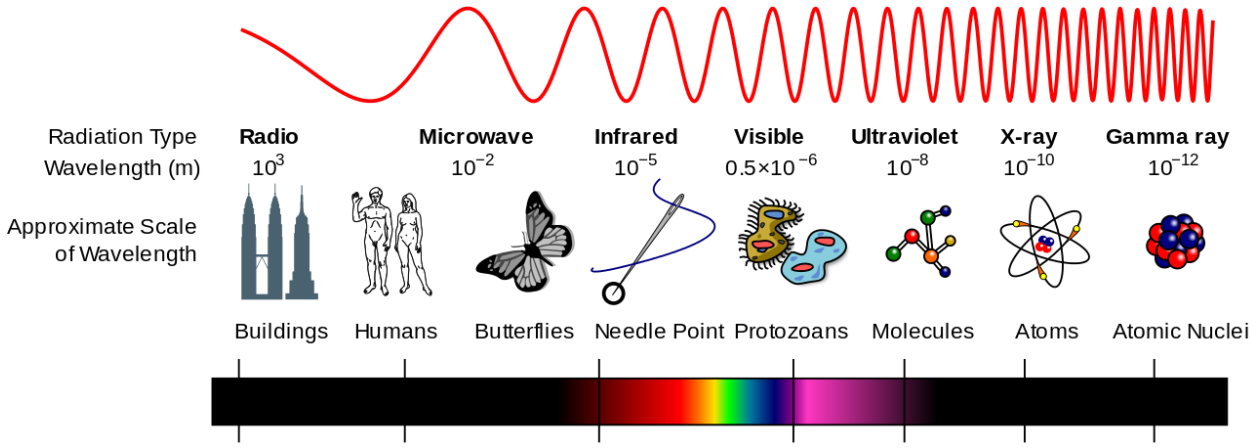
- Compare traditional x-ray tubes with synchrotrons.
- Describe different methods how x-rays are made.
- Predict the behaviour of a charged particle when a magnetic or electric field is applied



Starter

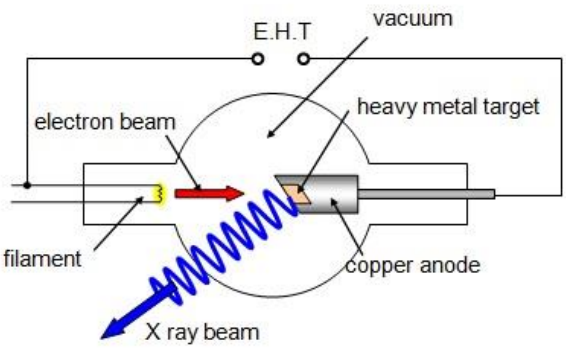
Look at the diagram below and discuss the following questions with your neighbour:

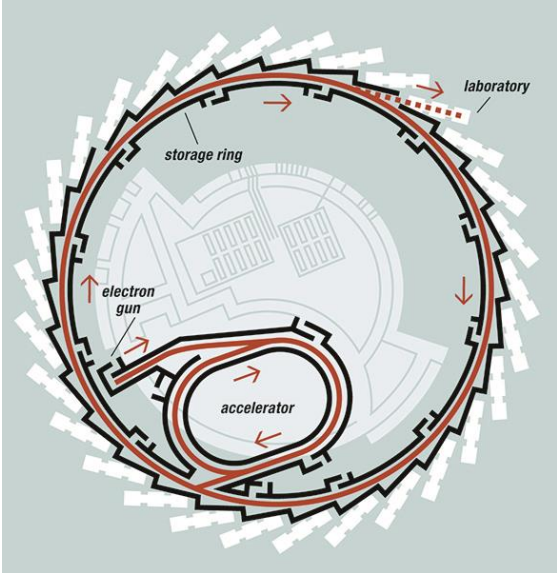
1) Why can radio waves travel through and around buildings?
2) What type of radiation would have the appropriate wavelength to study the spacing between atoms?



Activity 1 – Tubes or Doughnuts: two ways to make x-rays

Look at the diagrams of an x-ray tube (below left) and a synchrotron (below right).





X-ray Tubes
The most common method to produce x-rays (used in laboratories and hospital uses the apparatus shown in the diagram below.

This is called an **x-ray ray tube**. A metal filament is heated to a very high temperature until it releases electrons – this process is called thermionic emission. Electrons are accelerated by an electric field to strike a dense metal target at very high speed. The kinetic energy of the electrons is released as EM radiation. With sufficiently high electron energy, the radiation is released as x-rays.

Synchrotrons (Doughnuts)
Instead of shooting electrons in a straight line, synchrotrons store the rapidly moving electrons in a large **storage ring**. This is the reason synchrotrons have a distinctive doughnut shape! The storage ring of a synchrotron is typically several hundred metres in diameter!

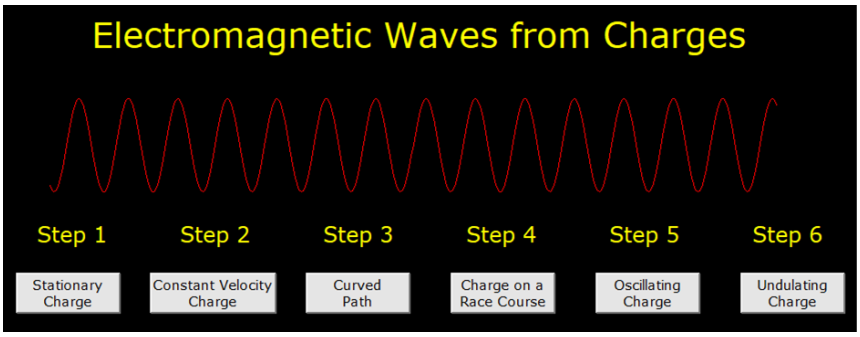
Similar to the x-ray tube, electrons are produced by thermionic emission and are accelerated, but instead of striking a target, they are directed around a circular path (the storage ring) and kept orbiting at high speed by magnets. By using a much more intense beam, it is possible to collect the data much more quickly than with an x-ray tube, and with far better quality.

Complete the table below which compares key features of x-ray tubes and synchrotrons.

Comparison	X-ray tube	Synchrotron
Cheapest to build		
Requires many staff to operate		
Simpler to operate		
Higher intensity beam		
Better quality data		
Less time needed to make measurements		

Activity 2 – How to produce EM waves

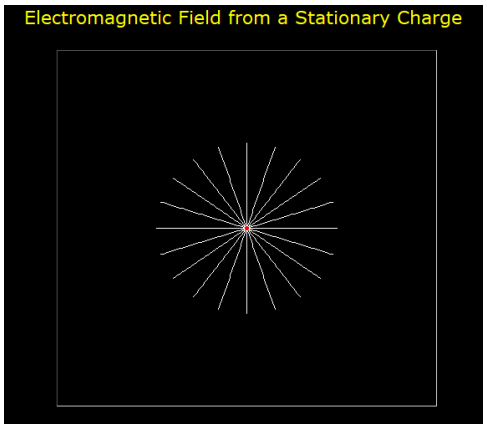
For this activity you will need access to a computer and the resources found at this website: https://www.diamond.ac.uk/Public/For-School/Resources/Simulations-and-Worksheets.html

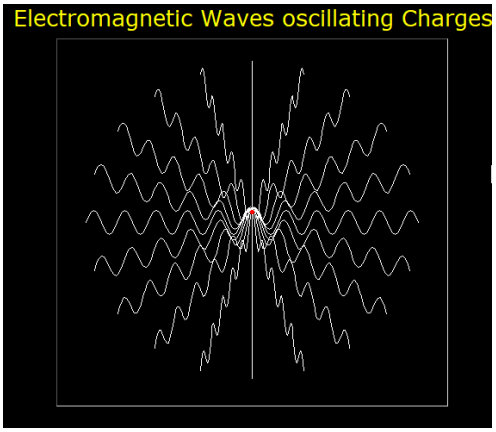


Use the Diamond simulations 'Electromagnetic Waves from Charges' to investigate the relationship between a charged particle and electric field. For each one, read the instructions and theory sections.

Open Step 1: 'Stationary Charge'. When the charge is stationary, it is not very interesting! Describe what you see. How fast do the electric field lines radiate out from the charge?

Open Step 2: 'Constant Velocity Charge'. Change the 'velocity' control. Follow the suggestions shown in the 'instructions' section – can you make any waves?

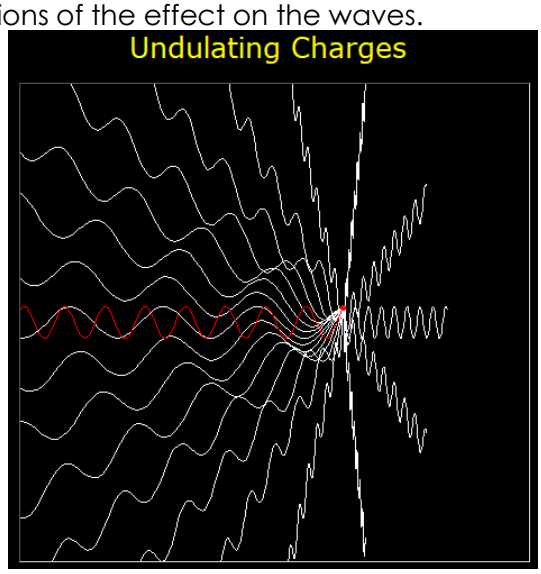




Open Step 5 'Oscillating Charge'. As you increase the frequency (rotate the frequency control clockwise), what happens to the wavelength?
There is an equation which describes between frequency and wavelength. Write this down.
Do waves with higher frequency have more energy or less energy?

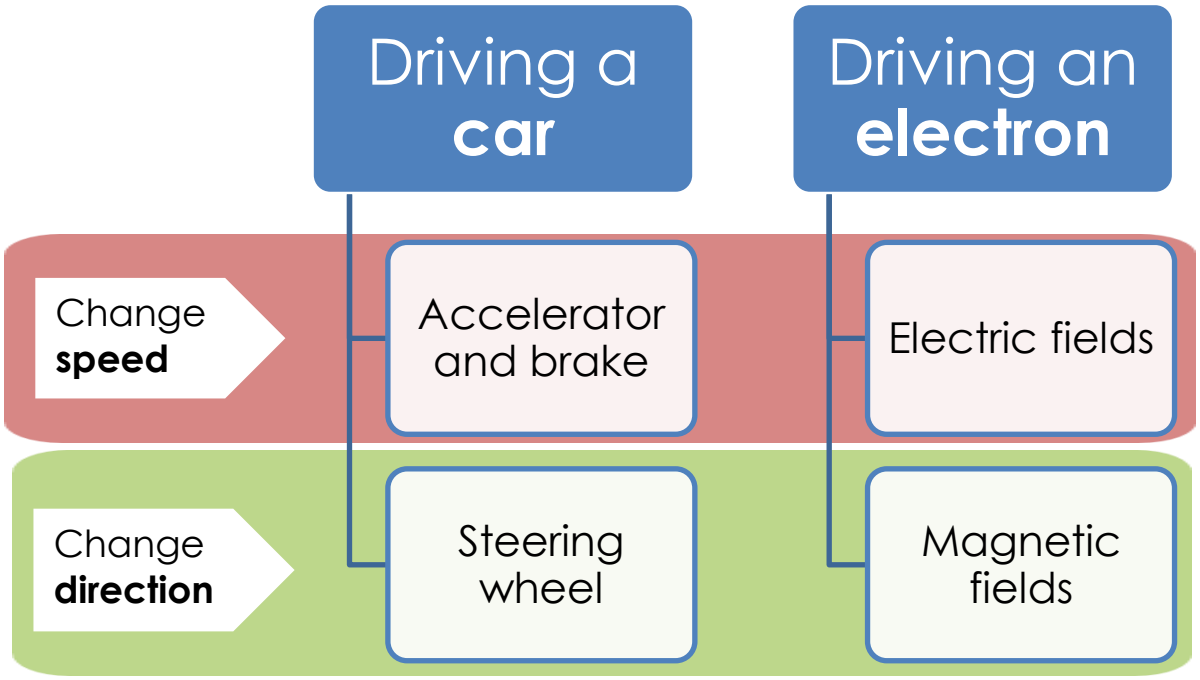
Open Step 6 'Undulating charge'.

Put the velocity knob at halfway and look at the waves being emitted from the particle.
Now put the velocity knob up to maximum.
Write down your observations of the effect on the waves.



Activity 3 – Driving electrons

Electrons can be controlled by **electric** and **magnetic fields**. Electric fields will accelerate or decelerate a charged particle. Magnetic fields bend the path of a moving charge.



Electric fields:

F = q E

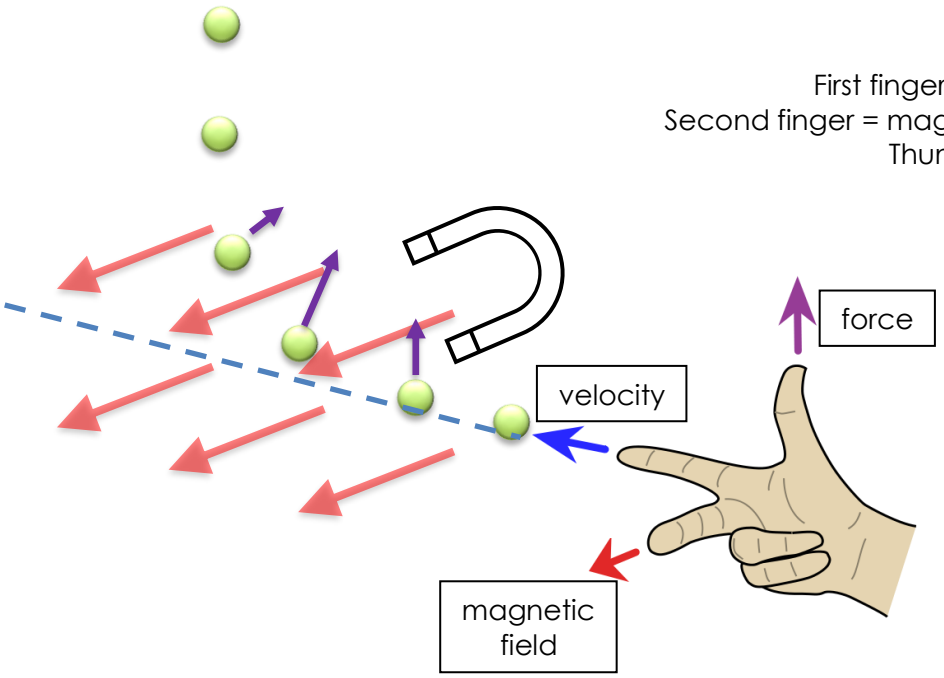
On the diagram above, draw the direction in which a **force** will act on a positive charge (the green particle).
Extension: draw arrows to represent the direction of the electric field lines radiating from the positive and negative charged circles.

The acceleration happens because the electric field exerts a force on the electron. The size of force is equal to the charge multiplied by the electric field strength.

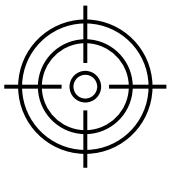
Magnetic fields:
A positive charge moving in a magnetic field:

First finger = velocity
Second finger = magnetic field
Thumb = force

F = qv x B



Draw on the diagram above the direction of the **velocity** for each of the positive charge positions.



Extension: Finding Focus

There are three types of magnet arrangements which are used in a synchrotron storage ring.

Dipole magnet (two poles) – bend the path of the electrons.
Quadrupole magnet (four poles) – focusses the bunch of electrons down to a tiny size.
Sextupole or hexapole magnet (six poles) – further improves the focus for different electron energies.

Use the Diamond Simulation 3: 'How are Electron Beams Focussed" to see how quadrupole magnets are used. You must make the electron bunch size as small as possible!

Homework 2

Write 300-500 words on 'X-rays from electrons'

Success criteria:

- Explain how EM waves are produced by using charged particles like electrons.
- Describe two devices use electrons to produce x-rays (x-ray tubes and synchrotrons).
- Explain how electrons are produced in a synchrotron.
- Explain the purpose of a storage ring and how the electrons are kept orbiting.
- Describe the effect of electric and magnetic fields on electrons.

Success criteria

- Use the suggested key points above.
- Make use of what you learned in the tutorial,
- Include further information from the suggested resource or your own research.

Resources:
https://www.diamond.ac.uk/Home/About/FAQs/Inside-the-Machine.html

Tutorial 3 – A super-microscope 10 billion times brighter than the sun

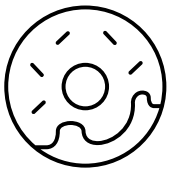
When old-fashioned x-ray tubes just aren't enough, you build one of these:

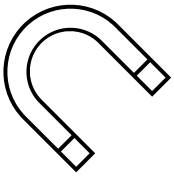
What is the Purpose of Tutorial 3?

- Explain why synchrotrons are needed and their advantages over x-ray tubes.
- Compare and contrast different types of accelerator.
- Identify the key features of an x-ray beamline.

There are about 70 synchrotrons around the world (shown in the map). The accelerator in the picture above is Diamond Light Source in Oxfordshire, the UK's synchrotron light source. It was named Diamond because it is a 'brilliant' light source. In science, 'brilliant' means **very bright**, and Diamond Light Source has extremely bright x-ray light.

Think, pair, share:
Why is Diamond Light Source doughnut-shaped? Discuss with your neighbour. Write your ideas down and we will share them with the group.



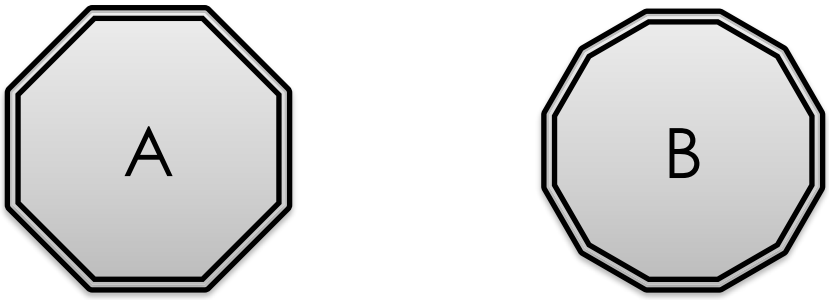


Activity 1 – How to steer a bunch of electrons

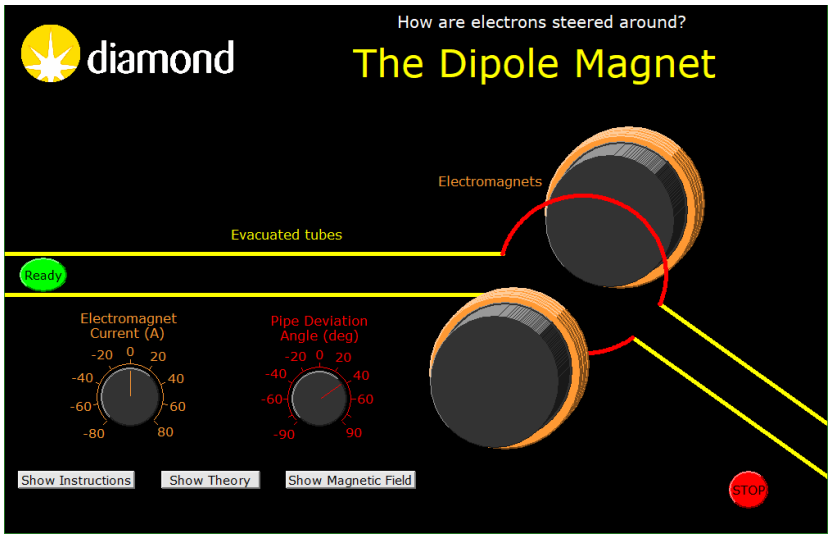
A synchrotron is actually not a perfect circle – it is a polygon with many straight sides.
At each 'corner', the path of the electrons is swerved slightly. Whenever the electrons change direction, they emit photons (x-rays).

Synchrotron light is emitted when a beam of electrons moving close to the speed of light is bent by a powerful magnetic field. The light that is produced spans the electromagnetic spectrum including infrared, visible light, ultra-violet light and x-rays.

Below are two examples of synchrotron storage rings **A** and **B**, with different number of straight sections. **Put circles on each picture** at every point where you would need to put a magnet to bend the path of the beam.



Load 'Diamond Simulation number 3' 'How Electrons Are Steered Around'.
The electrons are steered around bends by a dipole magnet. The magnetic field is increased or decreased depending on how much electric current is powering it.

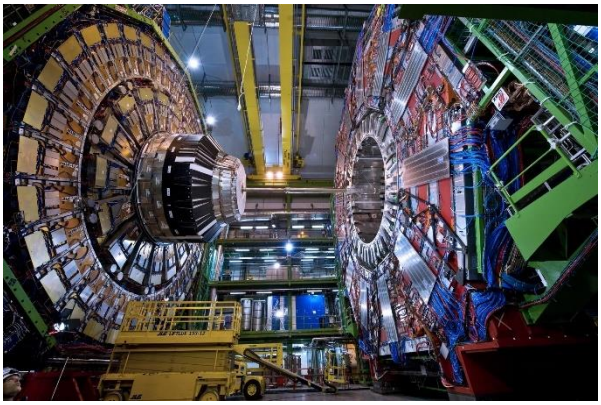


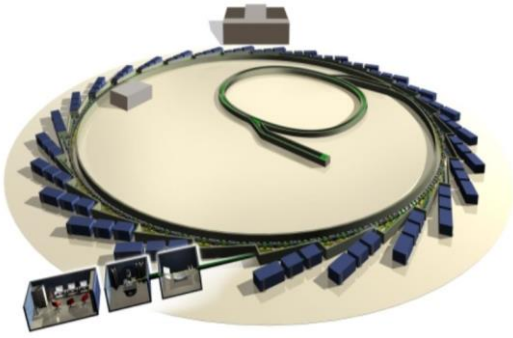
Which out of storage ring A and B (above) would require stronger or weaker magnets to bend the electrons without crashing?

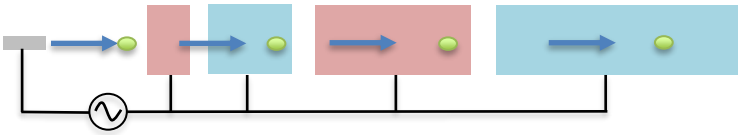
Activity 2 - Types of Particle Accelerators

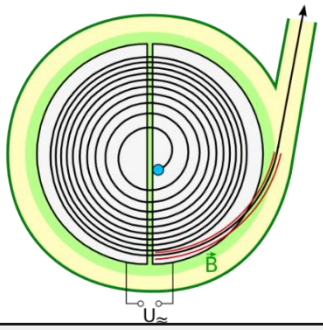
Type of accelerator	Accelerates	Used for
Linear accelerator AKA 'Linac'	Electrons, protons or ions	Accelerating electrons, protons or ions
Cyclotron	Electrons, protons or ions	Producing particle beams for physics and nuclear medicine
Synchrotron AKA 'light source'	Electrons	Producing high intensity light, particularly x-rays
Collider AKA 'atom smasher'	Electrons, protons or ions	Colliding high-energy particles to study the nature of subatomic matter

Each of the four accelerator types are shown in images below. **Label them** in the boxes provided.



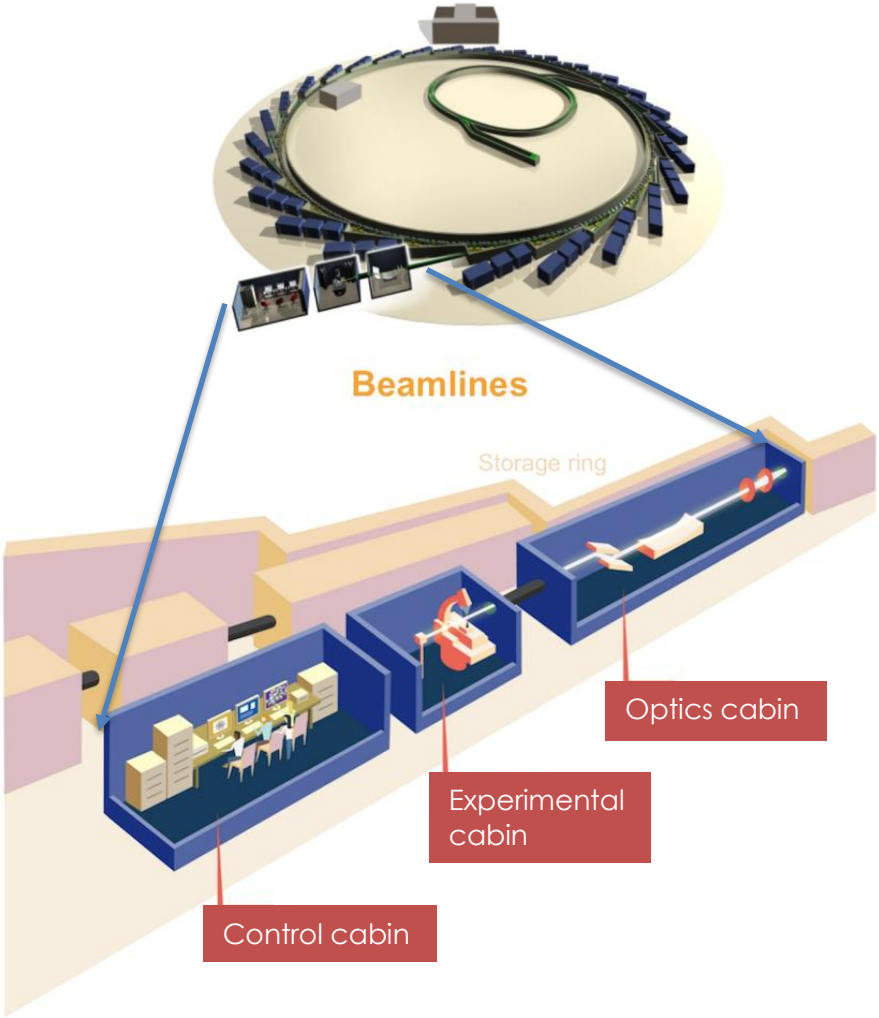






Activity 3 – Build a beamline

You are a Principle Beamline Scientist in responsible for building a brand-new beamline at the UK's synchrotron, Diamond Light Source. **The parts for the beamline have been delivered to you but with no instructions on what order to put them in.**

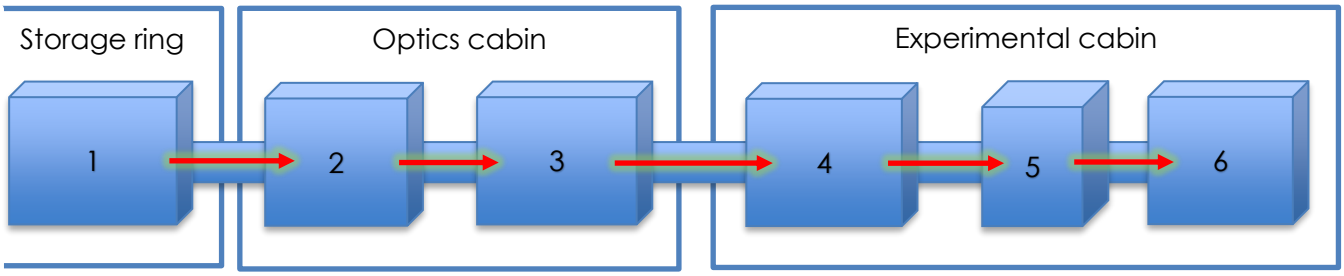


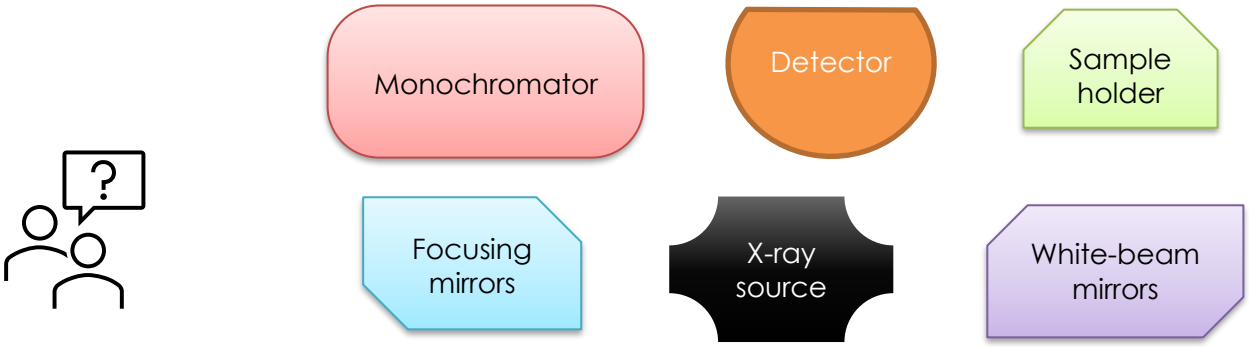
The beamline is split into three separate rooms, called 'cabins'.

- The **Optics cabin** is where the high energy x-rays first enter the beamline. No people are allowed inside the optics cabin while x-rays are being used because the radiation levels would be lethal.
- The **Experimental cabin** is where the actual science experiment takes place. The sample and detectors are situated here. No people are allowed inside the experimental cabin while the experiment takes place because the x-rays would be very harmful to health.
- The **Control cabin** is where the scientists remain during the experiment. From here, they have computer-control of the experiment and collect the data. In this room they are safely shielded from the potentially harmful x-rays which are being used in the experiment.

TASK: On the **next page**, match up the components of the beamline in the correct order. You will need to read the descriptions of each component to make sense of them.

My Beamline





You have the **descriptions** of the beamline parts below, but they are in *alphabetical order*, so it's up to you to work out what order they should be installed in the beamline (boxes 1 to 6 in the picture 'My Beamline' above).

Detector
This is 'eyes' of the beamline. This is used to see what x-rays pass through the sample or the fluorescence off the sample. This is the final part of the x-ray's journey. The signal detected by the detector is the data which scientists use to plot their graphs or images for analysis.

Focusing mirrors
These reflect and focus the x-rays to a tiny point. After the desired x-ray frequency has been selected by the monochromator, these are used to focus and concentrate the monochromatic x-rays so that they hit a tiny spot on the sample.

Monochromator
This is used to choose the frequency or 'colour' of x-rays we want. X-rays of many frequencies enter this device, and what comes out are monochromatic x-rays of the chosen frequency.

Sample holder
The sample is the material or substance which we want to measure. It is placed in a special sample holder and placed into the path of the x-ray beam.

White-beam mirrors
These mirrors receive the raw x-rays from the x-ray source. At this point the x-ray beam consists of many frequencies together (multiple 'colours'), so that's why it is called a 'white beam'. These mirrors are designed to withstand the intense energy from the white beam. They are used to reflect the x-rays to makes sure they follow the correct path onto the monochromator.

X-ray source
The x-ray source is installed in the storage ring, before the optics cabin. The x-ray source is either a Bending Magnet or an Undulator (these are a series of magnets which cause the electrons change oscillate or 'wiggle', causing them to produce very bright, high-energy x-ray light (remember Tutorial 2 where we oscillated a charged particle to make waves in the electric field).

Extension – Sample environments

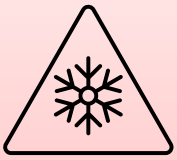
Often samples are measured at room temperature, in ambient conditions. However, it's sometimes necessary to study phenomena which only happen at different temperatures or pressures. Therefore, samples may be heated, cooled, or exposed to gas, liquid, or high-pressure environments.

Read the three **experiment types** below. Then read the three types of **sample environment**. In the empty boxes, write the sample environment type which would be most appropriate for each experiment.

Experiment types

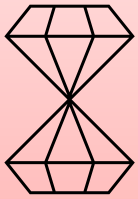
Extreme physics experiment: in this experiment, we want to know how hydrogen behaves deep in the atmosphere of gas giant planets like Jupiter, where the crushing pressures cause strange behaviour in hydrogen.	
Catalysis experiment: studying the efficiency of catalyst materials used in catalytic converters used in motor vehicles. The experiment must emulate the temperatures reached by gases in an internal combustion engine.	
Magnetism study: using x-rays to study the ordering of atoms in a material. However, the material only exhibits the interesting magnetic behaviour at very low temperatures.	

Sample environments



Cryostat – uses liquid nitrogen to cool the sample down to below minus 190 °C.

Diamond Anvil Cell (DAC) – squeezes a tiny amount of a sample between two diamonds to reach incredibly high pressures (many thousands of times atmospheric pressure).



Furnace reactor – capable of heating a sample up to a very high temperature (up to 1000 °C) and mixing it with reactive gases.

Homework 3

Write a 400–500-word essay titled 'Synchrotrons'.

Synchrotrons play a key role in the scientific infrastructure of most industrial nations. Many modern scientific experiments require the bright beams of light that can only be generated at a synchrotron.

Find the answers to the following questions, and include them in your report:

- How do we use electrons to produce radiation?
- How is an electron beam produced?
- How much did Diamond Light Source initially cost to build?
- Does Diamond have any economic benefits for the UK?
- What famous discoveries are linked to research done at synchrotrons?
- Include any other interesting facts you find

Visit these pages on the websites for Diamond Light Source or the ESRF (the European Synchrotron Radiation Facility, in France).

https://www.diamond.ac.uk/Home/About/How-Diamond-Works.html
https://www.diamond.ac.uk/Home/About/FAQs/Inside-the-Machine.html
http://www.esrf.eu/about/synchrotron-science

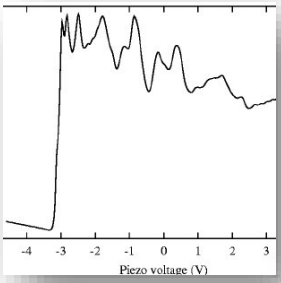
Success criteria:

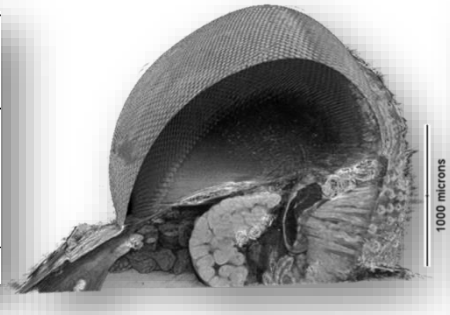
- Put any answers you find in your **own words**, do not just copy and paste from resources you find!
- Use what you have learned in tutorial 3.

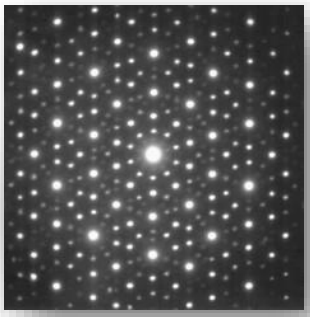
Tutorial 4 – Beyond x-ray vision

What is the Purpose of Tutorial 4?

- Describe the three main categories of x-ray techniques at synchrotrons.
- Determine what key information is obtained from each technique.
- Plot some spectroscopy data and identify the 'absorption edge'.







In this tutorial we reveal that we have powers beyond mere 'vision' and x-ray images: we will investigate some of the amazing abilities of synchrotron x-ray techniques.

Starter

1) What kind of field can you use to steer a moving electron?

   _____ field

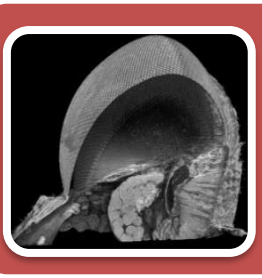
2) What is the name of the device used on a beamline to select a **single wavelength** of x-rays?

   M _ _ _ _ _ _ _ _ _ _ _ _

Another huge application is that of **x-ray crystallography**, using **diffraction**. The method has been massively important in revealing the structure and function of many biological molecules, notably vitamins, drugs, proteins, and DNA. The now-famous structure of DNA was resolved by Rosalind Franklin using X-ray crystallography.

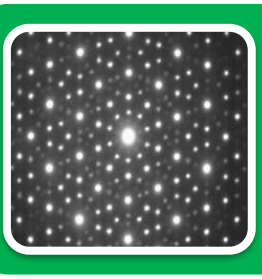
What is the name of the shape of the DNA molecule? D _ _ _ _ _ H _ _ _ _

Synchrotron beamlines can support a range of different experiments, but they are usually dedicated to a certain technique. The techniques usually fall into one of these **three** main categories:



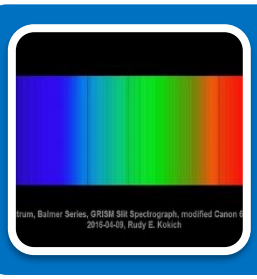
Imaging

- Like Superman's x-ray vision, but more detailed!
- Can make high resolution 2D and 3D images and also reveal cross-sections



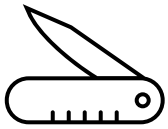
Diffraction

- Measures atomic spacing and ordering
- Used in X-ray Crystallography, extremely important for revealing structures of proteins



Spectroscopy

- Matches elements to a characteristic x-ray spectrum, like a 'rainbow fingerprint'
- Reveals which elements are present and their chemical state



Activity 1 – The Swiss-Army knife of science

Choose which of the three types of measurement (imaging, diffraction or spectroscopy) would be most suitable for the studies described below:

1) A scientist wants study the structure of insect eyes to understand better how insect vision works. They would need to see a three-dimensional image of a bee's compound eye so that they can understand its structure and function. https://www.diamond.ac.uk/Science/Research/Highlights/2019/bigger-is-better-for-bumblebee-eyes.html
2) Surgeons want to investigate why metal-on-metal hip replacements cause problems some for patients. They are concerned that the metals used might contain elements in a certain chemical state which is known to be carcinogenic in the body. https://www.diamond.ac.uk/Science/Research/Highlights/2010/study18.html
3) A pharmaceutical company developing anti-viral drugs needs to understand protein folding. A critical step in this is to resolve the protein's three-dimensional structure using x-ray crystallography. https://www.diamond.ac.uk/Science/Research/Highlights/2017/Insights-into-broad-spectrum-antivirals.html
4) An engineer needs to improve the safety of aeroplane. She is testing some new stronger alloys to see if they are suitable for use in aeroplanes. She needs to see what the alloy looks like inside in three dimensions, and to visualise how cracks spread when the alloy has been pushed to its limit. https://www.diamond.ac.uk/industry/Case-Studies/Case-Study-Rolls-Royce-fan-blade-strain.html

Activity 2 – Diamond the Game

This board game is available for free from the Diamond Light Source website.
The game places you as a scientist who needs to complete as many successful experiments as possible, to have the biggest impact on science research and elevate reputation as a scientist.

Experiments can be related to one or more of six specialisms – areas of scientific study.

Read the printed sheets you have been given (handout of Diamond The Game rule sheets). Explain to your partner 2 aspects of the game: these could be the aims, a rule, types of experiment, the types of cards used.

1) Choose a scientist you would prefer to be and write down their specialisms (they will have two from the box shown above).
2) Explain why you chose that scientist – what do you find intriguing about their work?

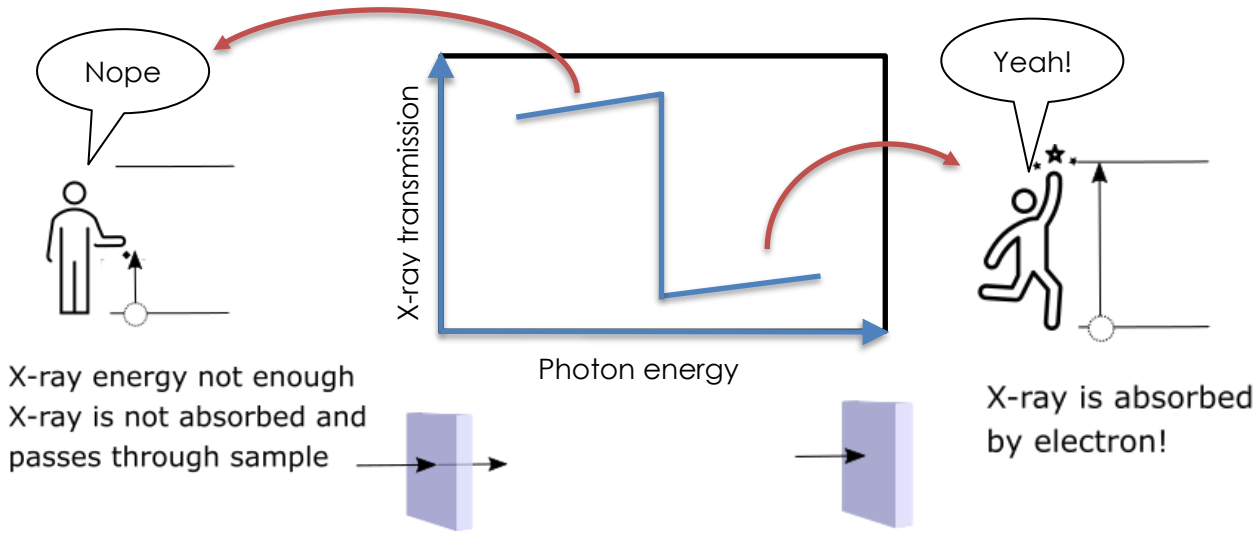
3) Look through the **experiment** cards and select **two** which you find interesting.
4) Can you think of your own idea for an experiment?
   Discuss with a partner and let your imaginations roam free! Write your thoughts and ideas below.

Activity 3 – Spectroscopy: identifying an element

When working as a beamline scientist at Diamond Light Source, you need to prepare the beamline for scientists who would visit to perform their experiments. One of your tasks is to select the appropriate energy (or wavelength) of x-rays.

The visiting scientist would like to study the x-ray absorption spectrum of copper (Cu). To acquire an absorption spectrum, we 'scan' the energy over energy range which matches the electron energy gap in the copper atoms.

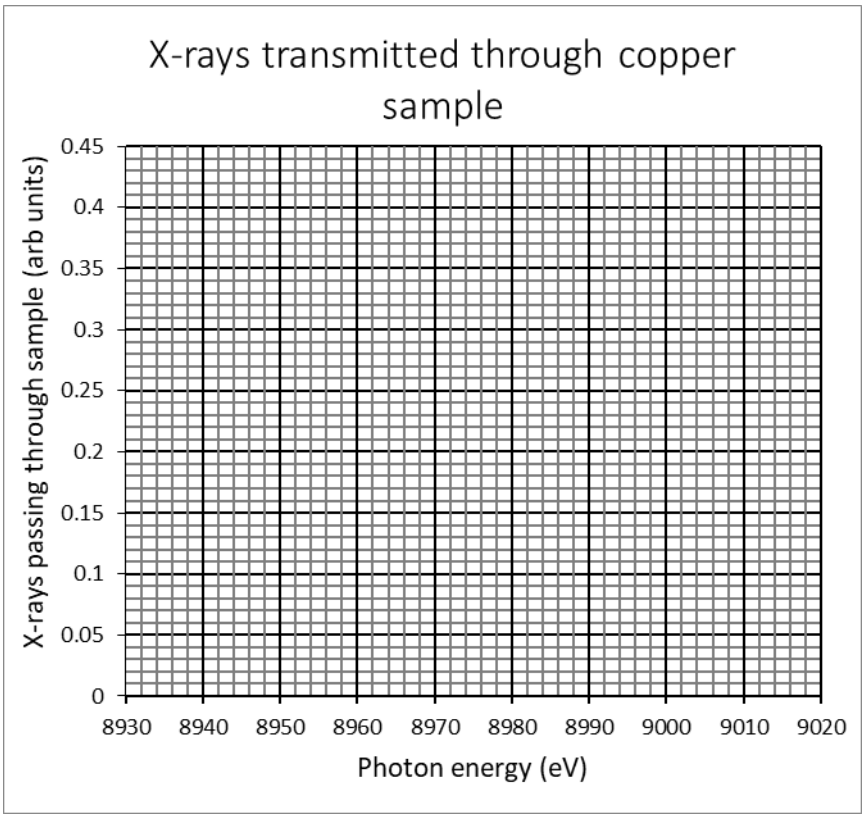
This is done by changing the x-ray energy to a point where the photons don't quite have enough energy to excite the copper electrons to the next energy level. The x-ray energy is then slowly increased until they have enough energy to 'lift' the copper electrons to their next energy level. At this point the photons are absorbed and the detector show that the x-rays are no longer passing through the sample (the transmission suddenly reduces).



One of the most important things we can do with spectroscopy is to identify the exact **elements** which are present in a sample, and what chemical state they are in, even if there is an absolutely tiny number of atoms.

TASK: **Plot** the data from the table below onto the graph.

Photon energy (eV)	X-ray transmission
8940	0.40
8950	0.40
8960	0.41
8970	0.41
8980	0.10
8990	0.11
9000	0.12
9010	0.13



- At what photon energy do you see a change?
- Why does this change happen suddenly? Explain your answer in terms in of the photon energy and electrons in the copper.

Extension

I need to select the photon energy for the copper K-absorption edge which occurs at the energy of 8979eV.
Photon energy *E* is related to wavelength *λ* by the equation:

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

Where $h = 6.63 \times 10^{-34}$ Js
and $c = 3 \times 10^{8}$ m/s

The angle ***θ*** *of* the crystals is related to the photon wavelength λ selected by Bragg's law:

$$2d \sin\theta = n\lambda$$

where ***d*** = 3.135×10^{-10} *m*

Calculate what the wavelength is for x-rays of 8979eV. What angle of crystal is this?

Homework 4

For this week's homework, write 400-500 words on "Applications of synchrotron research". Describe how we can use synchrotrons to study different areas of science, and show the wide range of topics that can benefit from the techniques available. Use what you have learned in Tutorial 4 along with the Useful links below.

What would you like to study? The structure of bees knees? Find out why phone batteries lose their life? Discover how magnets work? Your ideas don't have to perfect and don't worry about them sounding silly, just something that interests you!

Success criteria for this homework:

- Show your knowledge of some scientific equipment used in a synchrotron.
- Describe the three main categories of experiment which are done at synchrotrons. (Which of them is Superman not able to do with his x-ray vision?)

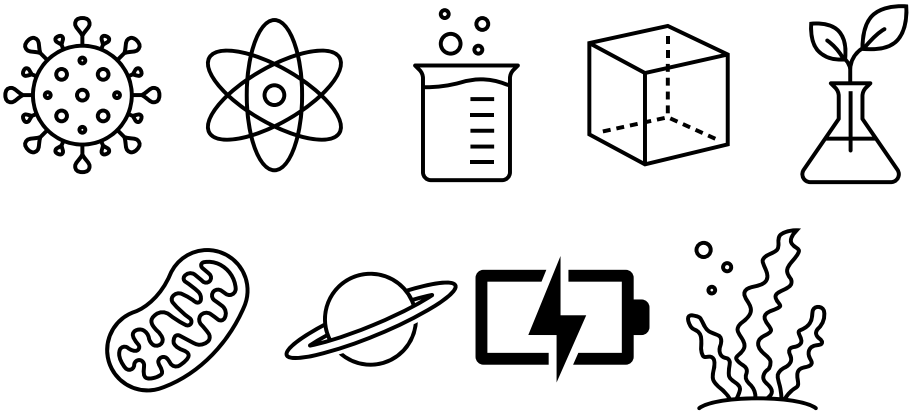
Useful links:

- Science research at Diamond: https://www.diamond.ac.uk/Science/Research.html
- How Diamond Light Source is shining a light on COVID-19 https://www.diamond.ac.uk/covid-19/for-public

Extension: Play 'Diamond the Board Game'

- I will host an after-school session to play the game this week.
- This may help you get an understanding and insight into what scientists are trying to do to make a successful experiment.
- It requires 2-5 players and 20-30 minutes to play a game.

Tutorial 5 – Endless applications



What is the Purpose of Tutorial 5?

- Explore how scientists are using synchrotrons to solve modern challenges
- Consider the benefits and disadvantages of synchrotrons.
- Describe a recent research topic which used synchrotron techniques.
- Plan an essay in the correct way.

Activity 1 – Cost-Benefit analysis

The Large Hadron Collider (LHC) is a type of 'atom-smasher'. It is the largest accelerator in the world. It had an estimate cost of £2.8 billion with contributions from many nations.

Diamond Light Source in the UK cost £263 million for its first phase of development. Further development phases have required significant further investment. In addition, the facility's operating costs have grown (£23 million in 2007/8, rising to £40 million in 2012/13). The facility employs more than 500 staff. The number of staff involved in technical operation and maintenance is around 165.

Write down a list of your ideas and thoughts for the advantages and disadvantages of 'Big Science' projects (such as synchrotrons colliders, space telescopes, etc).

- What are the benefits we get from them?
- Do you hear any concerns or criticisms of science projects in the media?

Fill out this table with your ideas.

Advantages	Disadvantages

Activity 2 – Areas of research

Areas of research & expertise

- Structural biology
- Medical advances
- Drug development
- Disease control
- Viruses and vaccines
- Biomaterials
- Nutrition
- Environment

- Archaeology and palaeontology
- Cultural conservation

- Fundamental science and physics
- Advanced materials
- Nanoscience
- Energy sources
- Novel engineering and design
- Space and planetary research

- Climate
- Natural disasters
- Environmental contamination
- Global resources

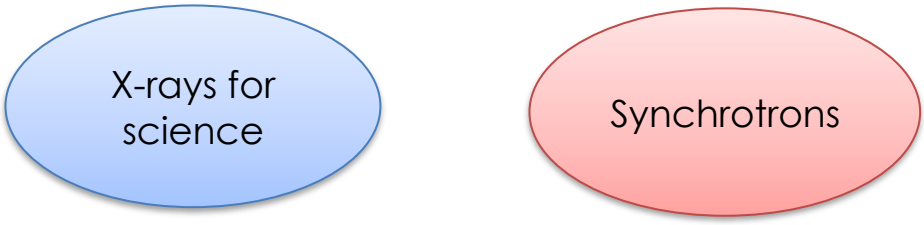
Consider the areas of research and expertise of scientists working at synchrotrons, shown in the box above.

- Which three would you say are the most important for society?
- Which three would be least important, in your opinion? Explain your reasons.
- Are any of these areas controversial?

Activity 3 – How to write an essay

Planning:
The hardest part is often knowing how to begin.
Make a **mind map** to help decide what will go into your final assignment.

As an example of how to start, choose one of these two bubbles to place in the centre of your mind map. Then link all your ideas to them:



Structure:
The next part is to think about the different parts of an essay and what fits into each of those parts. Work in pairs to help decide what parts should go into each section using the boxes below:

Introduction	Main body	Conclusion
•	•	•
•	•	•
•	•	•
•	•	•
•	•	•

Evaluating work

What makes the difference between a good essay and a great essay? It is a useful skill to review your work and to be able to evaluate the quality of your writing.

As practice, we can look at someone else's work and decide what works well and what if we might be able to do to improve it. Read the following short extract from the ESRF website:

> What can we discover with the synchrotron?
>
> It was possible to decipher the Greek letters in a rolled-up papyrus which had been burnt during the eruption of the volcano Vesuvius in South Italy, in A.D. 79, almost 2000 years ago.
>
> We discovered that the famous painter Leonardo Da Vinci painted the Mona Lisa with his fingers.
>
> We found out that some 125 million-year-old fossilised eggs found in China were in fact lizard eggs and not dinosaur eggs as everyone thought before using the synchrotron to look inside them.
>
> We can help to invent new medicines, for example researchers try to understand how the flu virus works so that they can come up with more efficient medicines or vaccines to fight against it.
>
> We can improve our understanding of our planet, so familiar and yet so strange and also our understanding of the Universe (Exoplanets).
>
> Researchers also get inspiration from nature to create new materials: a spider's web is as strong as steel, yet very elastic. By studying the silk the spider weaves to make a web, scientists will try to copy nature, for example to make more resistant clothing.

(from https://wwws.esrf.eu/home/education/for-kids.html)

Make notes below on what you thought worked well and what could be better. Give reasons and evidence to back up the points that you make. You might find the PEE structure helpful:

- Point – make the key point clear
- Evidence – explain the evidence for the point
- Explanation – explain why your point is relevant and important

What went well:

Even better if:

Final assignment

Your task is to write a 2000-word essay with the title: "Beyond X-ray Vision".

This may seem a daunting word-count, but you will have already written much more than 1000 words over the course of your homework assignments. Make use of your previous work and make sure it links together as a coherent essay.

Try to include the following to help you plan your essay:

- Describe what light waves are and their properties.
- Explain how x-rays are different to visible light.
- Describe what machines are used to produce x-rays.
- Explain how we can control the movement of electrons.
- Describe a synchrotron and the parts of an x-ray beamline.
- Describe the three main types of experiment possible at synchrotrons.
- Include **at least one** example of recent research carried out at a synchrotron and why you think it is important.
- Evaluate the benefits against the possible disadvantages of setting up a synchrotron research facility.

Success criteria:

- Demonstrate understanding of light in terms of the EM spectrum.
- Demonstrate knowledge of key concepts about how x-rays are produced.
- Describe scientific methods that are available at synchrotrons.
- Describe an example of recent research done at a synchrotron which you consider interesting or important.
- At least one information source referenced, independent of this workbook. Sources should be cited in an appropriate format according to guidance in this workbook.
- The word count must be between 1900 and 2100 words.

It is recommended that you search for information to discover stories about the latest synchrotron research. You may find the following web pages useful to get you started:
https://www.diamond.ac.uk/Science/Research/Highlights.html
http://www.esrf.eu/news/spotlight
https://lightsources.org/tag/latest-news/

Example studies
Below is a selection of example studies which you may find interesting.

Unravelling the Coronavirus

- https://vimeo.com/477488012

How Diamond Light Source is shining a light on COVID-19

- https://www.diamond.ac.uk/covid-19/for-public

Video of tomography of a bee's eye

- https://www.diamond.ac.uk/Science/Research/Highlights/2019/bigger-is-better-for-bumblebee-eyes.html
- https://www.diamond.ac.uk/Home/News/LatestFeatures/15_05__15.html

Engineering antibodies to treat cystic fibrosis:

- https://www.diamond.ac.uk/Science/Research/Highlights/2020/engineering-antibodies-treat-cystic-fibrosis-.html

X-ray diffraction yields clues to Martian cryosphere

- https://www.diamond.ac.uk/Science/Research/Highlights/2018/X-ray-diffraction-yields-clues-to-Martian-cryosphere.html

Corrosion of cannonballs from the Mary Rose:

- https://www.diamond.ac.uk/Home/News/LatestNews/2018/09-03-2018.html
- Simon, H et al. A Synchrotron-Based Study of the Mary Rose Iron Cannonballs. Angew. Chem. Int. Ed. (2018). DOI:10.1002/anie.201713120 https://onlinelibrary.wiley.com/doi/full/10.1002/anie.201713120

Dinosaur CSI – how scientists are learning new ways to deal with nuclear waste from dinosaur bones.

- https://www.diamond.ac.uk/Home/News/LatestFeatures/02-09-14.html

Synchrotron light for industrial battery research

- https://www.diamond.ac.uk/industry/Industry-News/Latest-News/Synchrotron-Industry-News-Batteries.html

Ocean acidification risks deep-sea coral reef collapse

- https://www.diamond.ac.uk/Home/News/LatestNews/2020/18-09-20.html

Tutorial 6 – Feedback tutorial

What is the Purpose of Tutorial 6?

- To receive feedback on your final assignment
- To respond to the feedback from your Uni Pathways teacher
- To write targets for improvement on your final assignment

Final assignment feedback from your Uni Pathways Teacher

(Remember to look at the mark scheme to help you understand what you have done well so far, and how you can do even better in your final assignment)

Here are three things that my Uni Pathways Teacher thought I did well in my draft assignment
•   •   •

Here are three things that my Uni Pathways Teacher thinks that I could do to get a higher mark in my final assignment
•   •   •

Tasks from my Uni Pathways Teacher to do during the feedback tutorial to help me improve
•   •   •
My response:

Actions I will take to improve my final assignment after this tutorial…
•   •   •

Hand in date for my final assignment:	

Tutorial 7 – Final tutorial

What is the Purpose of Tutorial 7?

- To receive feedback and a grade on your final assignment.
- To reflect on the programme including what you enjoyed and what was challenging.
- To ask any questions you may have about university.

Final assignment feedback from my Uni Pathways Teacher

Final mark:	University style grade:
Feedback: Here are three things that my Uni Pathways teacher thought I did well in my final assignment • • •	

Here are three things that my Uni Pathways teacher thinks I should remember for when I am doing this kind of study in the future
• • •

University

What questions do you still have about University after taking part in Uni Pathways?
• • •

Reflecting on Uni Pathways

What did you most enjoy about Uni Pathways?
• • •

What did you find challenging about the programme?	How did you overcome these challenges?
• • •	• • •

Appendix 1 – Referencing correctly

When you get to university, you will need to include references in the assignments that you write, so we would like you to start getting into the habit of referencing in your Brilliant Club assignment. This is really important, because it will help you to avoid plagiarism. Plagiarism is when you take someone else's work or ideas and pass them off as your own. Whether plagiarism is deliberate or accidental, the consequences can be severe. In order to avoid losing marks in your final assignment, or even failing, you must be careful to reference your sources correctly.

What is a reference?

A reference is just a note in your assignment which says if you have referred to or been influenced by another source such as book, website or article. For example, if you use the internet to research a particular subject, and you want to include a specific piece of information from this website, you will need to reference it.

Why should I reference?

Referencing is important in your work for the following reasons:

- It gives credit to the authors of any sources you have referred to or been influenced by.
- It supports the arguments you make in your assignments.
- It demonstrates the variety of sources you have used.
- It helps to prevent you losing marks, or failing, due to plagiarism.

When should you use a reference?

You should use a reference when you:

- Quote directly from another source.
- Summarise or rephrase another piece of work.
- Include a specific statistic or fact from a source.

How do I reference?

There are a number of different ways of referencing, and these often vary depending on what subject you are studying. The most important to thing is to be consistent. This means that you need to stick to the same system throughout your whole assignment. Here is a basic system of referencing that you can use, which consists of the following two parts:

1. **A marker in your assignment**: After you have used a reference in your assignment (you have read something and included it in your work as a quote, or re-written it your own words) you should mark this is in your text with a number, e.g. [1]. The next time you use a reference you should use the next number, e.g. [2].

2. **Bibliography**: This is just a list of the references you have used in your assignment. In the bibliography, you list your references by the numbers you have used, and include as much information as you have about the reference. The list below gives what should be included for different sources.

    a. **Websites** – Author (if possible), title of the web page, website address, [date you accessed it, in square brackets].

    E.g. Dan Snow, 'How did so many soldiers survive the trenches?', http://www.bbc.co.uk/guides/z3kgjxs#zg2dtfr [11 July 2014].

    b. **Books** – Author, date published, title of book (in italics), pages where the information came from.

    E.g. S. Dubner and S. Levitt, (2006) *Freakonomics*, 7-9.

    c. **Articles** – Author, 'title of the article' (with quotation marks), *where the article comes from* (newspaper, journal etc.), date of the article.

    E.g. Maev Kennedy, 'The lights to go out across the UK to mark First World War's centenary', Guardian, 10 July 2014.

Appendix 2 – Equations, units and standard form

Equations

The equation relating wavelength, frequency and the speed of light was given in Tutorial 1. Here is an explanation of the symbols used.

The speed of light is represented by c in the formula. λ (the Greek symbol called lambda) is the wavelength of the light, and *f* is the frequency. The frequency of light is the number of waves per second, measured in Hertz (*Hz*). See the note later about units.

For example, if we consider green light which has a wavelength of about 550nm (550×10^{-9} m), its frequency is given by $f = c/\lambda$, equal to 5.45×10^{14} Hz, or 545 TeraHertz, or 545 million, million vibrations per second.

Units

For frequencies above a thousand waves per second, we might use kiloHertz (kHz) and for a million waves per second we measure it in megaHertz (MHz).

Instead of writing Hz, we sometimes write s^{-1} which means 'per second'. This is done to help with calculations, and you will see this when we apply it to the equation relating the speed of light to frequency and wavelength.

Standard Form

Standard form is used to help write very large or very small numbers more easily. One million would be written as 1×10^{6}. Essentially this means you must move the decimal point six places to the right to give 1,000,000.0

Numbers smaller than one may be written with a negative index, for example one billionth of a metre is written 1×10^{-9}. This means you move the decimal point nine places to the left, to give 0.000000001.

Appendix 3 – Background information on x-rays

X-rays were discovered by Wilhem Roentgen in 1805 quite by accident when he noticed some crystals glowing in his laboratory – the light which shone on these crystals had passed through a thick piece of carboard intended to shield the equipment from light. He called the mysterious beam 'x-rays' because they were something unknown.

X-rays can help us "see" through solid objects. Visible light from the sun helps us see in the daytime, and we use light bulbs or candles help us see at night. These are sources of light energy. Similarly, we can use sources of x-rays to shine through objects to reveal things which visible light cannot, like bones within the body.

X-rays are a special type of light energy, also known as electromagnetic (EM) radiation. The light that we see with our own eyes is also a type of EM radiation. The different types of light all make up what is called the electromagnetic (EM) spectrum. Some types of radiation in the EM spectrum have different uses and dangers - depending on their wavelength and frequency.

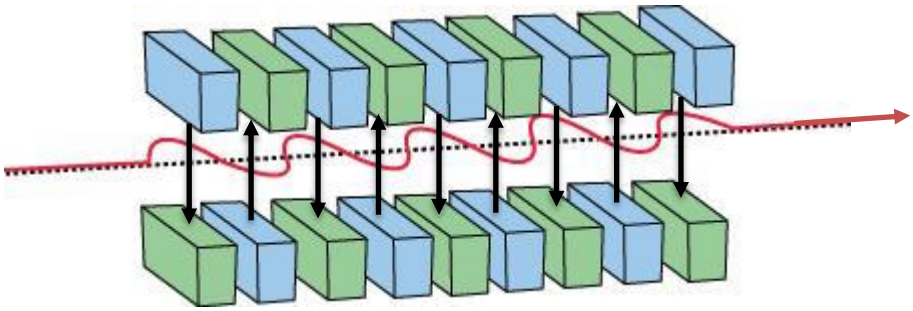
X-rays have a very short wavelength which makes them both potentially harmful and extremely useful:

- the can pass through some solid objects
- they can measure extremely tiny distances (even between atoms!)
- in high doses, they can be harmful to tissues of the body

Synchrotron light

Synchrotron light is produced when a beam of electrons moving at extremely high speed (close to the speed of light) is bent by a powerful magnetic field.
This can be done using dipole magnets (sometimes called 'bending magnets).

In addition to bending magnets, modern synchrotrons use devices called **undulators**. These are a long array of very strong magnets, so-called because they cause the electrons passing through them to undulate or 'wiggle' back and forth very rapidly. They are arranged to alternate the 'north' and 'south' magnetic poles so that the path of the electron is steered one direction and then the other, as shown by the red line. This rapid changing of direction causes the electron to emit EM radiation at every bend, creating a very intense beam of x-rays which pass down the beamline towards the sample.



An Undulator

Appendix 4 – Image references

Handbook cover image:

Tutorial 1:

- Hand mit Ringen (Hand with Rings): a print of one of the first X-rays by Wilhelm Röntgen (1845–1923) of the left hand of his wife Anna Bertha Ludwig. CC-0.
- An early X-ray picture (radiograph) taken at a public lecture by Wilhelm Röntgen (1845–1923) of Albert von Kölliker's left hand. CC-0.
- X-ray image of a backpack. Organic and inorganic materials are discriminated in using dual energy techniques. The original uploader was IDuke at English Wikipedia. - Transferred from en.wikipedia to Commons., CC BY 2.5, https://commons.wikimedia.org/w/index.php?curid=6240255
- "Vector Visible Light" by udaix. Royalty-free stock vector ID: 514067857, via Shutterstock.
- Transverse waves. Adapted from OpenStax College Physics. Original image from OpenStax, CC BY 4.0

Tutorial 2:

- "Cool Blog Sociale - 15 July 2008 - Homer Simpson's head through X-ray" by SOCIALisBETTER is licensed under CC BY 2.0
- "quest for the perfect donut." by caren_ep is licensed under CC BY-NC 2.0
- "EM Spectrum Properties Edit.svg" is licensed under CC BY-SA 3.0 https://en.wikipedia.org/wiki/File:EM_Spectrum_Properties_edit.svg.
- Dr. B Somanathan Nair, X-Ray Tube Working Principle https://www.electronicsandcommunications.com/2018/10/x-ray-tube-working-principle.html. [28/11/2020]
- Storage ring. https://ebmpapst-7237.kxcdn.com/en/files/2014/09/mag214_beschleuniger_EN_700px.jpg from https://mag.ebmpapst.com/en/industries/refrigeration-ventilation/fan-upgrade-diamond-light-source_8651/
- 'Right hand rule cross product.svg' by Acdx. Creative Commons Attribution-ShareAlike 3.0 Unported

Tutorial 3:

- Diamond Light Source aerial photograph, https://www.diamond.ac.uk/PressOffice/MediaResources.html [28/11/2020]
- Map data from Google. Map data ©2020, Imagery ©2020, © NASA, TerraMetrica. https://lightsources.org/lightsources-of-the-world/ [28/11/2020]
- Sketch of a cyclotron by Klaus Foehl (Zyklotron Prinzipskizze02.svg) is licensed with CC0 1.0
- "The Large Hadron Collider/ATLAS at CERN" by Image Editor is licensed under CC BY 2.0

Tutorial 4:

- 'x-ray specs' by i eated a cookie is licensed with CC BY 2.0.
- Tomogram showing a cross-section of a bee's eye. Data collected on the Diamond Manchester Imaging Branchline (I13- 2). Courtesy of Gavin Taylor, Emily Baird, and Andrew J Bodey
- "Zn-Mg-Ho Diffraction" by CORE-Materials is licensed with CC BY-SA 2.0. To view a copy of this license, visit https://creativecommons.org/licenses/by-sa/2.0/
- "Solar spectrum Balmer series uncalibrated" by rudykokich is marked under CC PDM 1.0. To view the terms, visit https://creativecommons.org/publicdomain/mark/1.0/

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