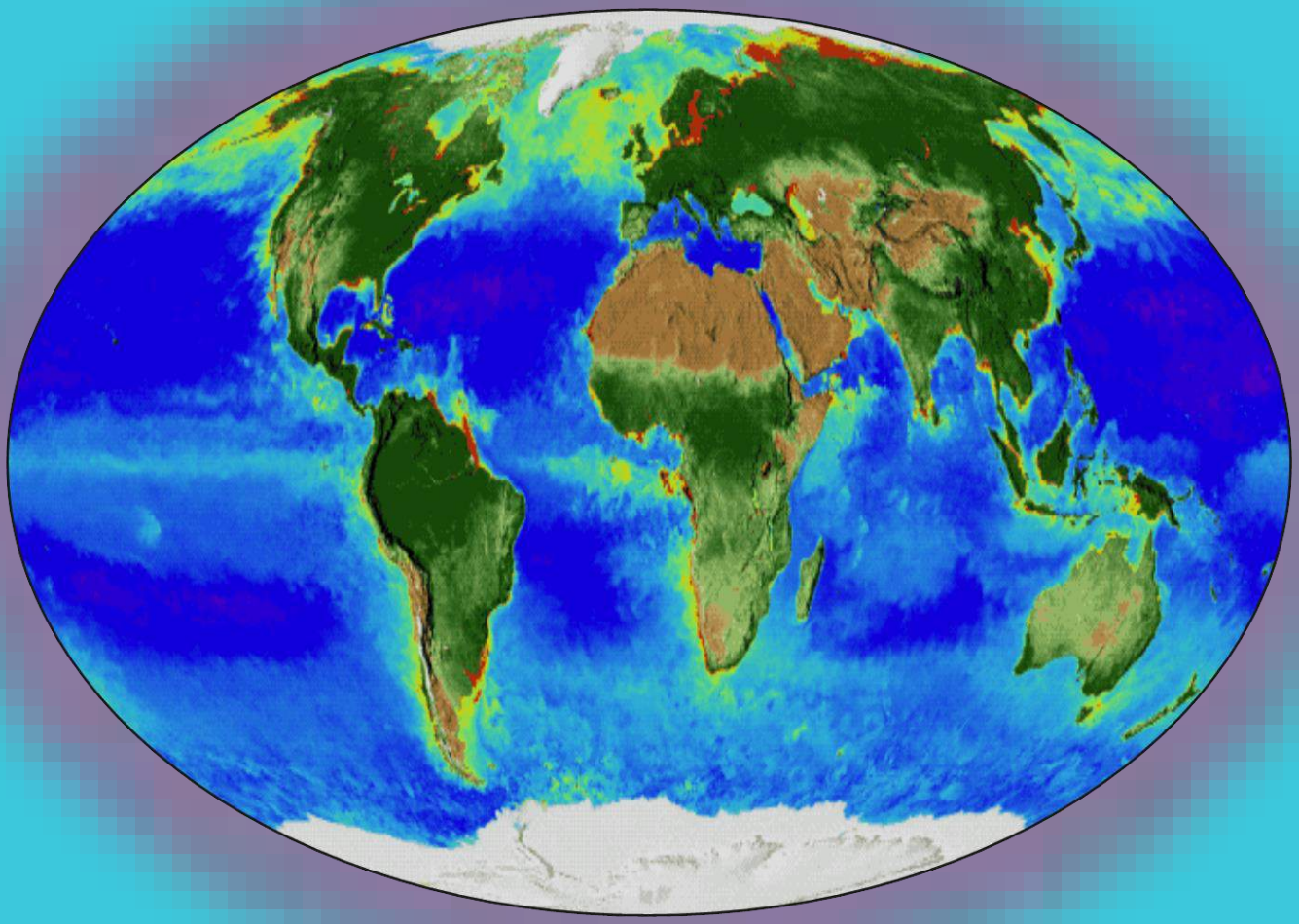

How the Earth Breathes:

Photosystem II

Key Stage 4 Programme

Pupil Name	
Handbook Designed by	Dr. Hall

Timetable and Assignment Submission

Timetable – Tutorials

Tutorial	Date	Time	Location
1	**12 December**	**Afternoon**	**King's College London**
2			
3			
4			
5			
6 (Feedback)			
7 (Feedback)			

Timetable – Homework Assignments

Homework Assignment	Description	Due Date
Tutorial 1		
Tutorial 2		
Tutorial 3		
Tutorial 4		
Tutorial 5		

Assignment Submission – Lateness and Plagiarism

Lateness	
Submission after the due date (3rd March)	10 marks deducted
Plagiarism	
Some plagiarism	10 marks deducted
Moderate plagiarism	20 marks deducted
Extreme plagiarism	Automatic fail

Uni Pathways – Pupil Feedback Report

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

Name of RIS teacher			
Title of Assignment			
Name of Pupil			
Name of School			
ORIGINAL MARK / 100		FINAL MARK / 100	
DEDUCTED MARKS		FINAL GRADE	

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

Knowledge and Understanding

Enter feedback here

Effectiveness of Communication

Enter feedback here

Structure and Presentation

Enter feedback here

Resilience Comment

Enter feedback here

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Course Rationale

$$CO_2 + H_2O \xrightarrow{\text{Light}} C_6H_{12}O_6 + O_2$$

"This is not the whole story!"

– Anyone who has really studied photosynthesis.

Photosynthesis not just a process that affects us all – it is the process that allows life as we know it to exist.

Humanity has known for a long time that plants turn carbon dioxide into carbohydrates using light energy, and that they give off oxygen gas which we need to breathe. These facts are traditionally taught in biology and perhaps in chemistry. But in the 21st century, our understanding of this process is much deeper. The discipline of photosynthesis is often described as *biophysical chemistry* – all three of the core sciences combined into one.

In this course we will learn in detail about the very first steps of photosynthesis: The capture of light energy and creation of oxygen by a special enzyme called Photosystem II. Throughout the course we will focus on three big questions:

1. What is Photosystem II?
2. How do plants capture light energy for use in photosynthesis?
3. How do plants make the oxygen gas that we breathe?

We will apply some methods that have been developed recently to understand the answers to these questions. We will learn how the disciplines of physics, biology and chemistry are much more powerful when all applied together. Hopefully, we will learn the excitement of knowing something very deep about life itself, and we will practice how to pass on that knowledge and excitement.

Mark Scheme

N.B. This mark scheme will be updated.

Skills	1st (70-100)	2:1 (60-69)	2:2 (50-59)
Knowledge and Understanding	• All content included is relevant to the general topic and to the specific question/title • Good understanding of all the relevant topics. • Scientific terms are defined and used accurately throughout • Clear justification on how the content included is related to the specific issues that are the focus of the assignment	• Most of the content included is relevant to the general topic and to the specific question/title • Good understanding of most the relevant topics • Scientific terms are used accurately but not always clearly defined. • Adequate justification on how the content included is related to the specific issues that are the focus of the assignment	• Some of the content included is relevant to the general topic and to the specific question/title • Good understanding on some of the relevant topics but occasional confusion on others. • Scientific terms are used mostly accurately with occasional confusion and often not defined. • Some justification on how the content included is related to the specific issues that are the focus of the assignment
Critical Evaluation/ Problem solving	• Moved beyond description to an assessment of the value or significance of what is described • Evaluative points are consistently explicit/systematic/reasoned /justified • Effective critiques on the reliability of sources provided • Consistently demonstrate clear, analytical and logical steps to solving problems	• Mostly description but some assessment of the value or significance of what is described • Evaluative points are mostly explicit/systematic/reasoned /justified • Some evidence of critiques on the reliability of sources provided • Some examples of solving problems but not consistently clear, analytical and logical	• Only description with minimal assessment of the value or significance of what is described • Evaluative points are at times explicit/systematic/reasoned /justified • Limited evidence of critiques on the reliability of sources provided • Demonstrate clear steps to solving problems but not consistently analytical or logical

Structure and Presentation	• Ideas are presented in paragraphs and arranged in a logical structure that is appropriate for the assignment • The introduction clearly outlines how the essay/report will deal with the issues • The conclusion summarises all the main points clearly and concisely • Any calculations, formulas and methods are clearly structured, clear to follow and correct • Tables and graphs are effectively constructed including appropriate headings, units and scales. • All sources are referenced correctly in an agreed format	• Ideas are presented in paragraphs and arranged in a structure that is mostly appropriate for the assignment • The introduction adequately describes how the essay/report will deal with the issues • The conclusion summarises most of the main points clearly • Calculations, formulas and methods are mostly structured, clear to follow and correct • Most tables and graphs are well constructed • Most sources are referenced correctly in an agreed format	• Ideas are presented in paragraphs and arranged in a structure • The introduction mentions how the essay/report will deal with the issues • The conclusion summarises some of the main points clearly • Calculations, formulas and methods are not always structured, clear to follow and correct. • Some tables and graphs are well constructed but contains some errors • Some sources are referenced correctly in the agreed format with occasional errors

N.B. This mark scheme will be updated.

Subject Vocabulary

Word	Definition	Biology? Chemistry? Physics?
Atom	The smallest thing that can exist by itself. Atoms are made of a nucleus surrounded by electrons.	1.= Chemistry ~~2.~~ 1= Physics 3. Biology
Molecule	More than one atom held together by chemical bonds. For example O_2 or H_2O	1. 2. 3.
Oxygen; O_2; Oxygen gas;	Oxygen: an element, chemical symbol: O. O_2 : A molecule with the structure O=O. Oxygen gas: O_2 (at temperatures above minus 183°C !)	1. 2. 3.
Compound	A substance containing only one type of molecule, but with more than one type of element. H_2O is a compound; O_2 an element.	1. 2. 3.
Protein	A type of very large molecule found in living things. Made up of smaller molecules called amino acids.	1. 2. 3.
Enzyme	A special type of protein which acts as a catalyst, to make a chemical reaction to occur	1. 2. 3.
Photosynthesis; Oxygenic photosynthesis	Process used by living things to convert light energy into chemical energy, in carbohydrates. Oxygenic photosynthesis results in the production of O_2.	1. 2. 3.
Element	A substance made of only one type of atom, like pure oxygen or pure iron.	1. 2. 3.
Anaerobic; Aerobic	Anaerobic: without oxygen. Aerobic: with oxygen.	1. 2. 3.
Chlorophyll	The pigment molecule that causes plants to be green. There are several types of chlorophyll – Chlorophyll *a* is the one of interest to us.	1. 2. 3.
Light Electromagnetic radiation	A transverse electromagnetic wave. Visible light has a wavelength of about 400-750 nm. The words "Light" and "Electromagnetic radiation" are used interchangeably in this book.	1. 2. 3..

Wavelength	The distance between two identical points in a wave, for example peak to peak or trough to trough.	1. 2. 3.
Spectrum	The range of wavelengths or colours of light.	1. 2. 3.
Amino acid	The small "building block" molecules that make up proteins.	1. 2. 3.
Protein complex	A group of two or more proteins in close contact with each other.	1. 2. 3.
Cofactor	A molecule within a protein that is important for the protein's function.	1. 2. 3.
Energy	*Energy has many definitions! A good scientific one is:* "The ability to move or heat up an object"	1. 2. 3.
Light energy	Energy stored in the form of electromagnetic radiation – the energy in a light wave.	1. 2. 3.
Chemical energy	Energy stored in the form of chemical bonds within molecules.	1. 2. 3.
Heat energy	Energy stored in the form of heat – the kinetic energy of the atoms or molecules in a substance.	1. 2. 3.
Energy transfer	Movement of energy from one place to another. Including from one type of energy store to another, e.g. light energy to chemical energy.	1. 2. 3.
Speed of light, c	The speed that light travels at in a vacuum. About 300,000,000 m/s or 3.0×10^8 m/s.	1. 2. 3.
Planck constant, h	A fundamental constant of the universe! $h = 6.26 \times 10^{-34}$ Js (very small!) Units are Joule-seconds.	1. 2. 3.

Pigment	A molecule that absorbs visible light. Pigments are always colourful because of their light absorption. They are often used as dyes.	1. 2. 3.
Absorption	The process by which light energy is transferred to matter, such as an electron or a molecule.	1. 2. 3.

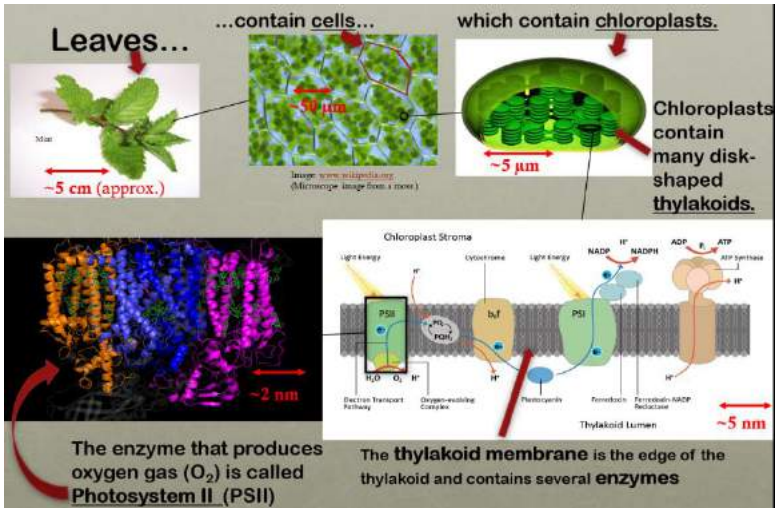
Knowledge Organiser : The Big Questions

1. What is Photosystem II (PSII)?

PSII is a **protein complex** and an **enzyme**. It is found in the **thylakoid membrane** of plants and other photosynthetic organisms.

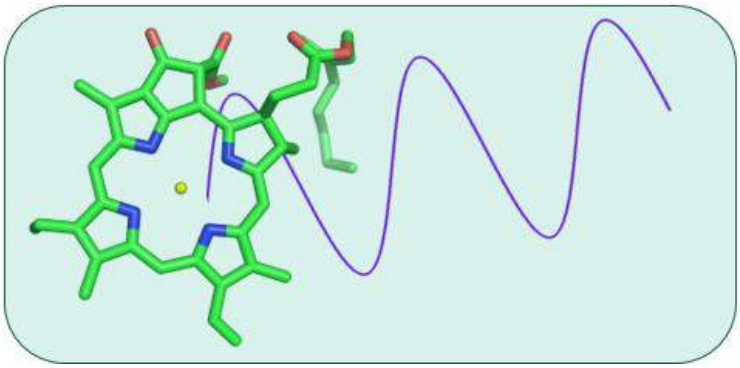
PSII functions to capture **light energy** and convert it to **chemical energy**. PSII als creates the **oxygen gas** that we breathe as a waste product from getting hydrogen from water.

PSII contains **chlorophyll**, the **pigment** that makes plants green. We know the exact structure of PSII from X-ray crystallography.



2. How do plants capture light energy for photosynthesis?

A light wave is a waving electromagnetic field. The electric field causes charged particles, like electrons, to move. When this happens, energy is transferred from light to matter. This is called **light absorption**. Pigment molecules like **chlorophyll** can absorb visible light. Normally the molecule then loses the energy as heat.

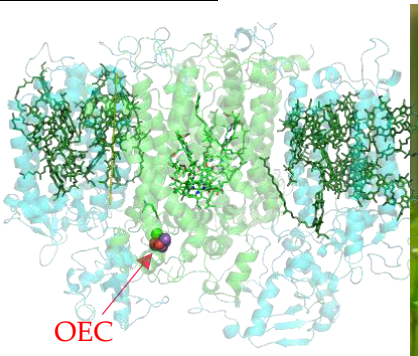


One special chlorophyll in photosystem II, called Chlorophyll D1 (also known as P680) can transfer an electron after it absorbs light energy. The electron moves along an electron transport chain without losing much of its energy. The **light energy** is thus captured as **chemical energy** which is used in photosynthesis.

3. How do plants make the oxygen gas that we breathe?

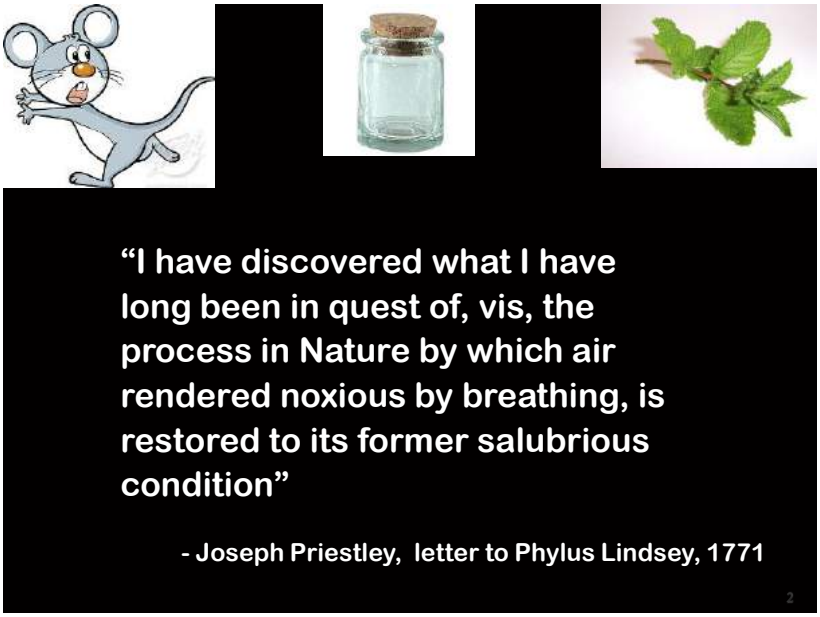
When the negative electron moves away from Chlorophyll D1, it leaves a positive charge behind. This positive charge "pulls" an electron from the oxygen-evolving cluster (OEC) of PSII.

The process repeats four times and the OEC ends up with a strong positive charge - enough to pull electrons out of water molecules.



Two water molecules break apart – hydrogen ions and oxygen atoms are left over. The hydrogen ions are taken away for use in photosynthesis. The two oxygen atoms combine to form O_2, – oxygen gas. This is a waste product of photosynthesis.

Tutorial 1 – The Oxygen Catastrophe



What is the Purpose of Tutorial 1?

- Know what photosystem II is, what it does, and how big it is
- Understand that photosynthetic life forms are the source of all oxygen gas (O_2) in the Earth's atmosphere.
- Be familiar with some of the new terms we will use in the course.

Staying alive: The Big Questions

Humans have always wondered about big questions. Even the earliest people must have realised that when we breath air, it goes "bad" - if you get stuck in an airtight box (or cave) you'd better get out, or make a hole for fresh air to come in!

Does something "replenish" the air so that we humans and our animal friends can keep breathing? Or is there simply so much air that it never runs out? Also, why do those bubbles form on underwater plants when the sun is on them?

How long do you think humans have known that you can "use up" air by breathing it?

How long do you think we have known that we need plants in order to breathe?

In the 1770s, nobody knew that **atoms** or **molecules** existed, and the idea of a chemical **element** was only just being born.

Joseph Priestley came from Yorkshire and was a clergyman, a teacher, a historian and a scientist (and had many other talents besides!). He learned a lot about gases, and invented carbonated water. Probably his greatest discovery was made using the apparatus shown below:

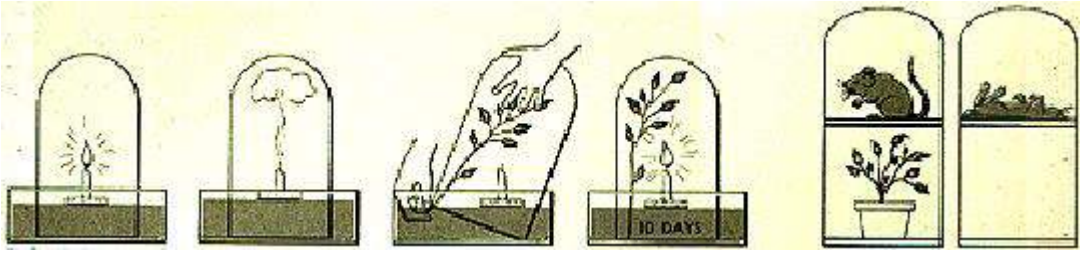


Figure 1.1: Joseph Priestley and some of his apparatus.

Look at the experiment diagram and the quotation from Priestley on the previous page.

What is the substance that makes air "noxious when it is breathed? What substance is needed to make air "salubrious"?

What process was he talking about? What did his experiments prove?

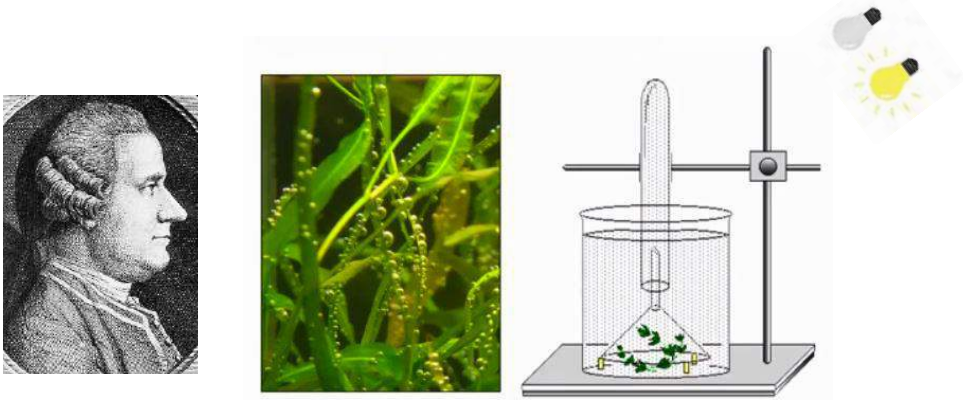


Figure 1.2: Jan Ingenhousz and one of his experiments

Jan Ingenhousz was a Dutch physiologist and chemist. He was an early pioneer of vaccination and helped begin the eradication of smallpox. He moved to England to pursue this work and visited Joseph Priestley at his house in Yorkshire in 1771. He was travelling at the time with *Benjamin Franklin* – a very famous American who also has a role later in this story.

Ingenhousz was inspired by Priestley to study the way plants could make "noxious" air breathable again. He discovered that the process **only worked when light was shining on the plants**.

How would he have used the experimental setup shown to discover this? (Is anything wrong with the picture, for 1771?)

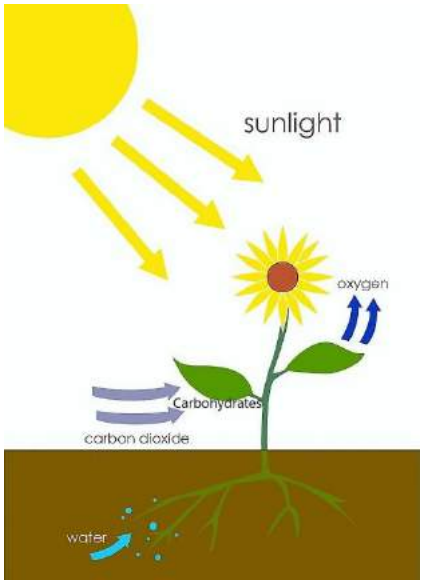


Figure 1.3: Photosynthesis.

"Photo" comes from a Greek work for light, and "synthesis" comes from the word for "putting together". The picture to the left shows the basic process of photosynthesis as we now understand it. Water and carbon dioxide are taken in, and those small molecules are put together into large molecules called carbohydrates, which make the plant grow. Light energy is needed to make this synthesis happen. Oxygen gas (O_2) is also formed – from the plant's point of view, O_2 is a waste product of photosynthesis!

All the oxygen gas that we breathe is made by plants and other photosynthetic organisms like algae. We owe our existence to them!

Below is the chemical equation for the overall reaction of photosynthesis. ***Can you write the names of each molecule underneath its chemical symbol?***
Hint: The large carbohydrate molecule is called glucose.

$$CO_2 + H_2O \xrightarrow{\text{Light}} C_6H_{12}O_6 + O_2$$

_____ + _____ _____ + _____

_____

Can you balance the chemical equation? How many CO_2 molecules are needed to get enough carbon for a glucose molecule?

This overall reaction occurs over many different steps. We will be looking at the very first step. It involves some **Big Questions**:

3. How do plants make the oxygen gas that we breathe?

This is one of the oldest questions in science. Nearly 250 years on from Priestley, it is still being answered!

2. How do plants capture light energy for use in photosynthesis?

We rely on energy from food to live, and plants provide this by harvesting the sun's energy. But how do they do it?

1. What is Photosystem II?

It's the topic of our course, and part of the answer to the other two questions!

Activity 1.1: Multi-disciplinary definitions

Photosynthesis is a very *multi-disciplinary* subject – it spans not only biology but also chemistry and physics!

Turn to the Subject Vocabulary and read the first SEVEN words and their definitions. For each word, rank Physics, Chemistry and Biology, in order of which subject you think uses that word the most often.

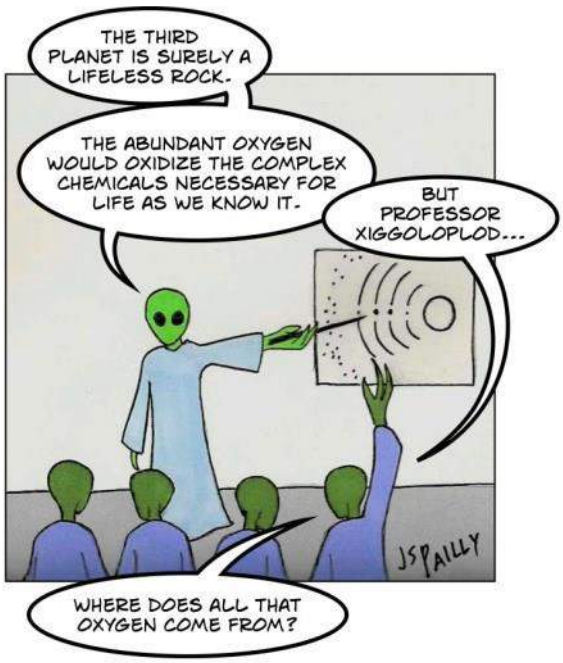
Definitions of physics, chemistry and biology are given below. These definitions are adapted from the Oxford English Dictionary – do you agree with them?

Physics: "The science concerned with the nature and properties of matter and energy. Physics includes mechanics, heat, light and other radiation, sound, electricity, magnetism, and the structure of atoms."

Chemistry: "The science concerned with the substances of which matter is composed, the investigation of their properties and the way they react to form new substances."

Biology: The study of living organisms, divided into many specialized fields that cover their morphology, physiology, anatomy, behaviour, origin, and distribution.

We will continue filling out the Subject Vocabulary each time we encounter a key word in our journey through biophysical chemistry (or should that be biochemical physics?)



The oxygen catastrophe!

It has been nearly 250 years since Priestley, and a lot has been learned since then. We now know that around 3 billion years ago, **there was no oxygen in the atmosphere** – so the only life that could exist was tiny **anaerobic** life forms.

Oxygenic photosynthesis evolved at this time – and this was perhaps the most monumental event in the history of life on Earth, because **Photosystem II produces oxygen gas**. Over the next 500,000 or so years, oxygen gas, which is poisonous to most anaerobic life, built up in the atmosphere. This Great Oxygenation Event (also known as the *oxygen catastrophe*) enabled animals and humans – which breathe using **aerobic** respiration – to evolve and thrive.
It's also why there is no pure iron in the earth's crust, along with many other metals – it has all been oxidised to form iron oxide.

As science and technology progressed, more and more detail was discovered. We are going nearly to the bottom, where we will find some things that are *really, really small!*

Fun fact: Some scientists searching for life on other planets look for signs of oxygen gas, because it is such an important part of life on Earth. But others think that alien life might not need oxygen!
(*Do you think the aliens in the cartoon breathe oxygen*?
What is the "third planet" that the Professor mentions?)

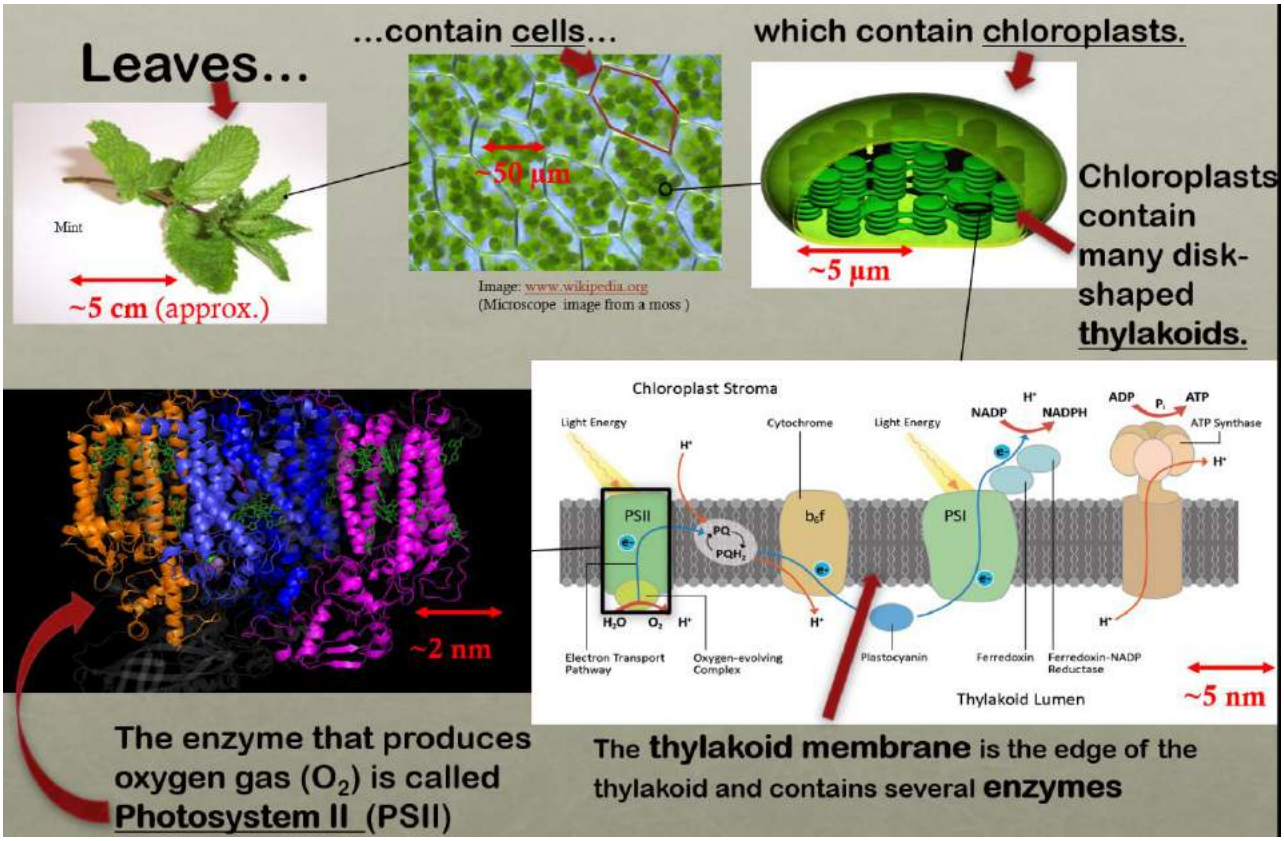


Figure 1.4: Zooming in to a leaf.

The Figure above summarises the last 250 years of discoveries about how plants make the oxygen gas we breathe.

- Photosynthesis occurs only in green **leaves**.
- Leaves are divided into **cells**, which are tiny but easy to see under a microscope.
- Inside cells are **chloroplasts**, which are the green part because they contain chlorophyll. (*chloros* was a Greek work for green).
- Inside chloroplasts are even smaller, disk-shaped structures called **thylakoids**.
- Around the outside of each thylakoid is a **thylakoid membrane** which is very, very thin.
- Insider the thylakoid membrane are the enzymes that carry out the first steps of photosynthesis. They are all **trans-membrane proteins** – they stretch right across the membrane..
- There are two **Photosystems** – called Photosystem I and Photosystem II. These are them enzymes that capture light energy.
- The enzyme that makes oxygen gas (O_2) is **Photosystem II**.

We have zoomed in to the main topic of our course!

Activity 1.2 : How big is a protein?

In science we sometimes encounter very large or small numbers. We use *prefixes* and *scientific notation* to make this easier. For example, a *gigabyte* in computing is a billion bytes.

Fill in the blank spaces in the table below.

Prefix	Symbol	Number	Scientific notation	English word:
Giga	G	1,000,000,000	10^9	Billion
		1,000,000		
			10^3	
----------	--------	1		One
		0.001	10^{-3}	Thousandth
	μ		10^{-6}	
Nano		0.000000001		
pico		0.000000000001		

Now look at the boxes below. Draw a line connecting each object to a size scale appropriate for describing the size of that object. You can use each length scale once, or more than once, or not at all.

Use Figure 1.4 for help - if you are unsure, draw no lines for now – future tutorials will reveal!

Protein molecule
Plant cell
Distance to space
Tree
Chloroplast
Chlorophyll molecule
Hydrogen atom

kilometres
metres
millimetres
micrometres
nanometres
picometres

What is the wavelength of visible light? How do the sizes above compare to this? What about microwaves? X-rays? We'll think more about light next week.

Homework: Baseline Assignment

Write a paragraph answering each of the three questions below (maximum of 100 words per question). Use what you have learned in the course so far and your own knowledge.

The preferred format is a Word document, but you can submit a written answer if you like. You will expand on the answers later and can use them in the final assignment. There is space below for making notes.

You will be assessed on your written communication including spelling, grammar and punctuation (SPaG), and your correct use of scientific terms.

1) What is Photosystem II?

2) How do plants capture light energy for use in photosynthesis?

3) How do plants make the oxygen that we breathe?

Tutorial 2 – Is a light wave longer than a protein molecule?

Image: www,biography.com

What is the Purpose of Tutorial 2?

- Know the wavelengths of different forms of electromagnetic radiation (especially visible light and X-rays)
- Understand how the size scales **from Figure 1.4** compare to the wavelength of visible light and X-rays.
- Know that proteins like are made from building blocks called *amino acids*
- Learn some basics of the PYMOL computer program for visualising X-ray structures of molecules. Use PYMOL to make a picture of Photosystem II like the one in Figure 1.4.

Isaac Newton was one of the fathers of modern science. He lived from 1642-1727 – well before Joseph Priestley, Jan Ingenhousz and Benjamin Franklin were meeting in Yorkshire and discussing photosynthesis (1771).

Newton made many dramatic discoveries in mathematics and science, including the work shown in the picture above: discovering that light can be split into different colours using a prism. Newton didn't know that light was a wave – he thought it was made of tiny particles. A Dutch physicist called Cristiaan Huygens did think that light was a wave – Newton and Huygens had a major argument about it. (The argument lasted for years and they got quite angry at each other!) The wave theory was finally proven correct in 1803, when Thomas Young demonstrated *interference* between light waves . But a century later in 1900, Max Planck proposed the "quantum theory", and in 1905 Albert Einstein suggested that light must act like a particle. Quantum physics was developed from 1900-1930, and it turned out that Newton and Huygens were both right – light acts as both a particle *and* a wave!

For now, we will focus on the waves…

Activity 2.1 : How long is a light wave?

The **wavelength** of a wave is defined as the distance from peak-to-peak. (or trough-to-trough). In fact, the change in position from any point on the wave to the next ***identical*** point is the wavelength.)

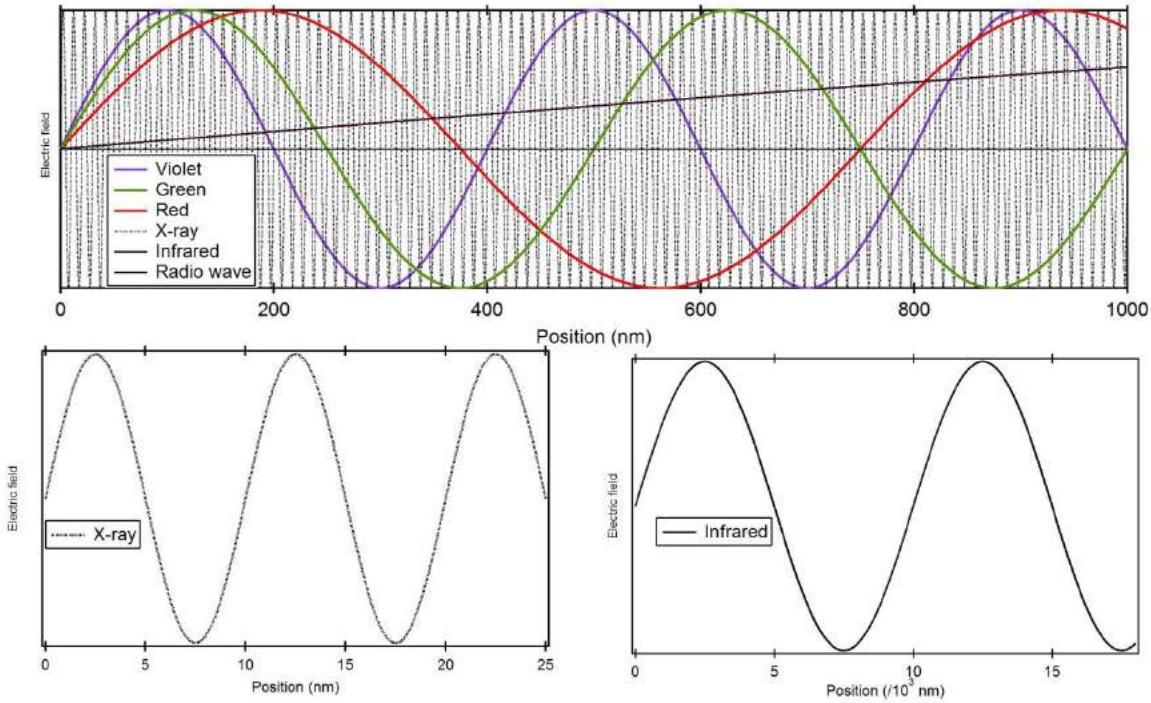


Figure 2.1: Graph showing wavelengths of some example light waves

a) Work out the wavelength of each wave shown in Figure 2.1. Fill in the wavelength in the middle column of the table below

b) In the right column, fill in the *wavelength range* for that type of wave, which you can find in Figure 2.2 below.

	Wavelength in Figure 2.1	**Wavelength Range (Figure 2.2)**
X-ray	10 nm	
Ultra-violet		
Visible light (violet)		
Visible light (green)		
Visible light (red)		
Infrared	10,000 nm (10 μm)	
Microwaves		1 - 300 mm
Radio waves		> 300 mm

Table 1: Wavelengths of electromagnetic radiation

Microwaves have a confusing name – they are on the millimetre to centimetre size scale, bigger than micrometers!

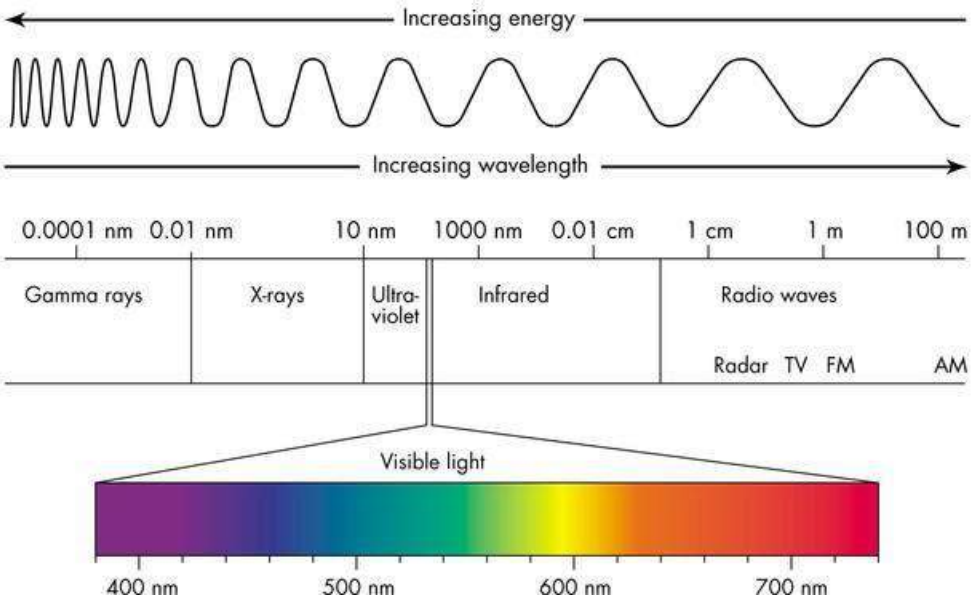


Figure 2.2: Wavelengths of light. *Note: microwaves (0.1 to 30 cm) are counted as radio waves in this figure.*

Discussion questions: What do our eyes detect when we see something?
What path has the light taken to arrive at your eyes and enable you to see an object?

How big do you think is the smallest thing you could see without using magnification? What about with the best microscope?

Activity 2.2 : *Is* a light wave longer than a protein molecule?

Which is longer, the **Wave** → or the **Object?** ↓	Wavelength→ Object size ↓	**Microwaves:** 1-30 cm	**Visible light:**	**X-rays:**
Leaf	cm	~same	leaf	leaf
Plant Cell	50-100 µm	microwave		
Chloroplast		microwave		
Protein complex (eg PSII)				
Chlorophyll molecule				

Fill in all the boxes you can with "Longer" if the wave is longer than the object, "Shorter" if the wave is shorter, or "Same" if the wave is about the same size.
For example, the wavelength of microwaves is about the same length as a leaf, but longer than a plant cell. A leaf is longer than either a visible light wave or an X-ray.

Refer to Figure 2.1 and your work in Activity 2.1 for help. If you aren't sure of a size, leave it blank for now – you will learn in the near future!

How can you take a picture of a molecule?

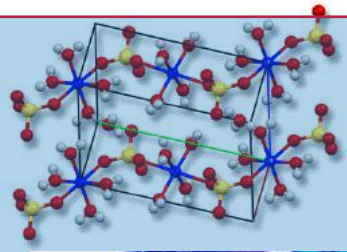
The smallest objects we can see, even under a microscope are **about the same size as the wavelength of the light we use to see them.** This is true even with the best microscopes!

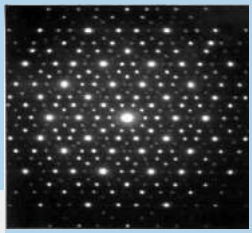
To "see" smaller objects, sophisticated technology has been developed. A powerful method known as "X-ray crystallography" lets us "see" even the positions of atoms within molecules.
The distance between atoms only is about 200 pm, or 0.2 nm.

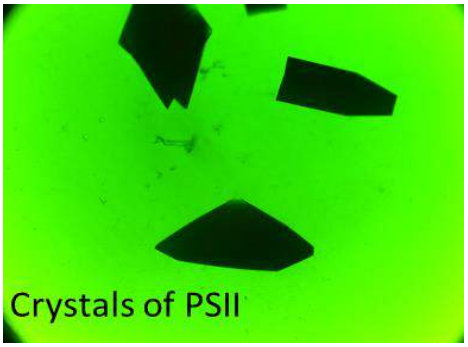
What type of light wave has its wavelength in this size range?

Using light with wavelength below 1 nm, you can *take a 3-dimensional picture of a molecule** showing where each atom within the molecule is! This the picture is commonly called an "X-ray crystal structure", or just a crystal structure.

***X-ray Crystallography** is a bit harder than just taking a picture of a molecule. The image has to be from a *crystal*. **In a crystal, all the molecules are lined up in a regular arrangement.** An image called a diffraction pattern is made by measuring the way X-rays bounce off the crystal, and it must be analysed using complex algorithms
An example is shown to the right: Blue crystals of copper sulphate, and the crystal structure obtained by analysing the "X-ray diffraction pattern" (far right).







Making crystals of small molecules is usually quite easy – you will probably do it in high school. Making crystals of very large molecules like proteins is extremely difficult!

*Professor **Jian-Ren Shen** from Okayama University (above right) and Professor **Petra Fromme** from Arizona State University (above left) may win a Nobel prize in the future, for their work making and studying crystals of Photosystem II.*

Activity 2.3: Make a picture of the Photosystem II protein complex

Professor Shen (pictured above) and his students at Okayama University have made crystals of Photosystem II and used X-rays to get a crystal structure. The structure is a list of coordinates, describing where each atom is in the molecule. The molecule can be displayed using computer software written for this purpose. You will use a program called PyMol to learn about the structure of photosystem II, and make a picture of your own.

You can look at the structure of nearly any protein yourself. PYMOL can be downloaded from www.pymol.org, and protein X-ray structures can be found in the Protein Data Bank at www.rcsb.org/.

Save your work after each step!

1. **Open the file containing the structure of Photosystem II**. This should display a picture of PSII. Spend a few moments learning how to rotate (left click), move (middle click), and zoom (right click).

2. **Display the amino acid sequence**.
Click Display >> Sequence. This shows the "amino acid sequence" at the top of the screen – each letter represents an *amino acid* molecule. These are the building blocks of proteins. Experiment with clicking on some amino acids on the molecule and on the sequence. Use the "selecting" option at the bottom right to select different-sized blocks of the protein complex. Selecting >> Residues lets you select single amino acids.

3. **Show a single amino acid.**
Let's look at one building block. First, hide the entire protein complex. (click H >> everything).
Select an amino acid (one letter) at random from the sequence at the top. Click Show > sticks. Zoom in. Each corner represents an atom. Check the amino acid list in Appendix A. Which amino acid have you chosen? Can you tell which colour corresponds to which element?

4. Show an alpha helix
Select a series of amino acids along the sequence, by clicking and dragging along the letters at the top of the screen. Can you find a series that makes a spiral structure? This is called an "alpha helix".
Show an alpha helix as sticks. Then hide it and show it as a cartoon.

5. Show a protein.
Photosystem II is a **protein complex**, which means it is made up of several proteins stuck together. In the sequence, the proteins are labelled A, B, C and D.

Scroll all the way to the left of the sequence, and you will see the label for protein A. Choose Selecting >> Molecules at the bottom and click on any amino acid letter from protein A. This will select that entire protein. Show the protein as a cartoon

6. Name your protein and change it's colour.
Protein A which you have selected is part of the Reaction Centre of photosystem II. It is also known as D1. This is where the capture of light energy for photosynthesis happens!

On the right, beside (sele), click A>>rename selection. Rename "sele" to "Reaction_Centre_D1"

Change the colour of the Reaction_Centre_1 protein by clicking on the colourful C next to it's name to the right. Choose a colour you like from the list.

7. Name the other proteins and change their colours.
The "D" protein should be called "Reaction_Centre_D2". The "B" protein should be called "CP47". The "C" protein should be called "CP43".
For each of these proteins, select it like you did in step 5, then rename it to the name given above. Then, choose a colour for the protein like you did in step 6.

8. Show the chlorophyll molecules
Photosystem II has many chlorophyll molecules bound to it – 35 in fact! They are in the sequence with the amino acids. Their code is CLA.

Scroll all the way through the sequence, and select every CLA you see. Rename the selection to "Chlorophyll". Choose a colour you like for the chlorophylls.

9. Make a picture of your Photosystem II protein complex with its bound chlorophylls.
Once you are happy with your colour scheme for the proteins and chlorophylls, orient the protein like in Figure 1.4, then make a picture by clicking Draw/Ray. Save your picture somewhere safe.

You can change the background colour under Display>>Background. Make one picture with a black background and one with a white background. Which do you prefer?

Below is a Figure from a scientific article showing some of the chlorophylls from Photosystem II, made using the same methods you have just learned.

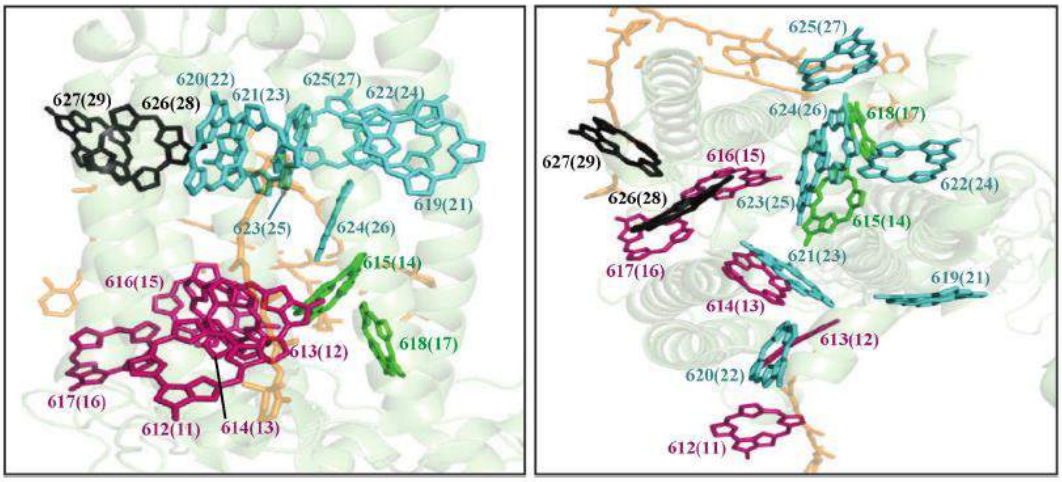


Fig. 1. Chlorophyll *a* (Chl) molecules of CP47 from the X-ray structure at 1.9 Å resolution [17]. Left: "Side-on" view, from in the membrane plane with stroma above and lumen below. Right: "Top-down" view from the stromal side. Chlorophylls are labeled with the numbering system of Umena et al. [17] (earlier numbering of Loll et al. [18] in brackets). Strongly-coupled domains as determined by Shibata et al. [19] are shown by color: red, green, and cyan (R, G and C) with isolated (weakly-coupled) chlorophylls in black. The protein backbone is shown in pale green and β-carotene molecules in orange. In both views, the reaction center is located to the right. Figure was rendered from the 1.9 Å crystal structure [17] (PDB ID: 3ARC) using Pymol software.

Source: J. Hall, T. Renger, F Müh, R. Picorel and E Krausz; Biochimica et Biophysica Acta 1857 (2016) 115–128

This research paper was about the chlorophylls of the CP47 protein (Protein B). This is an antenna protein.

All of the chlorophyll molecules in PSII are closely packed together. This means that when one of them absorbs light energy, the energy can bounced around over all every different chlorophyll.

Activity 2.4 (Homework): Charges, electric fields, and photosystems.

Benjamin Franklin is probably best-known as one of the Founding Fathers of USA – he was a leader of the American Revolution and helped write the Declaration of Independence in 1776 – but he was also a very great scientist. He spent a lot of time in England and was good friends with both Joseph Priestley and Jan Ingenhousz. Priestley later had to leave England because of his views supporting the Revolution!

One of Franklin's biggest contributions to science involved static electricity: he realised that there were two opposite types of electric charge, and he labelled them "positive" and "negative".

Questions:

1) What is the definition of electric charge?

_____

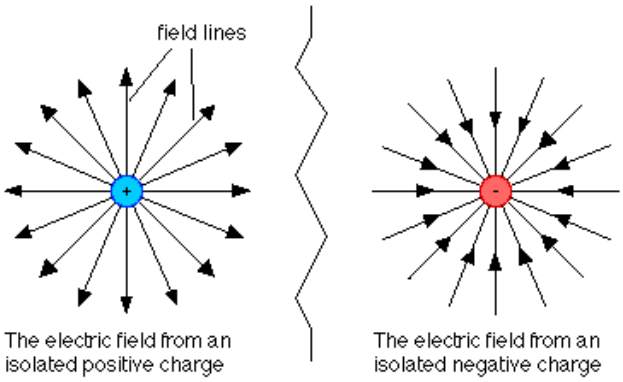
_____

2) Atoms are made from three types of "subatomic particles", called protons, neutrons and electrons.
Fill in the table with the charge and mass of each particle.
Clue: Neutrons are neutral

Particle	Charge	Relative Mass
Proton		
Neutron		
Electron		

3) Electric fields have a direction, which can be represented by arrows. The picture (right) shows the electric fields caused by the charges on a proton (blue) and an electron (red).

An electric field causes charged objects to experience a force. You should remember:
Like charges repel; Opposite charges attract.



If a proton were placed in an electric field, which direction would it move in – the same direction as the field lines, or the opposite direction? _____What about an electron? _____

4) We know that light is a wave. But what is it that actually "waves" up and down in a light wave?
(Hint: look at the y-axis of Figure 2.1, from the tutorial.

_____

5) Using the answers from questions 1-4**: Could a light wave make an electron move? _____**

6) **Using what you have learned in this tutorial, and your own research, expand on your earlier answer to the first Big Question – What is Photosystem II – to at least 300 words.**

You may wish to write about: -- Where *is Photosystem II found? – How big (or how small!) is PSII? -- How do we know the structure of PSII? -- What are the functions of PSII? – Whose experiments marked the beginning of modern research in this field? What impact has photosystem II had on our planet?*

WE WERE GOING TO USE THE TIME MACHINE TO PREVENT THE ROBOT APOCALYPSE, BUT THE GUY WHO BUILT IT WAS AN ELECTRICAL ENGINEER.

www.xkcd.com/567

Fun facts:

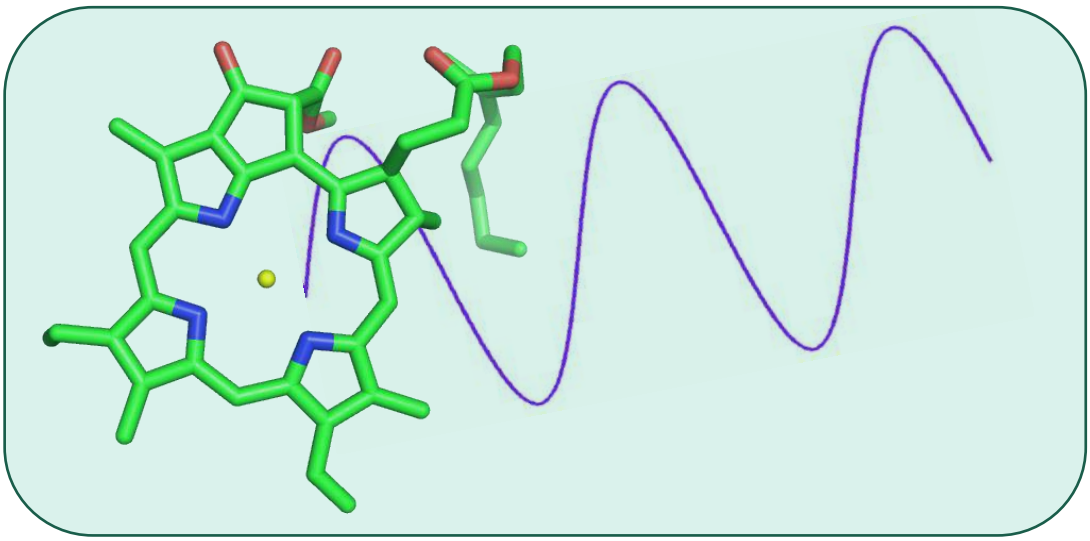
When silk or wool is rubbed on glass, static electricity builds up because electrons are transferred from the glass to the silk. But in the 1700s, Benjamin Franklin didn't know about electrons or protons.

Franklin chose to call the charge on the silk *negative* charge, and the charge on the glass *positive*. This arbitrary decision is why we now call the charge of electrons negative and the charge of protons is positive.

Electrical engineers would prefer if electrons had the positive charge, because it would make circuit diagrams and electric current easier to understand. Nobody else minds very much!

If you are interested in which substances can create static electricity, try searching for "Triboelectric series"

Tutorial 3 – How to Capture Light



What is the Purpose of Tutorial 3?

- Know that energy can be stored in different forms and change between forms;
- Understand how light waves can transfer their energy to matter (physical objects);
- Have a picture of the important functional parts of Photosystem II;
- Understand how light energy is captured by PSII.

The picture above represents a light wave with a molecule of Chlorophyll a. *Chlorophylls are quite large molecules, but far smaller than proteins. Each corner represents an atom; the green corners are carbon atoms, blue are nitrogen, red are oxygen. The yellow circle in the middle is magnesium.*

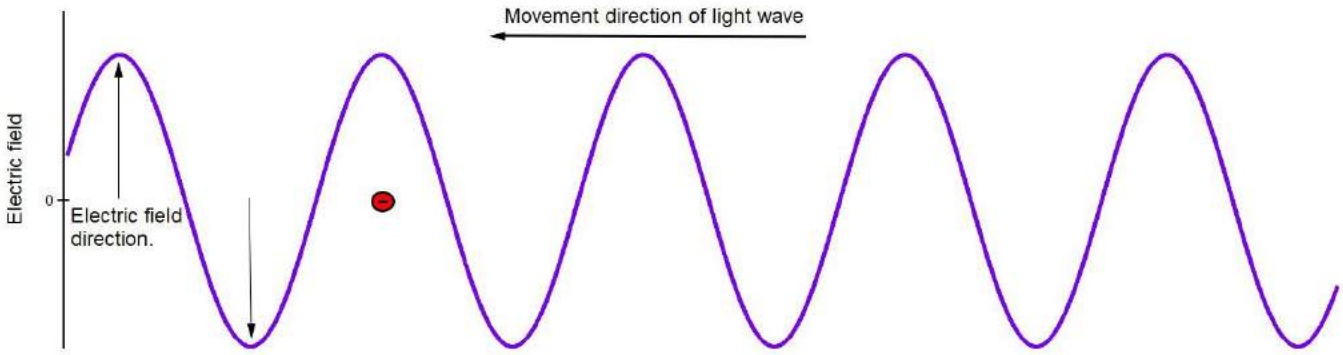
Activity 3.1: What is Energy?

Turn to the Subject Vocabulary and find the terms **"Energy", "Light energy", Chemical energy", "Heat energy"**. Read the definitions – do you think they are used in biology, chemistry or physics the most?

Discussion question: How can we observe each of the above types of energy?
When might you observe one type of energy being transferred into another type of energy?

Activity 3.2: How can light energy be captured? (It's the electrons!)

Electrons have charge, but are very light so they can move easily (see your table in Activity 2.4) The movement of electrons is very important in the processes of life. In this activity we will learn how light waves can make electrons move!



<u>Figure 3.1</u>: A light wave moving past a free electron.

Figure 3.1 represents a light wave travelling to the left, over an electron (the red circle). The electric field direction is shown at two points on the wave.

You have learned that charged particles experience a *force* when they are in an electric field.

The force experienced by a *positively* charged particle in an electric field is in the *same direction* as the field. For a *negatively* charged particle is in the *opposite* direction.

1) **Draw an arrow showing the direction is the light's electric field pointing at the place in the wave where the electron is?**

2) **In a different colour, draw an arrow showing the direction of the <u>force</u> that the electron feels.**

3) **Assuming the electron is free to move, what direction will it move in?** _____

4) The light wave is moving to the left**. Describe the movement of the free electron as the wave moves past it.**

_____

5) Complete the sentence: **If the electron starts moving because of the light wave, it means that**

_____ has been transferred from the _____ _____ to the _____.

This process is called _____ of light.

> This energy transfer to electrons is the what causes objects to absorb light energy!
>
> However: Electrons that are stuck inside a molecule are not totally free to move, which means they can only absorb ***certain wavelengths*** of light. Which wavelengths depends on the molecule.
>
> Wavelength that don't get absorbed can be reflected, and this determines the ***colour*** that we see.

Absorption of light energy by chlorophyll is the first step of light energy capture in photosynthesis.

What wavelengths of light do you think chlorophyll can absorb? Which wavelength does it reflect? Why do you think this?

Activity 3.3: The key to light capture: Electron transfer.

The very first step of light energy capture for photosynthesis is the absorption of light energy by chlorophyll.

But it's nothing special for a pigment molecule to absorb light – the pigments that colour your clothes are doing that right now, and they aren't photo-synthesising! The light energy they absorb is just turned into heat energy. (You'll notice this when you're in the sun, especially in dark clothing which absorbs lots of light energy!)

Instead of turning light energy to heat energy, Photosystem II captures it as chemical energy for use in photosynthesis. It does this by electron transport – the electron that absorbs the light energy is moved away and locked into it's high-energy state, before the energy can be lost as heat.

You will now make a picture showing the *electron transport chain* along which moves electrons move. Don't worry about the unfamiliar terms – they are just labels for each step in the chain. Our aim is to get a picture of the whole chain.

1. **Open your picture from last time and make sure the orientation is the same as in Figure 1.4**
   Remember to save your work after each step!

2. **Hide all of the chlorophylls, then make the alpha helices fade out so they are only just visible**.
   First click H>>everything next to your "Chlorophyll" selection,
   then click Display>>Transparency>>Cartoon>>80%

3. **Show the primary electron donor, Chlorophyll D1 (P680)**
   In the sequence of Protein A, find and select the CLA with number 406 above it.
   Next to (sele) click A>rename selection and rename "sele" to "Chl_D1_P680"
   Show >> Sticks and change the colour of Chl_D1 to something bright.

3. **This is a very special chlorophyll**. When it absorbs light, instead of losing the energy as heat, it transfers an electron and becomes **positively charged**.

4. **Show the primary electron acceptor, Pheophytin D1.**
   In the sequence of Protein A, find and select the first PHO (number 408)
   Click A>>rename selection and rename "sele" to "Pheo_D1"
   Show >> Sticks and change the colour of Pheo_D1 to something bright.

4. This is where the electron from Chl_D1 (P680) gets transferred to first. (Pheophytin is an almost identical molecule to chlorophyll)

5. **Show the secondary electron acceptors, Plastoquinones.**
   There are two "PL9" molecules in the sequence: Protein A no. 414 and protein D no 405. Select them both.
   Click A>>rename selection and rename "sele" to "Plastoquinones"
   Show >> Sticks and change the colour of Plastoquinones to something bright.

5. The electron is not finished moving: It moves to one of these molecules, on the very edge of Photosystem II. From here, it can be taken away and used for other reactions. **Light energy has been captured**!

6. **Show the chlorophyll called P_{D1}**
   In Protein A, find and select the CLA number 405.
   Click A>>rename selection and rename "sele" to "P_D1"
   Show >> Sticks and change the colour of P_D1 to something bright.

6. This chlorophyll is another part of the electron transport chain.

7. **Show the redox-active tyrosine.**
In the sequence of protein A, find the Y amino acid number 161.
Click A>>rename selection and rename "sele" to "Tyrosine"
Show >> Sticks and change the colour of Tyrosine to something bright.

7. Tyrosine is a special amino acid that can transfer electrons. This tyrosine is another step in the chain

8. **Show the Oxygen Evolving Cluster (OEC)**
In the sequence of Protein A, find and select OEX.
Next to (sele) Click A>>rename selection and rename "sele" to "OEC"
Now next to OEC, click show>> **Spheres.**

The positive charge that was left on Chl_D1 pulls an electron out of the OEC, through the tyrosine and the PD1 chlorophyll. The **positive charge** is now on the OEC. This will be used to make O_2 from two molecules of H_2O!

9. **Save a picture or two of PSII showing the electron transport chain!**
Make at least one picture with a white background (Display >> Background>>White)

The oxygen evolving cluster (OEC) contains manganese, calcium and oxygen**. (**it's formula is Mn_4CaO_5)
Each time Photosystem II absorbs light, an electron is moved along the electron transport chain from the OEC all the way to the plastoquinones.

What effect will this have on the charge of the OEC as more light is absorbed?

STILL UNKNOWN: The "Chlorophyll D1" molecule from step 3 is also known as P680. This is the chlorophyll that transfers an electron to capture it's chemical energy instead of losing the chemical energy as heat. There is something very special about the pigment and the protein around it that enables it to do this "charge separation". We still don't know exactly what it is!

Activity 3.4 (homework): Amino Acids and Energy Capture

The "building blocks" of proteins are small-ish molecules called **amino acids**. These consist of just a dozen or so atoms.

The chemical structures of some amino acids are shown in Appendix 1. *(Don't worry if you find them confusing – we are not concerned with the details of chemical structures in this course.)*

1) All amino acids contain Carbon, Nitrogen and Oxygen atoms.

What are the chemical symbols for each of these elements? _____ _____

2) There are 20 naturally-occurring amino acids. Appendix 1 shows all 20, plus 1 artificial amino acid.

Which is the artificial amino acid in Appendix 1? _____
Helpful hint: ***The element selenium (Se) is never found in natural amino acids.***

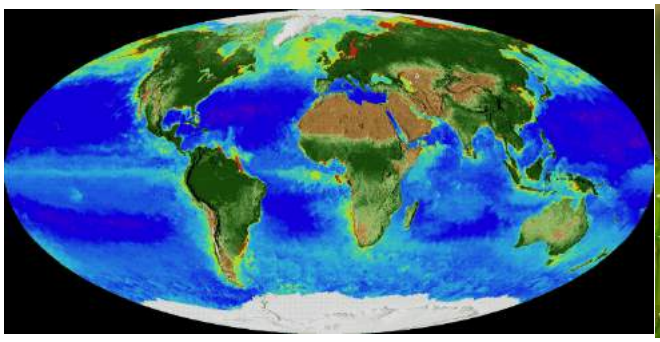
3) **What other element apart from carbon, nitrogen and oxygen can be found in *natural* amino acids?**

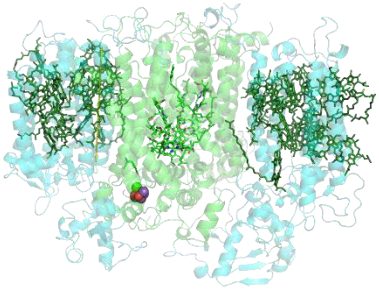
_____

4) **Using what you have learned in this tutorial, and your own research, expand on your earlier answer to our second big question – How do plants capture light energy for photosynthesis – to at least 300 words.**

You may wish to write about: -- *What is light, and how does it make electrons move? What type of energy is usually formed after "normal" pigment molecules absorb light? What molecules in plants can absorb light? What happens when those molecules absorb light in Photosystem II?*
You might also do your own research on Photosystem I, the Calvin Cycle, the Z-scheme, or other steps of photosynthesis.

Tutorial 4: How the Earth Breathes – *thanks to the plants*.





What is the Purpose of Tutorial 4?

- Learn where our oxygen comes from. (It involves the Oxygen Evolving Cluster of Photosystem II!)
- Draw a diagram showing where electrons move in Photosystem II.
- Try to understand what photons are. (The weirdness of quantum mechanics!)
- Use the simple equation relating light wavelength and "photon energy".

Activity 4.1: What powers life on Earth?

Complete after discussion in pairs and with the class.

What processes in biology involve the transfer of chemical energy into other forms of energy?

_____

_____

_____

_____

What processes involve the conversion of other forms of energy to chemical energy?

_____

_____

What do you think is a good, concise answer to the question: "What powers life on earth?

_____

_____

Activity 4.2: What makes the oxygen we breathe?

Take your picture of photosystem II showing the electron transport chain. Draw a series of arrows showing the individual steps along the chain.

Answer the questions after discussion with the group and teacher.

1) What happens each time a chlorophyll molecule in Photosystem II absorbs light?

_____

2) Each plastoquinone molecule can accept two electrons.

Once four electrons have been moved, what is the total charge on the Oxygen Evolving Cluster? _____

3) When the OEC is fully charged, two water molecules bind to it next to each other. This results in a very special chemical reaction:

$$OEC^{4+} + 2H_2O \rightarrow OEC + O_2 + 4H^+$$

Before the reaction (left hand side) the OEC has gained a charge of 4+. How did this happen?

_____

4) After the reaction, the OEC has lost its 4+ charge. What happened to cancel out the OEC's positive charge?

_____

_____

5) Where did the four hydrogen ions (H^+) in the product of the reaction (right hand side) come from?

_____

6) What is left over from the two water molecules when four electrons and four hydrogen ions are gone? What happens to these atoms?

_____

7) Write a short paragraph describing how O_2 is produced in the oxygen evolving complex of Photosystem II.

_____

_____

_____

_____

Oxygen gas isn't important to plants for photosynthesis – they want the hydrogen!

In the overall reaction for photosynthesis (Tutorial 1), you can see that hydrogen from water (H_2O) is added to carbon dioxide (CO_2) to make glucose**.** Humans would like to know how to this reaction works – it would help us to create a sustainable, carbon-neutral fuel from CO_2. But it turns out that getting rid of the oxygen is the tricky part.

STILL UNKNOWN:
The precise mechanism of the oxygen evolution reaction is still not known by biophysicists. In particular, the way the O=O bond is formed remains one of the great unresolved questions of photosynthesis research.

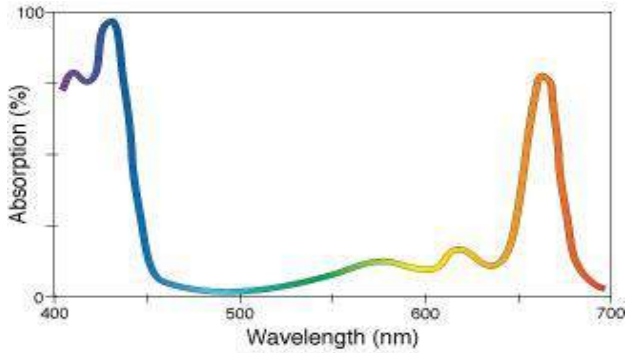
Activity 4.3: (homework)

Using what you have learned in this tutorial, and your own research, expand on your earlier answer to the third Big Question – How do plants make the oxygen we breathe – to at least 300 words.

You might want to include: *Which enzyme creates the oxygen? – A description of the functional parts of the enzyme -- How water is "split" by removing its electrons and hydrogen ions, and what happens to the leftover oxygen atoms.*

It may be helpful to write out the answer to each question in activity 4.2 as a sentence.
Space for notes is below.

Tutorial 5 – Why Are Plants Green?



What is the Purpose of Tutorial 5?

- The main purpose of tutorial 5 is to learn about the final assignment and start planning your assignment.
- With some help from quantum physics, we will also learn some more about the answer to another big question: *Why are plants green?*

Activity 5.1: The quantum strangeness of light.

Waves are smooth and continuous. But you may have felt that when light is absorbed by a molecule (like chlorophyll), things are not entirely "wavelike". The molecule is either absorbs light or it does not – it is a *discrete* event, with no smooth in-between.

This is an example of light acting like a *particle* instead of a wave. This behaviour can only be understood using quantum physics. In 1900, Max Plank solved a bad problem for physics (it was called the Ultraviolet Catastrophe!) by suggesting that light came in discrete packets and that each light particle, or *photon*, had an energy that depends on it's wavelength.

Planck's formula was $E = hc/\lambda$

E is the *photon energy*, λ is wavelength, c is the **speed of light,** and h is the **Planck constant**.

What is the speed of light? (include units) _____

What is the Planck constant? (include units) _____

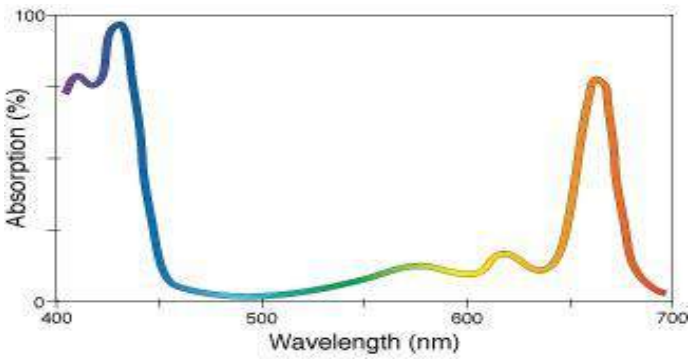
Chlorophyll in a cell. Light of known wavelengths can be shined through the cell and detected, to measure the absorption spectrum, like the one shown above.

Activity 5.2: The absorption spectrum

As we have discussed previously, plants are green because chlorophyll absorbs both red light and blue light, but *not* green light.

A chlorophyll molecule is far smaller than the wavelength of visible light. Why should it care if the wavelength is red, green or blue? The answer is that a molecule can only absorb light with certain *photon energies*.

In tutorial 3, we learned that an electron can absorb light provided it can move. But when the electrons are confined in a small space, they follow the rules of quantum physics. Because of this they have not only limited movement but also limited possible **energy.** This is why only certain photon energies can be absorbed.



Above is the **absorption spectrum** of chlorophyll. It shows which wavelengths of light are absorbed by a chlorophyll solution.

1. What is the wavelength of light at the red absorption peak? (estimate to the nearest 10 nm) _____

2. What is the wavelength of light the blue absorption peak? _____

Using Planck's formula:

3. What is the photon energy of light at the red absorption peak? _____

_____

4. What is the photon energy of light at the blue absorption peak? _____

_____

5. Complete the sentence:

"Plants contain the pigment _C_____ which can absorb visible light. However, it can only absorb visible light with __P_____ energy of around _____ or _____. The wavelengths that this corresponds to are _____ and _____ which are the wavelengths of _____ and _____ light respectively. Therefore, these colours are absorbed, and the other light, whose colour is mainly _____ ___ is reflected."

What question have you just answered? _____

Final Assignment

A popular science article should be engaging, interesting, accessible, and accurate.
You are a science writer for a popular science magazine. Your editor thinks that the story of Photosystem II could be interesting and informative for the magazine's readers. Using what you have learned in the course and your own research, write a story about photosynthesis with an emphasis on Photosystem II. The target audience is the readers of a popular science magazine – i.e. intelligent laypeople who are interested in science.

A good science magazine article should:

- Begin with a strong opening paragraph that captures the imagination and makes the reader interested to learn more.
- Justify to the reader why the subject is interesting, important, or relevant to them.
- Have a logical order, structure and flow using good English.
- Use scientific terms, but make sure they are clearly explained so that an "intelligent layperson" can understand
- Make good use of illustrations or figures, to communicate ideas and make the article visually attractive. This may include a large "cover illustration" for the first page of the article.
- Contain some "human interest" – stories involving people as well as science.
- Discuss a range of interesting ideas without straying too far from the main topic.
- Give some history of the subject.
- Be engaging, interesting, accessible, and accurate.

The word limit for your article is 3000 words. However, a good, relevant picture can be worth a few hundred words! You may choose to present your article with a strong emphasis on illustration and presentation.
The minimum word count is 1500 – in this case, you should have several high-quality illustrations that help to communicate your ideas and are attractive to look at.

A good place to begin planning your story is with the big questions that you have already given some thought to. You can add anything that we have covered in the course, or anything that is related to the subject from your own research.

Tutorial 6 – Feedback tutorial 1

What is the Purpose of Tutorial 6?

- To receive feedback on draft assignments.
- To share examples of best practice with the other pupils in your group.
- To write targets for improvement for your final submission .
- To ask any questions you may have about the assignment, the course, or science. (Anything, really!)

Draft assignment feedback

What I did well…	What I can improve on…
•	•
•	•
•	•

My targets for my final submission are…

Tutorial 7 – Final Feedback tutorial

What is the Purpose of Tutorial 7?

- To receive feedback on final assignments.
- To share examples of best practice with the other pupils in your group.
- To write targets for improvement in school lessons.
- To reflect on the programme including what was enjoyed and what was challenging.

Final assignment feedback

What I did well…	What I could have improved on…
•	•
•	•
•	•

My target for future work is…

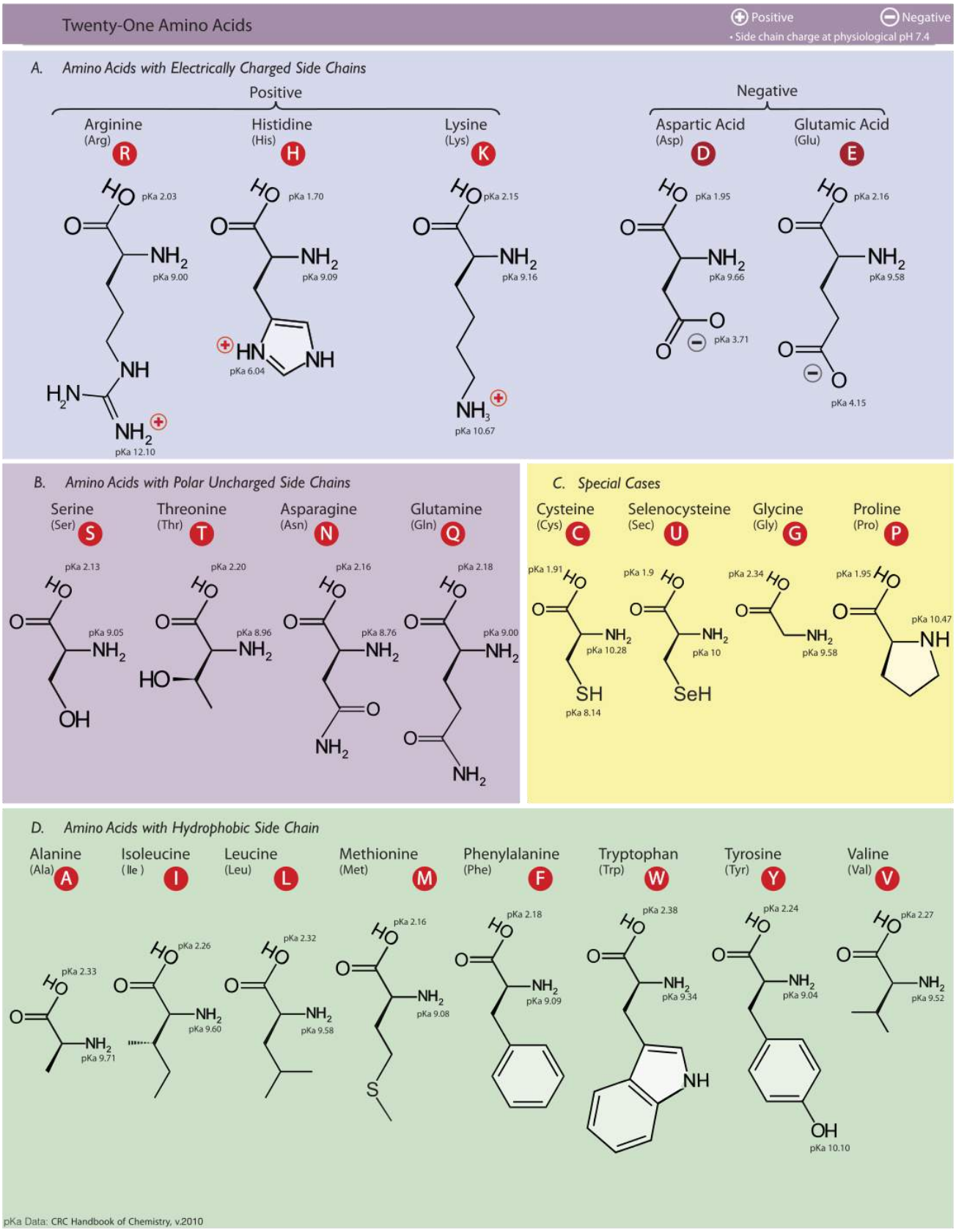
Reflecting on Uni Pathways

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

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

Appendix 1 – Chemical structures of amino acids

The chemical structures of the amino acids are shown below. The molecules below join together as building blocks to form all the proteins that are essential to life.
They are drawn in a style used at university-level: Each line represents a chemical bond, and each corner between bonds represents a carbon atom. Non-carbon atoms are represented by their chemical symbol. Hydrogen atoms attached to carbon atoms are not shown.



Dan Cojocari, Department of Medical Biophysics, **University of Toronto**, 2010

Appendix 2 – 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 I 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.

Notes

Notes

Notes

How the Earth Breathes:
Photosystem II

Key Stage 4 Programme

Cover image credit: NASA

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