State that photosynthesis involves the conversion of light energy into chemical energy.

- Location: chloroplast or prokaryotic equivalent.
- Reaction: Traps light energy (photons) and converts it into chemical energy.
- Organisms: Prokaryotic and Eukaryotic
- Substrate: Inorganic CO$_2$ and H$_2$O
- Products: Organic compounds (sugars) and O$_2$
- Environments: Aquatic environments with light, terrestrial environments with light. There are even extremophiles that can photosynthesis at some extreme latitudes and altitudes. At extreme high temperatures we see photosynthesis in geothermal active regions.

State that light from the Sun is composed of a range of wavelengths (colors).
▪ Light form the sun is composed of a range of wavelengths (colors).

▪ The visible spectrum to the left illustrates the wavelengths and associated color of light.

▪ Combined together these wavelengths give the 'white' light we associate with full sunlight.

▪ The shortest wavelengths are the 'blues' which have more energy.

▪ The longer wavelengths are the 'reds' which have less energy.

**State that chlorophyll is the main photosynthetic pigment.**

▪ **Chlorophyll is the main photosynthetic pigment.** This is where light energy is trapped and turned into chemical energy.

▪ The head of the molecule is polar and composed of a ring structure. At the heart of this ring structure is the inorganic ion magnesium. This is the light trapping region of the chlorophyll molecule.
▪ The tail of the molecule is non polar and embeds itself in membranes in the chloroplast.

▪ There are other pigments, reds, yellows and browns but these are only usually seen in the experimental chromatography or if you have been lucky enough to witness the autumnal colors of deciduous trees in a temperate climate.

Outline the differences in absorption of red, blue and green light by chlorophyll.

▪ The details of this image are not important and need not be learned for the SL course.

▪ The 'peaks' show which wavelength of light are being absorbed.

▪ Look at the x-axis for colors of light absorbed at the 'peaks'.

▪ **The main color of light absorbed by chlorophyll is red and blue.**

▪ **The main color reflected (not absorbed) is green.**

▪ Hence why so many plants are seen as green, the light is reflected from the chlorophyll to your eye.
State that light energy is used to produce ATP, and to split water molecules (photolysis) to form oxygen and hydrogen.

- (a) Light is absorbed by chlorophyll molecules (green) on membranes inside the chloroplast.
- This is the light trapping stage in which photons of light are absorbed by the chlorophyll and turned into chemical energy (electrons).
- (b) The chemical energy (electrons) is trapped in making ATP.

Photolysis (c):
- Water used in photosynthesis is split which provides:
  - hydrogen for the formation of organic molecules. \((C_6H_{12}O_6)\)
  - oxygen gas is given off.
State that ATP and hydrogen (derived from the photolysis of water) are used to fix carbon dioxide to make organic molecules.\(^{(1)}\)

State means to give a specific name, value or other brief answer without explanation or calculation.

- H\(^+\) from the splitting of water are combined with carbon dioxide to form organic compounds like sugar.

- Bonds are formed between the carbon, hydrogen and oxygen using the energy from ATP (which came from the sun).

- C, H, O are enough to form lipids and carbohydrates.

- With a Nitrogen source amino acids and therefore proteins can be made.

- Plants have this remarkable ability to manufacture all their own organic molecules and by definition all the basic organic molecules required by all life forms.
Explain that the rate of photosynthesis can be measured directly by the production of oxygen or the uptake of carbon dioxide, or indirectly by an increase in biomass.

Processes like photosynthesis and respiration can be measured by either:

- Depletion of substrate.

- Accumulation of products

**Investigation:** Photosynthesis: Carbon dioxide + water ----> Organic molecule + Oxygen

The rate of photosynthesis can therefore be measured by:

- Depletion of substrate which includes measuring how much carbon dioxide has been used or how much water is used.

- Accumulation of product which might include measuring how much oxygen is produced or organic molecules (biomass) produced.

- In this simple experiment the accumulation of oxygen is measure of rate of reaction.

- Independent variable: Light Intensity or wavelength of light.

- Dependent variable $O_2$ volume against time
▪ Method the collection of gas over water.

▪ Specimen: Pond weed Elodea

The above set up represents a typical school laboratory experiment. Perhaps on a preparatory course for IB Biology you carried out this experiment. It is normal to count the bubbles per minute but it is possible to be more rigorous than this in determining and quantifying your dependent values. Spend some time revising the diagram, make modifications to improve the collection of valid and reliable data.

Outline the effects of temperature, light intensity and carbon dioxide concentration on the rate of photosynthesis.

The effect of temperature on the rate of photosynthesis:

Photosynthesis is a biological reaction and like all other such reactions there are steps that require the presence of enzymes.
Temperature as we have already met is a change in the average kinetic energy of the particle.

The graph the left should look familiar as this is the same one covered in the section on the effect of temperature on the rate of an enzyme catalysed reaction.

(a) Increasing rate of photosynthesis as the kinetic energy of reactants increases.

(b) Maximum rate of reaction of photosynthesis at the 'optimal' temperature.

(c) Decrease in rate of photosynthesis as the enzymes become unstable and denature.

The effect of carbon dioxide concentration on the rate of photosynthesis:

Carbon dioxide is one of the reactants of the reaction so this graph is very much like the effect of substrate on the rate of reaction.

(a) O₂ is used up as the plant is not photosynthesizing but only respiring.
(b) As the concentration of the carbon dioxide (substrate) increases the rate of reaction increases.

(c) The atmospheric levels of carbon dioxide and the associate rate photosynthesis.

(d) Maximum rate of photosynthesis (see section e).

(e) The is a range of values for different plants reaching their saturation level with carbon dioxide. One the saturation level has been reached there is no further increase in the rate of photosynthesis.

▪ The effect of light intensity on the rate of reaction.

▪ Light energy absorbed by chlorophyll is converted to ATP & H⁺

▪ At very low light levels (a) the plant will be respiring only not photosynthesizing.

▪ As the light intensity increases then the rate of photosynthesis increases.

▪ At high light intensities the rate becomes constant, even with further increases in light intensity there are no increases in the rate.
The plant is unable to harvest the light at these high intensities and indeed the chlorophyll system can be damaged by very intense light levels.

**Forms of oxidation and reduction.**

- In respiration the oxidation of organic compounds is coupled to the reduction of ADP to ATP.

- The oxidation of ATP is then coupled to biological processes such as muscle contraction of protein synthesis.

![Chemical reaction diagram]

**Oxidation:** often associated with the release of energy

\[ \text{A} \rightarrow \text{A}^+ + e^- \quad \text{loss of electrons} \]

\[ \text{A} + \text{O}_2 \rightarrow \text{A} \rightarrow \text{O} \quad \text{gain of oxygen} \]

\[ \text{A} + \text{H} \rightarrow \text{A} + \text{H}^+ \quad \text{loss of hydrogen} \]

**Reduction:** often associated with the gain of energy

\[ \text{A} + e^- \rightarrow \text{A}^- \quad \text{gain of electrons} \]

\[ \text{A} \rightarrow \text{O} \rightarrow \text{A} + \text{O}_2 \quad \text{loss of oxygen} \]

\[ \text{A} + \text{H}^+ \rightarrow \text{A} \rightarrow \text{H} \quad \text{gain of hydrogen} \]
Draw and label a diagram showing the structure of a chloroplast as seen in electron micrographs.
State that photosynthesis consists of light-dependent and light-independent reactions.

Explain the light-dependent reactions.

- **Role of Light**: Photosynthesis occurs inside chloroplasts. Chloroplasts contain chlorophyll, a green pigment found inside the thylakoid membranes. These chlorophyll molecules are arranged in groups called photosystems.
- There are two types of photosystems, Photosystem II and Photosystem I.
- When a chlorophyll molecule absorbs light, the energy from this light raises an electron within the chlorophyll molecule to a higher energy state. The chlorophyll molecule is then said to be photoactivated.
- Excited electron anywhere within the photosystem are then passed on from one chlorophyll molecule to the next until they reach a special chlorophyll molecule at the reaction center of the photosystem. This special chlorophyll molecule then passes on the excited electron to a chain of electron carriers.
- The light-dependent reactions starts within Photosystem II. When the excited electron reaches the special chlorophyll molecule at the reaction center of Photosystem II it is passed on to the chain of electron carriers. This chain of electron carriers is found within the thylakoid membrane.
- As this excited electron passes from one carrier to the next it releases energy. This energy is used to pump protons (hydrogen ions) across the thylakoid membrane and into the space within the thylakoids. This forms a proton gradient.
- The protons can travel back across the membrane, down the concentration gradient, however to do so they must pass through ATP synthase.
- ATP synthase is located in the thylakoid membrane and it uses the energy released from the movement of protons down their concentration gradient to synthesise ATP from ADP and inorganic phosphate. The synthesis of ATP in this manner is called non-cyclic photophosphorylation (uses the energy of excited electrons from photosystem II).
- **The electrons from the chain of electron carriers are then accepted by Photosystem I.** These electrons replace electrons previously lost from Photosystem I. Photosystem I then absorbs light and becomes photoactivated. The electrons become excited
again as they are raised to a higher energy state. These excited electrons then pass along a short chain of electron carriers and are eventually used to reduce NADP+ in the stroma.

- NADP+ accepts two excited electrons from the chain of carriers and one H+ ion from the stroma to form NADPH.
- If the light intensity is not a limiting factor, there will usually be a shortage of NADP+ as NADPH accumulates within the stroma (see light independent reaction). NADP+ is needed for the normal flow of electrons in the thylakoid membranes as it is the final electron acceptor. If NADP+ is not available then the normal flow of electrons is inhibited.
- However, there is an alternative pathway for ATP production in this case and it is called cyclic photophosphorylation. It begins with Photosystem I absorbing light and becoming photoactivated.
- The excited electrons from Photosystem I are then passed on to a chain of electron carriers between Photosystem I and II. These electrons travel along the chain of carriers back to Photosystem I and as they do so they cause the pumping of protons across the thylakoid membrane and therefore create a proton gradient.
- As explained previously, the protons move back across the thylakoid membrane through ATP synthase and as they do so, ATP is produced. Therefore, ATP can be produced even when there is a shortage of NADP+.
- In addition to producing NADPH, the light dependent reactions also produce oxygen as a waste product. When the special chlorophyll molecule at the reaction center passes on the electrons to the chain of electron carriers, it becomes positively charged.
- With the aid of an enzyme at the reaction center, water molecules within the thylakoid space are split. Oxygen and H+ ions are formed as a result and the electrons from the splitting of these water molecules are given to chlorophyll. The oxygen is then excreted as a waste product. This splitting of water molecules is called photolysis as it only occurs in the presence of light.
Explain photophosphorylation in terms of chemiosmosis.

Photophosphorylation is the production of ATP using the energy of sunlight. Photophosphorylation is made possible as a result of chemiosmosis. Chemiosmosis is the movement of ions across a selectively permeable membrane, down their concentration gradient. During photosynthesis, light is absorbed by chlorophyll molecules. Electrons within these molecules are then raised to a higher energy state. These electrons then travel through Photosystem II, a chain of electron carriers and Photosystem I. As the electrons travel through the chain of electron carriers, they release energy. This energy is used to pump hydrogen ions across the thylakoid membrane and into the space within the thylakoid. A concentration gradient of hydrogen ions forms within this space. These then move back across the thylakoid membrane, down their concentration gradient through ATP synthase. ATP synthase uses the energy released from the movement of hydrogen ions down their concentration gradient to synthesise ATP from ADP and inorganic phosphate.

**Explain the light-independent reactions.**

The light-independent reactions of photosynthesis occur in the stroma of the chloroplast and involve the conversion of carbon dioxide and other compounds into glucose. The light-independent reactions can be split into three stages, these are carbon fixation, the reduction reactions and finally the regeneration of ribulose bisphosphate. Collectively these stages are known as the Calvin Cycle.
Stage 1: During carbon fixation, carbon dioxide in the stroma (which enters the chloroplast by diffusion) reacts with a five-carbon sugar called ribulose bisphosphate (RuBP) to form a six-carbon compound. This reaction is catalysed by an enzyme called ribulose bisphosphate carboxylase (large amounts present within the stroma), otherwise known as rubisco. As soon as the six-carbon compound is formed, it splits to form two molecules of glycerate 3-phosphate. Glycerate 3-phosphate is then used in the reduction reactions.

Stage 2: Glycerate 3-phosphate is reduced during the reduction reactions to a three-carbon sugar called triose phosphate. Energy and hydrogen is needed for the reduction and these are supplied by ATP and NADPH + H+ (both produced during light-dependent reactions) respectively. Two triose phosphate molecules can then react together to form glucose phosphate. The condensation of many molecules of glucose phosphate forms starch which is the form of carbohydrate stored in plants. However, out of six triose phosphates produced during the reduction reactions, only one will be used to synthesise glucose phosphate. The five remaining triose phosphates will be used to regenerate RuBP.

Stage 3: The regeneration of RuBP is essential for carbon fixation to continue. Five triose phosphate molecules will undergo a series of reactions requiring energy from ATP, to form three molecules of RuBP. RuBP is therefore consumed and produced during the light-independent reactions and therefore these reactions form a cycle which is named the Calvin cycle.

Explain the relationship between the structure of the chloroplast and its function.

The stroma - Contains many enzymes, including rubisco, which are important for the reactions of the Calvin cycle.

The thylakoids - Have a large surface area for light absorption and the space within them allows rapid accumulation of protons.