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8.3 Photosynthesis

IB Biology - Revision Notes

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8.3.1 Light-dependent Reactions

Location of the Light-dependent Reactions

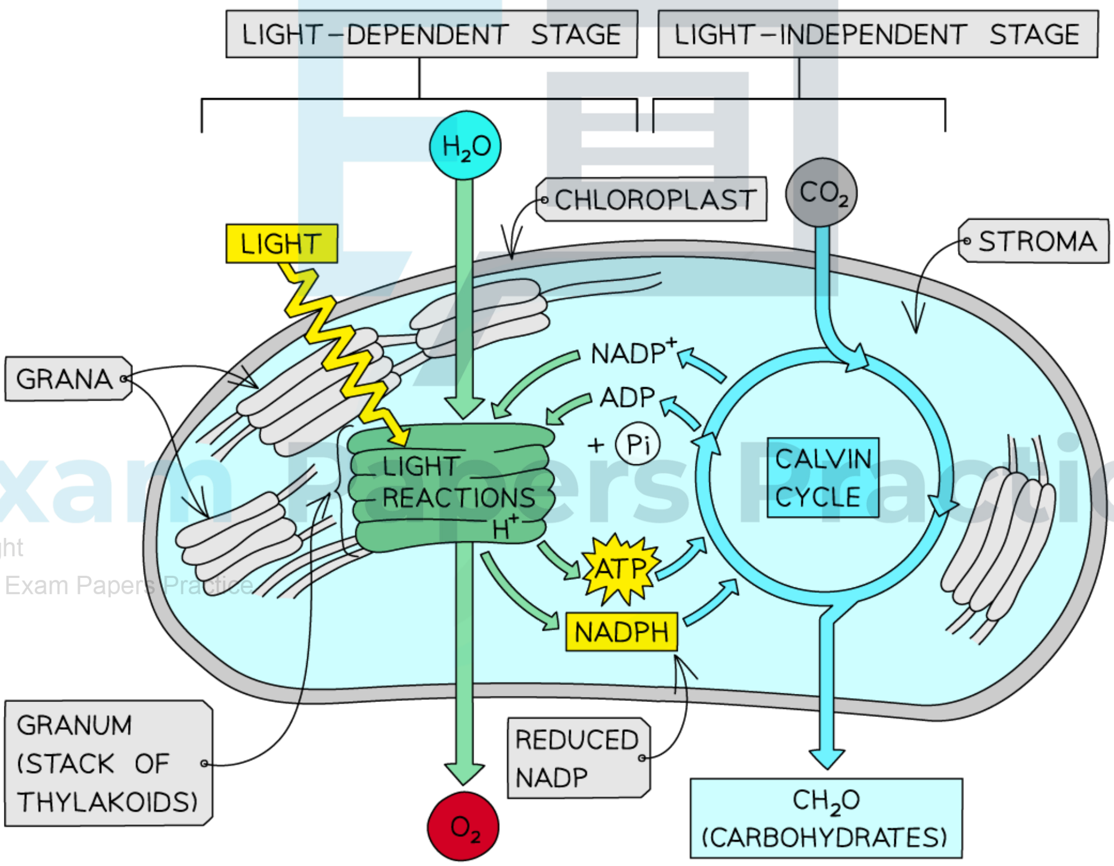
- Photosynthesis takes place in two distinct stages:
  - The **light-dependent reaction**, which relies on light directly
  - The **light-independent reaction**, which does not use light directly
- Both these reactions take place within the **chloroplast**
  - The light-dependent reaction takes place in the **thylakoid intermembrane space** and across the **thylakoid membrane**
    - **Thylakoids** are disc like structures which make up the grana in stacks of up to 100. They contain the photosynthesis pigment chlorophyll. Some may have tubular extensions (intergranal lamellae) which join up with thylakoids in adjacent grana
    - The **thylakoid membrane** contains a transfer chain where electrons are passed along a number of electron carriers in a series of oxidation-reduction reactions

Exam Tip

The thylakoid intermembrane space is also referred to as the thylakoid lumen.

Products of the Light-dependent Reactions

- During the light-dependent reaction light energy is converted into chemical energy in the form of **ATP** and **reduced NADP**
- ATP and reduced NADP are produced from the **photolysis** of water by light energy:
  - Water is split into protons, electrons and oxygen
  - The protons are picked up by the hydrogen acceptor NADP$^+$ thereby reducing it (NADPH, also called reduced NADP)
  - ATP is generated from the **phosphorylation** of ADP
- The useful products of the light-dependent reaction are transferred to the light-independent reaction within the chloroplast
- **Oxygen** is given off as a **waste product** of the light-dependent reaction



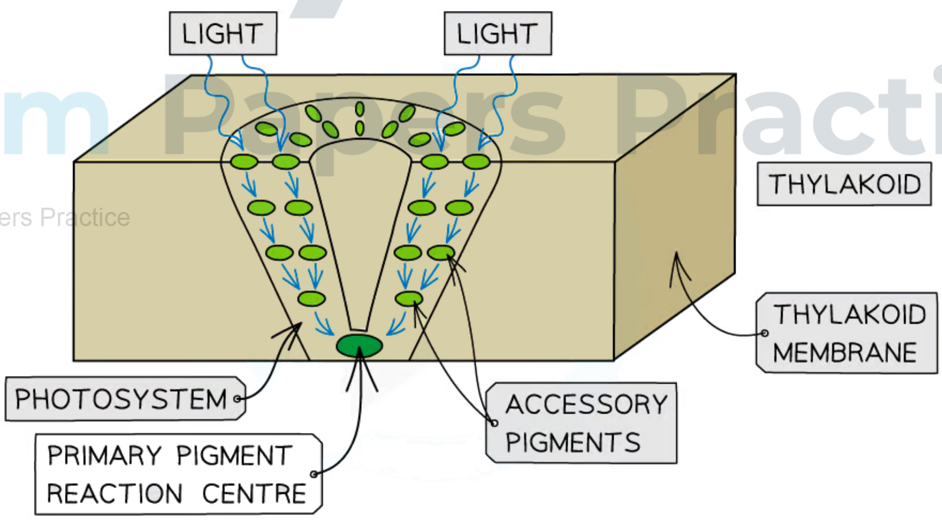
The two stages of photosynthesis

Exam Tip

NADP is an electron carrier that is important in photosynthesis. When it takes up protons the NADP becomes reduced and can be written as NADPH. NADP can also be written as NADP$^+$.

Excitation of Electrons

- Chloroplasts contains the pigment **chlorophyll**, plus other accessory pigments
- These are grouped together as structures called **photosystems** which are located in the thylakoids
- Photosystems contain many chlorophyll molecules and a **reaction centre**
- Two types of photosystems exist:
  - **Photosystem I** - contains the reaction centre P700 (as it is activated by a wavelength of light of 700nm)
  - **Photosystem II** - contains the reaction centre P680 (as it is activated by a wavelength of light of 680nm)
- Chlorophyll molecules within Photosystem II absorb light energy, in the form of photons, and pass it to the reaction centre P680
- **Electrons** within the reaction centre of Photosystem II are then excited to a **higher energy level** by the photons of light
- The chlorophylls within the reaction centre are said to be **photoactivated**
- Excited electrons are able to be **donated** to an **electron acceptor** in a **reduction reaction**
  - In the light-dependent reaction the electron acceptor is called **plastoquinone**
  - **Plastoquinone accepts two electrons** from Photosystem II and is reduced
  - It then moves to another position in the thylakoid membrane
- This process is repeated with another plastoquinone molecule
- In total **two plastoquinone** molecules are **reduced** and **four electrons are lost** from the reaction centre



A photosystem used in the light-dependent reaction to excite electrons

Exam Tip

Rather confusingly, the first photosystem to be activated in the light-dependent reaction is Photosystem II. Later in the reaction, Photosystem I is involved. This is because Photosystem I was the first to be discovered and therefore was named first.

Photolysis

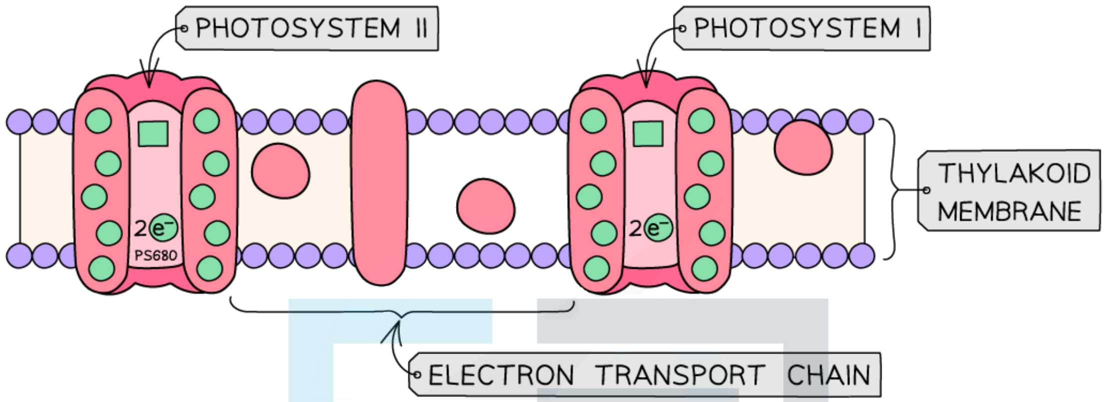
- Photolysis occurs in Photosystem II during the **light-dependent reaction** of photosynthesis
- This occurs following the **reduction of plastoquinone** in Photosystem II:
  - The reaction centre acts as an **oxidising agent** and causes water molecules (that have been moved into the leaf by transport up the xylem vessels) to split during photolysis
- **Water splits into protons, electrons and oxygen**
  - The oxygen diffuses out of the leaf through stomata
  - The electrons are passed into the electron transport chain
  - The protons are picked up by the carrier molecules NADP forming reduced NADP
- The reaction can be summarised as $2H_2O \rightarrow O_2 + 4H^+ + 4e^-$
- The photolysis of water generates the electrons needed for:
  - **Replacement** of the electrons lost from the reaction centre in Photosystem II
  - **Subsequent reactions** of the light-dependent reaction

8.3.2 Photophosphorylation

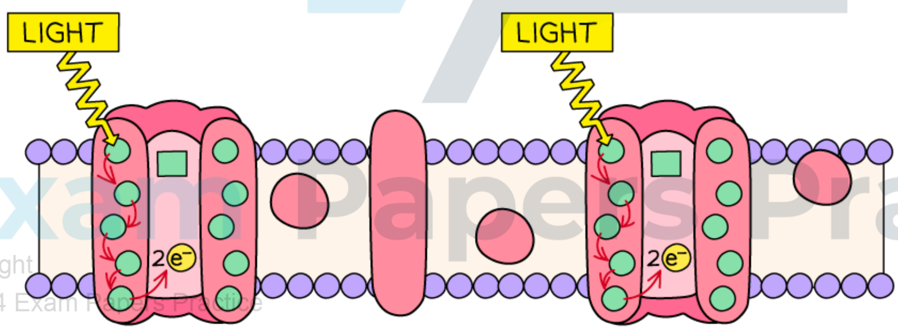
The Electron Transport Chain in Photosynthesis

- Photophosphorylation is the term for the overall process of using **light energy** and the **electron transport chain** to **generate ATP** from ADP
- During photophosphorylation excited electrons (from Photosystem II) are passed down a series of **electron carriers** that form the **electron transport chain**
- The electron transport chain occurs on the **thylakoid membranes** within the chloroplast
- Thylakoid membranes contain the following structures:
  - Photosystem II
  - ATP synthase
  - A series of electron carriers
  - Photosystem I
- The reduced plastoquinone (an electron acceptor forming part of the electron transport chain) carries a pair of **excited electrons** from Photosystem II
- **Plastoquinone** carries the electrons to the start of a chain of electron carriers
- The electron carriers undergo a series of **redox reactions** as electrons are gained and lost from each carrier
- Excited electrons gradually release their energy as they pass through the electron carriers which is used to generate a **proton gradient**
- The **excitation** of the electrons **falls** and they are eventually picked up by the reaction centre in **Photosystem I**
- Finally the pair of electrons are used to **reduce NADP** (along with protons from the photolysis of water) which is then passed into the light-independent reaction
- The pathway of electrons is linear, photophosphorylation is referred to as **non-cyclic photophosphorylation**
- **ATP** and **reduced NADP** are the **main products** of photophosphorylation and are immediately passed to the light-independent reaction

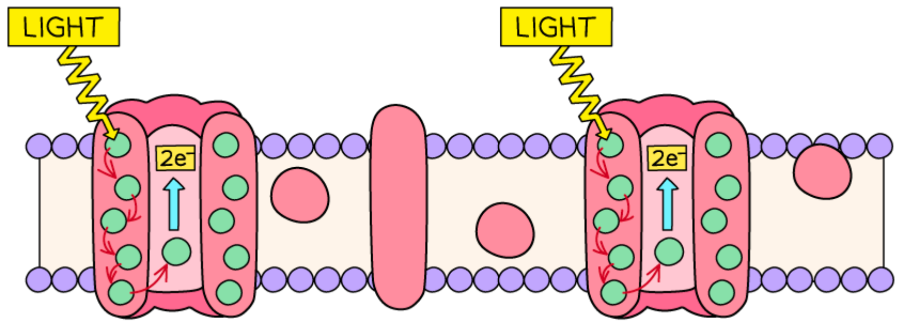
1 NON–CYCLIC PHOTOPHOSPHORYLATION INVOLVES BOTH PHOTOSYSTEM I AND PHOTOSYSTEM II



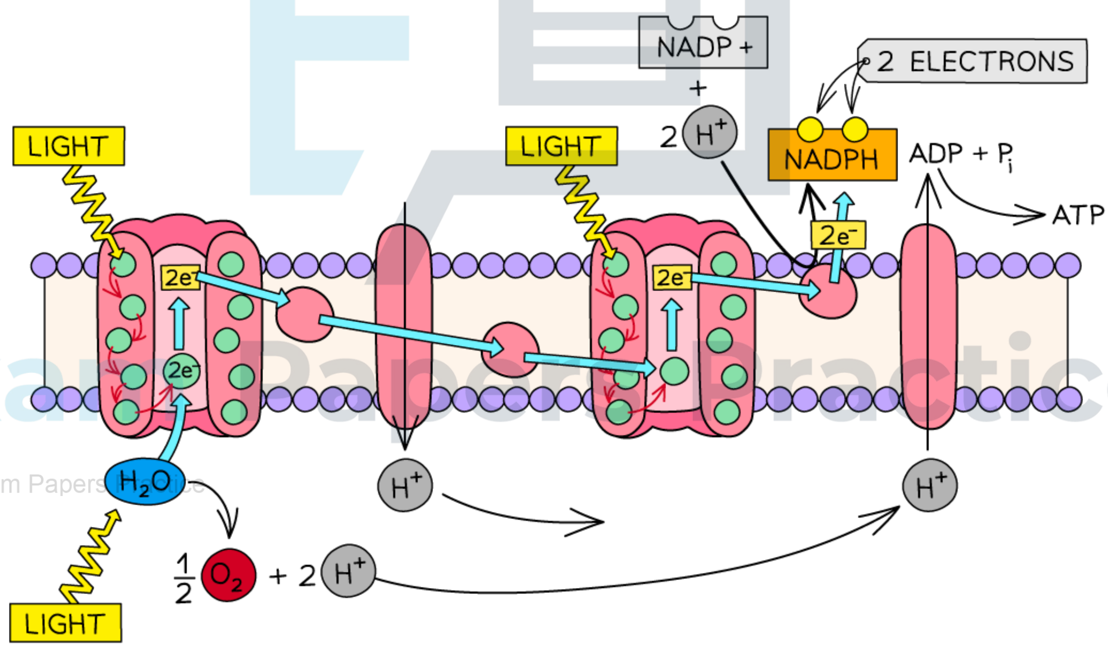
2 LIGHT IS ABSORBED BY BOTH PHOTOSYSTEMS. THE LIGHT IS PASSED TO THE PRIMARY PIGMENT OF EACH PHOTOSYSTEM



3 PHOTOACTIVATION – ELECTRONS IN THE PRIMARY PIGMENT MOLECULE OF EACH PHOTOSYSTEM ARE EXCITED TO A HIGHER ENERGY LEVEL



4 EXCITED ELECTRONS FROM PHOTOSYSTEM II ARE PASSED TO PHOTOSYSTEM I VIA AN ELECTRON TRANSPORT CHAIN, RELEASING SUFFICIENT ENERGY TO SYNTHESISE ATP



5 ELECTRONS FROM THE PHOTOLYSIS OF WATER REPLACE THOSE LOST FROM PHOTOSYSTEM II

6 EXCITED ELECTRONS FROM PHOTOSYSTEM I AND HYDROGEN IONS FROM THE PHOTOLYSIS OF WATER BOTH COMBINE WITH NADP TO FORM REDUCED NADP

Non cyclic phosphorylation involving the electron transport chain and the production of ATP and reduced NADP

Exam Tip

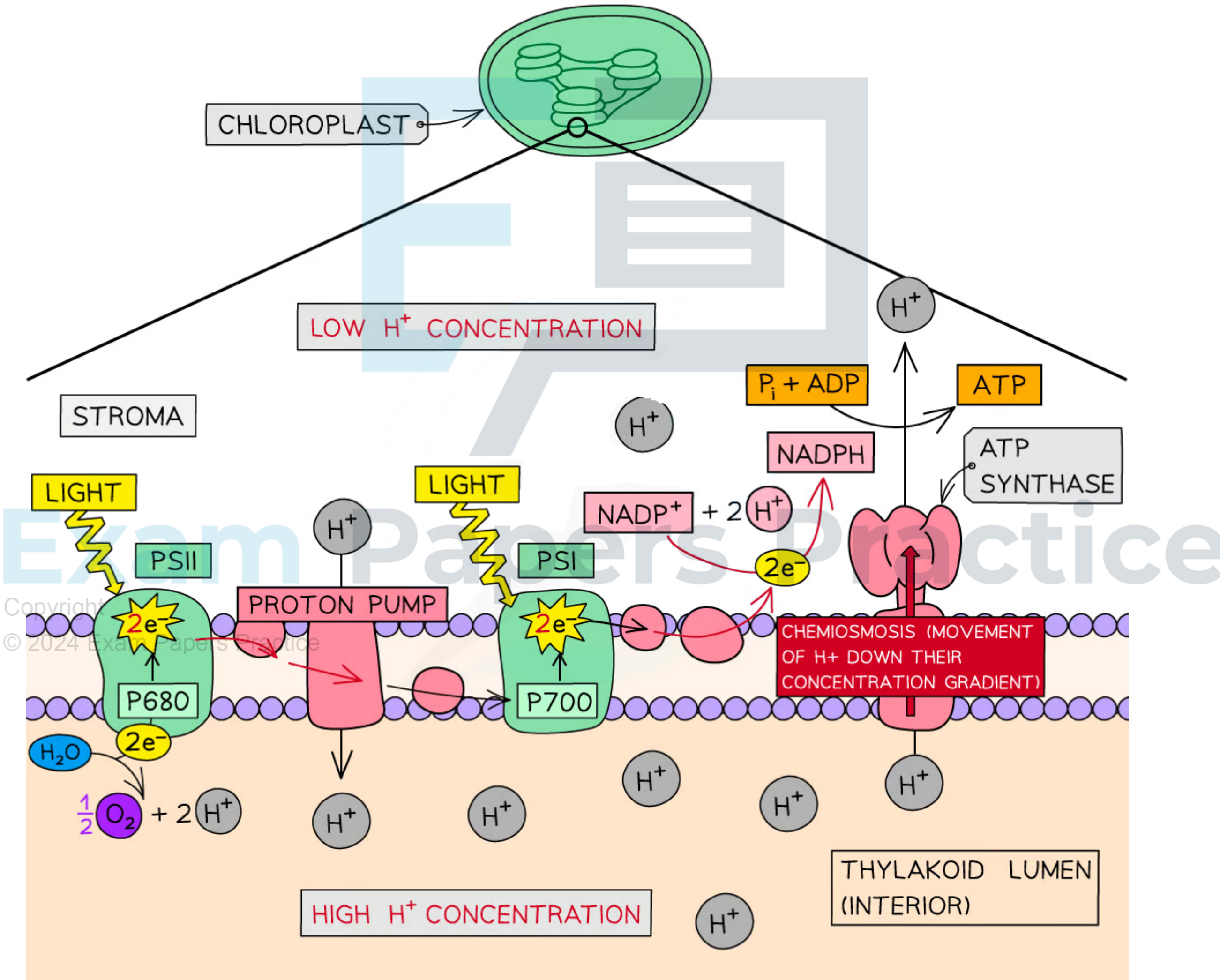
Remember a redox reaction is one where reduction reactions (gain of electrons or hydrogen, loss of oxygen) and oxidation reactions (loss of electrons or hydrogen, gain of oxygen) happen alternately. This happens along the series of electron carriers in the thylakoid membrane as part of the electron transport chain.

Forming the Proton Gradient

- Electrons are passed from carrier to carrier in the electron transport chain
- As they do so they **release energy** which is used to **pump protons** from the stroma across the thylakoid membrane and into the intermembrane space (also known as the the thylakoid lumen)
- The protons move via a proton pump
- A **high concentration** of protons builds inside the intermembrane space creating a concentration gradient
- **Photolysis of water** contributes to the proton gradient

Chemiosmosis in Photosynthesis

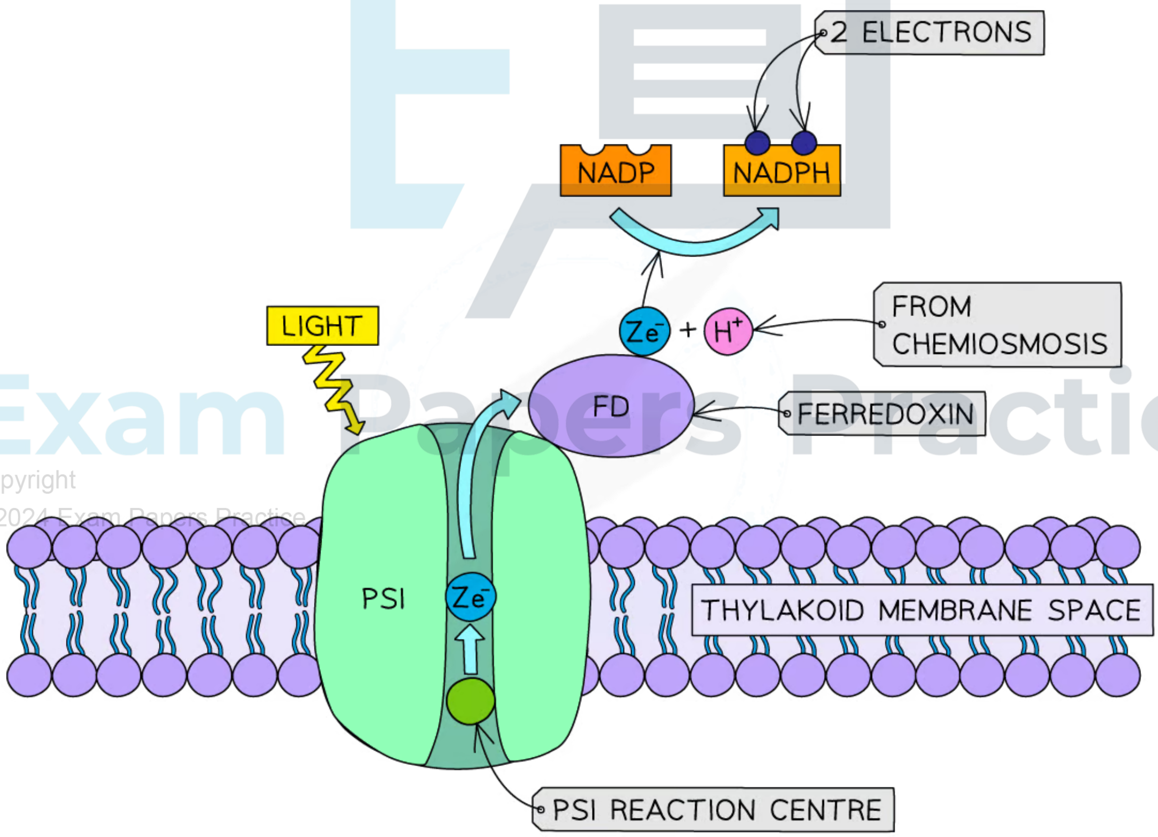
- The proton gradient within the intermembrane space of the thylakoid powers the **synthesis of ATP**
  - The protons travel down their concentration gradient through the membrane protein **ATP synthase**
  - Energy is released by the movement of protons and is used to make ATP from the phosphorylation of ADP
- This process is called **chemiosmosis**
- The ATP produced is used in the light-independent reaction



Photophosphorylation and chemiosmosis

Reduction of NADP

- **Photosystem I** is involved in the reduction of NADP which is a key molecule used in the light-independent reaction
  - Chlorophyll molecules in the reaction centre **absorb photons** of light energy
  - **Electrons** within the reaction centre are **photoactivated** to a higher energy level
  - They are passed to a **protein** on the outside of the thylakoid membrane called **ferredoxin** and reduce it
  - The reduced ferredoxin, along with **protons** that have passed through ATP synthase during chemiosmosis, are used to reduce NADP to NADPH (reduced NADP)
    - **NADP + 2H⁺ + 2e⁻ → NADPH**
  - The ferredoxin is now oxidised and free to be reused in this reaction again
  - Reduced NADP now carries a pair of electrons and can be passed into the light-independent reactions of photosynthesis



Reduction of NADP in Photosystem I

8.3.3 Light-independent Reactions

Location of the Light-independent Reactions

- The light-independent reactions of photosynthesis take place in the **stroma** of the chloroplasts
- The stroma is within the double membrane and is a thick protein rich environment containing the **enzymes** needed for the light-independent reactions

Carbon Fixation

- The light-independent reactions of photosynthesis are also known as the **Calvin cycle**
- There are three main steps within the Calvin cycle:
  1. **Carbon fixation**: The enzyme **rubisco** catalyses the **fixation of carbon dioxide** by combination with a molecule of ribulose bisphosphate (RuBP), a 5C compound, to yield two molecules of glycerate 3-phosphate (GP), a 3C compound
  2. **Reduction: GP is reduced** to triose phosphate (TP) in a reaction involving reduced NADP and ATP
  3. **Regeneration: RuBP is regenerated** from TP in reactions that use ATP
- **Carbon dioxide** is converted into carbohydrates, namely **glucose**, during the cycle in a series of **anabolic** reactions
  - **Anabolic reactions** require energy in order to build large complex molecules from smaller simpler ones
- The Calvin cycle relies on the **products of the light-dependent reactions** namely ATP and reduced NADP
- During the cycle **endergonic** reactions take place that involve the hydrolysis of ATP and oxidation of reduced NADP
  - An **endergonic reaction** requires energy to be absorbed before the reaction can proceed

Carbon fixation details

- Carbon dioxide is the source of carbon for all organisms that carry out photosynthesis
- Carbon fixation involves carbon dioxide (1C) being removed from the external environment and becoming part of the plant, and is then said to be "fixed"
  - It is transformed into a three-carbon compound (3C) called **glycerate-3-phosphate** (sometimes shortened to as GP)
- During the fixation step of the Calvin cycle **carbon dioxide** is combined with a five-carbon compound (5C) called **ribulose bisphosphate (RuBP)** to make an **unstable** six-carbon (6C) compound that splits into **two** molecules of **glycerate-3-phosphate**
- This reaction is catalysed by the enzyme **rubisco**
- Glycerate-3-phosphate is then used in the next step of the cycle

Role of Reduced NADP and ATP

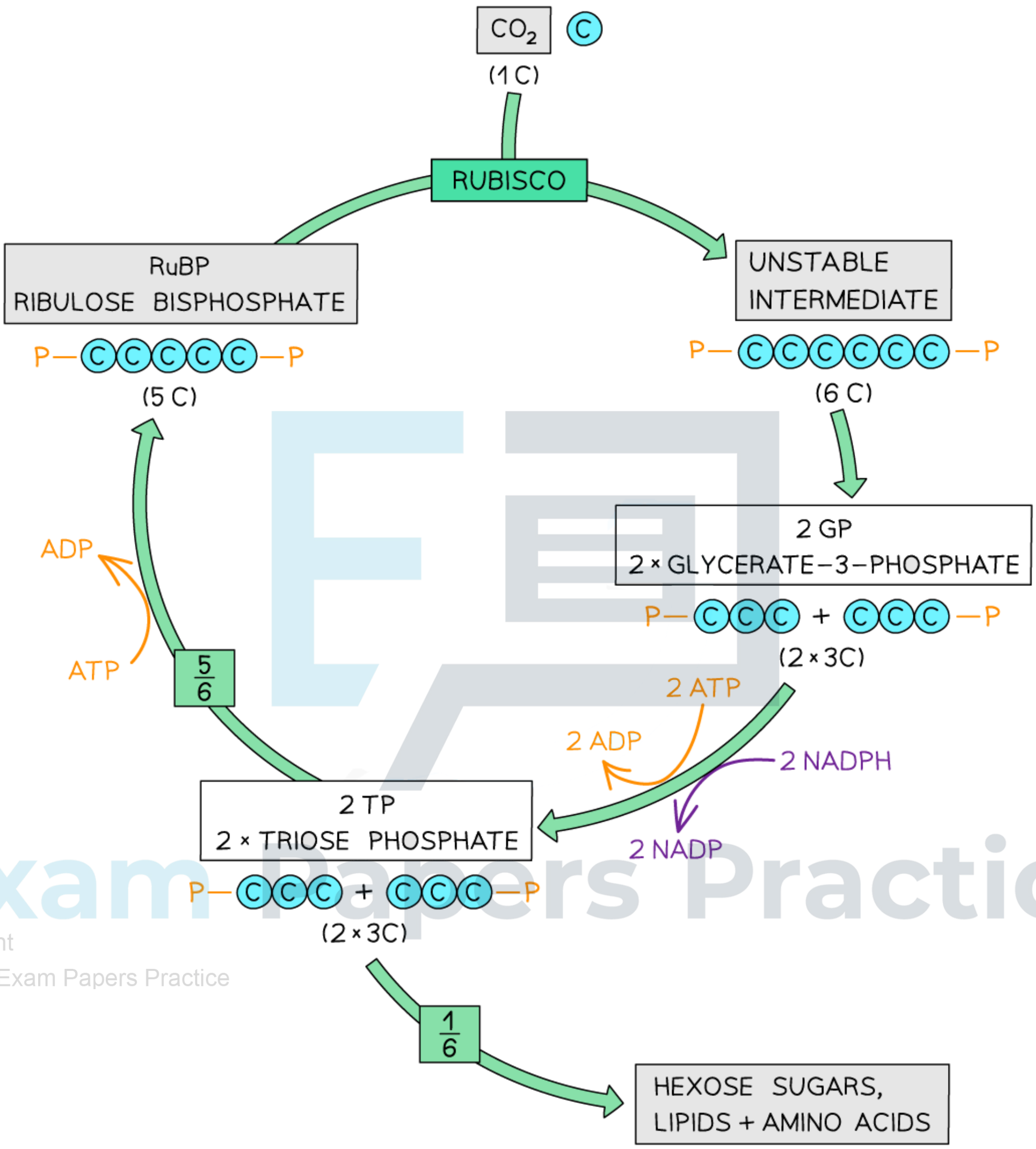
- **Energy** from ATP and **hydrogen** from reduced NADP (from the light-dependent reactions) are used to **reduce glycerate-3-phosphate** to a phosphorylated three-carbon molecule called **triose phosphate** (sometimes shortened to TP)
- After the reduction step **one sixth** of the triose phosphate is converted into **usable products** for the plant:
  - Hexose phosphates which can be used to produce carbohydrates such **starch, sucrose or cellulose**
  - **Glycerol** and **fatty acids** which join to form cell membranes
  - Production of **amino acids** for protein synthesis
- It is important that not all the triose phosphate is converted to alternative compounds for the plant, or the supplies of ribulose bisphosphate would run out
- The remaining triose phosphate is used to regenerate RuBP

Exam Tip

For the Calvin cycle to continue it needs a constant supply of RuBP and carbon dioxide. As much RuBP must be produced as is consumed. If three RuBP molecules are used then this generates six triose phosphates. Five of the triose phosphate molecules are needed to regenerate the three RuBPs molecules. So there would only be one left over to convert into other usable molecules for the plant (such as starch). To produce just one molecule of glucose, six turns of the Calvin cycle are needed.

Regeneration of RuBP

- The remaining five sixths of triose phosphate are used to **regenerate** the four-carbon compound ribulose bisphosphate **(RuBP)**
- This process requires **ATP** (from the light-dependent reaction)
- Once RuBP been has regenerated it can go on to fix further carbon dioxide and the cycle can begin again



The Calvin cycle of the light-independent reactions showing the regeneration of RuBP

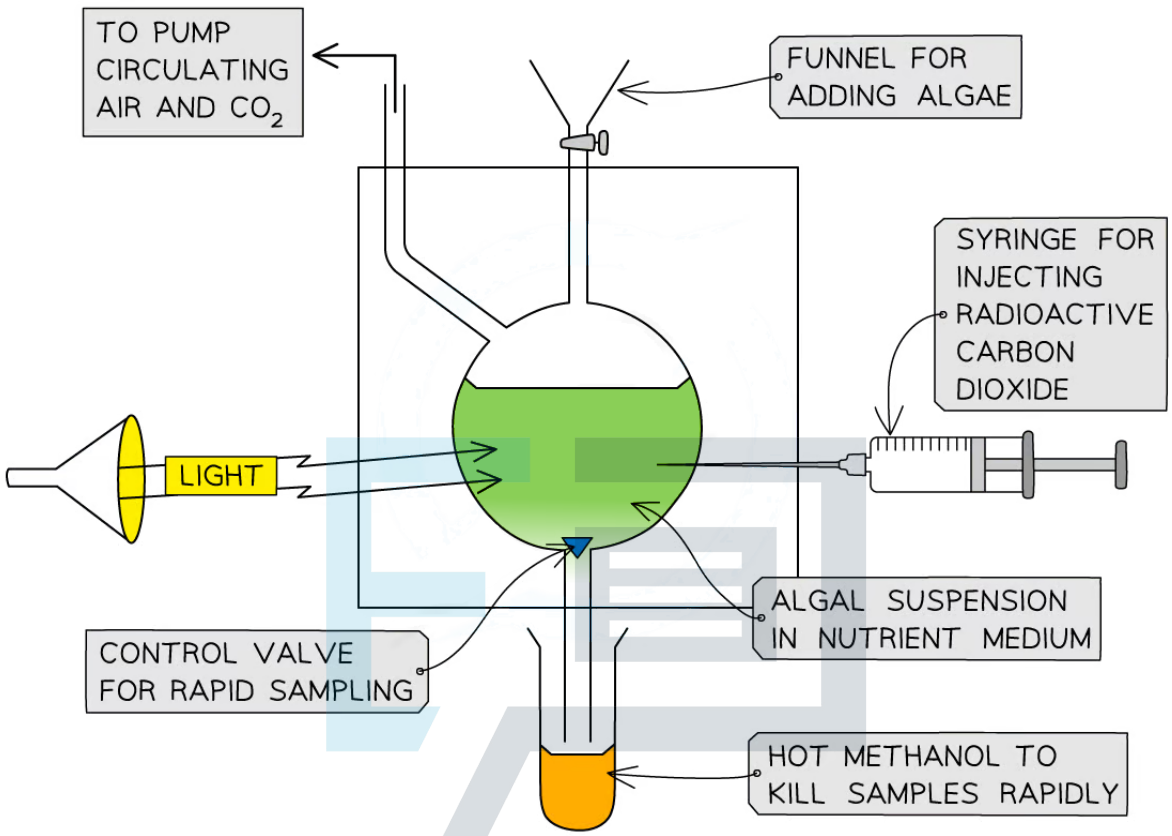
8.3.4 Investigating Carbon Fixation in Photosynthesis

Investigating Carbon Fixation in Photosynthesis

NOS: Developments in scientific research follow improvements in apparatus: sources of ^{14}C and autoradiography enabled Calvin to elucidate the pathways of carbon fixation

- The Calvin cycle was named after American biochemist **Melvin Calvin** for his work in mapping the complete conversion of carbon dioxide to glucose
- The techniques used at the time were novel and showed developments in scientific research
- Calvin developed methods for growing algae in an apparatus he named "the lollipop" due to its shape
- This apparatus enabled Calvin to introduce radioactive carbon dioxide to the algae in order to study photosynthesis
- He also used paper chromatography and production of x-ray chromatograms to enable Calvin to identify compounds using in reactions during photosynthesis
- His approaches and methods were novel at the time and were only possible because of advancements in apparatus and technologies

- The experiments performed by Calvin show process of using **radioactive carbon dioxide** and **autoradiography** in explaining the reactions of the Calvin Cycle:
  - **Radioactively labeled carbon-14** (^{14}C) was introduced to the **algae *Chlorella*** in an apparatus called a lollipop (the experiments are sometimes referred to as the "lollipop experiment" due to the shape of the apparatus)
  - **Light** was shone on the lollipop vessel containing the *Chlorella* to **induce photosynthesis** and carbon-14 was **incorporated** into the algae
  - After varying time periods the **algae was killed** by heated alcohol which denatures proteins and enzymes within the cells and stops metabolic processes
  - The **pathway** of the radioactive carbon was **mapped and analysed** throughout the algae using two-dimensional **paper chromatography**
  - Chromatography **separated** out the different carbon compounds that had been made by the algae
  - Any **radioactive carbon-14 atoms** (that had been incorporated into either intermediates or products of photosynthesis) were **identified** using **autoradiography (x-ray)**
  - By **comparing** the different **time periods** in which the carbon compounds formed Calvin was able to map the order in which they were generated
- The results of the experiments showed that carbon was **converted** to carbohydrates during the **light-independent reactions** of photosynthesis
- Today, the method Calvin used is called "feeding experiments"



Calvin's lollipop experiments for determining the reactions in the light-independent reaction

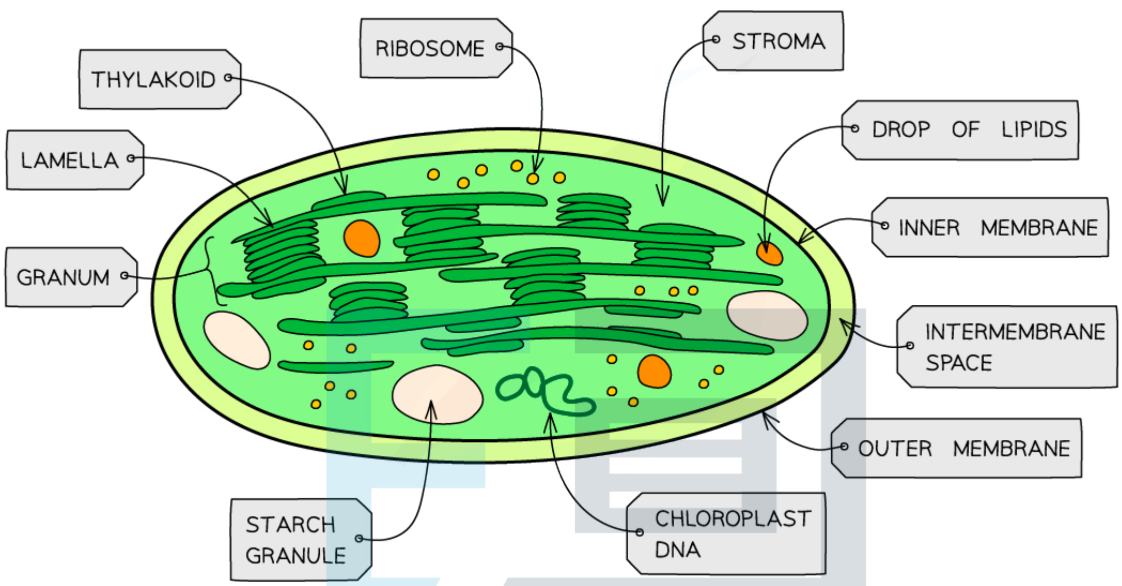
8.3.5 Chloroplast

Chloroplast Structure & Function

Structure

- Chloroplasts are the organelles in plant cells where **photosynthesis** occurs
- These organelles are roughly **2 – 10 µm** in diameter (they are larger than mitochondria)
- Each chloroplast is surrounded by a **double-membrane envelope**
  - Each of the envelope membranes is a phospholipid bilayer
  - The **outer membrane** is permeable to a range of ions and small molecules
  - The **inner membrane** contains transport proteins that only allow certain molecules or ions to enter or leave the chloroplast
- Chloroplasts are filled with a cytosol-like fluid known as the **stroma**
  - CO_2, sugars, enzymes and other molecules are dissolved in the stroma
  - If the chloroplast has been photosynthesising there may be **starch grains** or **lipid droplets** in the stroma
- A separate system of membranes is found in the stroma
- This membrane system consists of a series of flattened fluid-filled sacs known as **thylakoids**
  - The **thylakoid membranes** contain pigments, enzymes and electron carriers
  - These thylakoids stack up to form structures known as **grana** (singular – granum)
  - Grana are connected by membranous channels called **stroma lamellae**, which ensure the stacks of sacs are connected but distanced from each other

CHLOROPLAST



Chloroplast structure

- The membrane system provides a large number of **pigment molecules** that ensure as much light as necessary is absorbed
- The pigment molecules are **arranged** in light-harvesting clusters known as **photosystems**
  - In a photosystem, the different pigment molecules are arranged in funnel-like structures in the thylakoid membrane
  - Each pigment molecule passes energy down to the next pigment molecule in the cluster until it reaches the primary pigment reaction centre

Adaptations of chloroplasts to photosynthesis

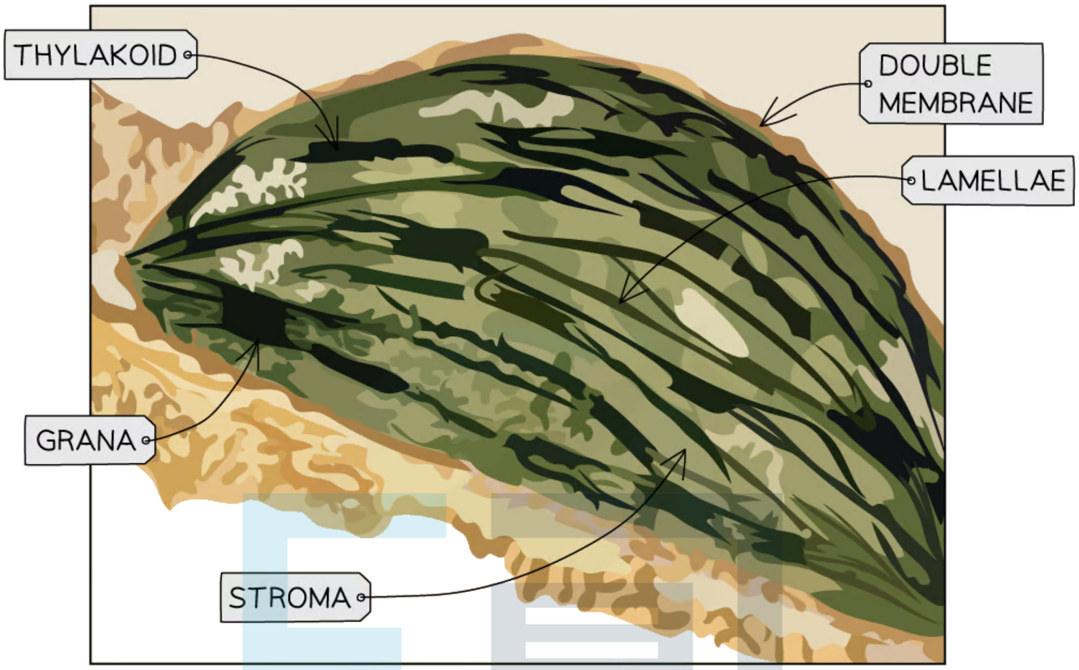
- **Stroma**:
  - The gel-like fluid contains **enzymes** that catalyse the reactions of the light-independent stage
  - The stroma surrounds the grana and membranes, making the **transport** of products from the light-dependent stage into the stroma **rapid**
- **Grana**:
  - The granal stacks create a **large surface area** for the presence of many photosystems which allows for the **maximum** absorption of light
  - It also provides **more membrane space** for electron carriers and ATP synthase enzymes

- **DNA**:
  - The chloroplast DNA contains **genes** that code for some of the proteins and enzymes used in photosynthesis
- **Ribosomes**:
  - The presence of ribosomes allows for the **translation of proteins** coded by the chloroplast DNA
- **Inner membrane of chloroplast envelope**:
  - The selective transport proteins present in the inner membrane **control** the flow of molecules between the stroma and cytosol (the cytoplasm of the plant cell)
- **Thylakoid space**:
  - This is where a **proton gradient develops** (to generate ATP)
  - The space has a very small volume so a proton gradient can develop very **quickly**

8.3.6 Skills: Photosynthesis

Skills: Annotating Chloroplasts

- Electron micrographs may **differ** in shape and size depending on where the cross section of the organelle was taken
- Usually the following features should be notable and visible:
  - **Round** in shape
  - A **double membrane** exterior
  - Flattened discs, the **thylakoids**, arranged in stacks, the grana, **connected by** thin tubes, the **lamellae**
  - Ribosomes and DNA are not usually visible
  - **Starch granules** may be visible as dark spots within the stroma



THYLAKOID – SMALL INTERNAL VOLUME TO CREATE A PROTON GRADIENT QUICKLY	

LAMELLAE – CONNECTS GRANA FOR MAXIMUM PHOTOSYNTHESIS	

GRANA – LARGE SURFACE AREA FOR MAXIMUM ABSORPTION OF LIGHT	

STROMA – CONTAINS ENZYMES FOR CALVIN CYCLE	