SLE 132 – Form and Function
Photosynthesis

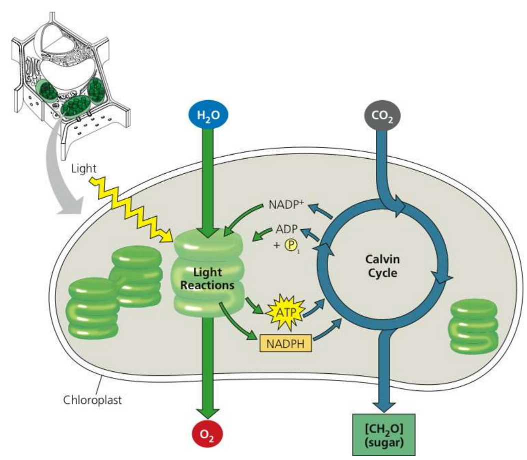

DEAKIN COLLEGE in association with DEAKIN UNIVERSITY AUSTRALIA

Photosynthesis consists of 2 stages:

- **The light reactions** (*photo) – use light to make ATP and NADPH*
- **The Calvin cycle** *(carbon fixation) – Products from light reactions are used to ‘fix’ carbon molecules*

The light reactions (in the thylakoids):

- split H_2O
- release O_2
- reduce $NADP^+$ to NADPH (Hydrogen ions and electrons)
- generate ATP from ADP by **Photo-phosphorylation**



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- Pigments occur in groups called photosystems
- There are two types of photosystems
  - Photosystem 1 (ps I)
  - Photosystem 2 (ps II)

Each photosystem has a different chlorophyll- a light trap

- Photosystem 1 has P700
- Photosystem 2 has P680

- The two work together simultaneously and continuously

Photosynthesis

https://drive.google.com/file/d/0B6L5B3wsaT99aTFSMVJPYkJIVWc/view?usp=sharing

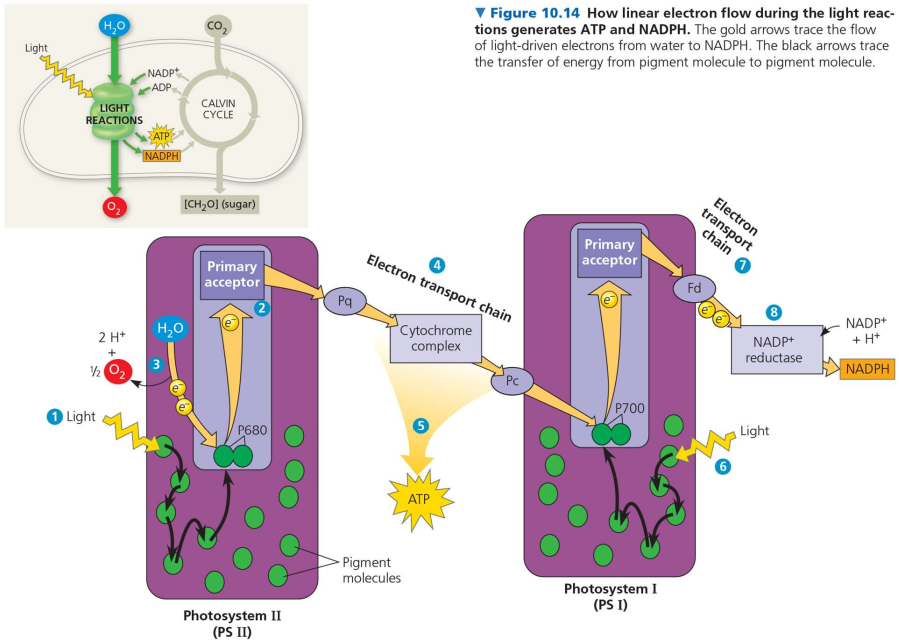
The light reactions

- **A photon hits a pigment** and the energy is passed among pigment molecules until it **excites P680** (Photosystem II primary donor.)
- An excited electron from P680 is transferred to the primary electron acceptor **(Pheophytin)**
- **$P680^+$** (P680 that is missing an electron) is a very strong oxidising agent.
- H_2O is split by enzymes, and the electrons are transferred from the hydrogen atoms to $P680^+$, thus reducing it to P680.
- **O_2** is released as a by-product of this reaction.

The light reactions

- Each electron 'falls' down an electron transport chain, from the primary electron acceptor of PS II to PS I.
- Energy, released by the fall, drives the creation of a **proton gradient** across the thylakoid membrane.
- Diffusion of **H^+ (protons)** across the membrane drives ATP synthesis.

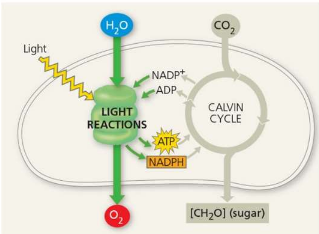
(Much like what was seen in Cellular Resp. in SLE111)

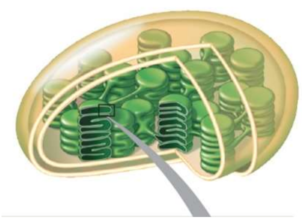


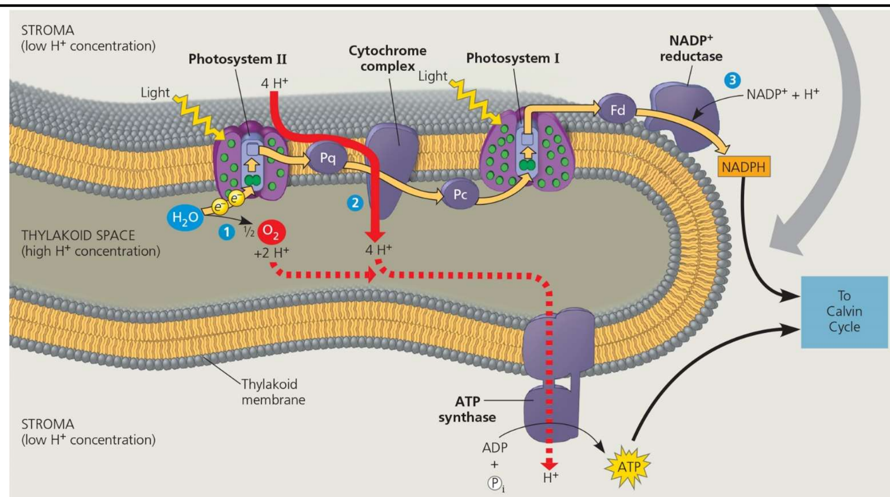
▼ **Figure 10.14 How linear electron flow during the light reactions generates ATP and NADPH.** The gold arrows trace the flow of light-driven electrons from water to NADPH. The black arrows trace the transfer of energy from pigment molecule to pigment molecule.

The light reactions – linear electron flow

- In PS I (like PS II), transferred light energy excites **P700**, which loses an electron to an electron acceptor.
- **P700⁺** (P700 that is missing an electron) accepts an electron passed down from PS II via the electron transport chain.
- Each electron 'falls' further down an electron transport chain, from the primary electron acceptor of PS I to the protein **ferredoxin (Fd)**
- The electrons are then transferred to $NADP^+$ and reduce it to **NADPH.**
- The electrons of NADPH are available for the reactions of the **Calvin cycle.**







▲ **Figure 10.18 The light reactions and chemiosmosis: Current model of the organisation of the thylakoid membrane.** The gold arrows track the linear electron flow outlined in Figure 10.14. At least three steps in the light reactions contribute to the H^+ gradient by increasing H^+ concentration in the thylakoid space: 1 Water is split by photosystem II on the side of the membrane facing the thylakoid space; 2 as plastoquinone (Pq) transfers electrons to the cytochrome complex, four protons are translocated across the membrane into the thylakoid space; and 3 a hydrogen ion is removed from the stroma when it is taken up by $NADP^+$. Notice that in step 2, hydrogen ions are being pumped from the stroma into the thylakoid space, as in Figure 10.17. The diffusion of H^+ from the thylakoid space back to the stroma (along the H^+ concentration gradient) powers the ATP synthase. These light-driven reactions store chemical energy in NADPH and ATP, which shuttle the energy to the carbohydrate-producing Calvin cycle.

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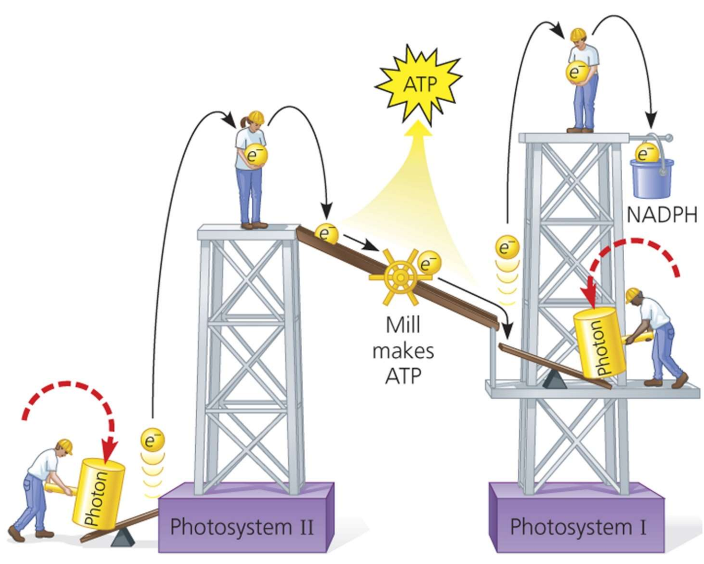
- Light energy (**photons**) excite electron into a higher energy state
- The e^- can then provide this energy to the transport chain, losing energy
- These low energy electrons are passed to PSII
- Then further excited by light energy (**photons**)



▲ **Figure 10.14 A mechanical analogy for the light reactions.**

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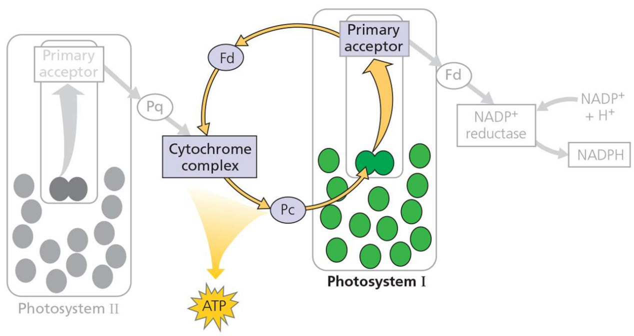
Cyclic Electron Flow

- Cyclic electron flow uses only photosystem I producing ATP
  - but not NADPH
- Cyclic electron flow generates surplus ATP
  - satisfying the higher demand in the Calvin Cycle

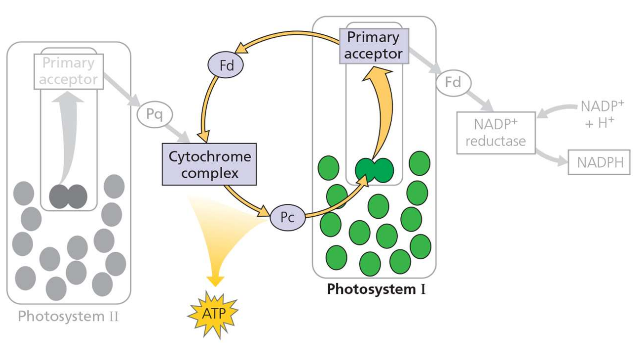


◀ **Figure 10.16 Cyclic electron flow.** Photoexcited electrons from PS I are occasionally shunted back from ferredoxin (Fd) to chlorophyll via the cytochrome complex and plastocyanin (Pc). This electron shunt supplements the supply of ATP (via chemiosmosis) but produces no NADPH. The "shadow" of linear electron flow is included in the diagram for comparison with the cyclic route. The two Fd molecules in this diagram are actually one and the same—the final electron carrier in the electron transport chain of PS I—although it is depicted twice to clearly show its role in two parts of the process.

? *Look at Figure 10.15, and explain how you would alter it to show a mechanical analogy for cyclic electron flow.*

Cyclic Electron Flow

- Cyclic electron flow thought to have evolved first, before linear electron flow
- May protect cells from light-induced damage



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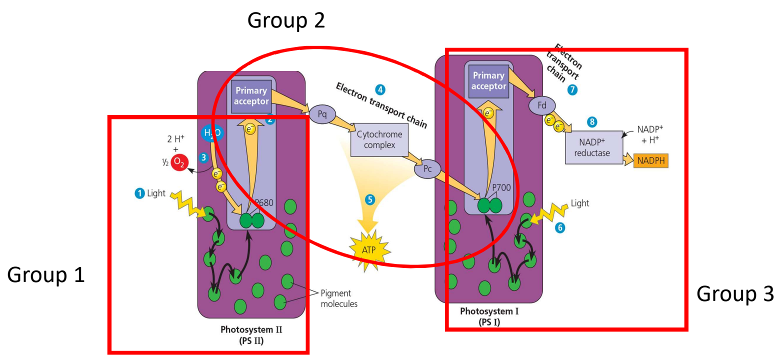
Light reactions activity

- Divide into three groups – Expert groups
- Each group to learn the detail of their section of the linear electron flow in the light reactions. (15 min)



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Light reactions activity

- Now you are all experts, get into groups of three
  - with one member from each expert group.
- Use the labels provided to reconstruct a flow diagram of linear electron flow in the light reactions of photosynthesis (15 min)

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The Calvin Cycle

- The Calvin cycle, like the citric acid cycle, regenerates its starting material after molecules enter and leave the cycle.

- The cycle builds sugar from smaller molecules by using ATP and the reducing power of electrons carried by NADPH.

https://www.youtube.com/watch?v=0UzMaoaXKaM

The Calvin Cycle

- Carbon enters the cycle as CO_2 and leaves as a sugar named **glyceraldehyde-3-phospate** (G3P).
- For net synthesis of 1 G3P, <u>the cycle must take place three times</u>, fixing 3 molecules of CO_2.

- The Calvin cycle has three phases:
  - **carbon fixation** (catalysed by **rubisco**)
  - **reduction**
  - **regeneration of the CO_2 acceptor** (RuBP)

Calvin Cycle phase 1 – Carbon fixation

- Calvin cycle incorporates each CO_2 molecule, one at a time, by attaching it to **ribulose bisphosphate (RuBP)**
- The enzyme that catalyses this first step is **rubisco**
- The product is a short lived intermediate that immediately splits into 3 molecules of **3-phosphoglycerate**

Calvin Cycle phase 2 – Reduction

- Each molecule of **3-phosphoglycerate** receives additional phosphate groups from ATP
- This forms **1, 3, biphosphoglycerate**, which then loses a phosphate to become **G3P**.
- Only one net molecule of G3P is made per 3 molecules of CO2 that enter the Calvin cycle.
- The other molecules of G3P must be used in the next step to regenerate RuBP

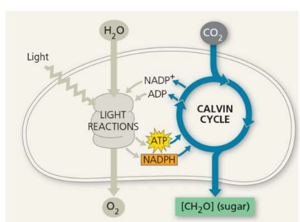
Calvin Cycle phase 3 – Regeneration of RuBP

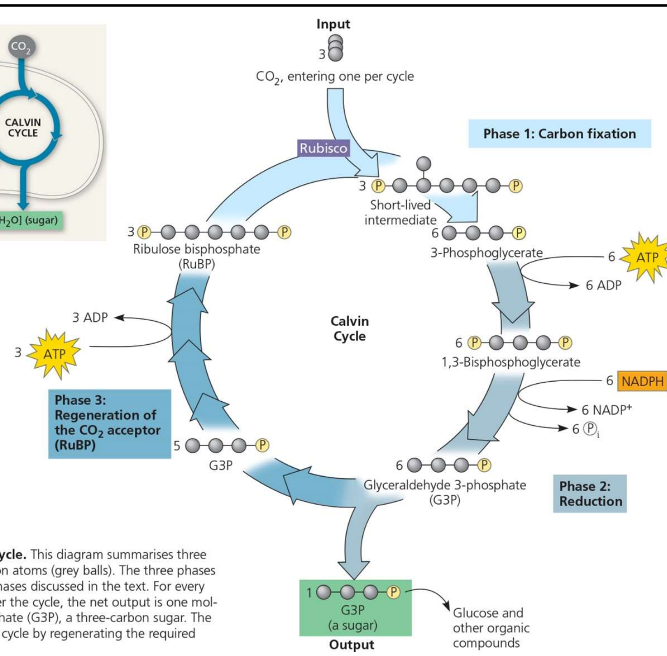
- In a complex series of reactions the **5 molecules of G3P** are converted back into **3 molecules of RuBP**
- RuBP can then accept CO_2 again to <u>start the Calvin Cycle again</u>

Calvin cycle uses ATP and NADPH to convert CO_2 to sugar

The cycle builds sugar from smaller molecules by using:

- ATP
- the reducing power of electrons carried by NADPH





▲ **Figure 10.19 The Calvin cycle.** This diagram summarises three turns of the cycle, tracking carbon atoms (grey balls). The three phases of the cycle correspond to the phases discussed in the text. For every three molecules of CO_2 that enter the cycle, the net output is one molecule of glyceraldehyde 3-phosphate (G3P), a three-carbon sugar. The light reactions sustain the Calvin cycle by regenerating the required ATP and NADPH.

What happens to the products of photosynthesis?

- 50% is used in **cellular respiration** (mitochondria)
- **Sucrose** (disaccharide) shipped throughout the plant
- **Glucose** is stored as starch
- **Cellulose** added to cell walls
- Every year about 10% of the atmospheric CO_2 is consumed in photosynthesis

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C3 Plants

- 'Normal' Photosynthesis, where initial fixation occurs via **Rubisco**
- Called C3 because the CO_2 is first incorporated into a 3-carbon compound
- C3 cycle occurs in the mesophyll
  - Temperature dependant
  - Thermochemical reaction

What controls the rate of photosynthesis?

- Light, temperature, water, CO_2 and O_2

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Photosynthesis can be affected by these factors independently or synergistically

Increased Light intensity
– Increases photochemical reactions, thus increasing rate of photosynthesis - rate is limited by CO_2 fixation

Increased temperature
– Increases CO_2 fixation, and thus rate of photosynthesis BUT rate is limited by light reactions

Increased CO_2
– Increases rate of photosynthesis BUT can be limited by light and/or temperature

C3 plants – what happens on a hot, dry day?

Dehydration is a problem for plants, sometimes requiring trade offs with other metabolic processes

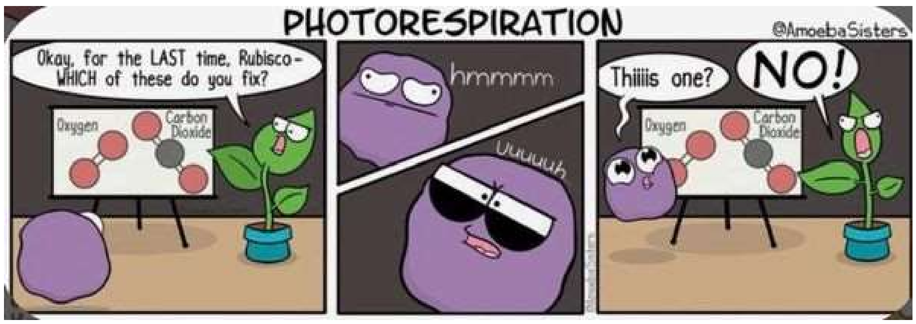
- On hot dry days **plants close stomata**
- This conserves water but limits photosynthesis
- Because closing of stomata reduces CO_2 and causes O_2 to build up

Increased Oxygen can inhibit Photosynthesis by:

- Interfering with electron transport
- Destroying pigment
- Binding to RuBP instead of CO_2 → **photorespiration**

C3 plants - Photorespiration

- Rubisco feed O_2 instead of CO_2 into the Calvin cycle
- The product splits into a **two carbon compound** and leaves the chloroplast
- Peroxisomes and mitochondria rearrange and split the two carbon compound **releasing carbon dioxide**.
- Uses ATP but doesn't produce sugar.



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C3 Plants

- C3 photosynthesis is most efficient under **cool and moist conditions**
  - requires fewer enzymes and no specialized anatomy.
- However it is less efficient under hot and dry condition
- In many plants, photorespiration is a problem because in hot dry conditions it **can drain as much as 50% of the carbon** fixed by the Calvin cycle.
- Evolution of **C4** and **CAM** plants which enables plants to efficiently photosynthesis even when hot and dry

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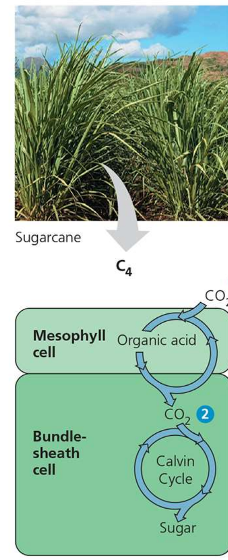
C4 plants

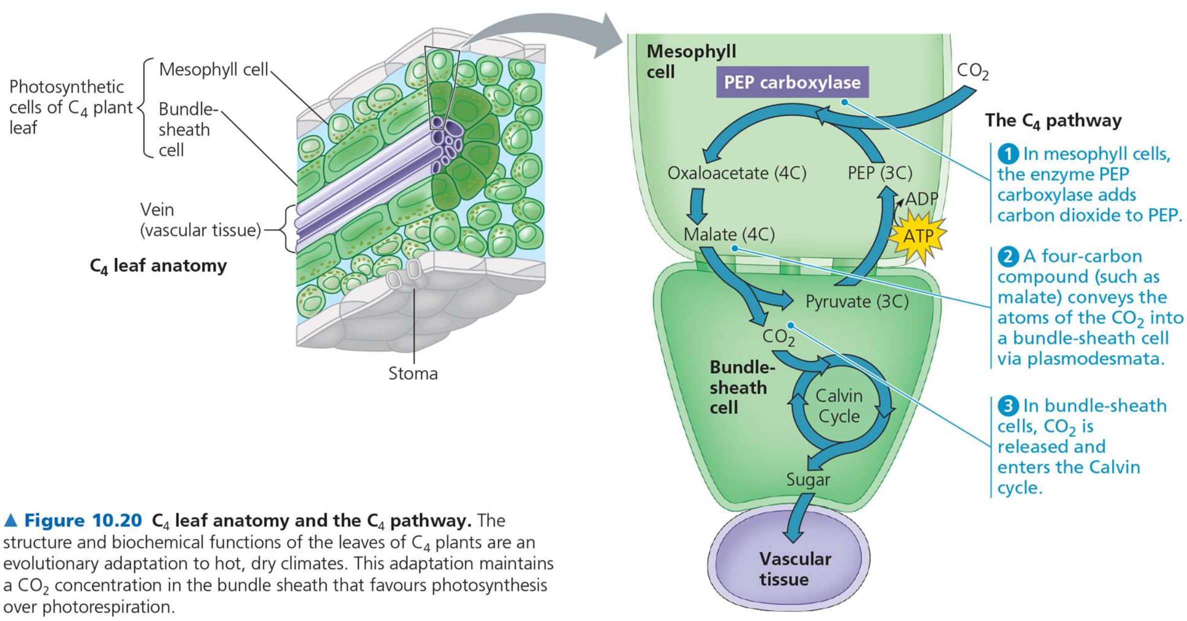
- C4 plants **minimise the cost of photorespiration**, by incorporating CO_2 into four-carbon compounds in mesophyll cells.

- This step requires the enzyme **PEP carboxylase**:
  - it has a <u>higher affinity for CO_2</u> than rubisco does
  - it can also fix CO_2 even when CO_2 concentrations are low.

- These four-carbon compounds are **exported to bundle-sheath cells**, where they release CO_2 that is then used in the Calvin cycle.



(a) Spatial separation of steps. In C_4 plants, carbon fixation and the Calvin cycle occur in different types of cells.



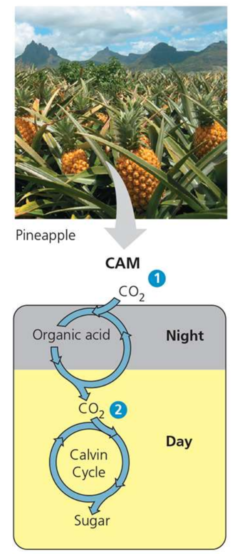
▲ **Figure 10.20 C_4 leaf anatomy and the C_4 pathway.** The structure and biochemical functions of the leaves of C_4 plants are an evolutionary adaptation to hot, dry climates. This adaptation maintains a CO_2 concentration in the bundle sheath that favours photosynthesis over photorespiration.

CAM Plants

- Some plants, including succulents, use **crassulacean acid metabolism** (CAM) to fix carbon.

- CAM plants **open their stomata at night**, incorporating/storing CO_2 into organic acids.

- Stomata close during the day (preventing water loss), and CO_2 is released from organic acids and used in the Calvin cycle.



(b) Temporal separation of steps. In CAM plants, carbon fixation and the Calvin cycle occur in the same cell at different times.

▼ **Figure 10.22 A review of photosynthesis.** This diagram shows the main reactants and products of photosynthesis as they move through the tissues of a tree (left) and a chloroplast (right).

MAKE CONNECTIONS *Can plants use the sugar they produce during photosynthesis to directly power the work of the cell? Explain. (See Figures 8.10, 8.11, and 9.6.)*