

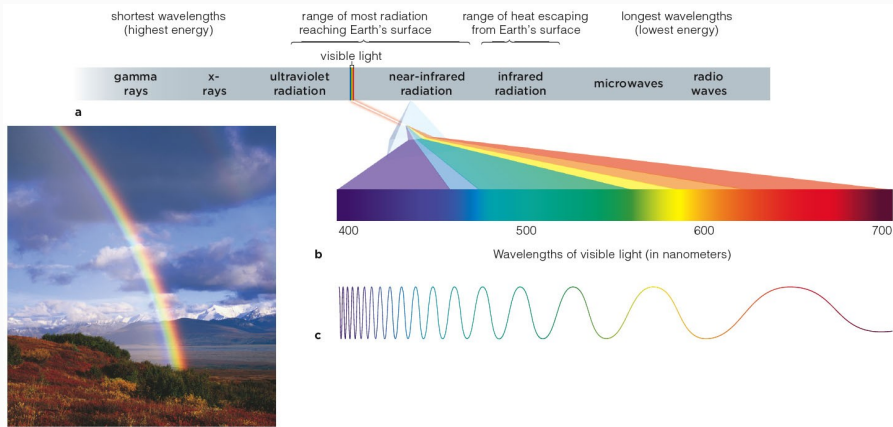
# **Chapter 6 - Photosynthesis**

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# Sunlight as an Energy Source

## ■ Photosynthesis

- The synthesis of organic molecules from inorganic molecules using the energy of light



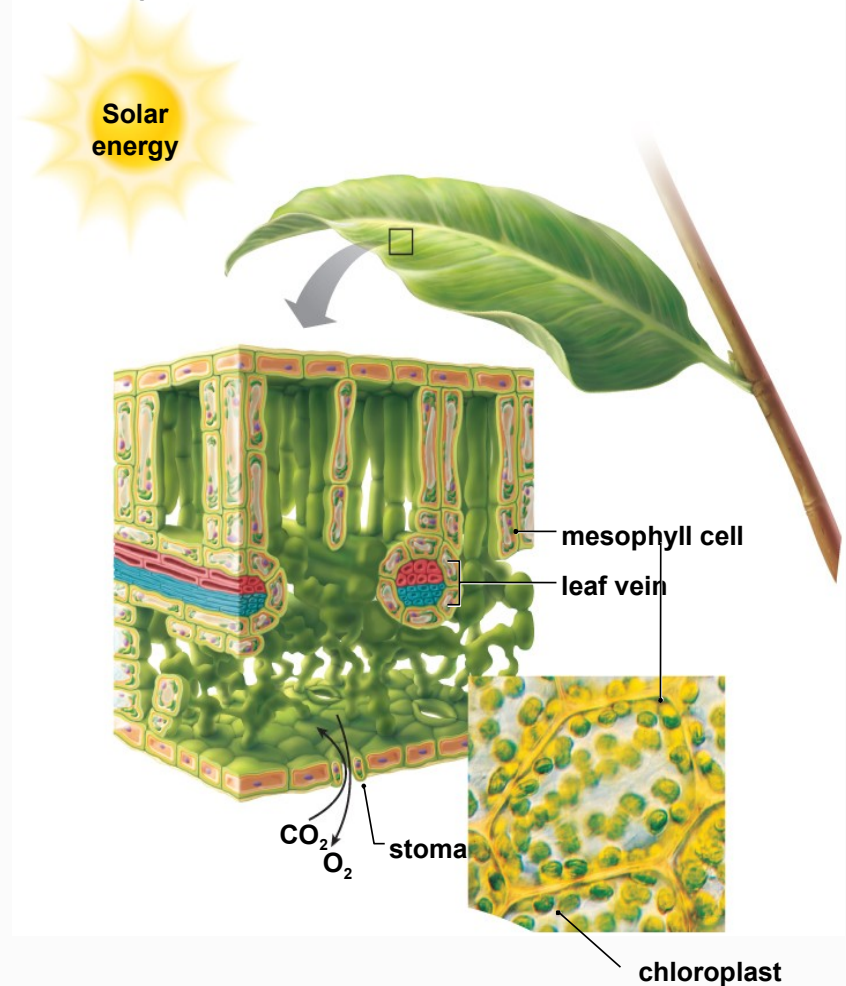
# Sites of Photosynthesis in Plants

CO<sub>2</sub> enters through stomata to mesophyll to chloroplasts

O<sub>2</sub> exits through stomata

## ■ Chloroplast

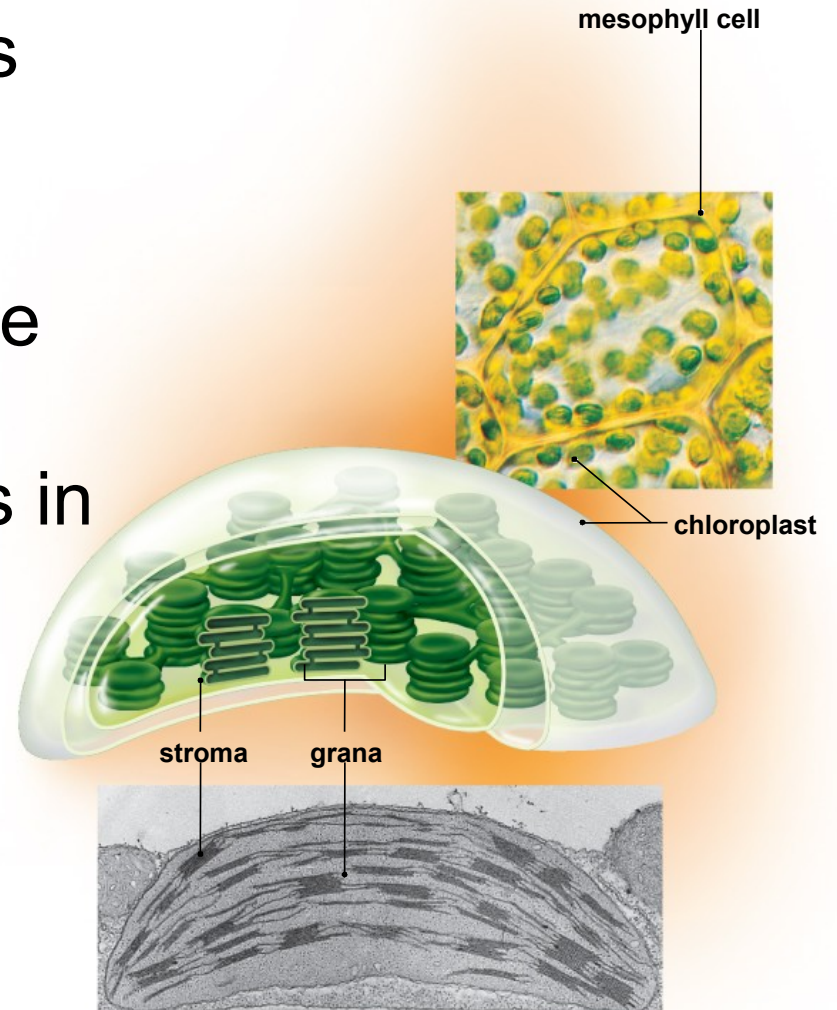
- An organelle that specializes in photosynthesis in plants and many protists



# Chloroplast close up

- Double membrane surrounds stroma
  - Semifluid matrix
  - Sugars (glucose) built here
- Third membrane – thylakoids in stacks called grana
  - Chlorophyll and other pigments are found here
    - Pigments absorb solar energy

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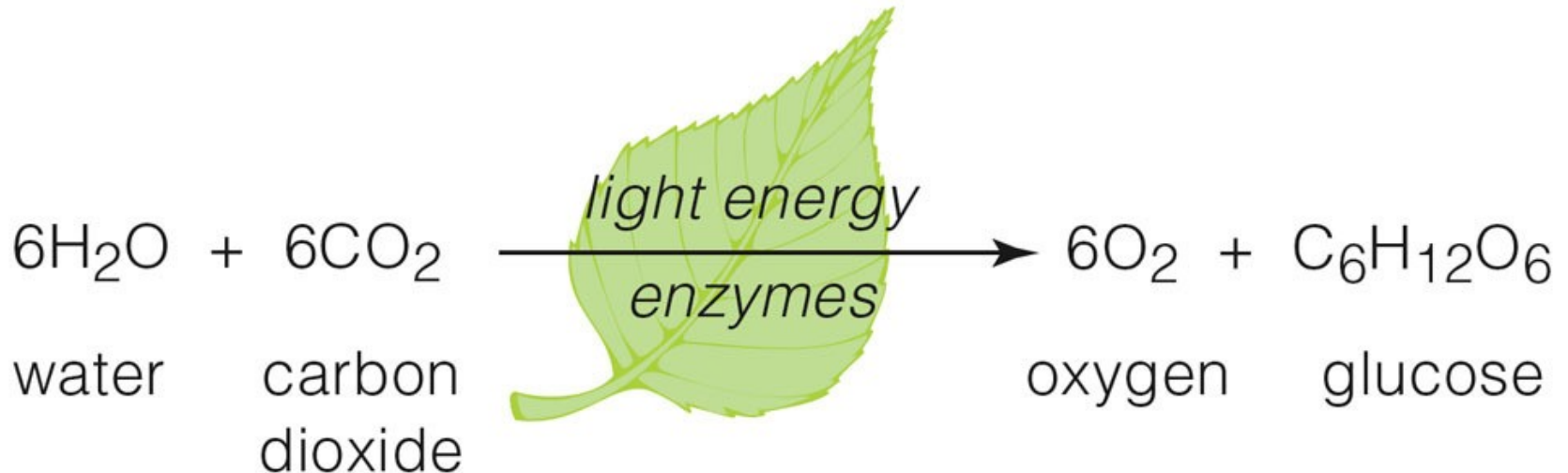
# Overview of Photosynthesis

## 1. Light-dependent reactions (thylakoid membrane)

- Light energy is transferred to ATP and NADPH
- Water molecules are split, releasing O<sub>2</sub>

## 1. Light-independent reactions (stroma)

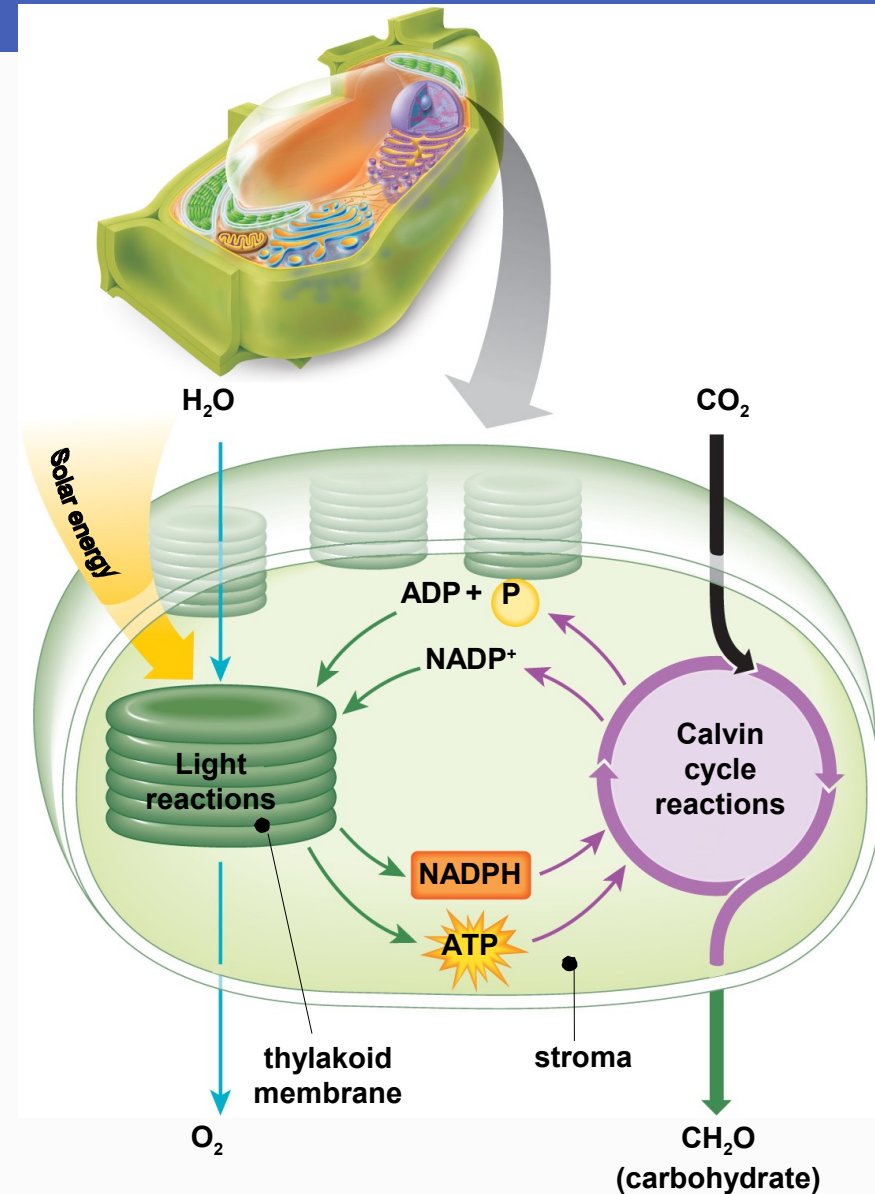
- Energy in ATP and NADPH drives synthesis of glucose and other carbohydrates from CO<sub>2</sub> and water



# 2 reactions in Photosynthesis

## 1. Light-dependent reactions

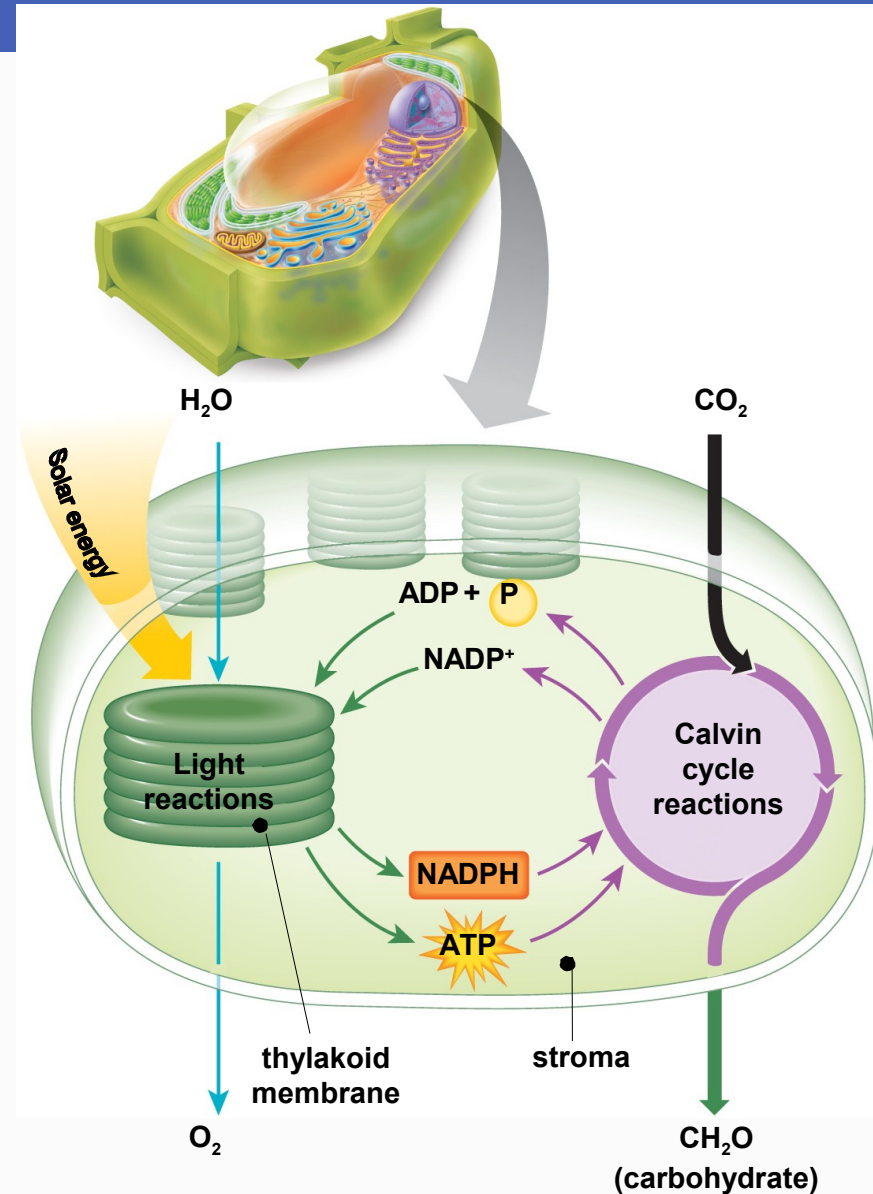
- In thylakoid membrane
- Chlorophyll (the main pigment) absorbs solar energy
- Electrons get excited!
- ATP produced
- $\text{NADP}^+$  to NADPH



# 2 reactions in Photosynthesis

## 2. Light-independent reactions (Calvin cycle)

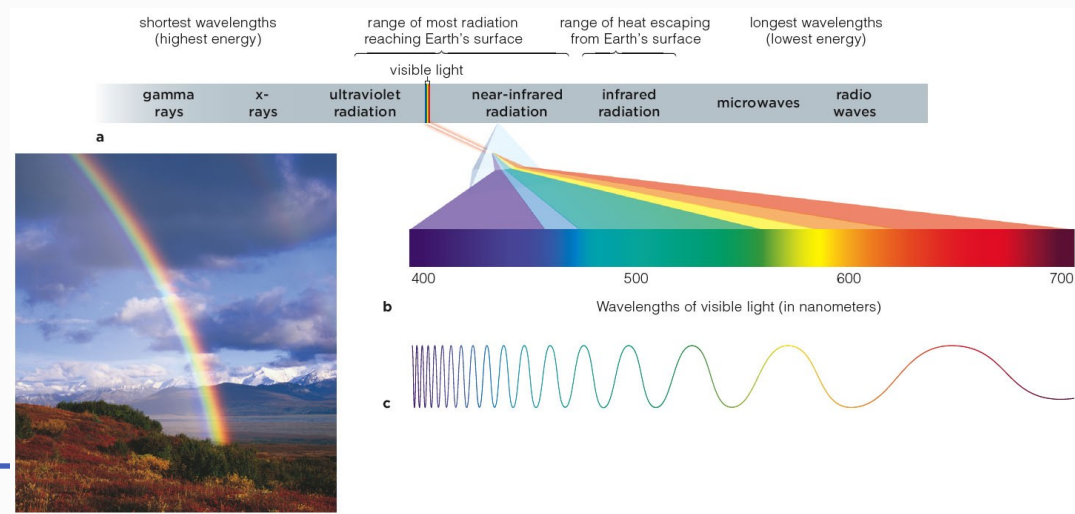
- Occur in stroma
- $\text{CO}_2$  taken up
- ATP and NADPH used to form carbohydrate from  $\text{CO}_2$



[http://www.youtube.com/v/C1\\_uez5WX1o](http://www.youtube.com/v/C1_uez5WX1o)

# Light-Dependent Reactions: 1. Pigments

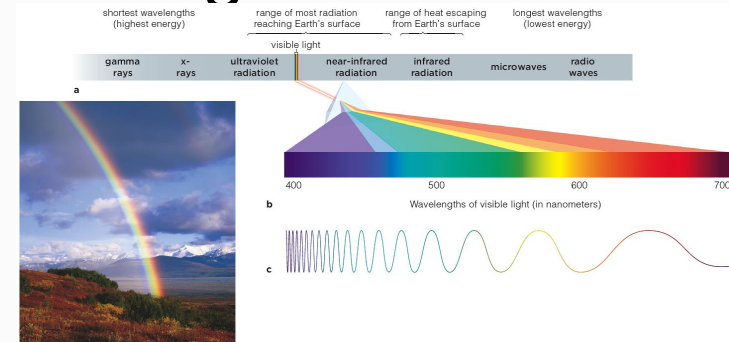
- **Pigments in thylakoids absorb solar energy**
  - Only about 42% of the solar radiation hits the Earth's surface
    - Ozone layer
    - Water vapor
- Vision and photosynthesis are adapted to use the wavelengths that hit the Earth!





# Light-Dependent Reactions: 1. Pigments

- Photosynthesis uses wavelengths of 380-750 nm
- Color you see are the wavelengths *not* absorbed – why the ocean is blue and leaves are green!!!

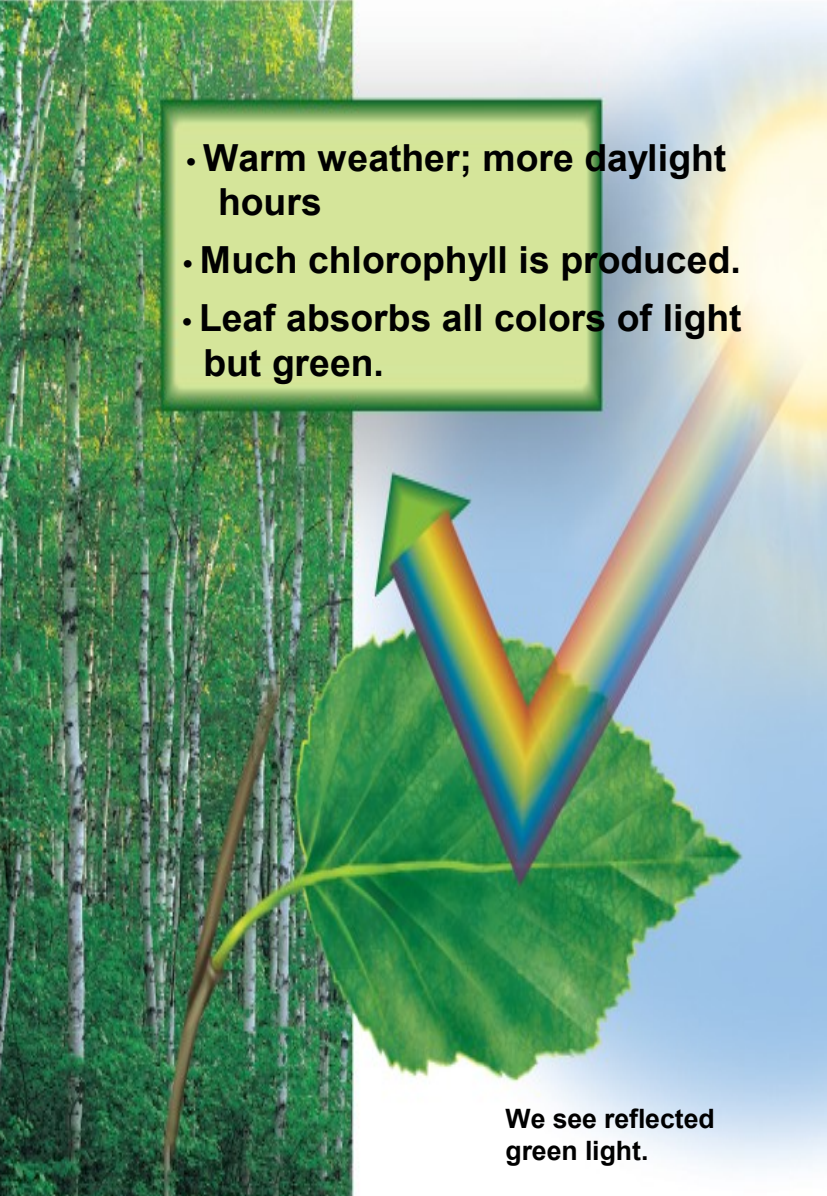


- **Chlorophyll (a & b)**


- The most common photosynthetic pigment
  - Absorbs violet and red light (appears green)
  - Carotenoids – an accessory pigment found in photosynthesizers
-

**Chlorophylls cover up other pigments that ARE there.**

**When chlorophylls no longer produced, we see carotenoids**

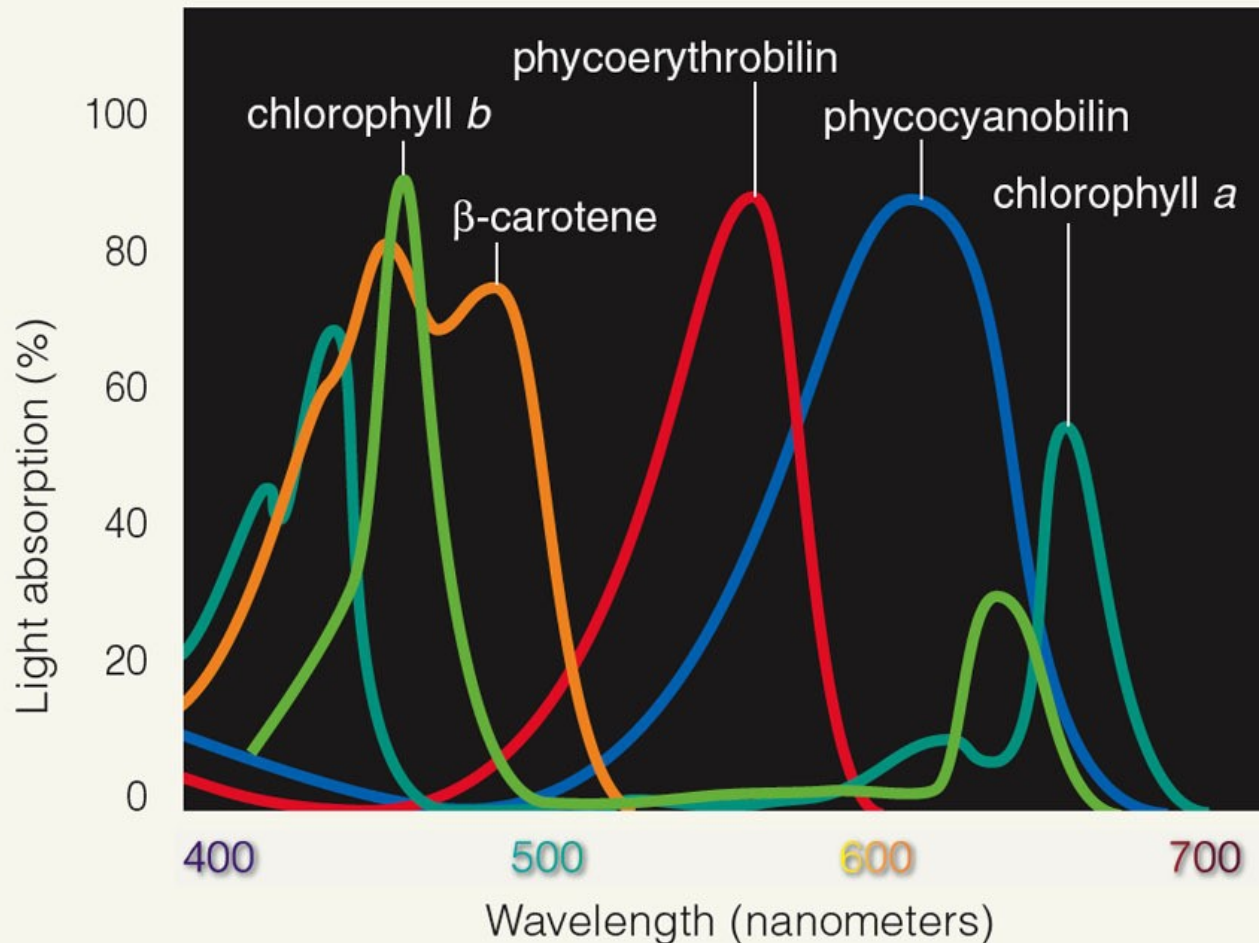
- 
- Warm weather; more daylight hours  
• Much chlorophyll is produced.  
• Leaf absorbs all colors of light but green.
- The diagram shows a green leaf in a forest. A rainbow arrow points down towards the leaf, representing incoming light. A second rainbow arrow points away from the leaf, representing reflected light. The leaf is green, indicating that chlorophyll is present and reflecting green light.

**We see reflected green light.**

- 
- Cool weather; fewer daylight hours  
• Little chlorophyll is produced.  
• Leaf absorbs all colors but yellow to orange.
- The diagram shows a yellow leaf in a forest. A rainbow arrow points down towards the leaf, representing incoming light. A second rainbow arrow points away from the leaf, representing reflected light. The leaf is yellow, indicating that chlorophyll is absent and carotenoids are reflecting yellow to orange light.

**We see reflected yellow to orange light.**

# Why are accessory pigments important???



<http://www.youtube.com/v/IJCVg9M-7S0>

**C** Absorption spectra of a few photosynthetic pigments. Line color indicates the characteristic color of each pigment.

# The Light Reactions – 2. The electron pathway

2 photosystems used

- PS II & PS I

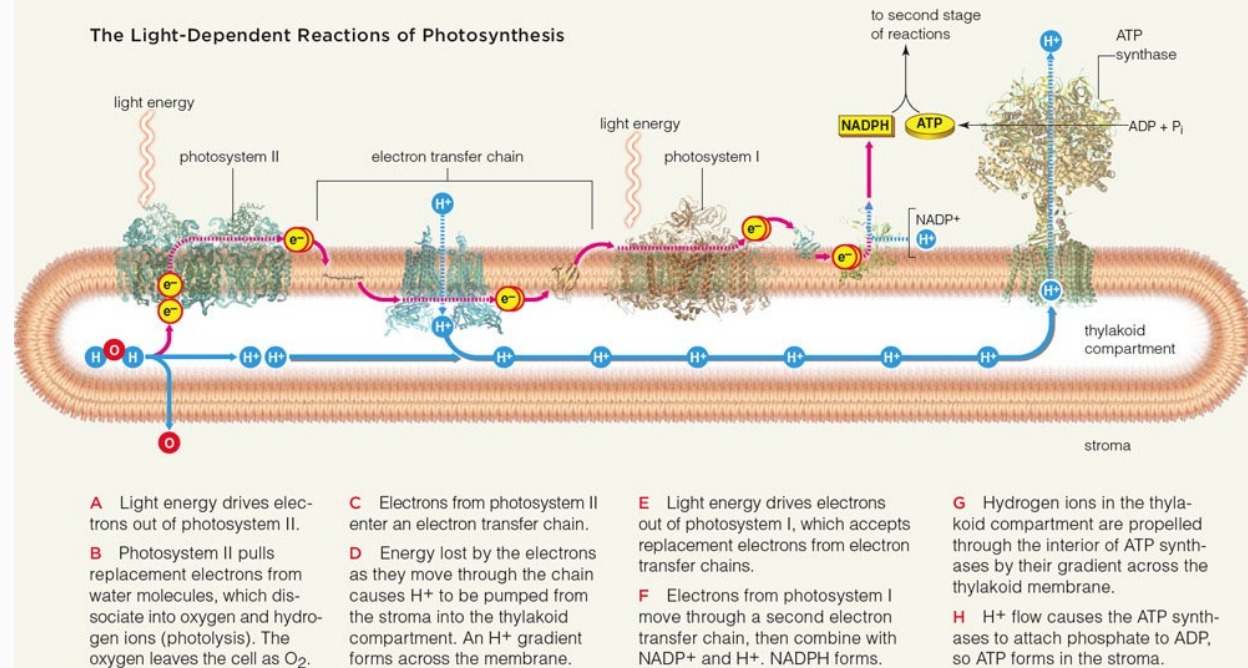
- Pigment complexes & e- acceptor

- e- move down e- transport chain

- PS II first one discovered

- PS I  $\text{NADP}^+$  becomes NADPH

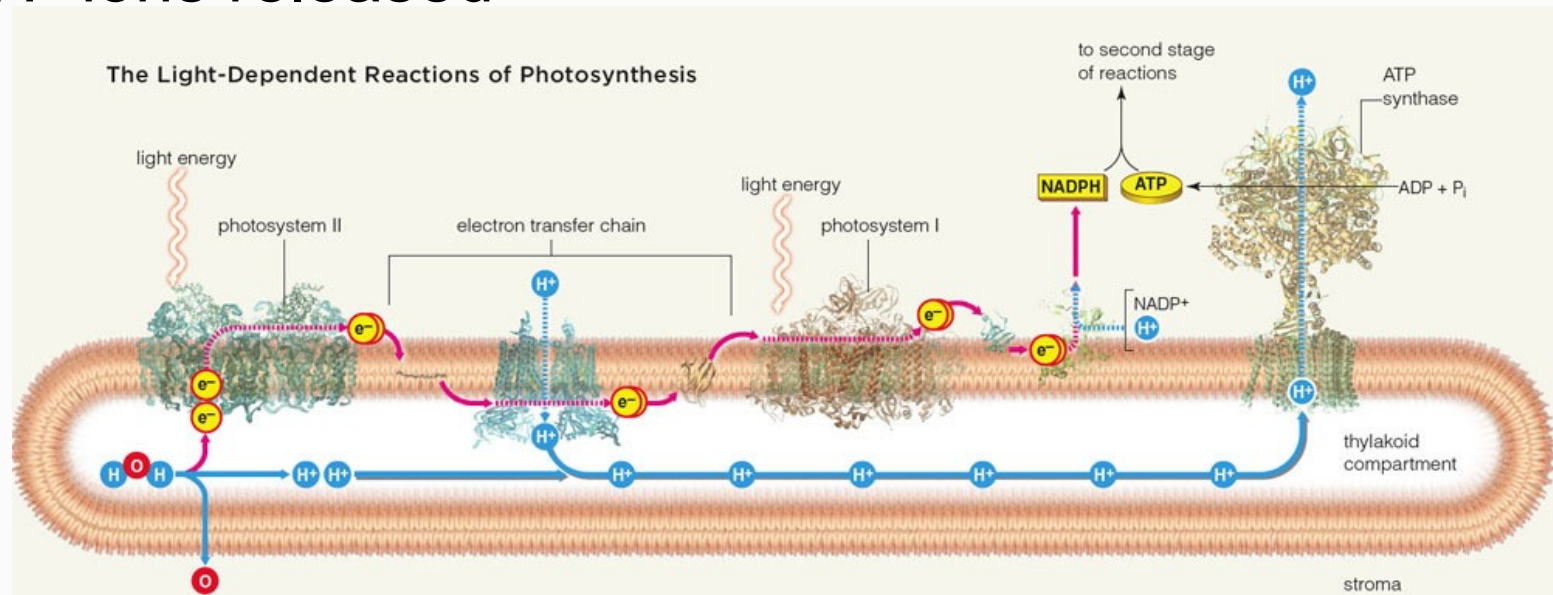
Where do replacement electrons come from???



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# The Light Reactions: 3. Replacing Lost Electrons

- Electrons lost from photosystem II are replaced by splitting of water molecules
  - $O_2$  &  $H^+$  ions released



**A** Light energy drives electrons out of photosystem II.

**B** Photosystem II pulls replacement electrons from water molecules, which dissociate into oxygen and hydrogen ions (photolysis). The oxygen leaves the cell as  $O_2$ .

**C** Electrons from photosystem II enter an electron transfer chain.

**D** Energy lost by the electrons as they move through the chain causes  $H^+$  to be pumped from the stroma into the thylakoid compartment. An  $H^+$  gradient forms across the membrane.

**E** Light energy drives electrons out of photosystem I, which accepts replacement electrons from electron transfer chains.

**F** Electrons from photosystem I move through a second electron transfer chain, then combine with  $NADP^+$  and  $H^+$ . NADPH forms.

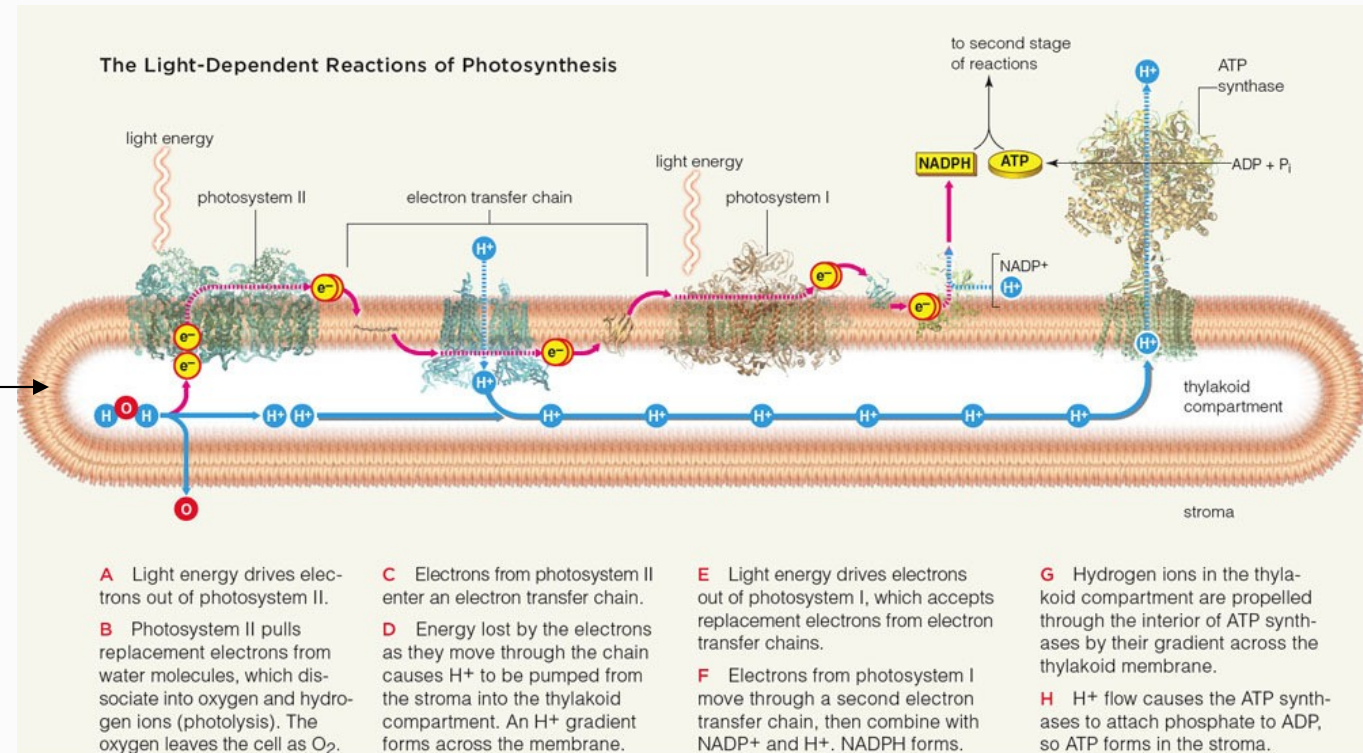
**G** Hydrogen ions in the thylakoid compartment are propelled through the interior of ATP synthases by their gradient across the thylakoid membrane.

**H**  $H^+$  flow causes the ATP synthases to attach phosphate to ADP, so ATP forms in the stroma.

# The Light Reactions: 4. The electron transport chain

- Organized arrays of enzymes, coenzymes, and other proteins that accept and donate electrons in a series
  - Energy released at each “step”.
  - H<sup>+</sup> gradient
  - Efficient transfer of e<sup>-</sup>

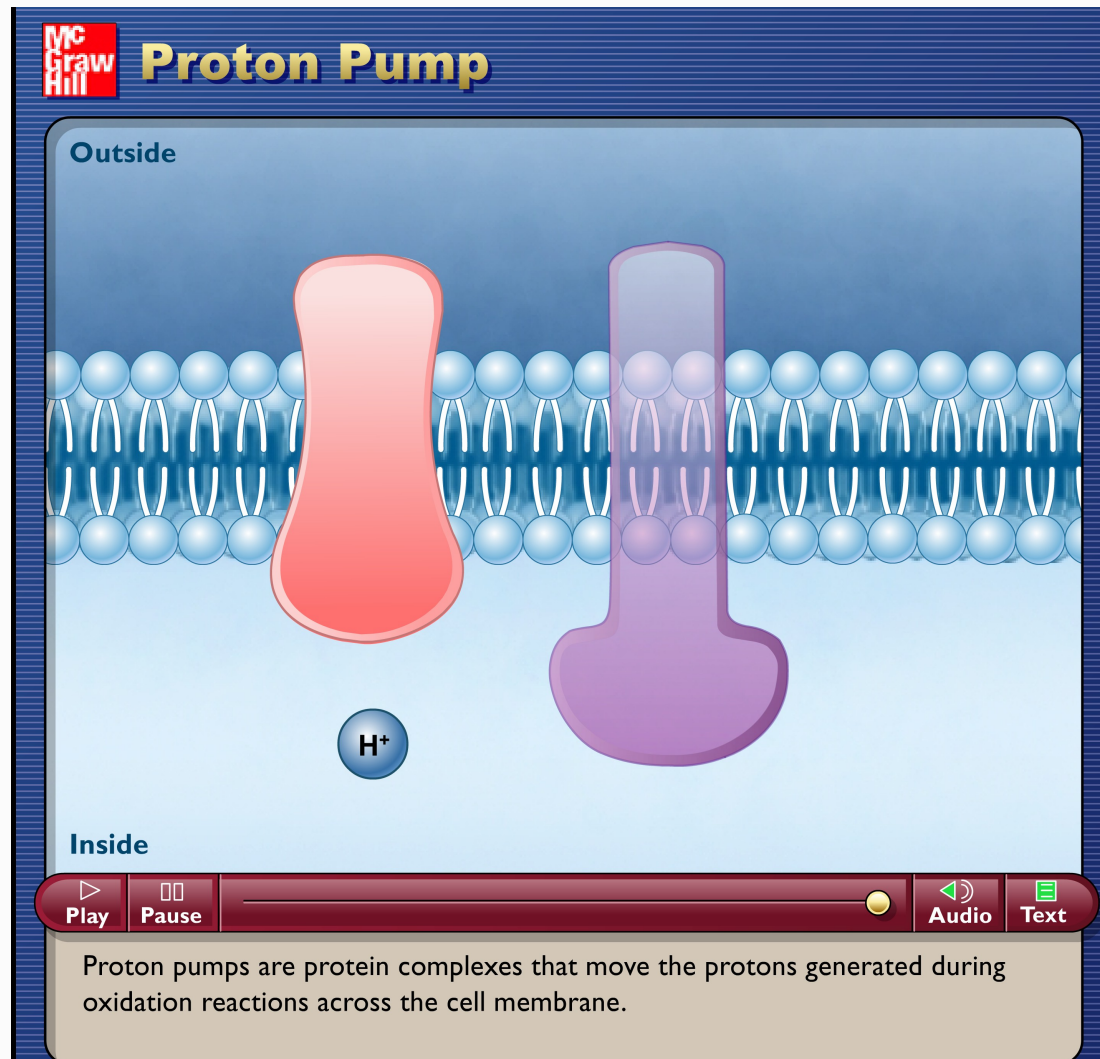
Thylakoid membrane



# The Light Reactions: 5. Harvesting Electron Energy

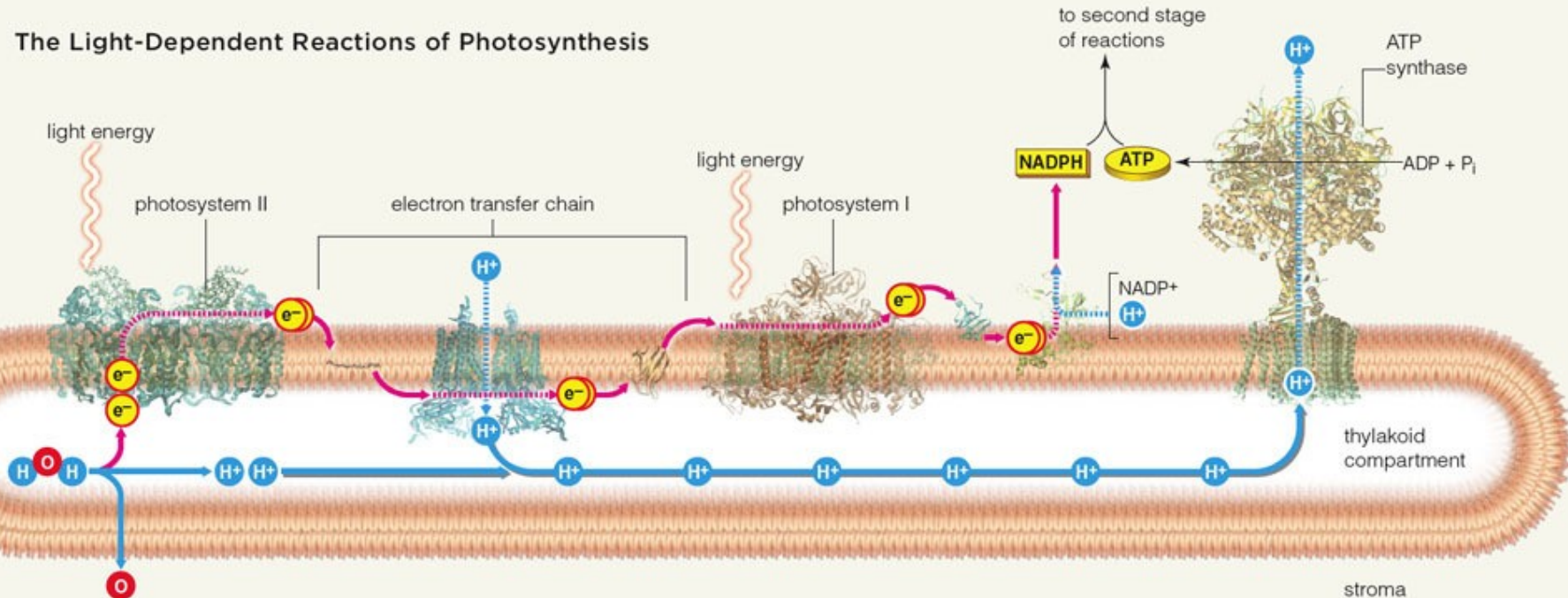
## ATP Production

- ATP synthase complex is also on thylakoid membrane
- Many  $H^+$  in thylakoid space
  - Water split
  - $H^+$  pumped in from stroma
  - $H^+$  gradient formed
  - Where do  $H^+$  want to go???



# Light reactions of Photosynthesis

The Light-Dependent Reactions of Photosynthesis



**A** Light energy drives electrons out of photosystem II.  
**B** Photosystem II pulls replacement electrons from water molecules, which dissociate into oxygen and hydrogen ions (photolysis). The oxygen leaves the cell as O<sub>2</sub>.

**C** Electrons from photosystem II enter an electron transfer chain.  
**D** Energy lost by the electrons as they move through the chain causes H<sup>+</sup> to be pumped from the stroma into the thylakoid compartment. An H<sup>+</sup> gradient forms across the membrane.

**E** Light energy drives electrons out of photosystem I, which accepts replacement electrons from electron transfer chains.  
**F** Electrons from photosystem I move through a second electron transfer chain, then combine with NADP<sup>+</sup> and H<sup>+</sup>. NADPH forms.

**G** Hydrogen ions in the thylakoid compartment are propelled through the interior of ATP synthases by their gradient across the thylakoid membrane.  
**H** H<sup>+</sup> flow causes the ATP synthases to attach phosphate to ADP, so ATP forms in the stroma.

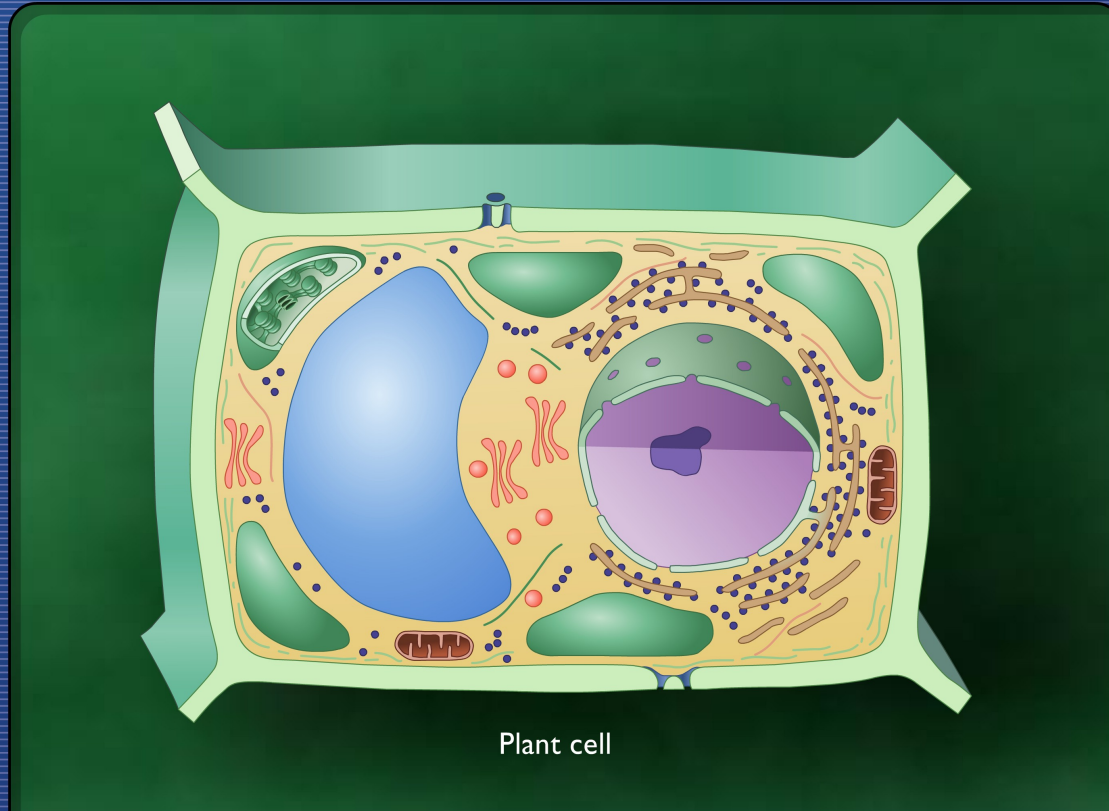
ATP forms in the stroma when H<sup>+</sup> ions travel through ATP synthase



# Animation: Light-dependent reactions



## Photosynthetic Electron Transport and ATP Synthesis



Plant cell

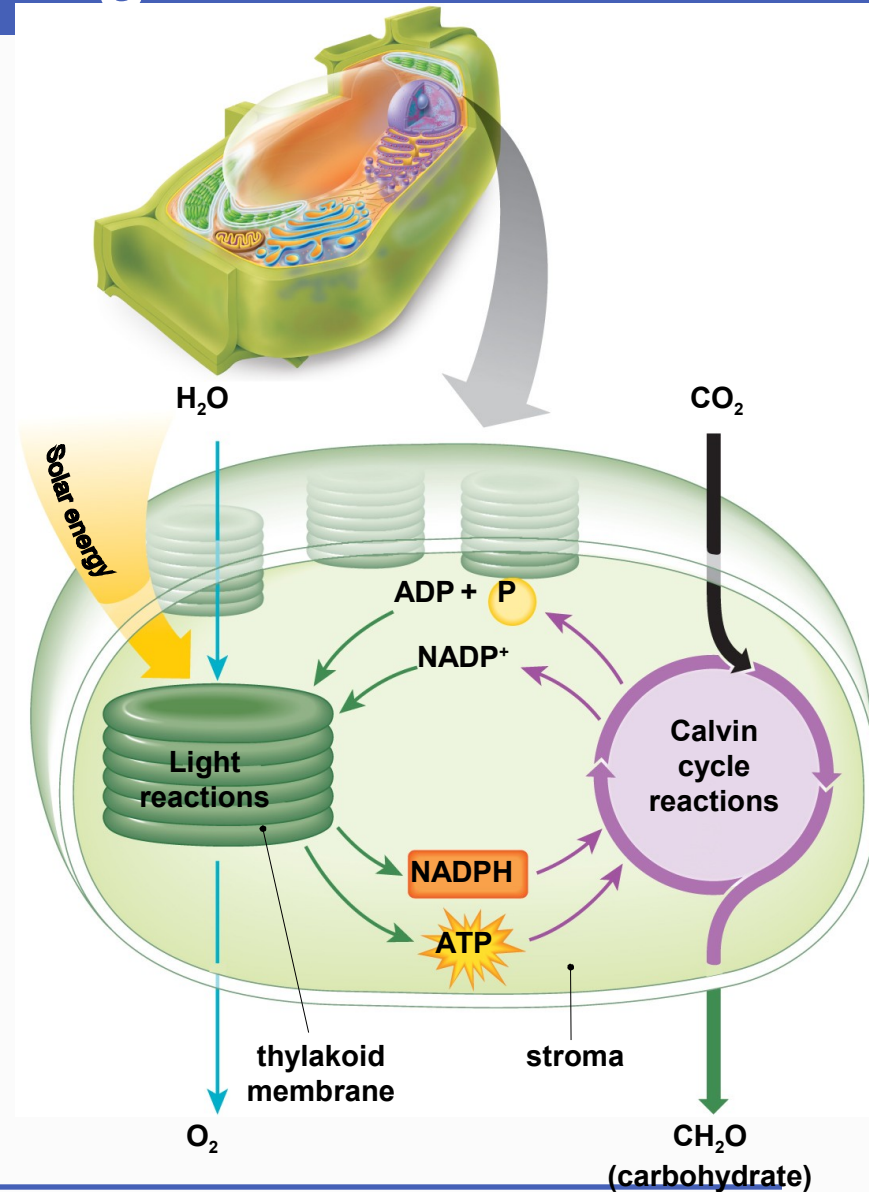
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In plants, photosynthesis occurs in specialized organelles called chloroplasts. The internal membranes of chloroplasts are organized into sacs called thylakoids.

# Light-Independent Reactions: The Calvin Cycle – making sugars!

## Calvin cycle

- Rxns that build sugars in stroma
- Powered by ATP & NADPH
- End product is glucose:  
 $C_6H_{12}O_6$



# The Calvin Cycles' 3 Steps

1. Carbon dioxide fixation
2. Carbon dioxide reduction
3. Regeneration of 1<sup>st</sup> substrate (RuBP)

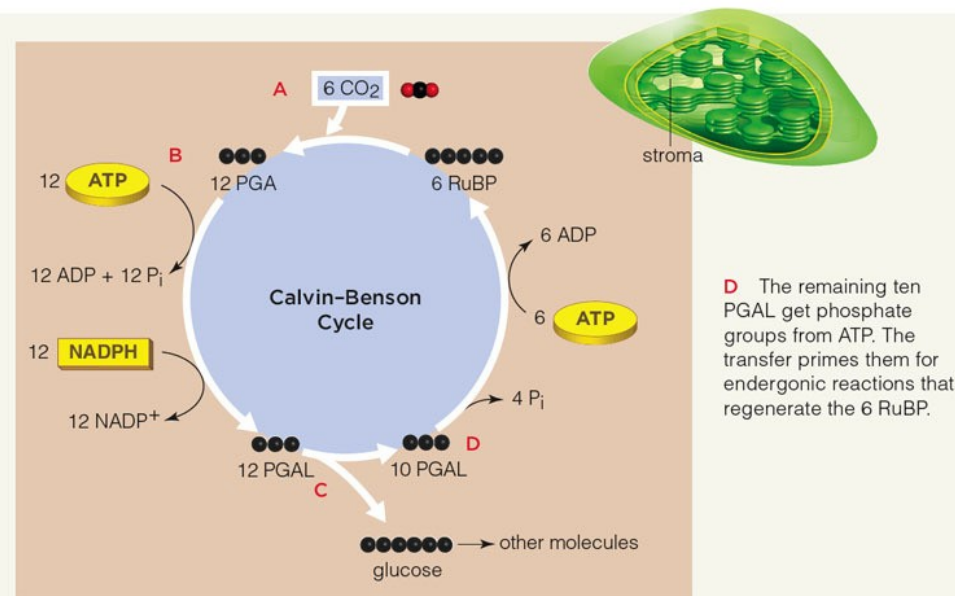
1. Carbon dioxide fixation
  - Enzyme **rubisco** attaches  $\text{CO}_2$  to RuBP forming 6 carbon molecule
  - 6 carbon molecule splits into two 3 carbon molecules (PGA)

**A** Six  $\text{CO}_2$  in air spaces inside of a leaf diffuse into a photosynthetic cell. Rubisco attaches each to a RuBP molecule. The resulting intermediates split, so twelve molecules of PGA form.

**B** Each PGA molecule gets a phosphate group from ATP, plus hydrogen and electrons from NADPH. Twelve intermediate molecules (PGAL) form.

**C** Two of the PGAL combine and form one molecule of glucose. The glucose may enter reactions that form other carbohydrates, such as sucrose and starch.

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**D** The remaining ten PGAL get phosphate groups from ATP. The transfer primes them for endergonic reactions that regenerate the 6 RuBP.

# The Calvin Cycles' 3 Steps

1. Carbon dioxide fixation
2. Carbon dioxide reduction
3. Regeneration of 1<sup>st</sup> substrate (RuBP)

## 2. Carbon dioxide reduction

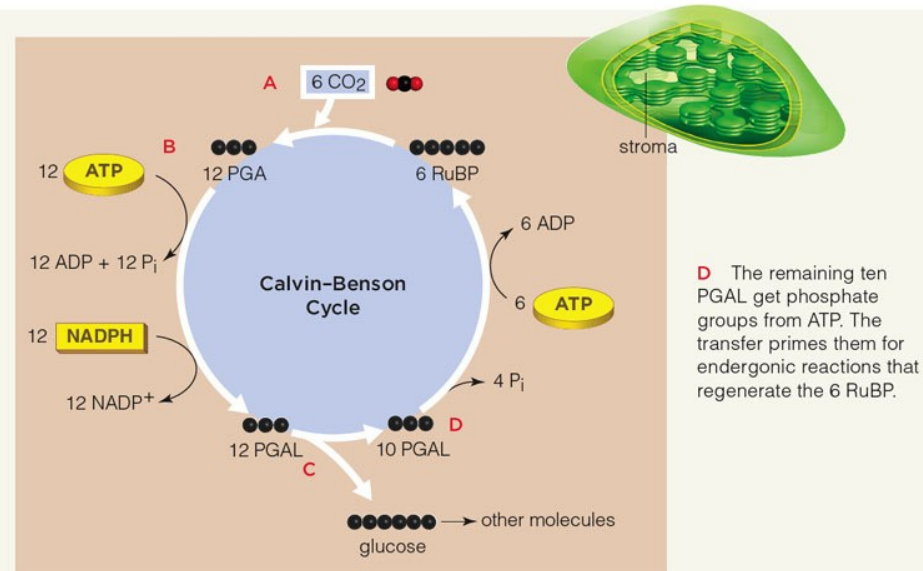
- PGA converted into PGAL (G3P) using NADPH (for H) and ATP (energy)
- PGAL (G3P) can become glucose

**A** Six  $\text{CO}_2$  in air spaces inside of a leaf diffuse into a photosynthetic cell. Rubisco attaches each to a RuBP molecule. The resulting intermediates split, so twelve molecules of PGA form.

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# The Calvin Cycles' 3 Steps

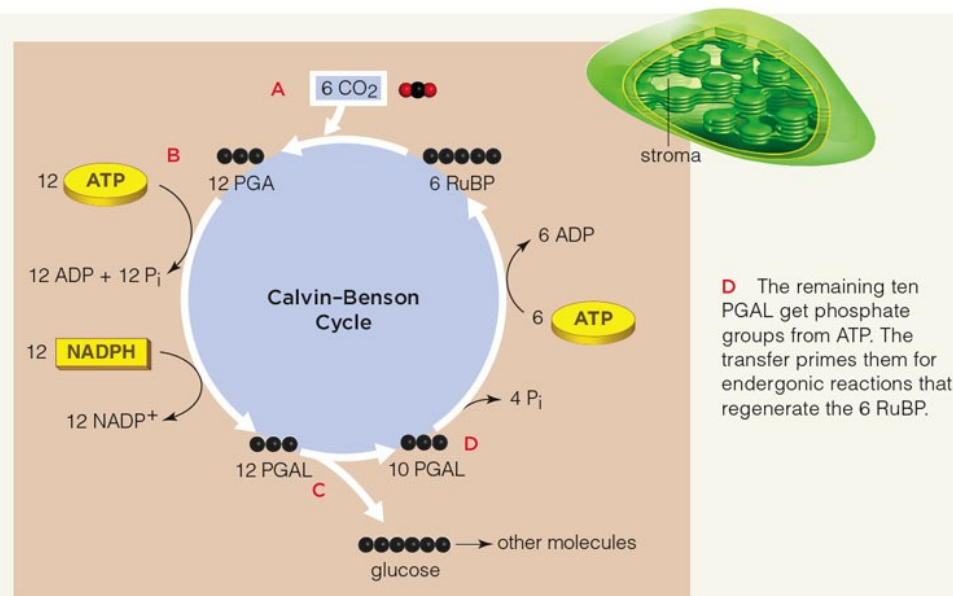
1. Carbon dioxide fixation
  2. Carbon dioxide reduction
  3. Regeneration of 1<sup>st</sup> substrate (RuBP)
- 
3. Regeneration of RuBP
    - PGAL (G3P) used to reform RuBP
    - Uses ATP

**A** Six CO<sub>2</sub> in air spaces inside of a leaf diffuse into a photosynthetic cell. Rubisco attaches each to a RuBP molecule. The resulting intermediates split, so twelve molecules of PGA form.

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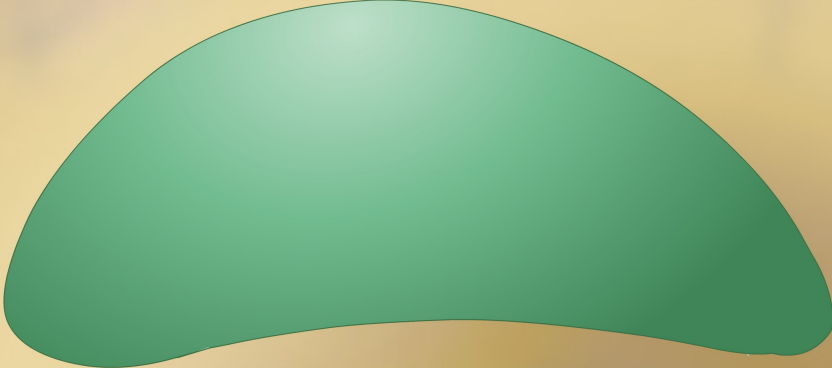







**D** The remaining ten PGAL get phosphate groups from ATP. The transfer primes them for endergonic reactions that regenerate the 6 RuBP.

# Calvin Cycle animation

 **How the Calvin Cycle Works**

Chloroplast

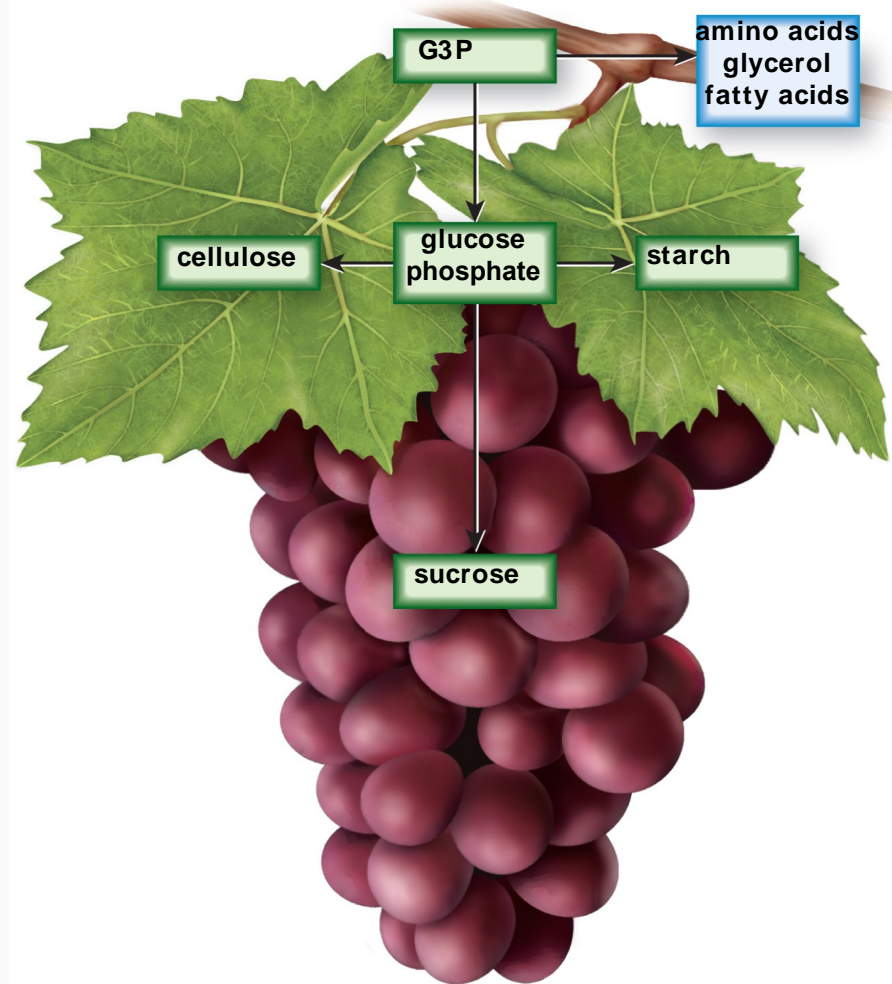
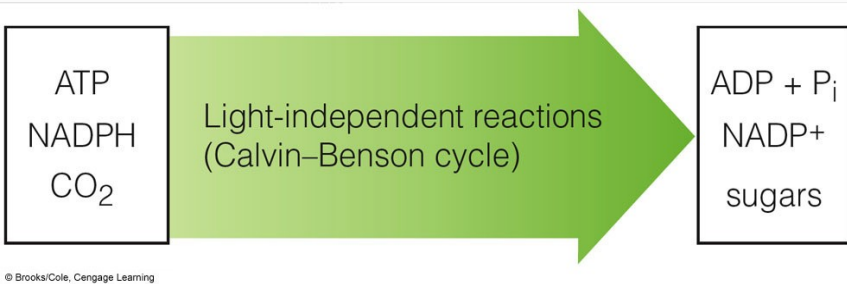


The Calvin cycle is a series of reactions that results in conversion of carbon dioxide into the organic molecules needed to build new cells.

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# Inputs and Outputs of the Calvin-Benson Cycle



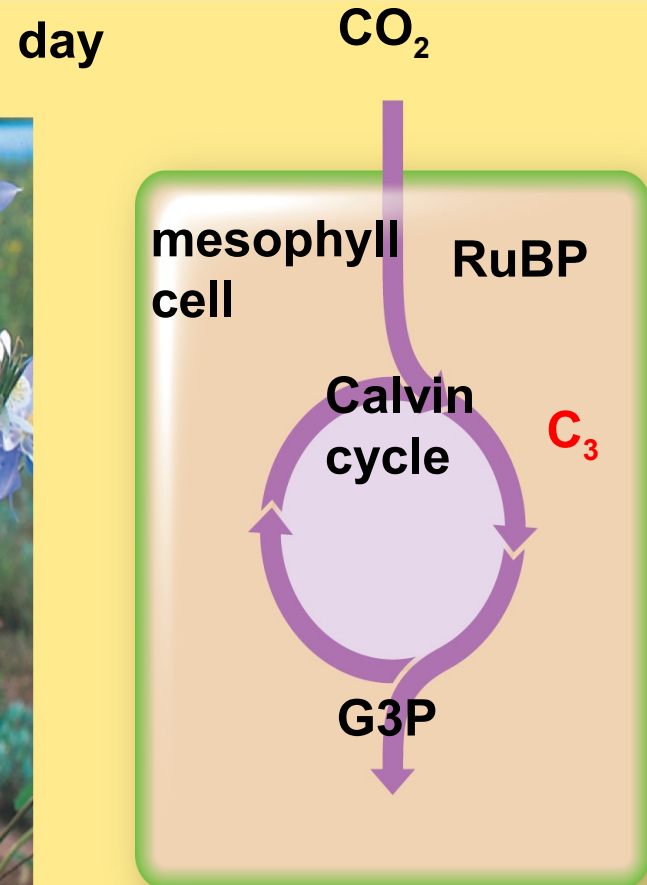
**Figure 6.9 The fate of G3P (PGAL)**

# Other types of Photosynthesis

- Plants in different habitats photosynthesize differently
  - Moderate light and rainfall =  $C_3$  plants

$C_3$  compound formed first in carbon fixation (like we saw)

All occurs in mesophyll cells

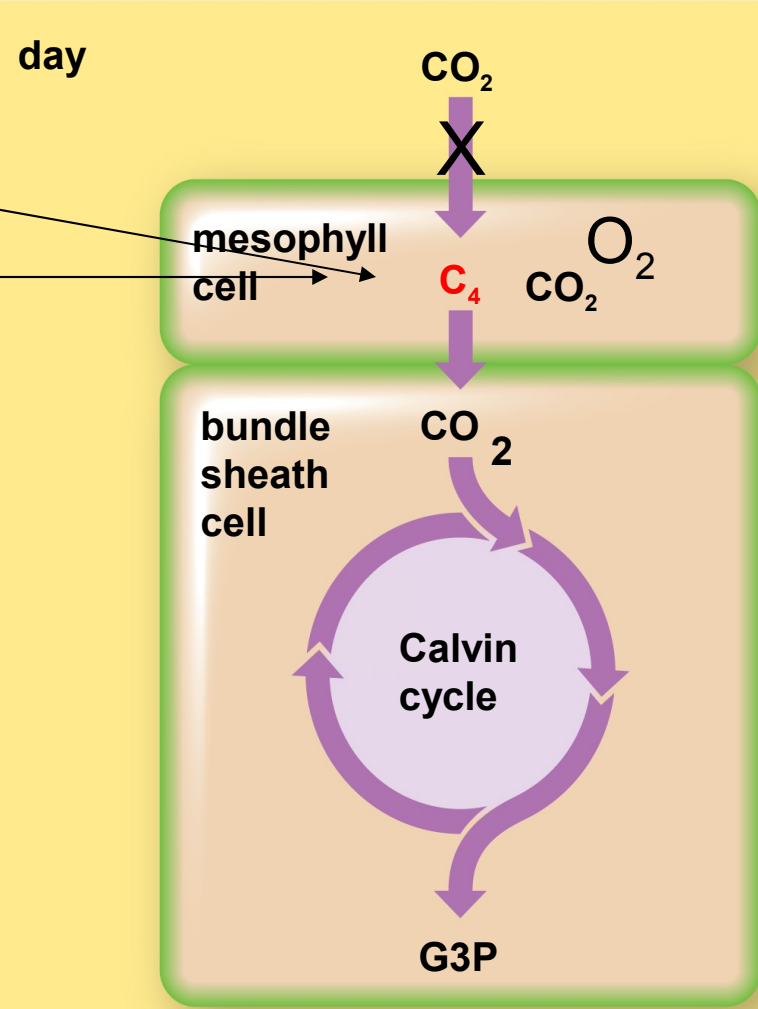




# Other types of Photosynthesis – preventing water loss!

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- Hot and dry climates =  $C_4$  plants
- To preserve water: Stomata closes – limits  $CO_2$  uptake, water loss; traps  $O_2$
- There's a problem!!!
- $O_2$  competes with  $CO_2$  for rubisco – so less  $C_3$  would be produced in Calvin Cycle if photosynthesis were the same as in  $C_3$  plants (in the

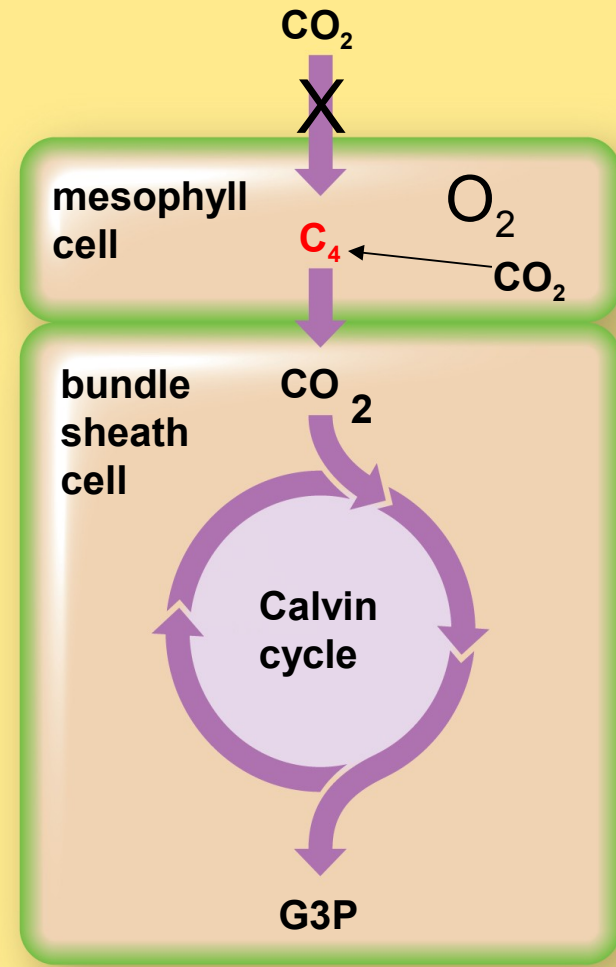


# Other types of Photosynthesis – preventing water loss!

- $C_4$  plants do it differently!
- Rxns are divided by space!  $CO_2$  is fixed in mesophyll cells FIRST!!!
- Fixed carbon then enters bundle sheath cells for Calvin cycle – separated from  $O_2$

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day

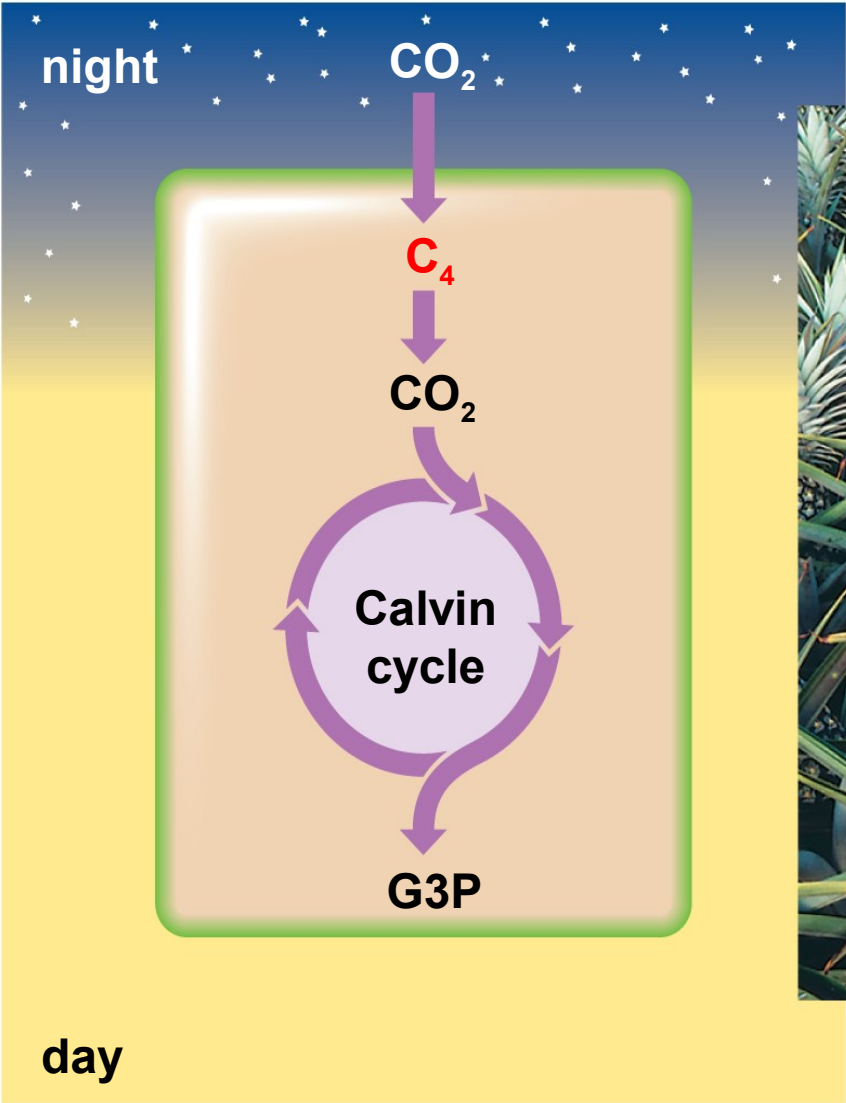


# Differences between C<sub>3</sub> and C<sub>4</sub> plants – a summary

- C<sub>3</sub> plants
    - Calvin cycle occurs in the mesophyll cells
    - CO<sub>2</sub> is fixed as C<sub>3</sub>
    - Advantageous in moderate weather
  - C<sub>4</sub> plants
    - CO<sub>2</sub> is fixed in mesophyll cells as C<sub>4</sub>
    - Calvin cycle occurs in bundle sheath cells, away from oxygen
    - Advantageous in hot, dry weather
-

# Other types of photosynthesis

- Ve



ace

light

CO<sub>2</sub> fixation in a CAM plant, pineapple

# The Spinach Battery!!!

