

Lecture Series 10  
Photosynthesis: Energy  
from the Sun

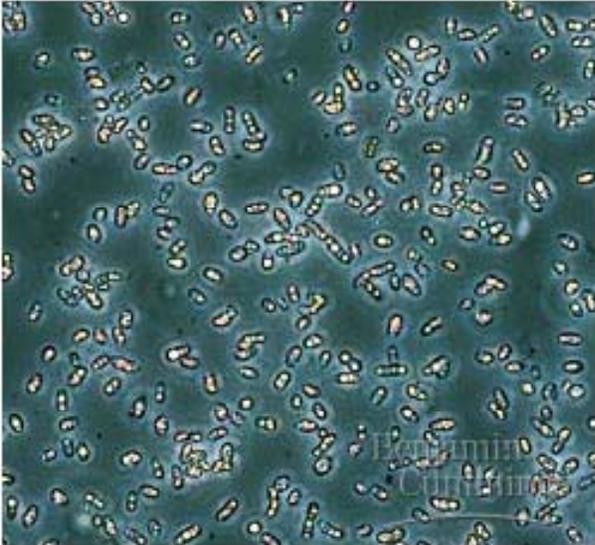
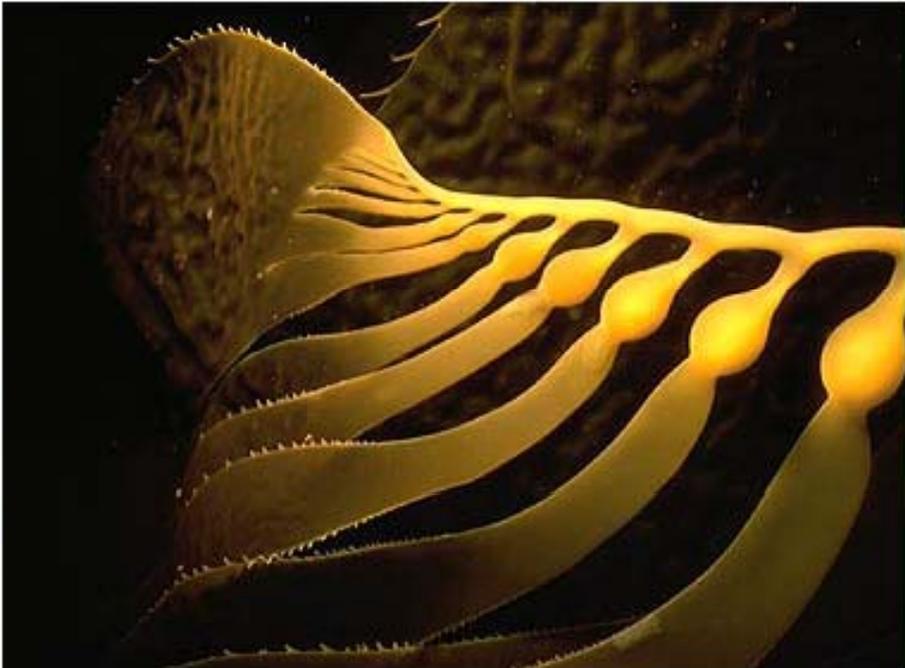
# Reading Assignments

- Review Chapter 3  
Energy, Catalysis, & Biosynthesis
- Read Chapter 13  
How Cells obtain Energy from Food
- Read Chapter 14  
Energy Generation in Mitochondria &  
Chloroplasts

# Photosynthesis In General

- Life on Earth depends on the absorption of light energy from the sun.
- In plants, photosynthesis takes place in chloroplasts.

# Photoautotrophs



# A. Identifying Photosynthetic Reactants and Products

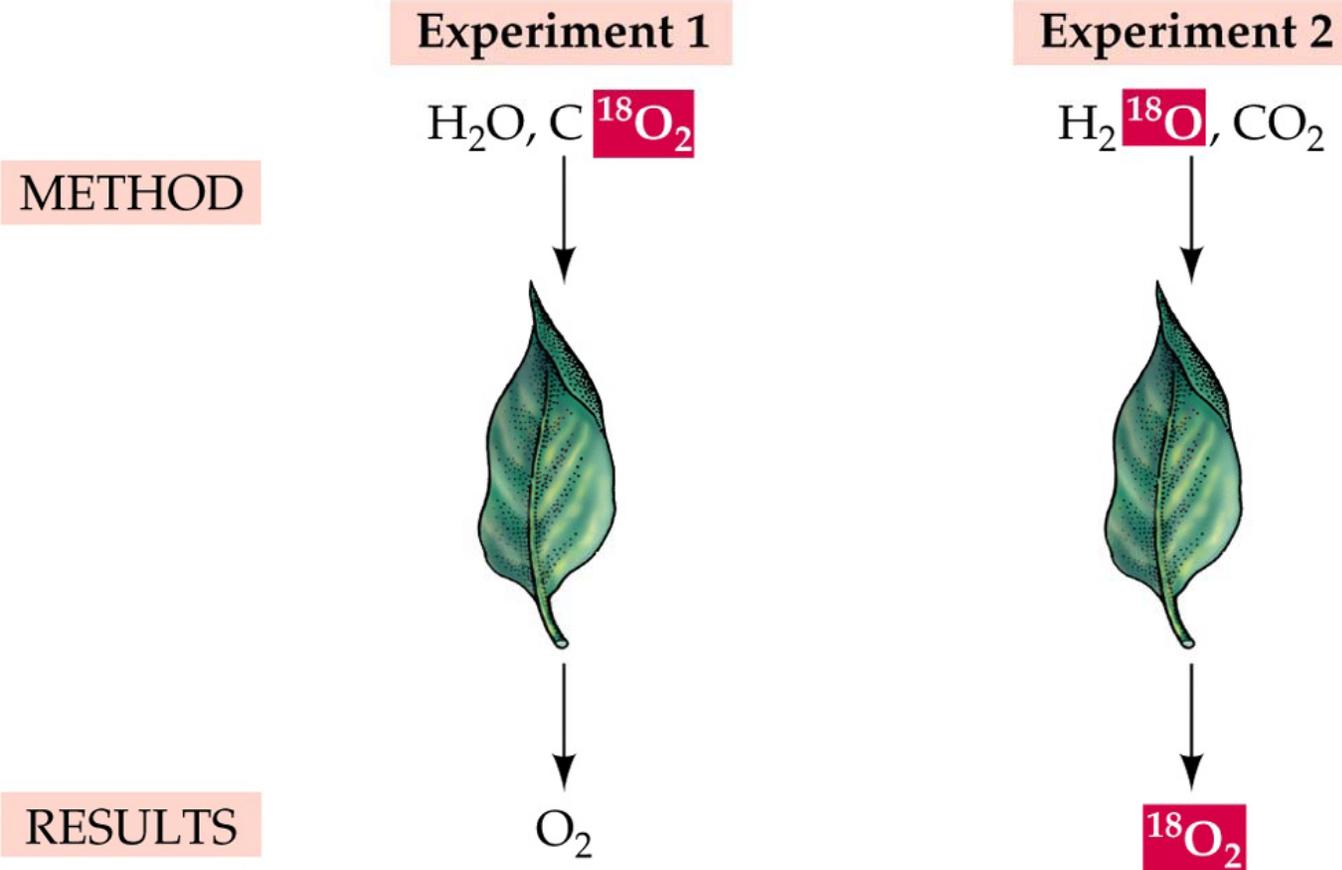
- Photosynthesizing plants take in  $\text{CO}_2$ , water, and light energy, producing  $\text{O}_2$  and carbohydrate. The overall reaction is



- The oxygen atoms in  $\text{O}_2$  come from water, not from  $\text{CO}_2$ .

## EXPERIMENT

**Question:** What is the source of the  $O_2$  produced by photosynthesis?



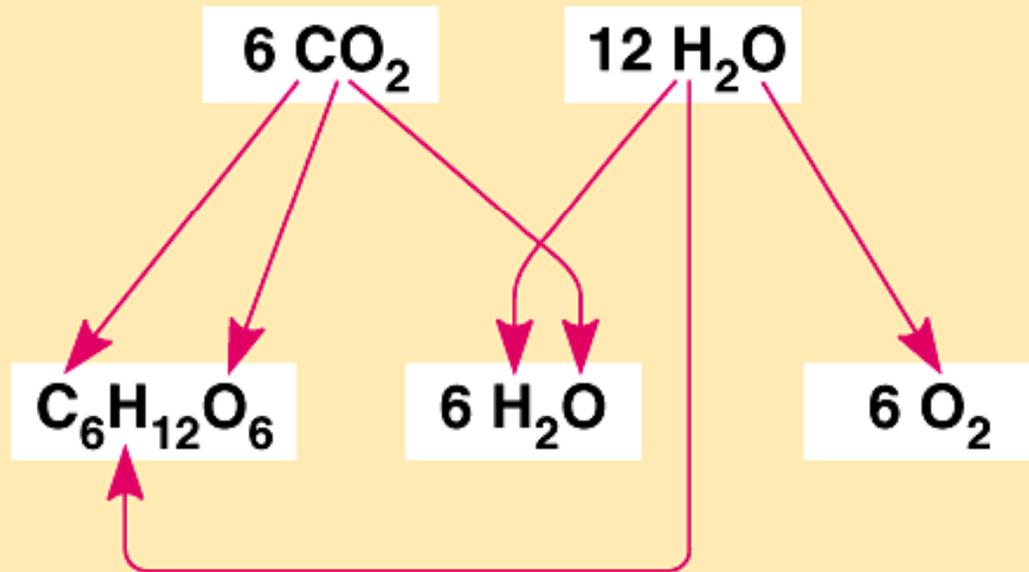
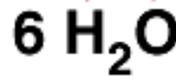
**Conclusion:** Water is the source of the  $O_2$  produced by photosynthesis.

## Tracking atoms through photosynthesis

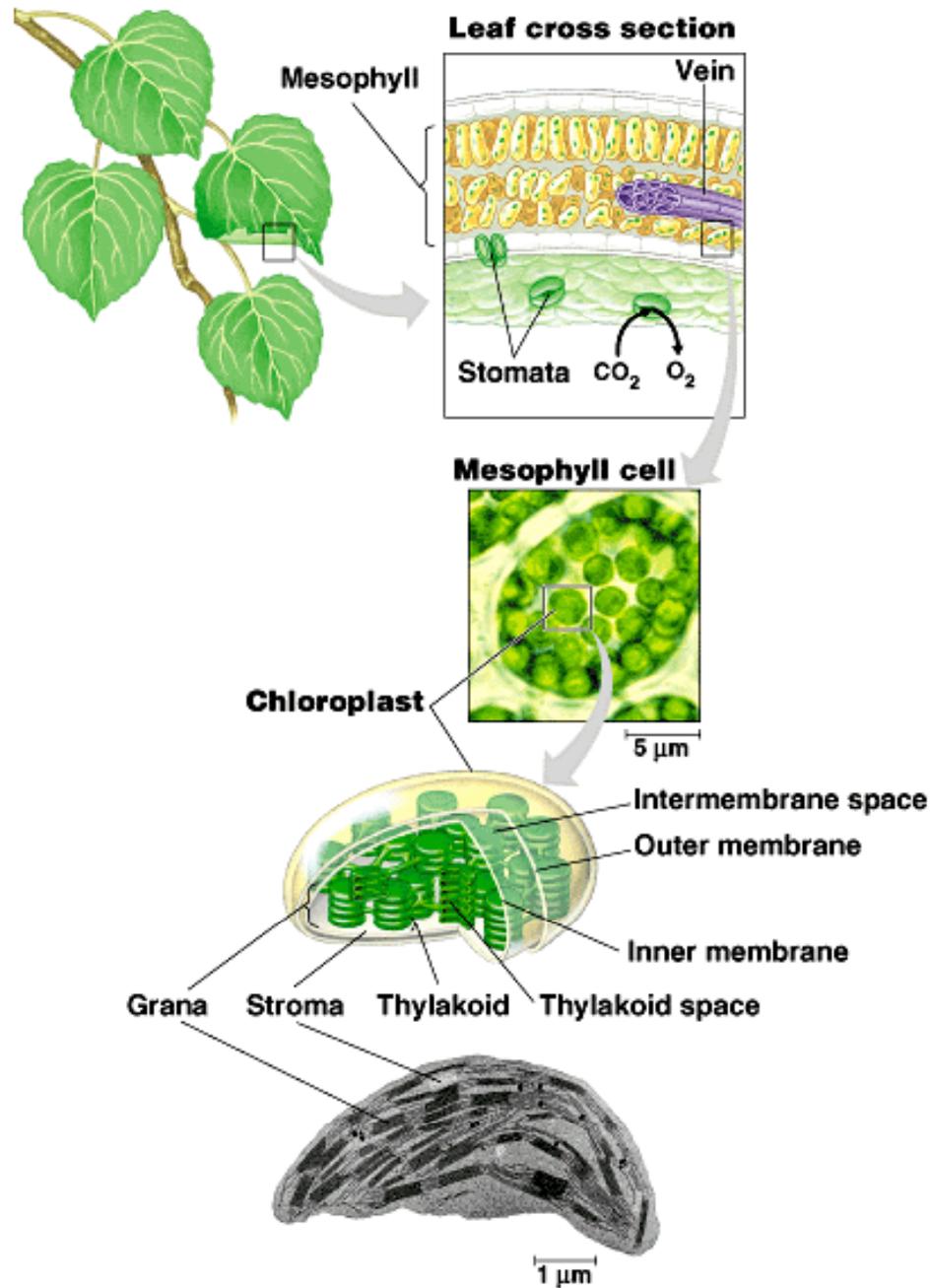
**Reactants:**



**Products:**



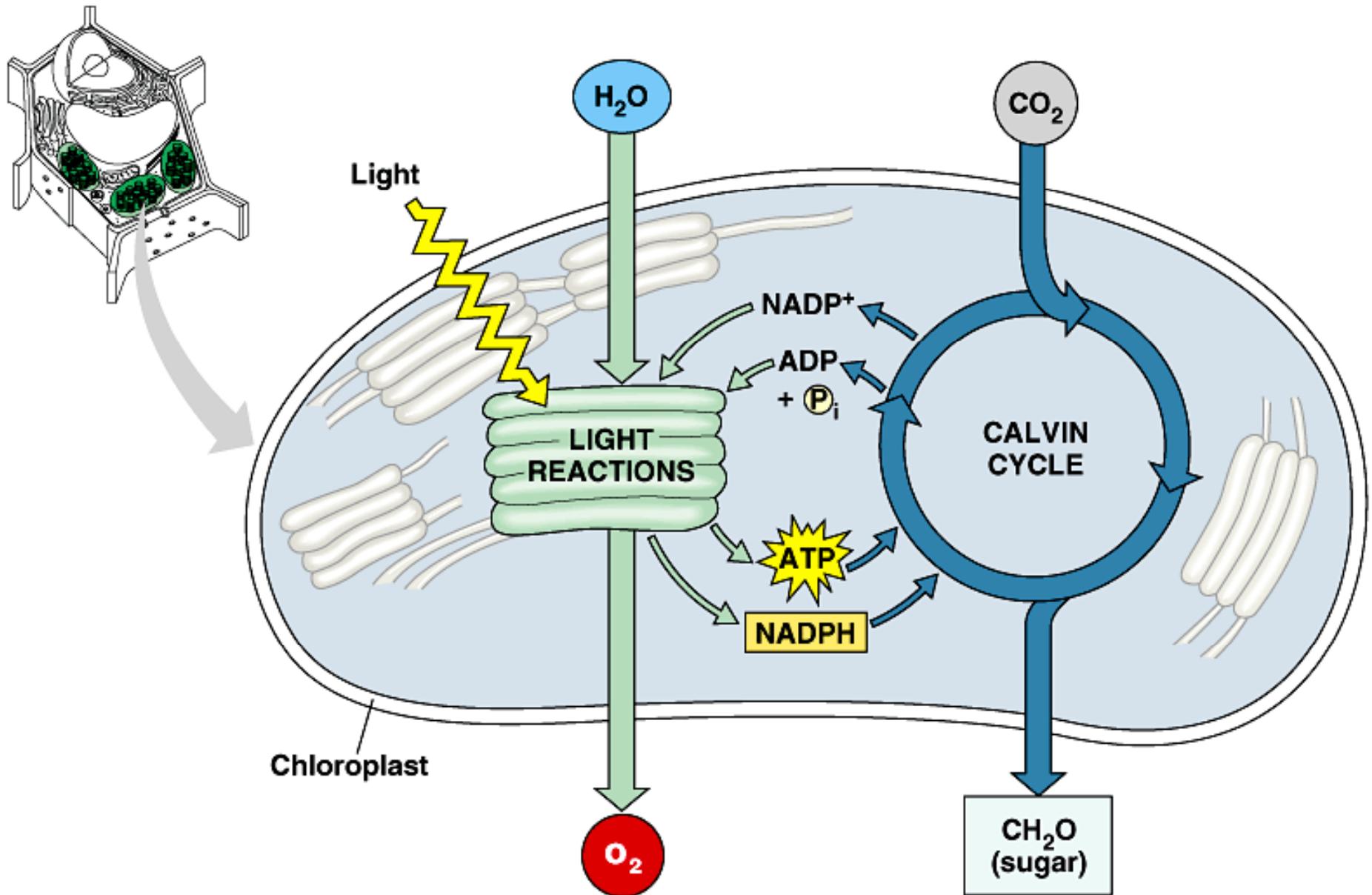
# Focusing in on the location of photosynthesis in a plant



## B. The Two Pathways of Photosynthesis: An Overview

- In the light reactions of photosynthesis, electron flow and photophosphorylation produce ATP and reduce  $\text{NADP}^+$  to  $\text{NADPH} + \text{H}^+$ .
- ATP and  $\text{NADPH} + \text{H}^+$  are needed for the reactions that fix and reduce  $\text{CO}_2$  in the Calvin-Benson cycle, forming sugars. These are sometimes erroneously referred to as the dark reactions.

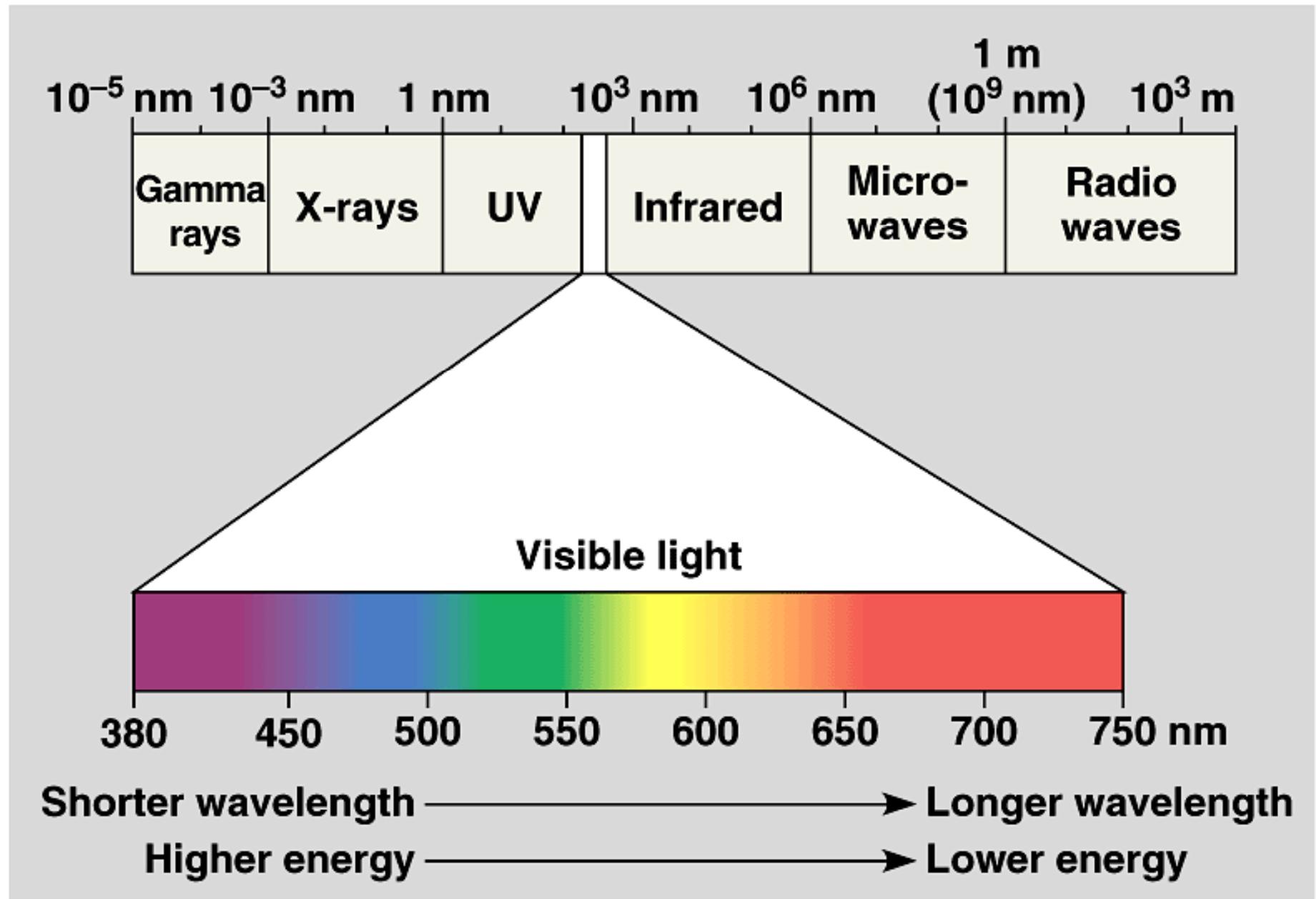
# An overview of photosynthesis: cooperation of the light reactions and the Calvin cycle



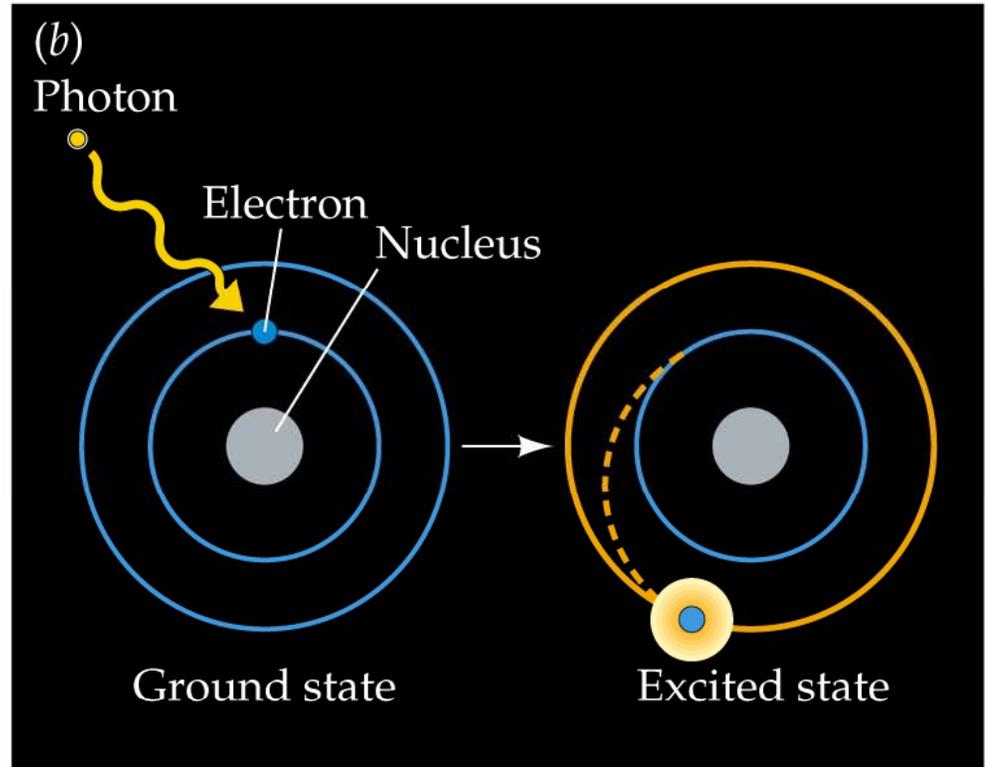
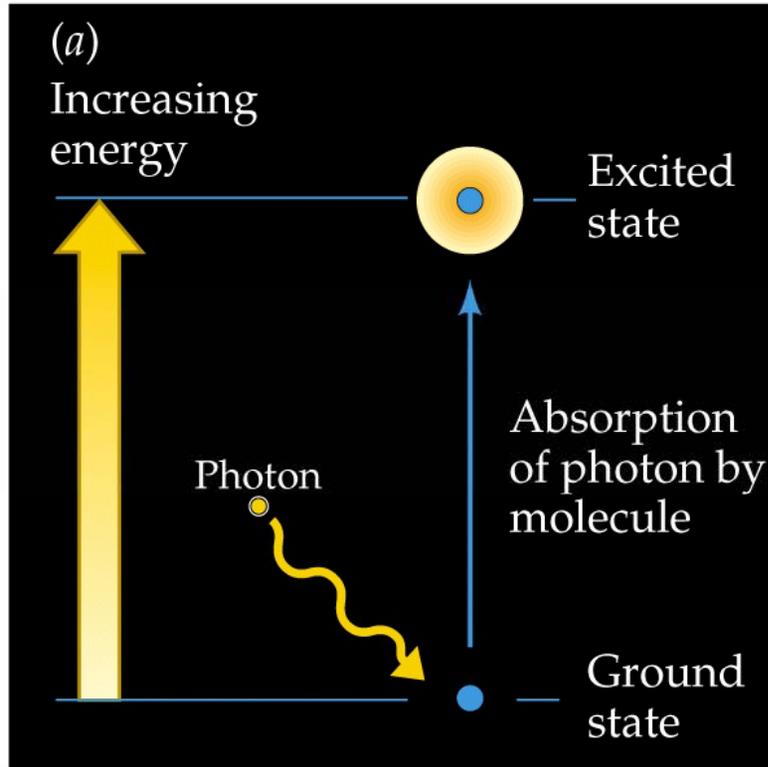
## C. Properties of Light and Pigments

- Light energy comes in packets called photons, but it also has wavelike properties.
- Pigments absorb light in the visible spectrum.
- Absorption of a photon puts a pigment molecule in an excited state with more energy than its ground state.

# The electromagnetic spectrum



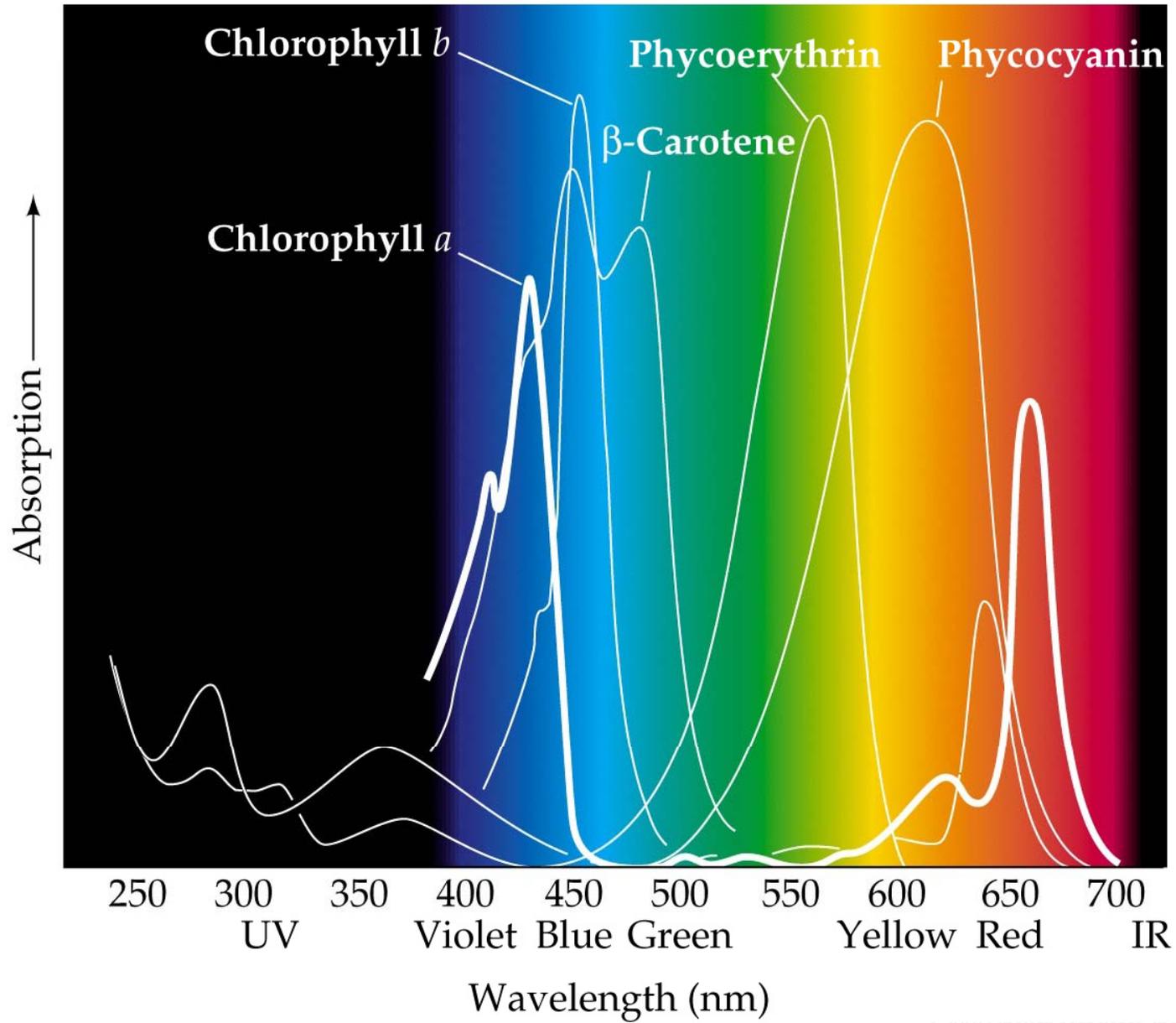
# Exciting a Molecule



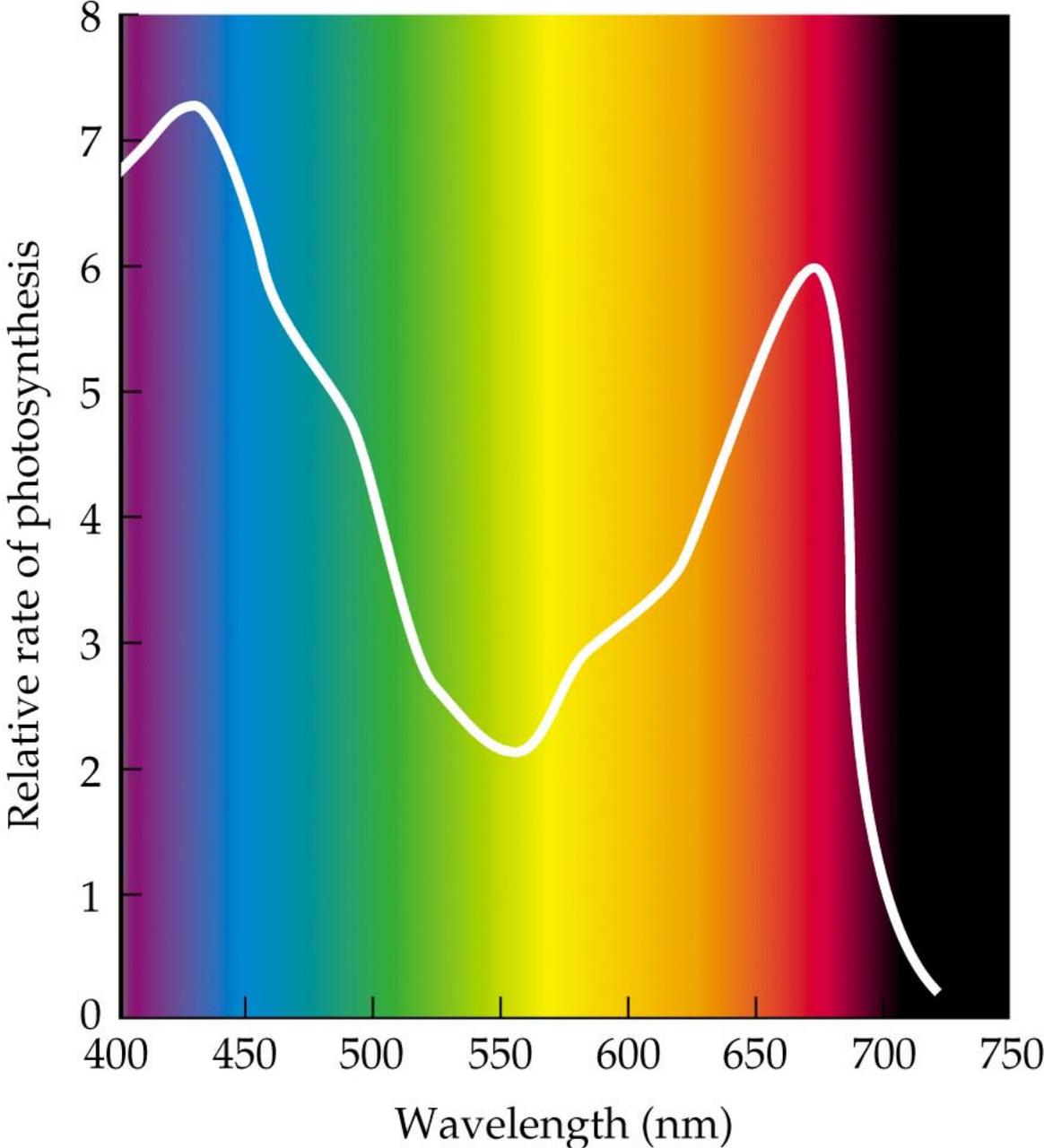
## C. Properties of Light and Pigments

- Each compound has a characteristic absorption spectrum which reveals the biological effectiveness of different wavelengths of light.
- An action spectrum plots the overall biological effectiveness of different wavelengths for an organism.

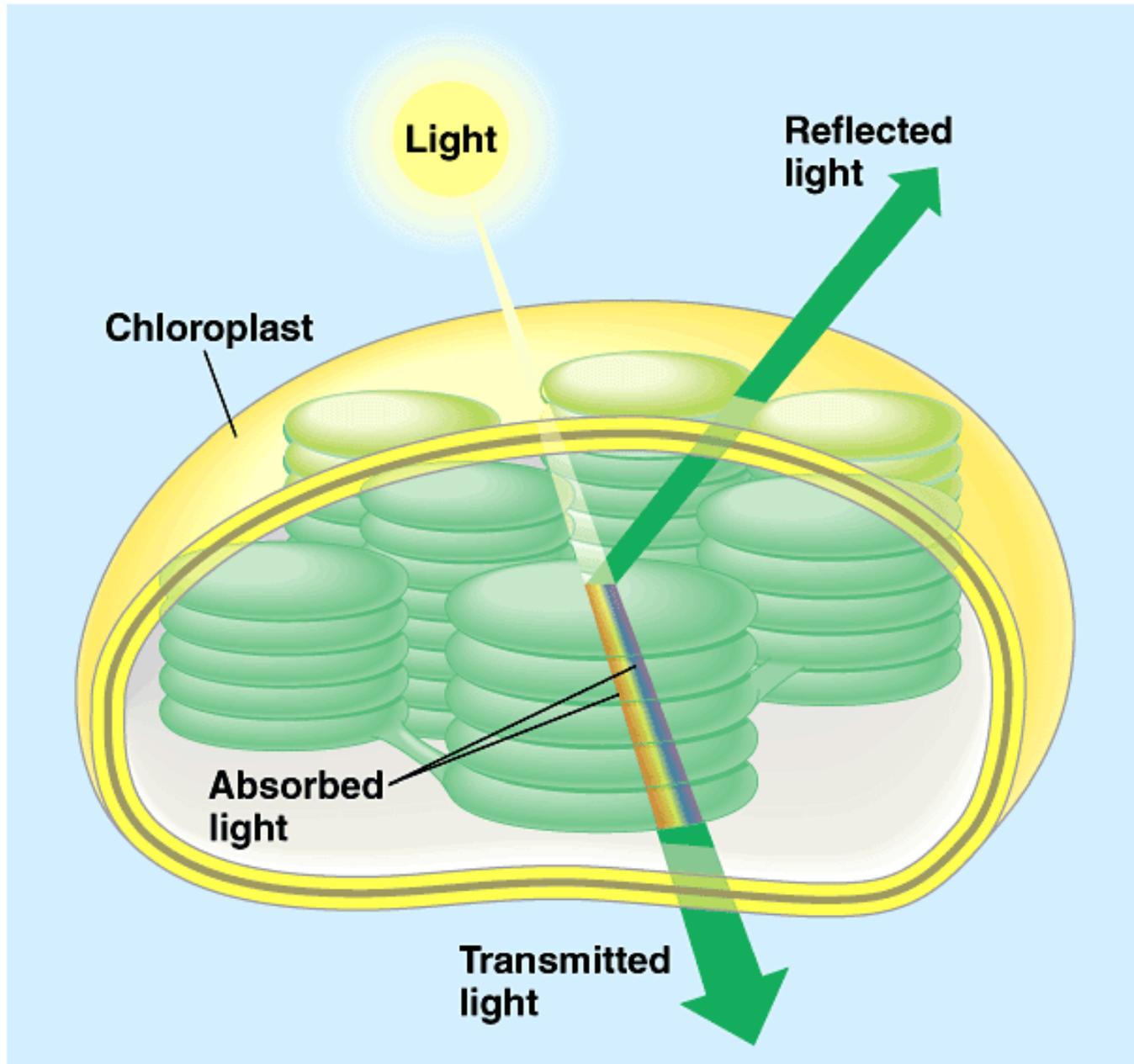
# Absorption Spectra



# Action Spectrum



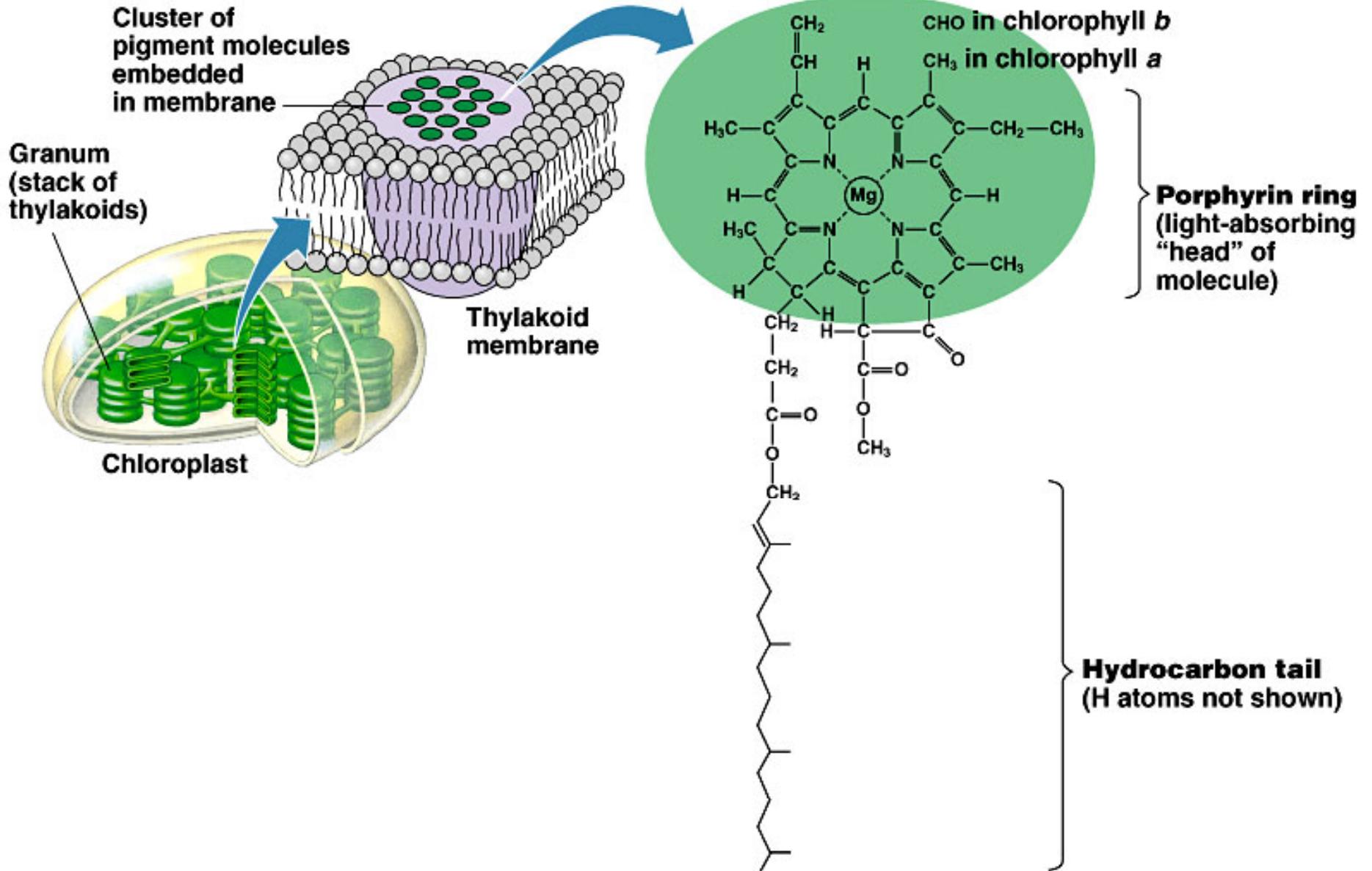
## Why leaves are green: interaction of light with chloroplasts



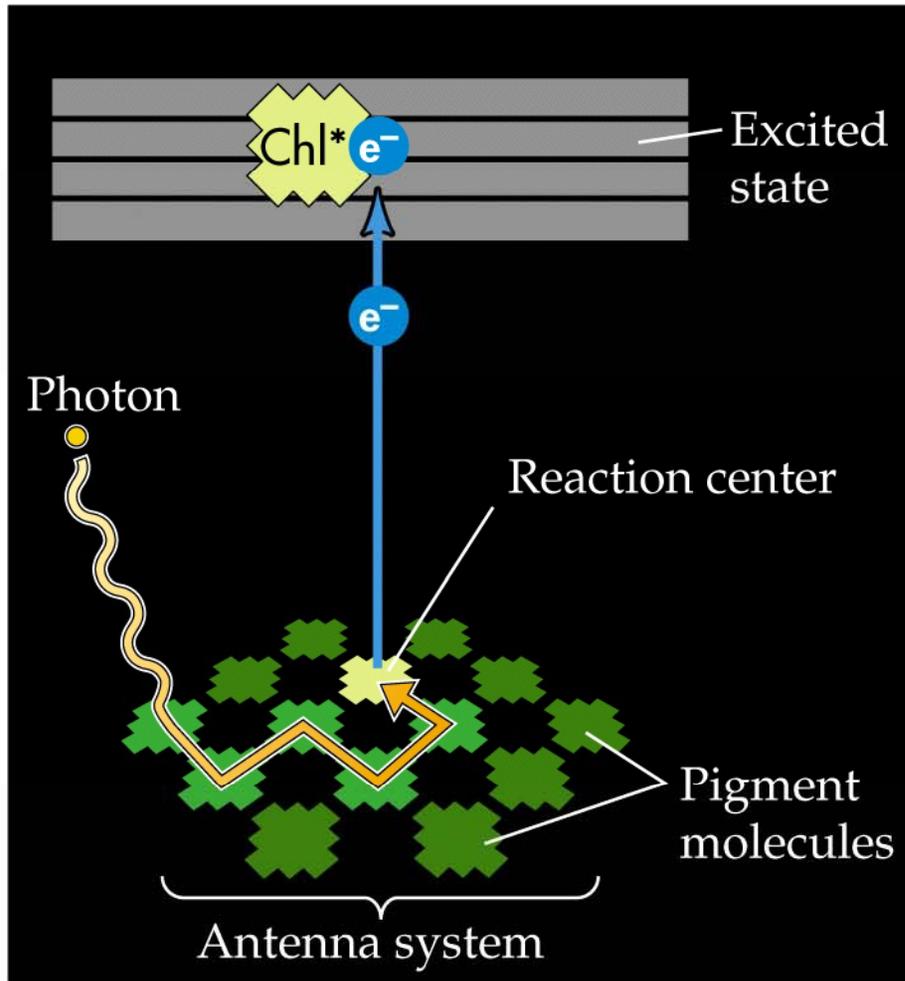
## C. Properties of Light and Pigments

- Chlorophylls and accessory pigments form antenna systems for absorption of light energy.
- An excited pigment molecule may lose its energy by fluorescence, or by transferring it to another pigment molecule.

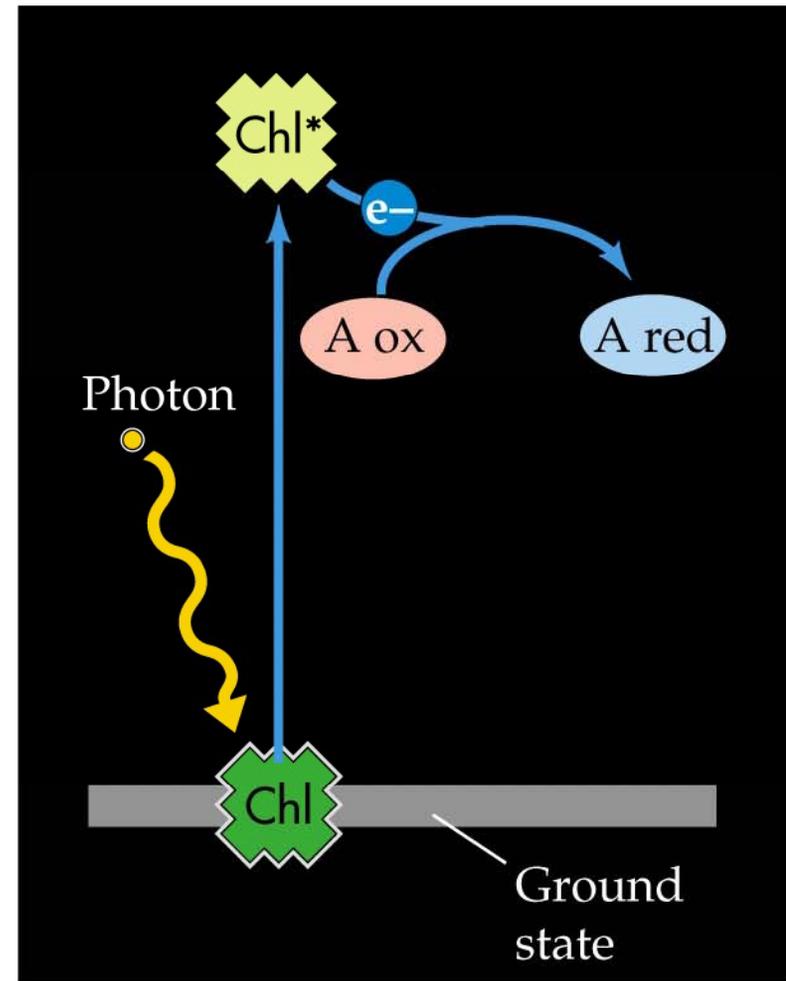
# Location and structure of chlorophyll molecules in plants



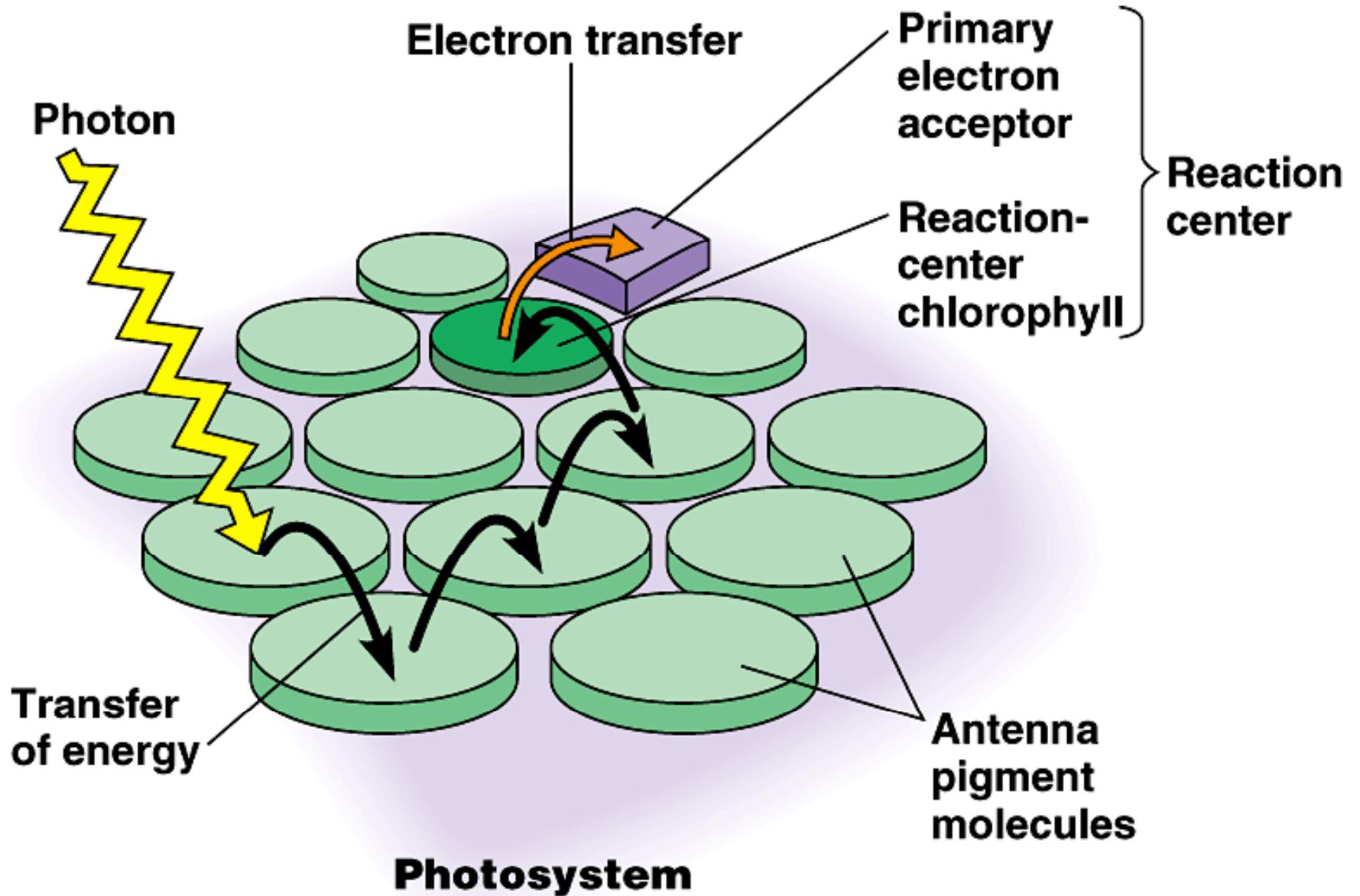
(a) Energy transfer

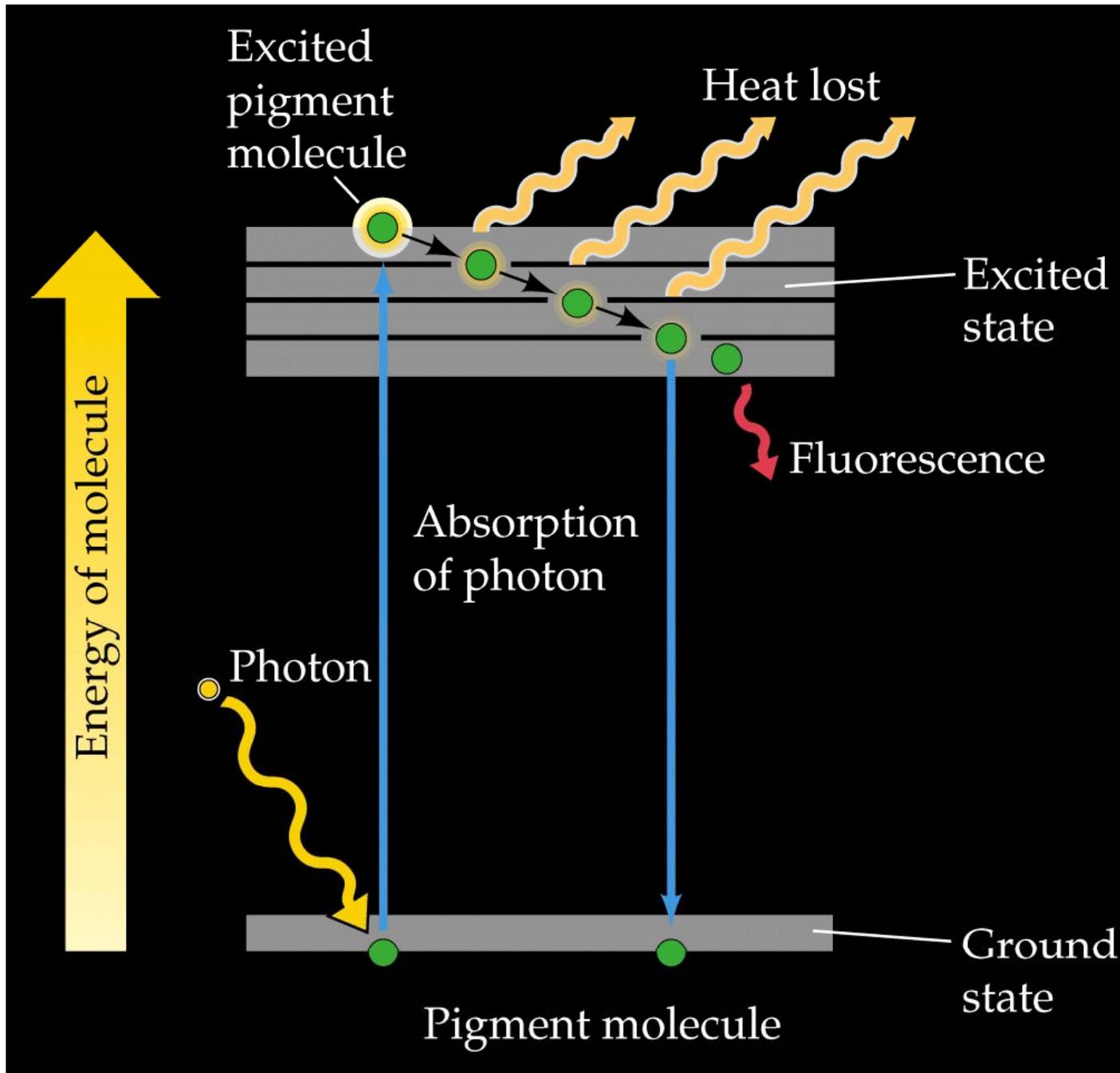


(b) Electron flow

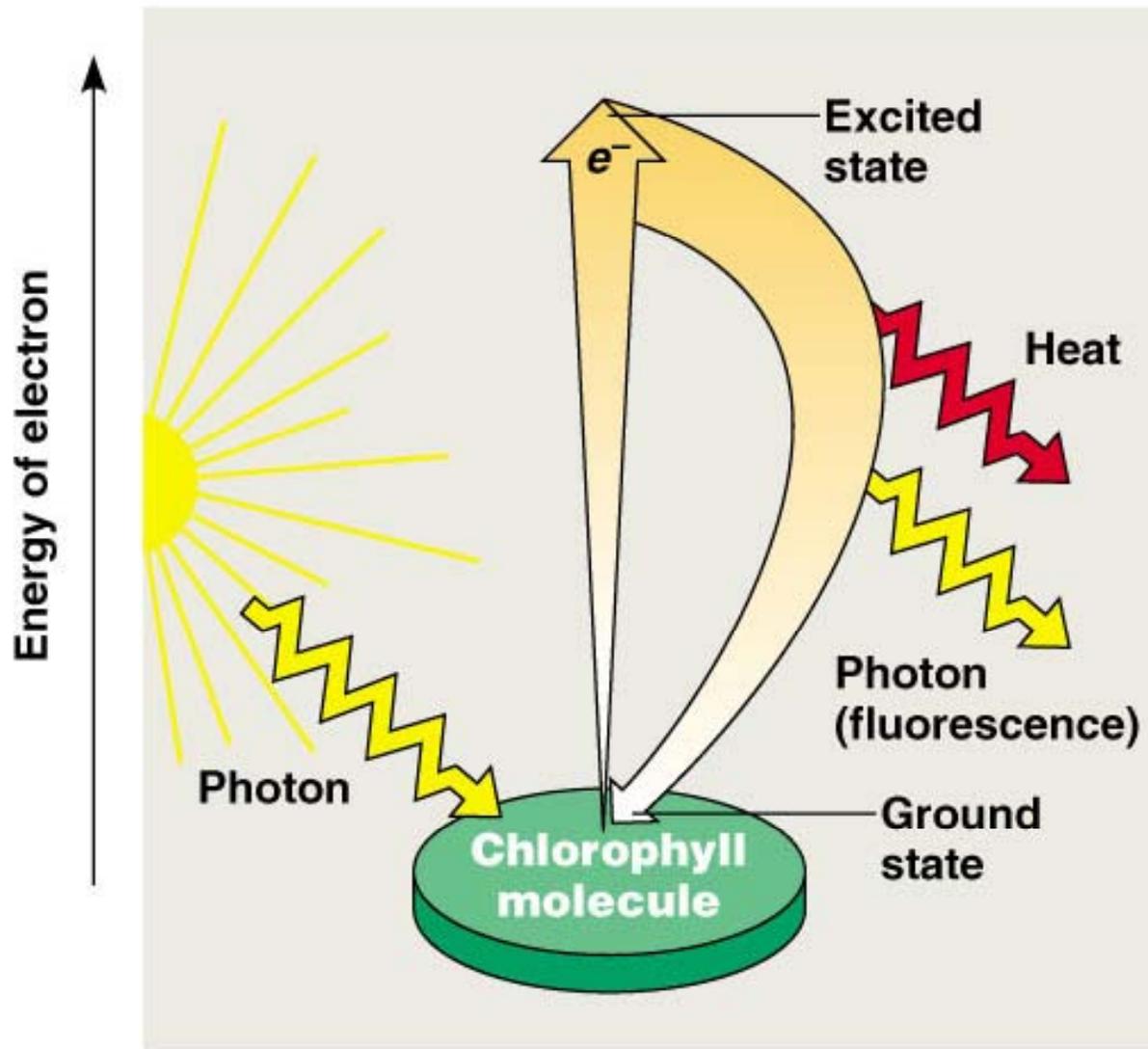


# How a photosystem harvests light

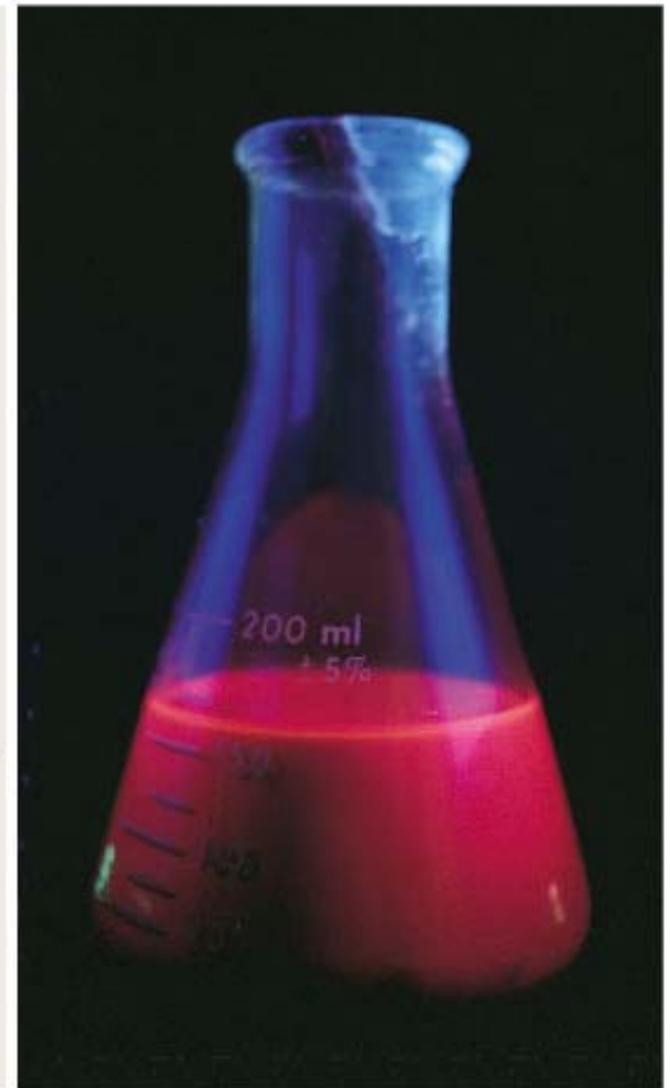




# Excitation of isolated chlorophyll by light



(a) Excitation of isolated chlorophyll molecule



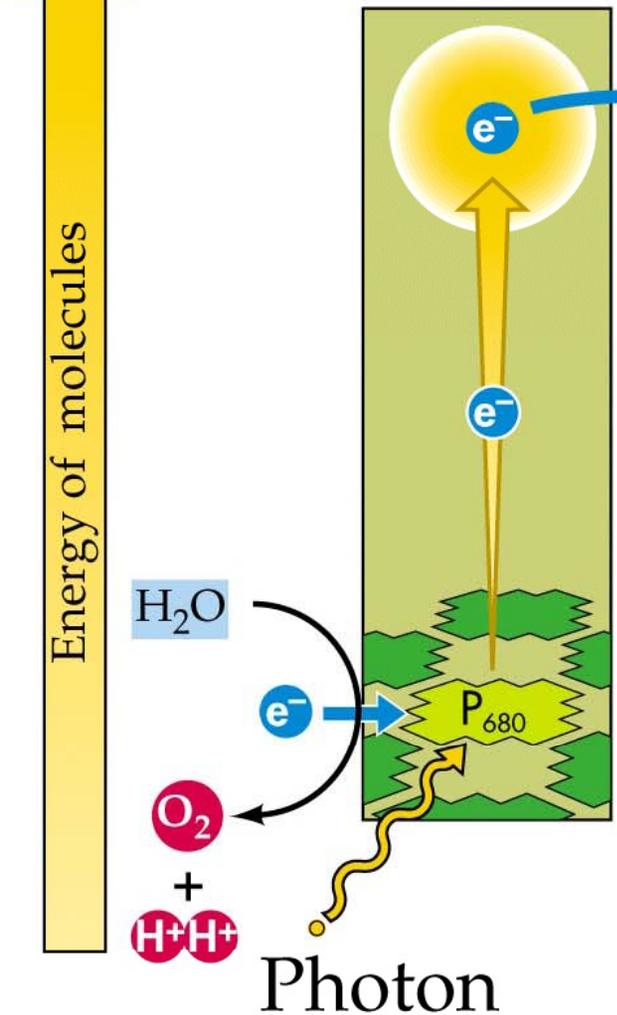
(b) Fluorescence

## D. Electron Flow, Photophosphorylation, and Reductions

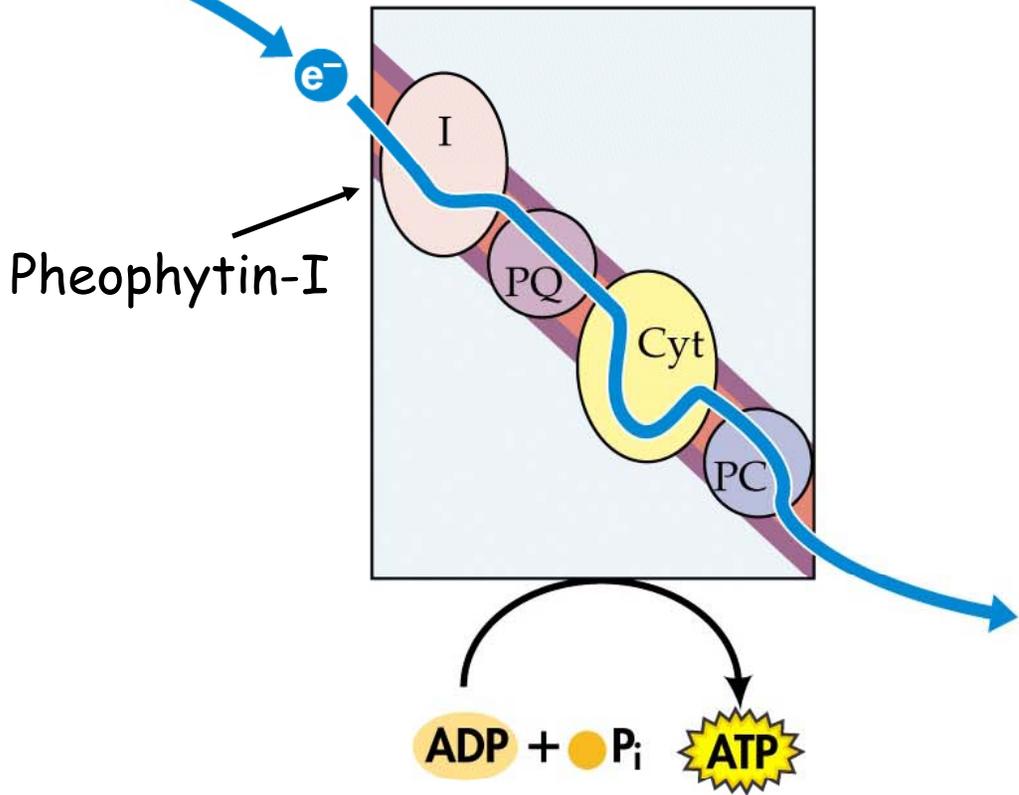
- Noncyclic electron flow uses two photosystems.
- Photosystem II uses  $P_{680}$  chlorophyll, from which light-excited electrons pass to a redox chain that drives chemiosmotic ATP production. Light-driven water oxidation releases  $O_2$ , passing electrons to  $P_{680}$  chlorophyll.
- Photosystem I passes electrons from  $P_{700}$  chlorophyll to another redox chain and then to  $NADP^+$ , forming  $NADPH + H^+$ .

# ELECTRON FLOW

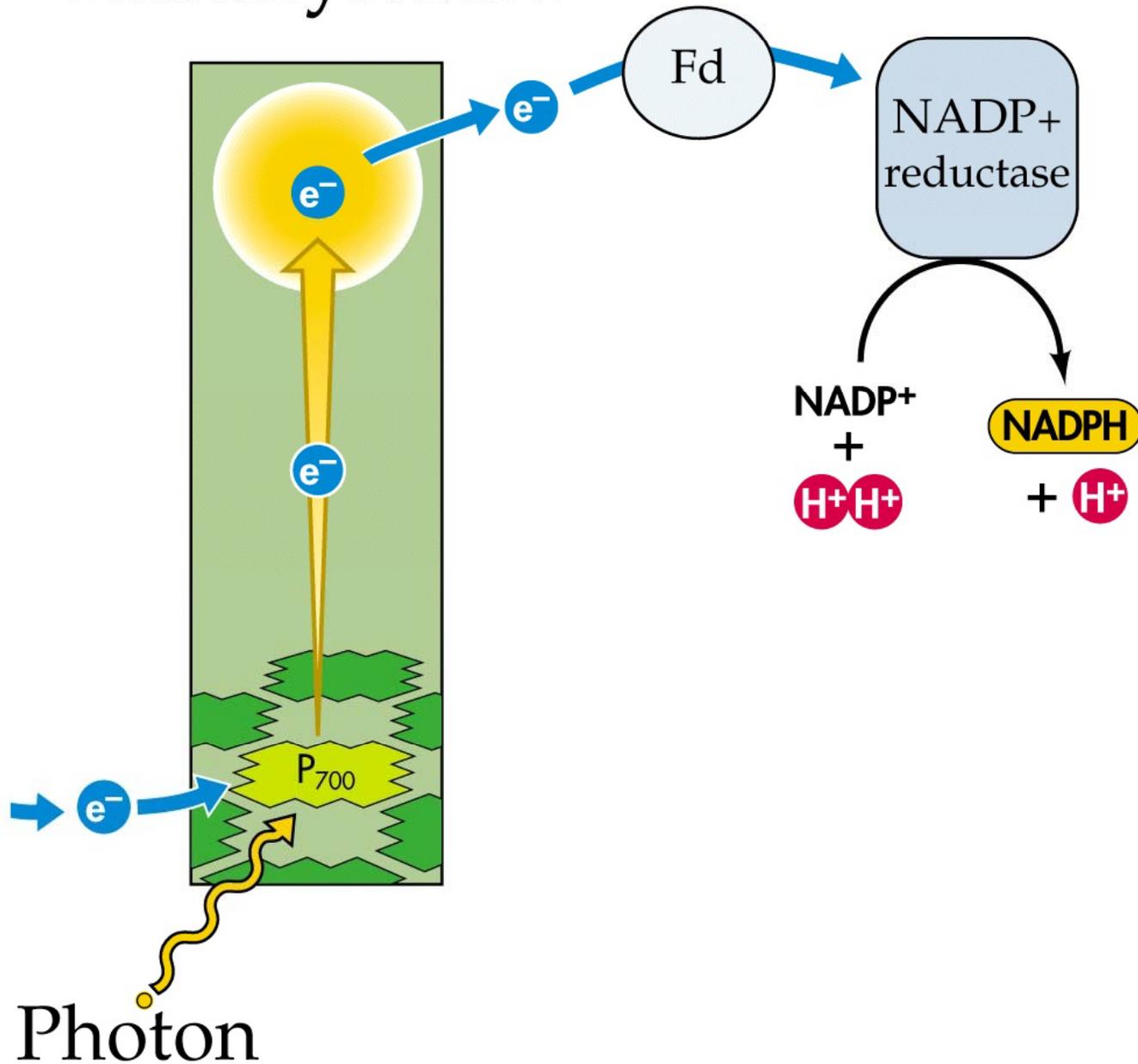
## Photosystem II



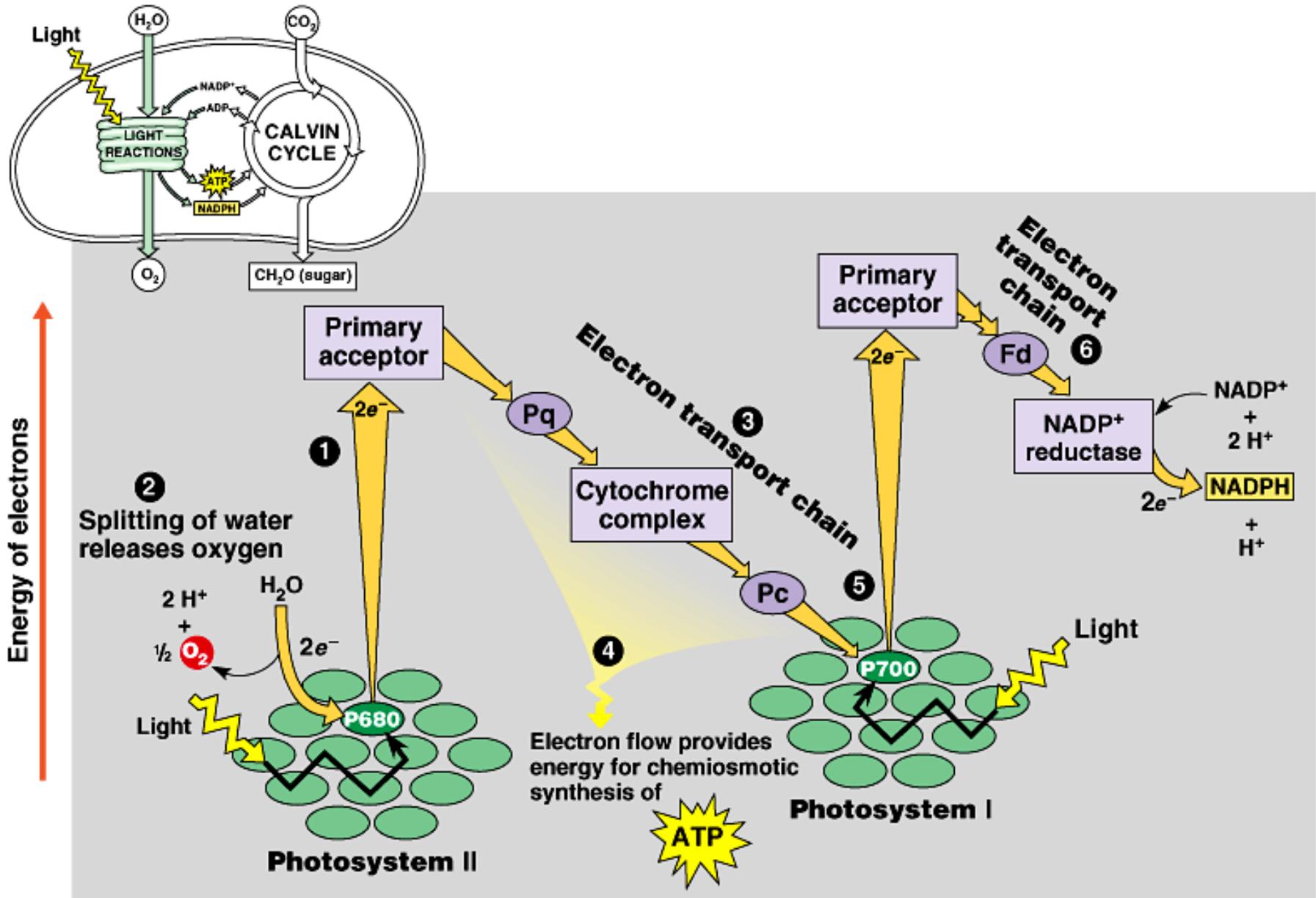
## Electron transport chain



# Photosystem I

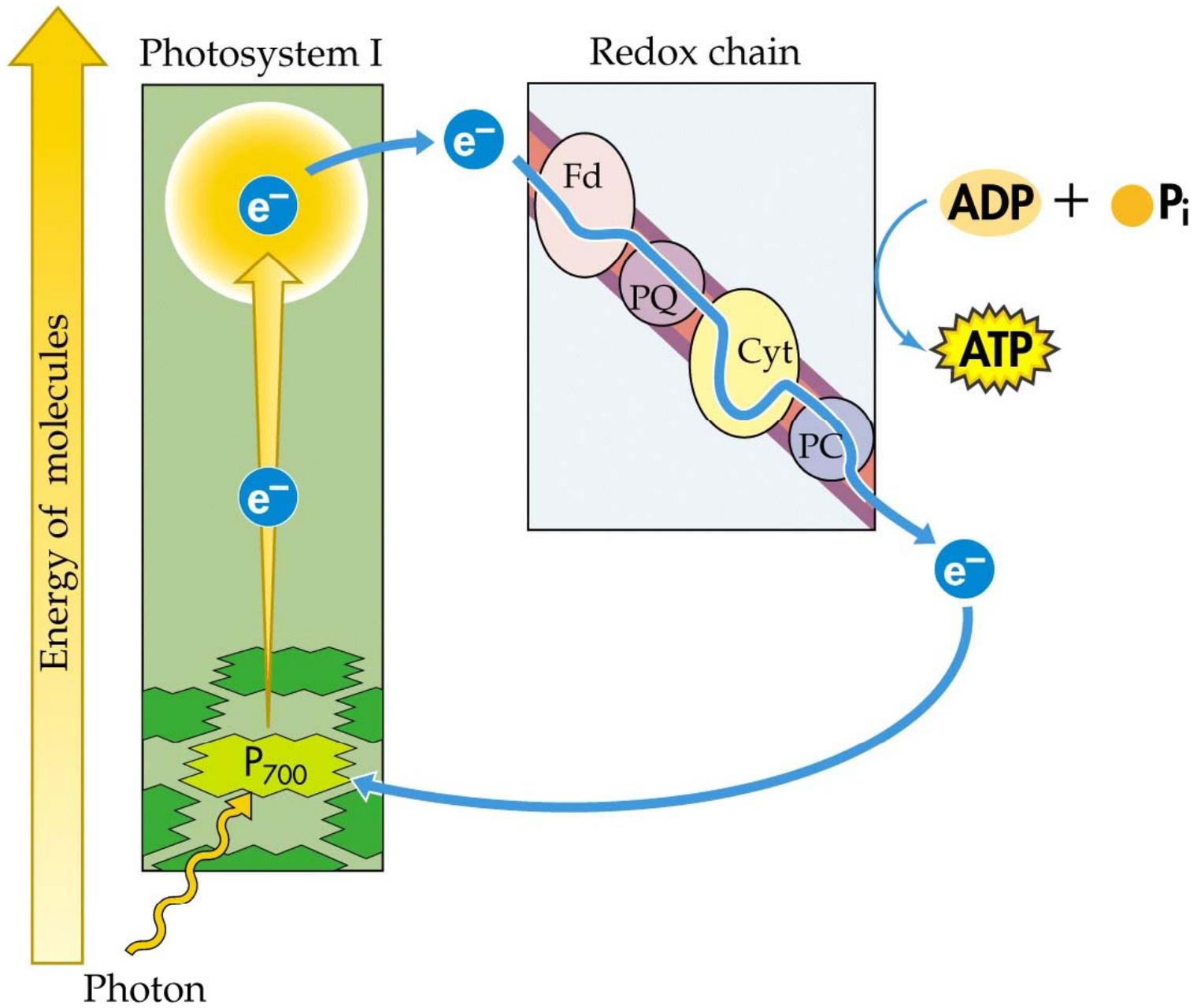


# How noncyclic electron flow during the light reactions generates ATP and NADPH

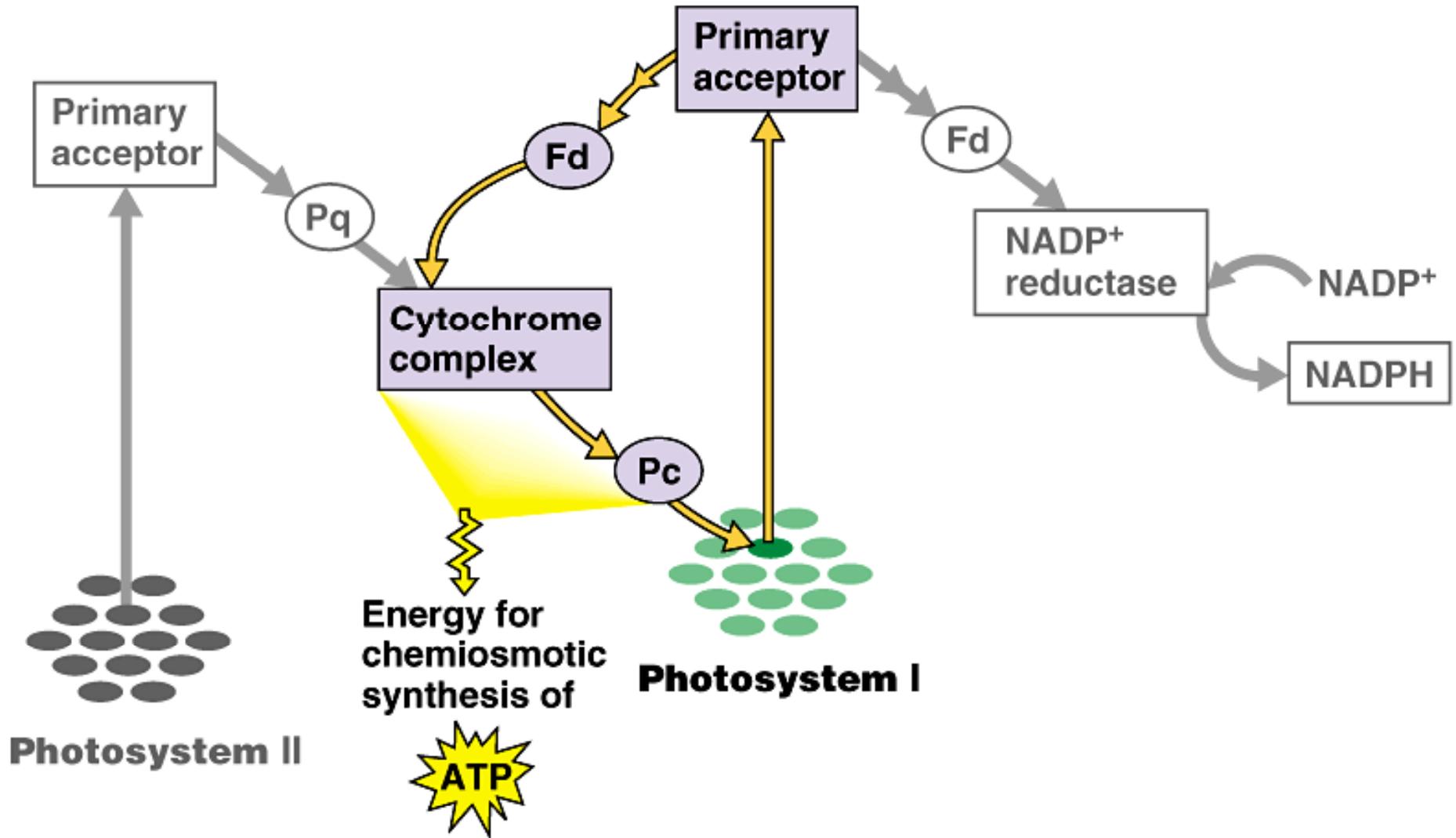


## D. Electron Flow, Photophosphorylation, and Reductions

- Cyclic electron flow uses  $P_{700}$  chlorophyll producing only ATP. Its operation maintains the proper balance of ATP and  $NADPH + H^+$  in the chloroplast.

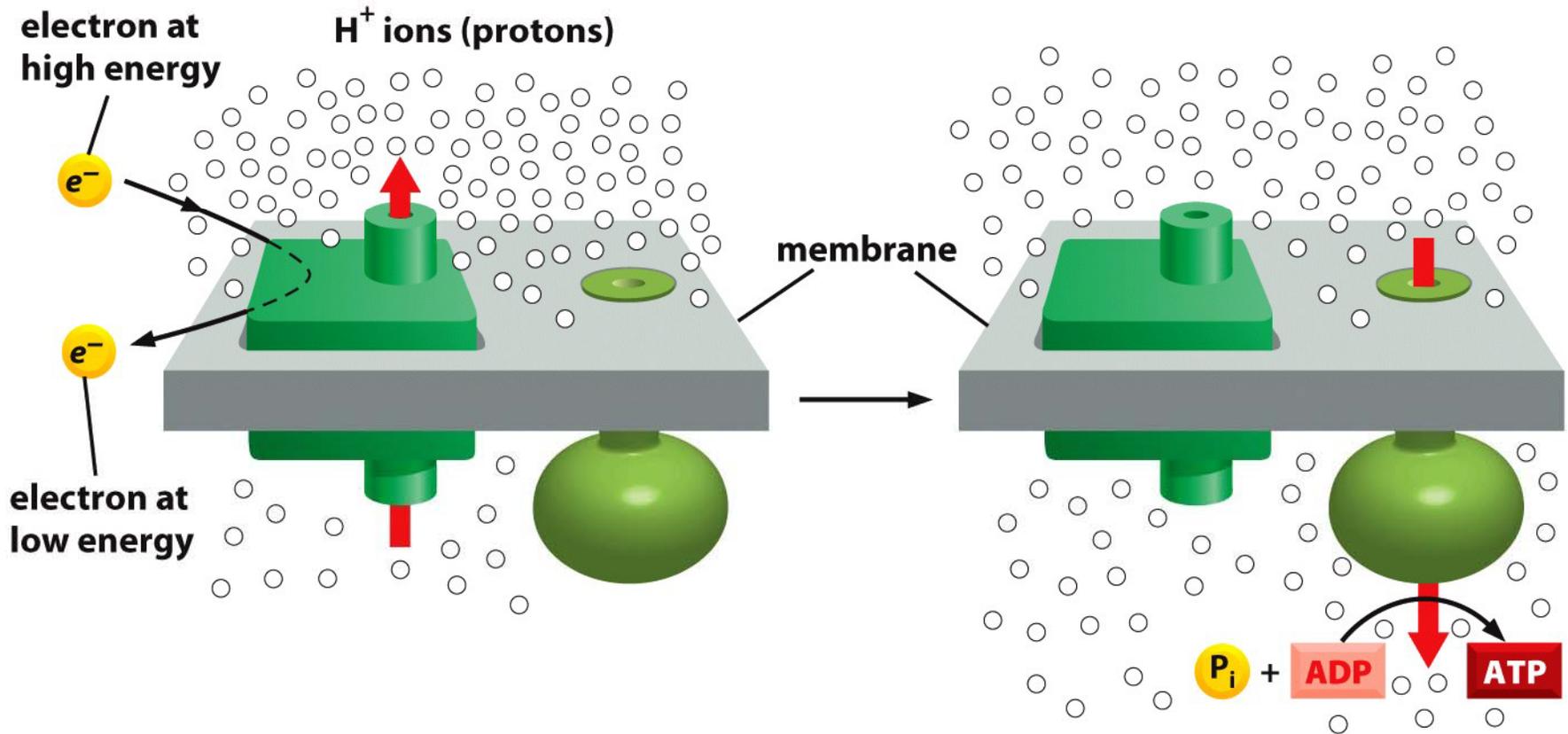


# Cyclic electron flow



## D. Electron Flow, Photophosphorylation, and Reductions

- Chemiosmosis is the source of ATP in photophosphorylation.
- Electron transport pumps protons from stroma into thylakoids, establishing a proton-motive force.
- Proton diffusion to stroma via ATP synthase channels drives ATP formation from ADP and  $P_i$ .



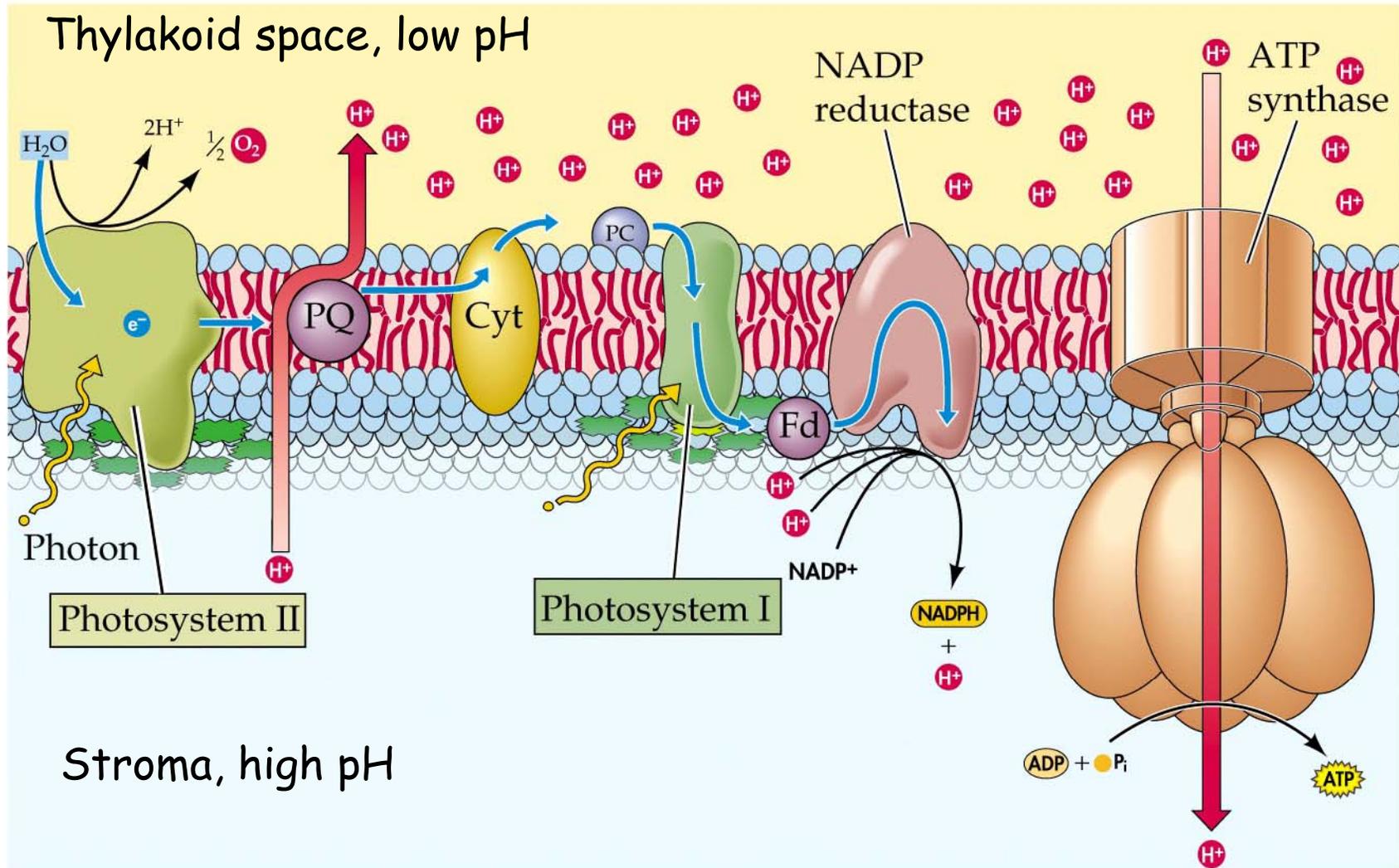
**STAGE 1: ENERGY OF ELECTRON TRANSPORT IS USED TO PUMP PROTONS ACROSS MEMBRANE**

(A)

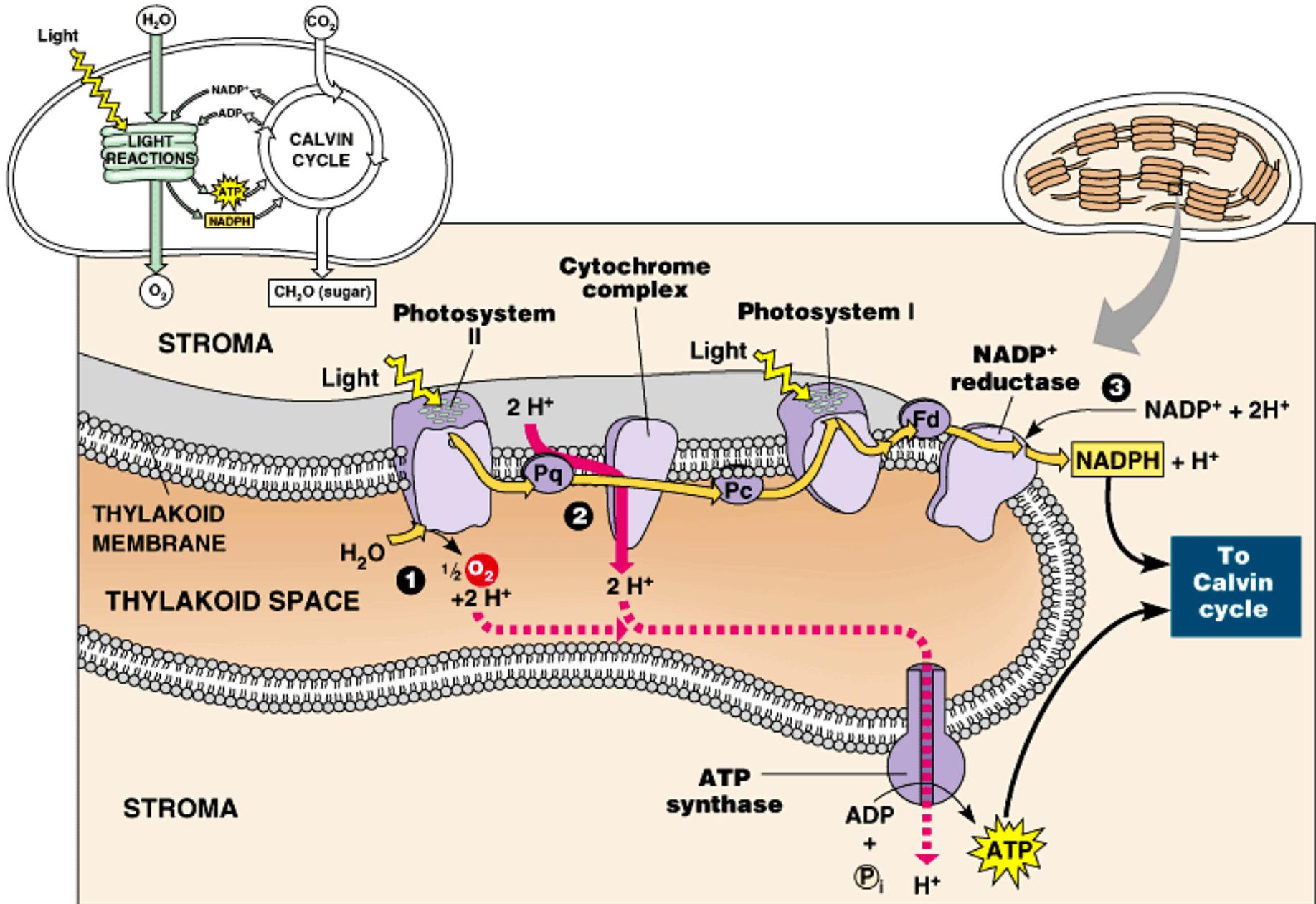
**STAGE 2: PROTON GRADIENT IS HARNESSSED BY ATP SYNTHASE TO MAKE ATP**

(B)

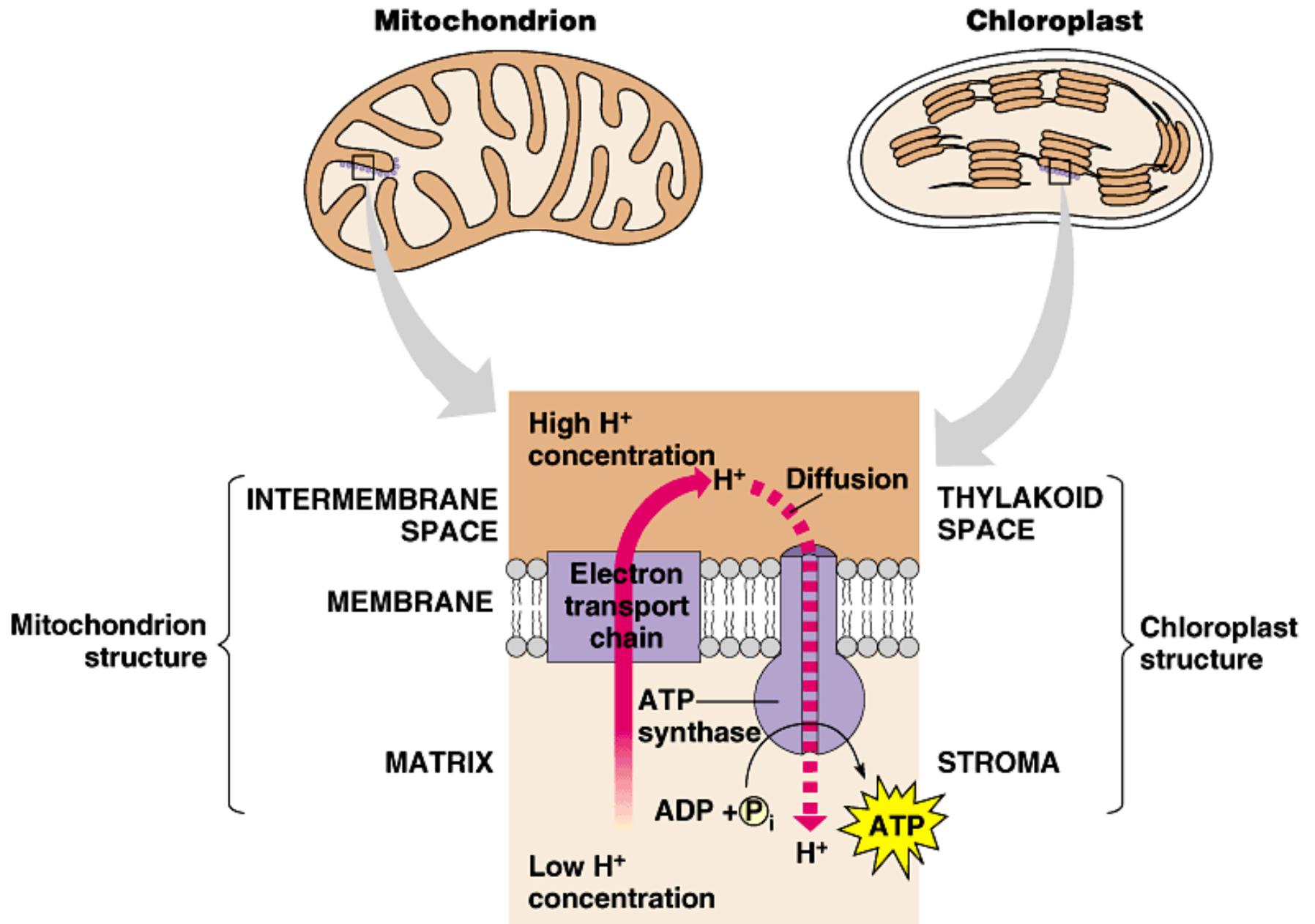
# Chloroplast forms ATP Chemiosmotically



# The light reactions and chemiosmosis: the organization of the thylakoid membrane



# Comparison of chemiosmosis in mitochondria and chloroplasts



## D. Electron Flow, Photophosphorylation, and Reductions

- Photosynthesis probably originated in anaerobic bacteria that used  $\text{H}_2\text{S}$  as a source of electrons instead of  $\text{H}_2\text{O}$ .
- Oxygen production by bacteria was important in eukaryote evolution.

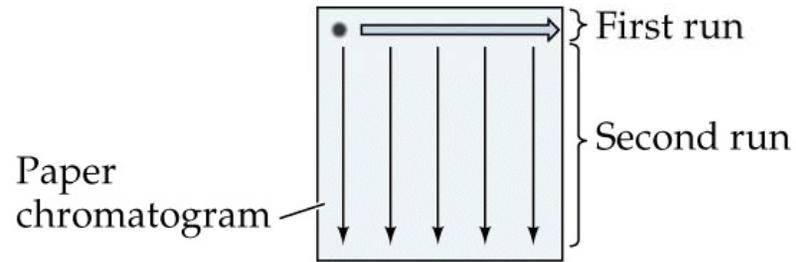
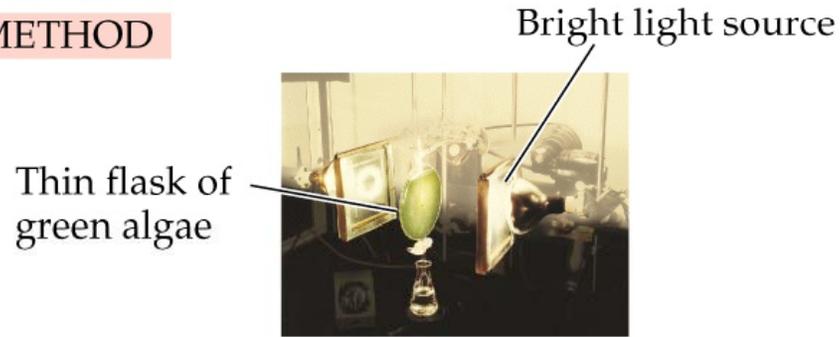
## E. Making Sugar from $\text{CO}_2$ : The Calvin-Benson Cycle

- The Calvin-Benson cycle makes sugar from  $\text{CO}_2$ . This pathway was elucidated through use of radioactive tracers.

## EXPERIMENT

**Question:** What is the pathway of CO<sub>2</sub> fixation in photosynthesis?

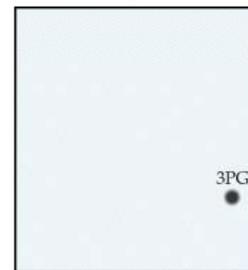
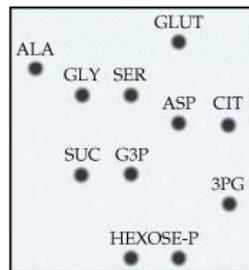
### METHOD



30 sec

3 sec

### RESULTS



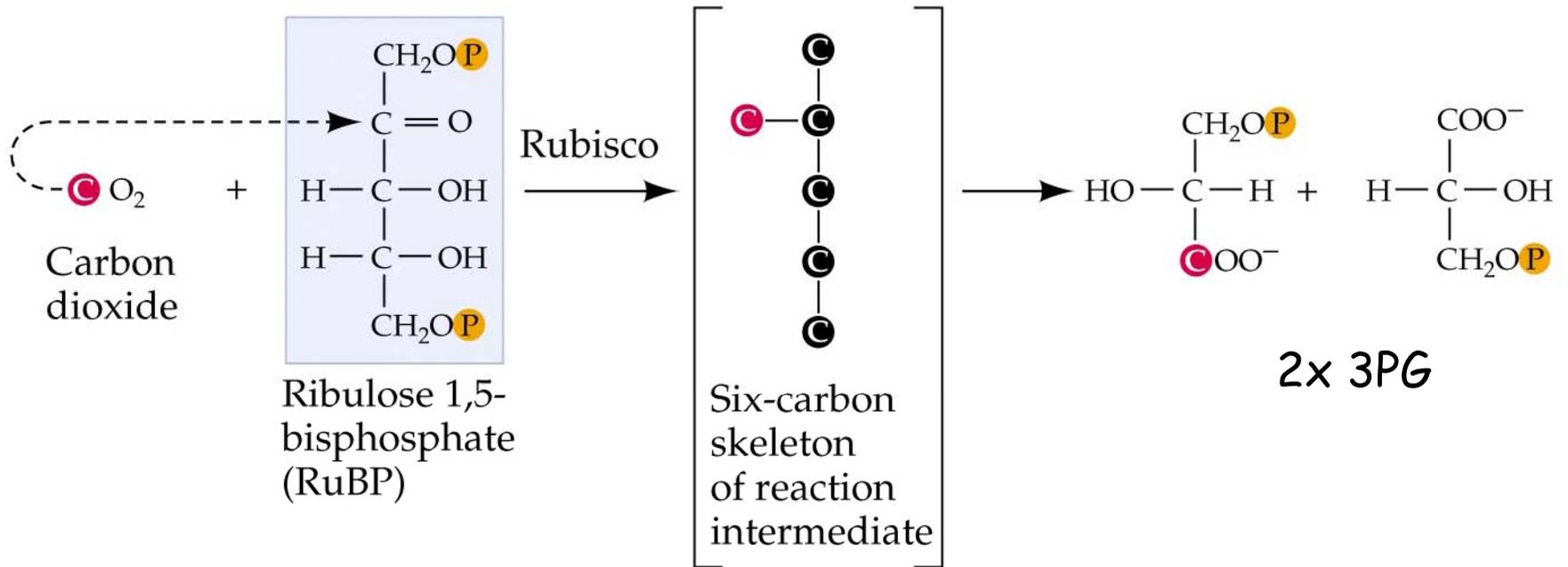
**Conclusion:** The carbon from CO<sub>2</sub> ends up in many molecules.

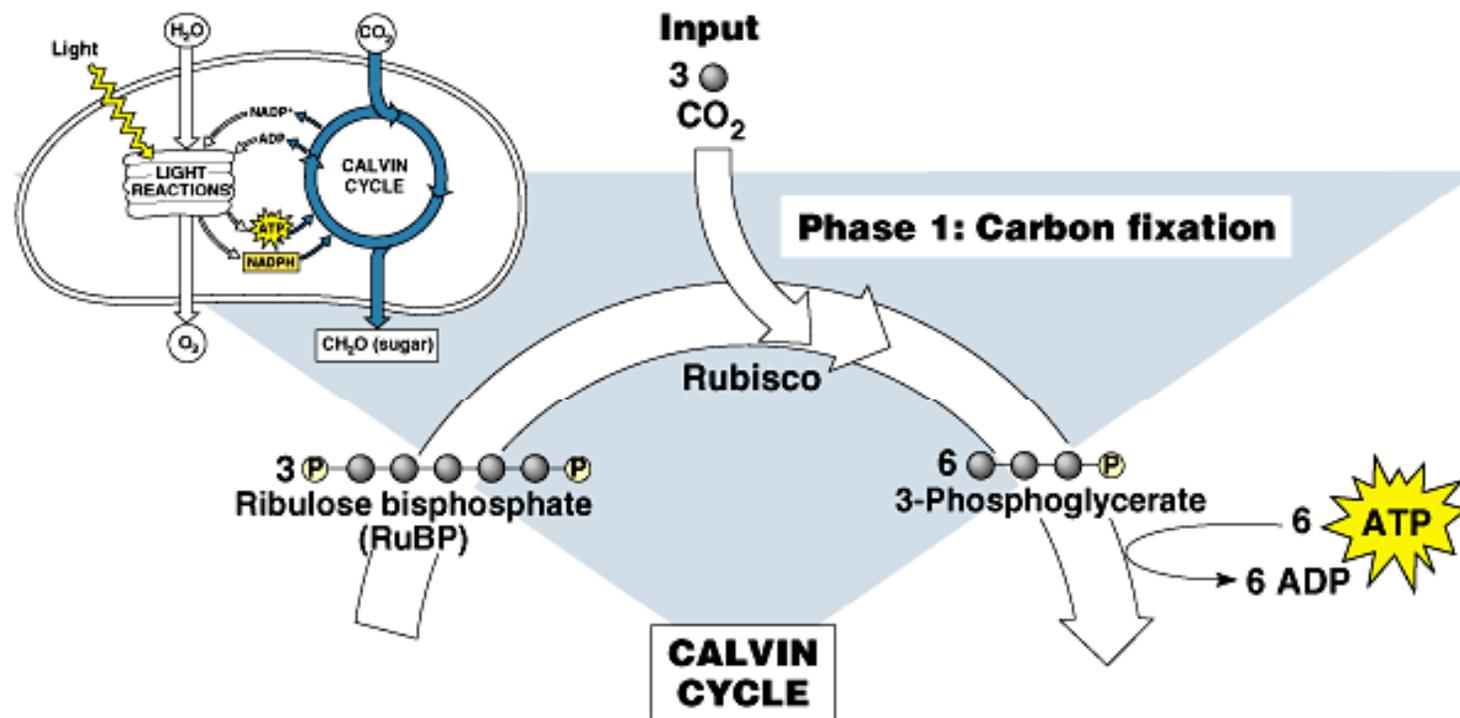
**Conclusion:** The initial product of CO<sub>2</sub> fixation is 3PG.

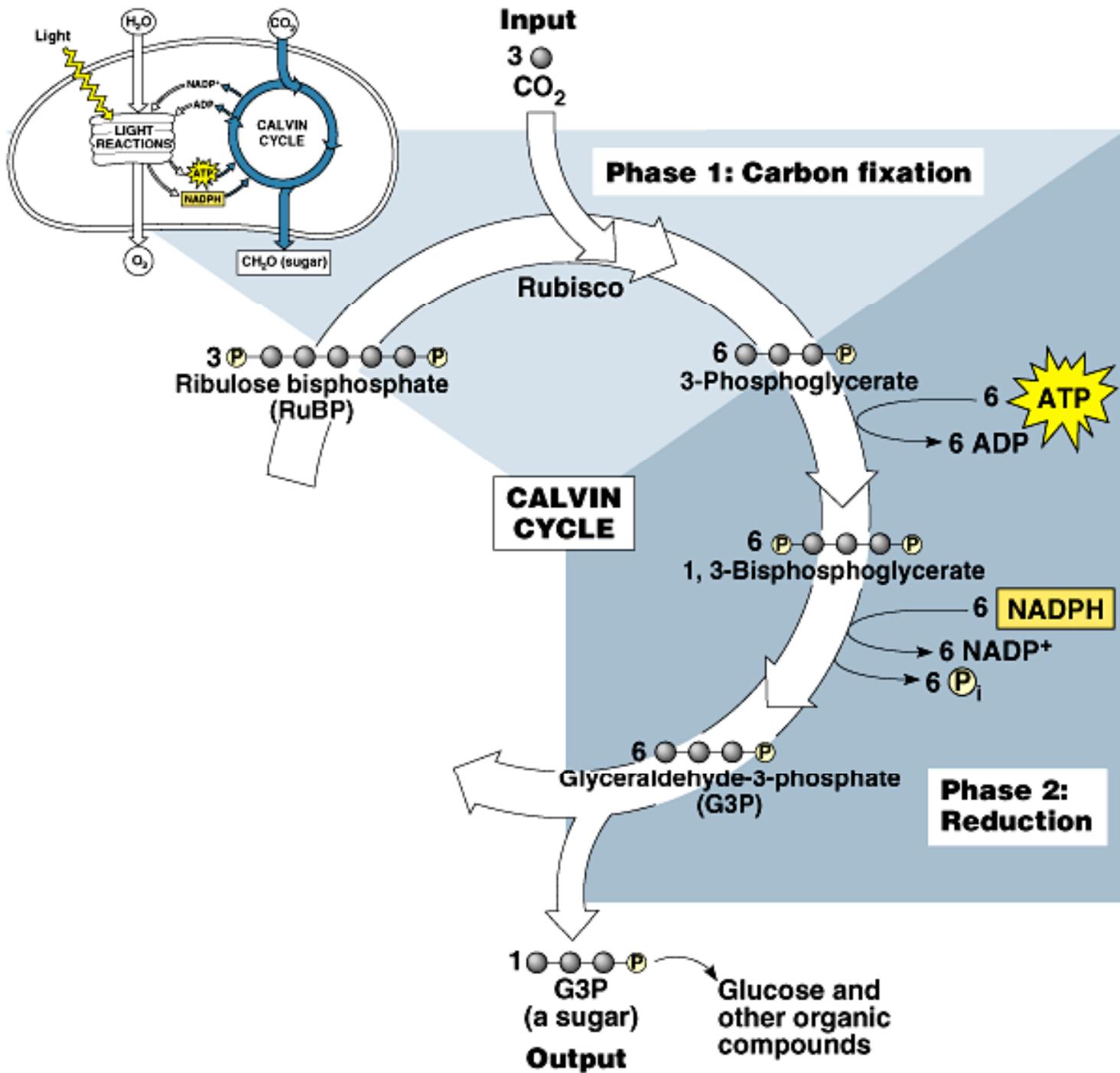
## E. Making Sugar from $\text{CO}_2$ : The Calvin-Benson Cycle

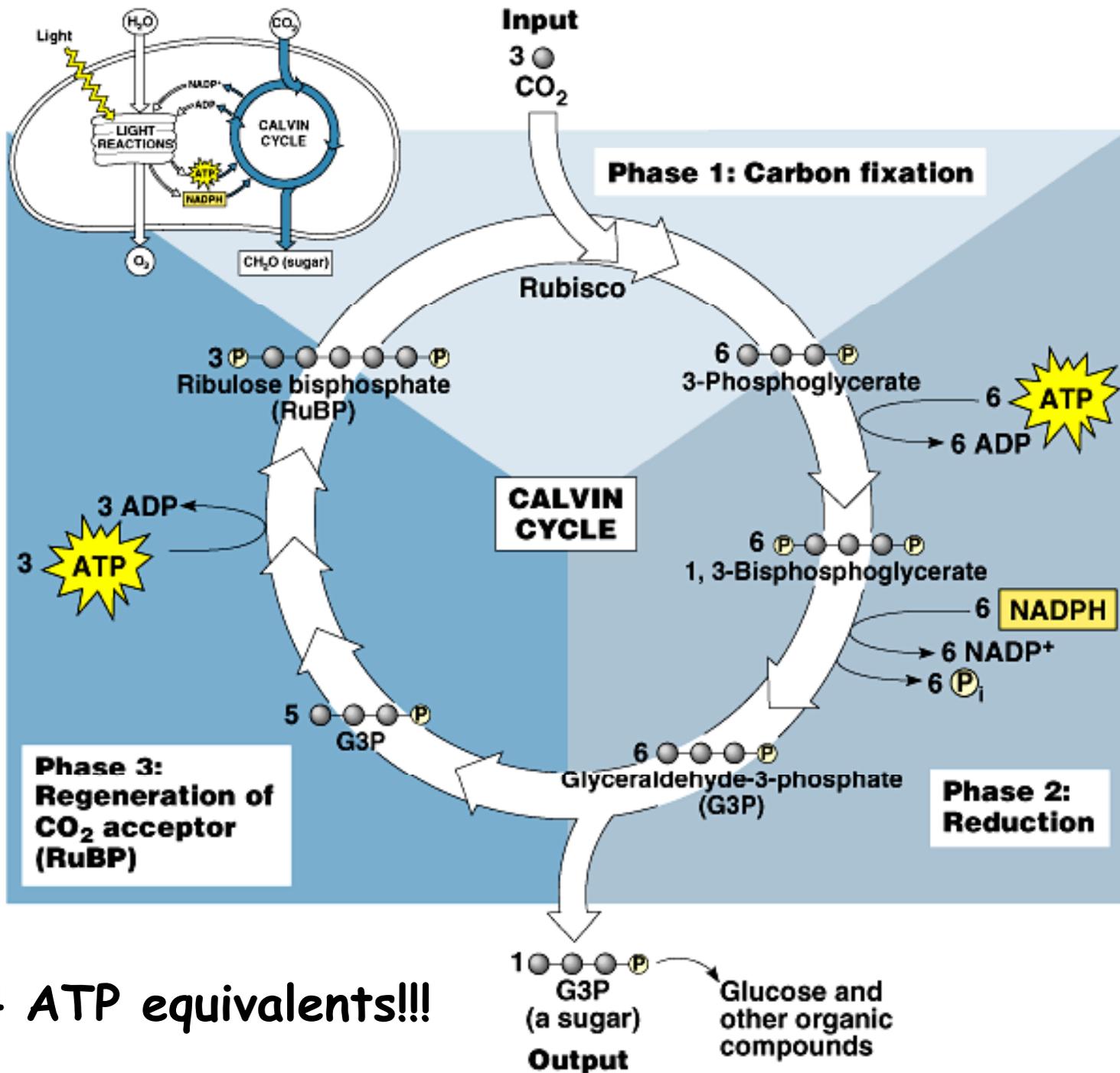
- The Calvin-Benson cycle has three phases:
- Fixation of  $\text{CO}_2$
- Reduction (and carbohydrate production)
- Regeneration of RuBP.
- RuBP is the initial  $\text{CO}_2$  acceptor, 3PG is the first stable product of  $\text{CO}_2$  fixation. Rubisco catalyzes the reaction of  $\text{CO}_2$  and RuBP to form 3PG.

## RuBP is the CO<sub>2</sub> Acceptor



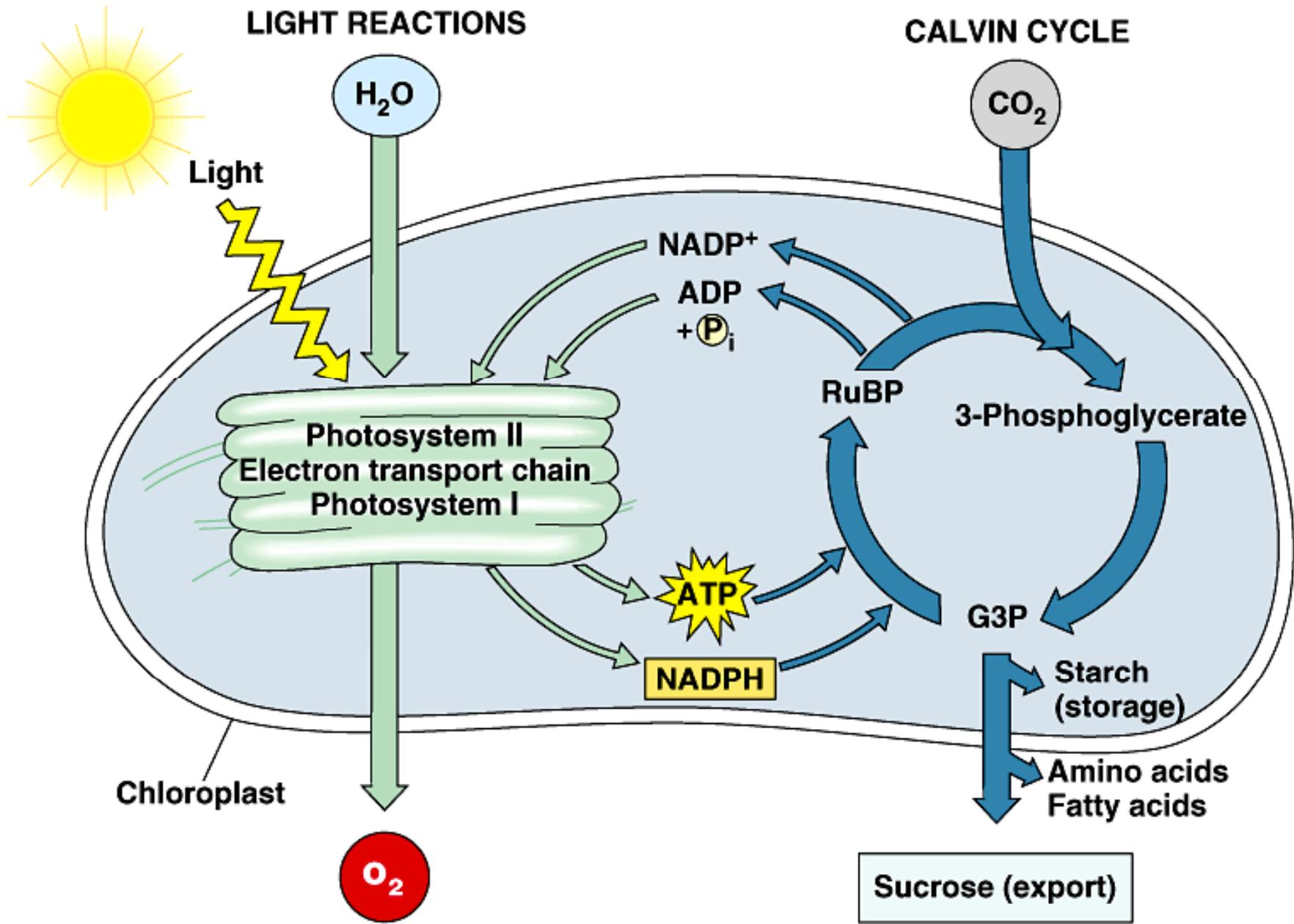






54 ATP equivalents!!!

# A review of photosynthesis



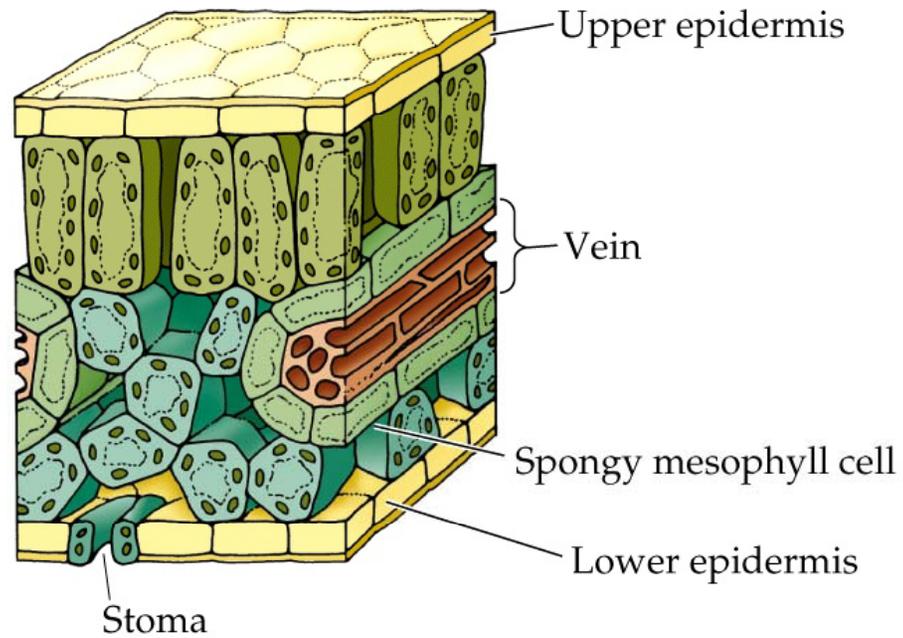
# F. Photorespiration and Its Consequences

- Rubisco catalyzes a reaction between  $O_2$  and RuBP (forming phosphoglycolate + 3PG) in addition to the usual route of  $CO_2$  and RuBP.
- Photorespiration byproducts are processed by chloroplasts, peroxisomes, and mitochondria.
- Photorespiration significantly reduces photosynthesis efficiency.

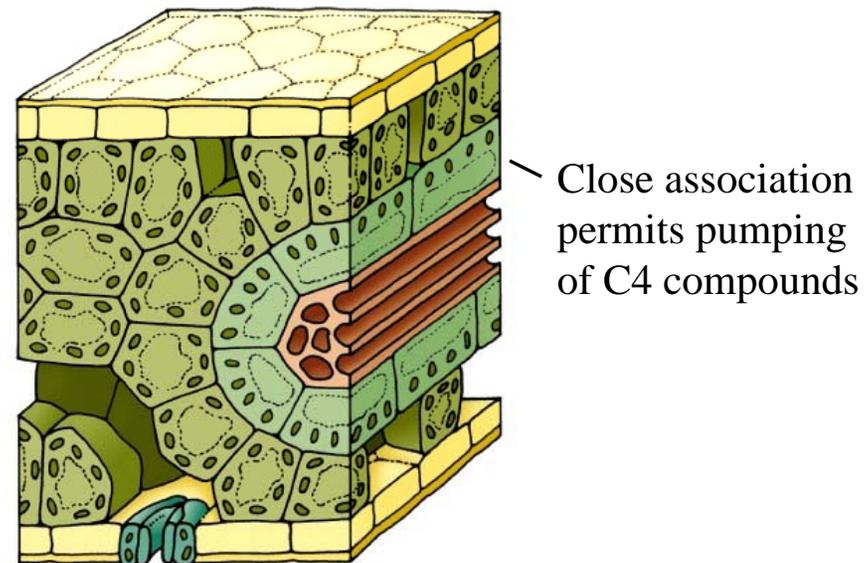
## F. Photorespiration and Its Consequences

- Higher temperatures and dryer climates increase the effects of photorespiration; the oxygenase function of rubisco is then favored.
- $C_4$  plants bypass photorespiration. PEP carboxylase in mesophyll chloroplasts initially fixes  $CO_2$  in four-carbon acids, which diffuse into bundle sheath cells, where their decarboxylation produces locally high concentrations of  $CO_2$ .

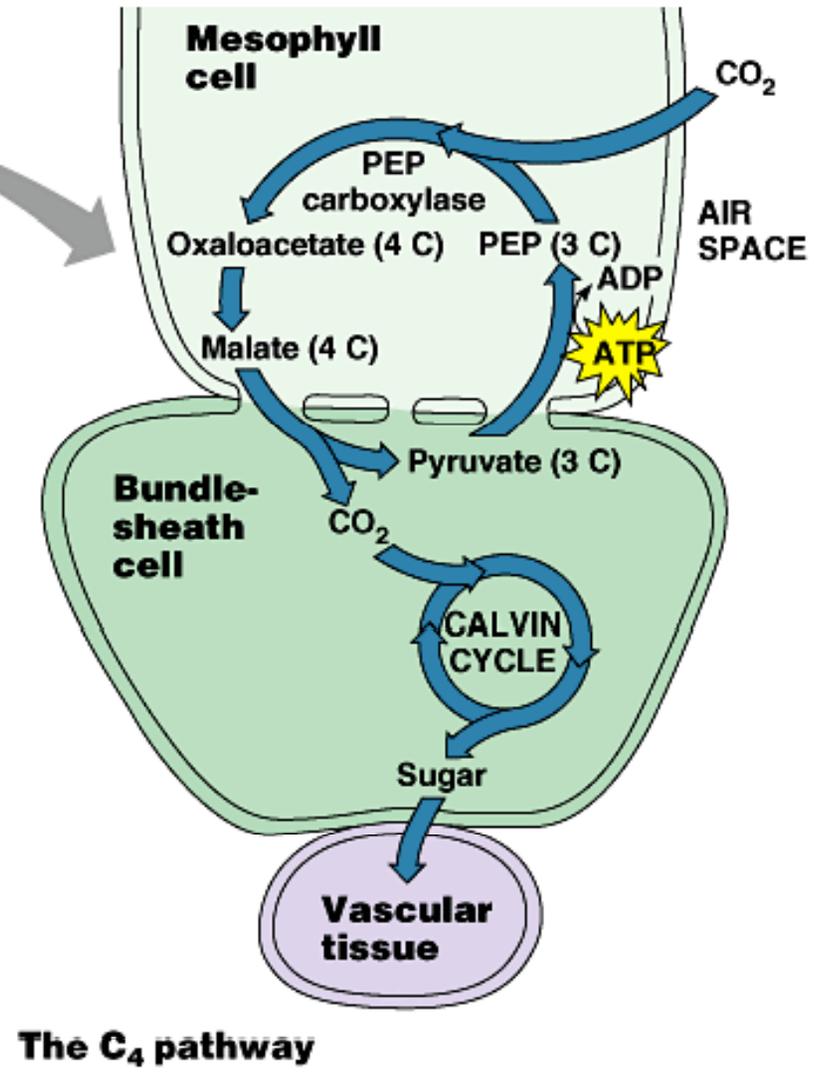
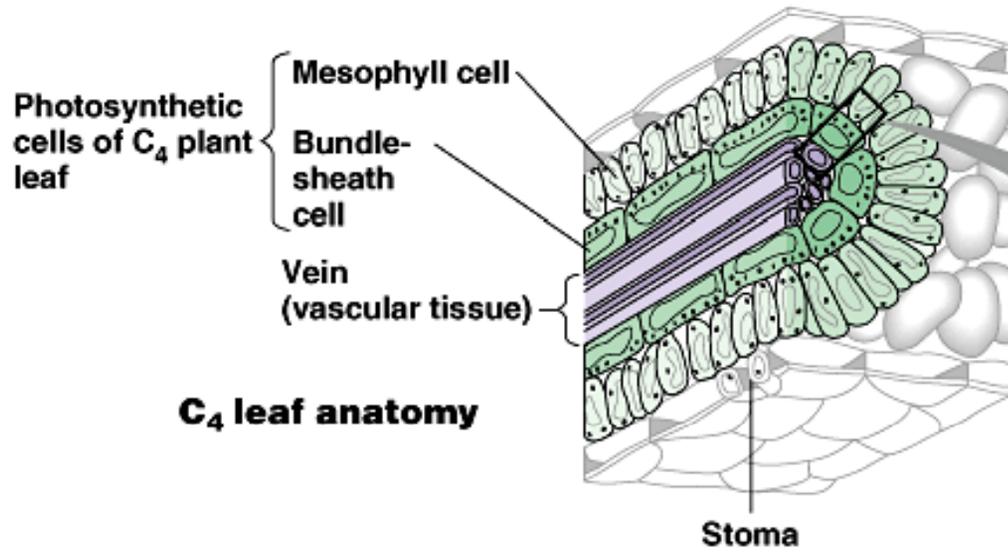
(a) Arrangement of cells in a  $C_3$  leaf



(b) Arrangement of cells in a  $C_4$  leaf



# C<sub>4</sub> leaf anatomy and the C<sub>4</sub> pathway



## F. Photorespiration and Its Consequences

- Higher temperatures and dryer climates increase the effects of photorespiration; the oxygenase function of rubisco is then favored.
- CAM (crassulacean acid metabolism) plants operate much like  $C_4$  plants, but their initial  $CO_2$  fixation by PEP carboxylase is temporally separated from the Calvin-Benson cycle, rather than spatially separated.

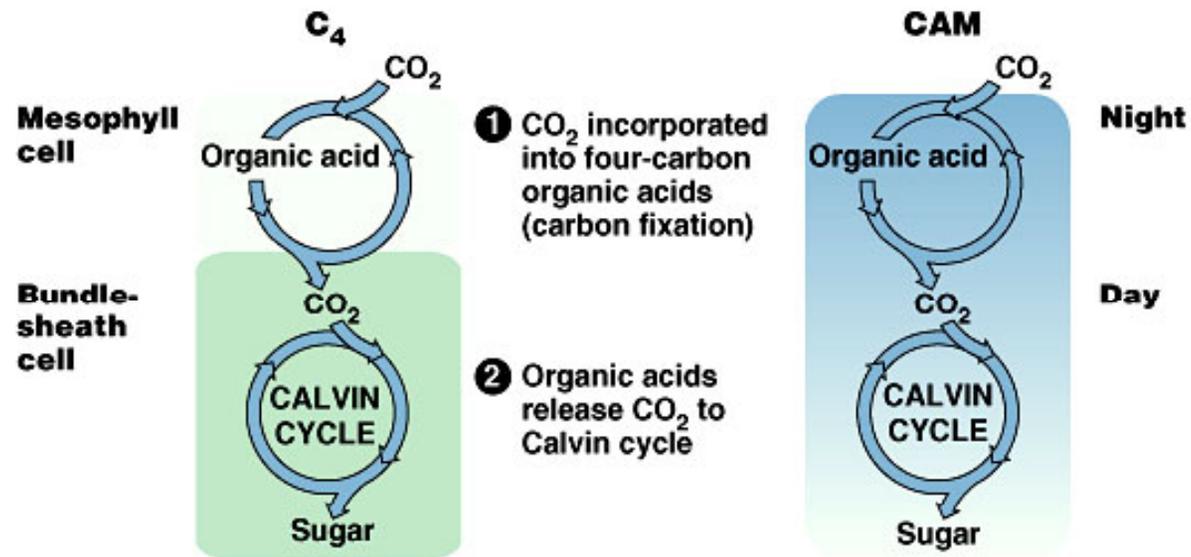
# C<sub>4</sub> and CAM photosynthesis compared



Sugarcane



Pineapple



(a) Spatial separation of steps

(b) Temporal separation of steps

# Photorespiration

## Enzymes

- 1 RubisCO
- 2 Phosphoglycolate phosphatase
- 3 Glycolate oxidase
- 4 Glutamate-Glyoxylate aminotransferase
- 5 Glycine decarboxylase complex
- 6 Serin-Glyoxylate aminotransferase
- 7 Pyruvate reductase
- 8 Glycerate kinase
- 9 Katalase
- 10 Glutamate synthase & Glutamine synthetase

## Translocators

- A Glycerate-Glycolate translocator
- B Malate-Glutamate/2-Oxoglutarate translocator
- C Amino acid translocator

## Abbreviations

- $P_i$  /  $(PO_3H_2)$  Phosphate  
 ATP/ADP Adenintri/diphosphate  
 NADH<sub>2</sub> Nicotinamide adinine dinucleotide  
 NH<sub>4</sub><sup>+</sup> Ammonium  
 NH<sub>2</sub> Amino group  
 H<sub>2</sub>O<sub>2</sub> Hydrogen peroxide  
 RubisCO Ribulose-1,5-bisphosphate carboxylase/oxygenase

Not drawn to scale! Enzymes and some compounds not directly involved in photorespiration are omitted for clarity.

Buchanan BB, Grisse W, Jones RL (2000). Biochemistry and Molecular Biology of Plants. Am Soc Plant Phys (Rockville).

