Lecture Series 10

Photosynthesis: Energy from the Sun

Reading Assignments

- Review Chapter 3
  Energy, Catalysis, & Biosynthesis

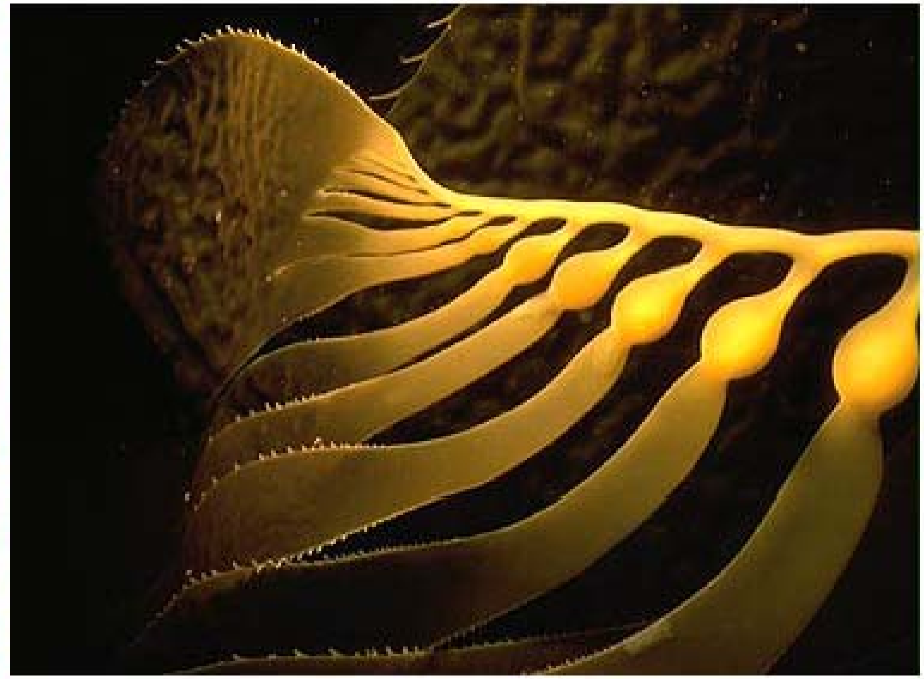
- Read Chapter 13
  How Cells obtain Energy from Food

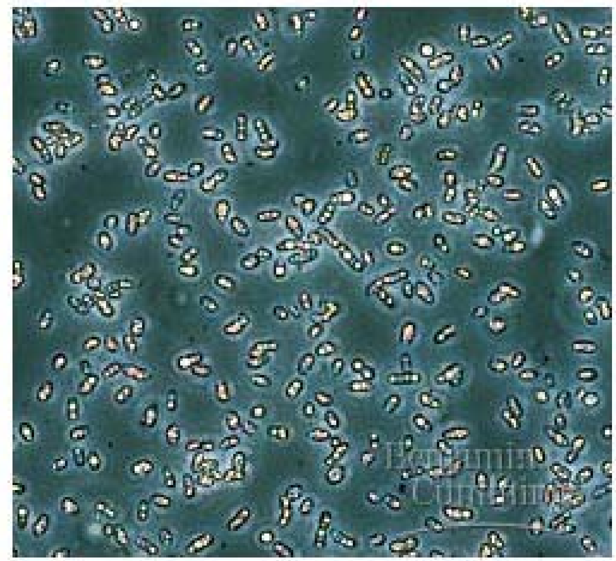
- Read Chapter 14
  Energy Generation in Mitochondria & Chloroplasts

Photosynthesis In General

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

Photoautotrophs

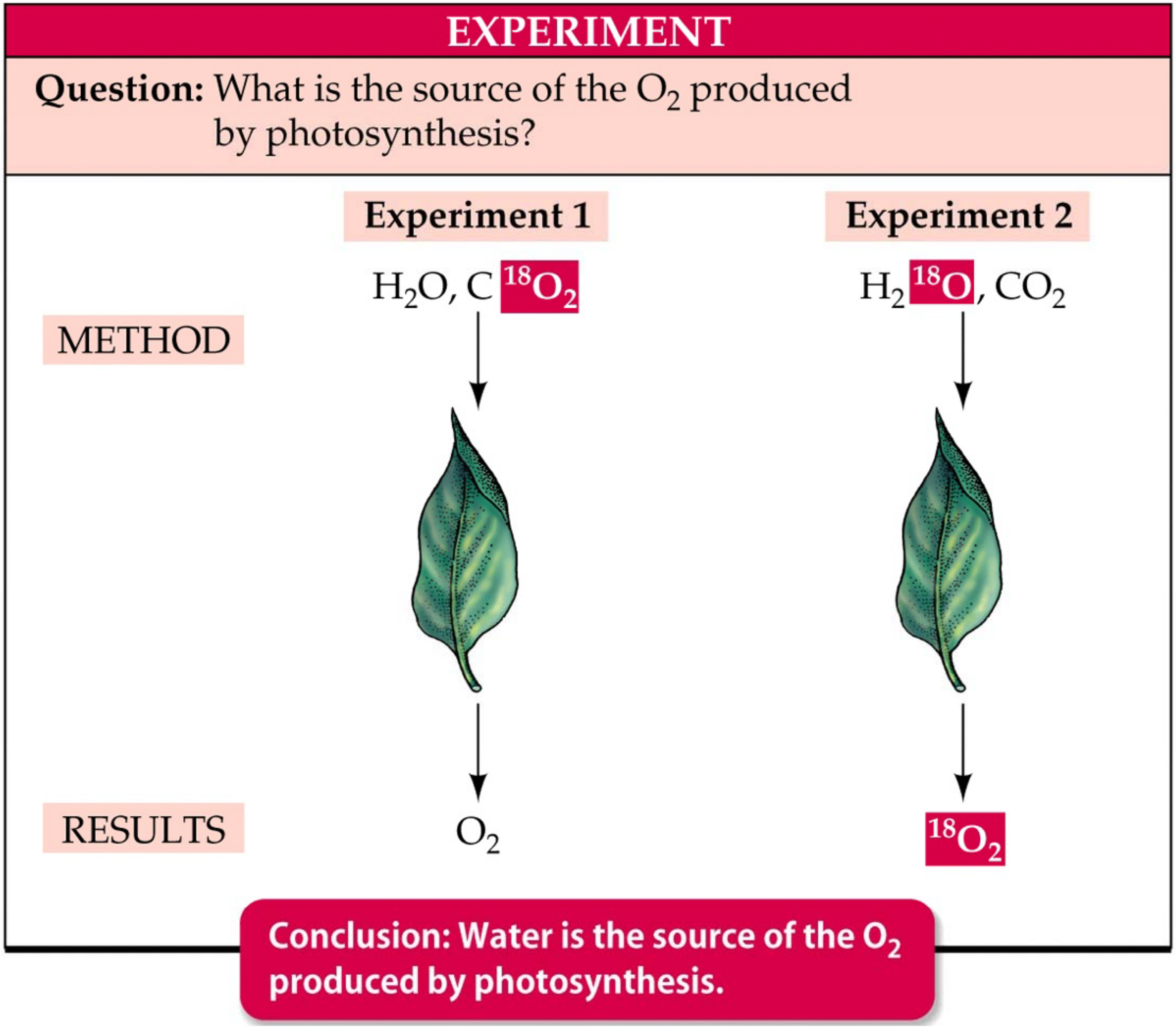



A. Identifying Photosynthetic Reactants and Products

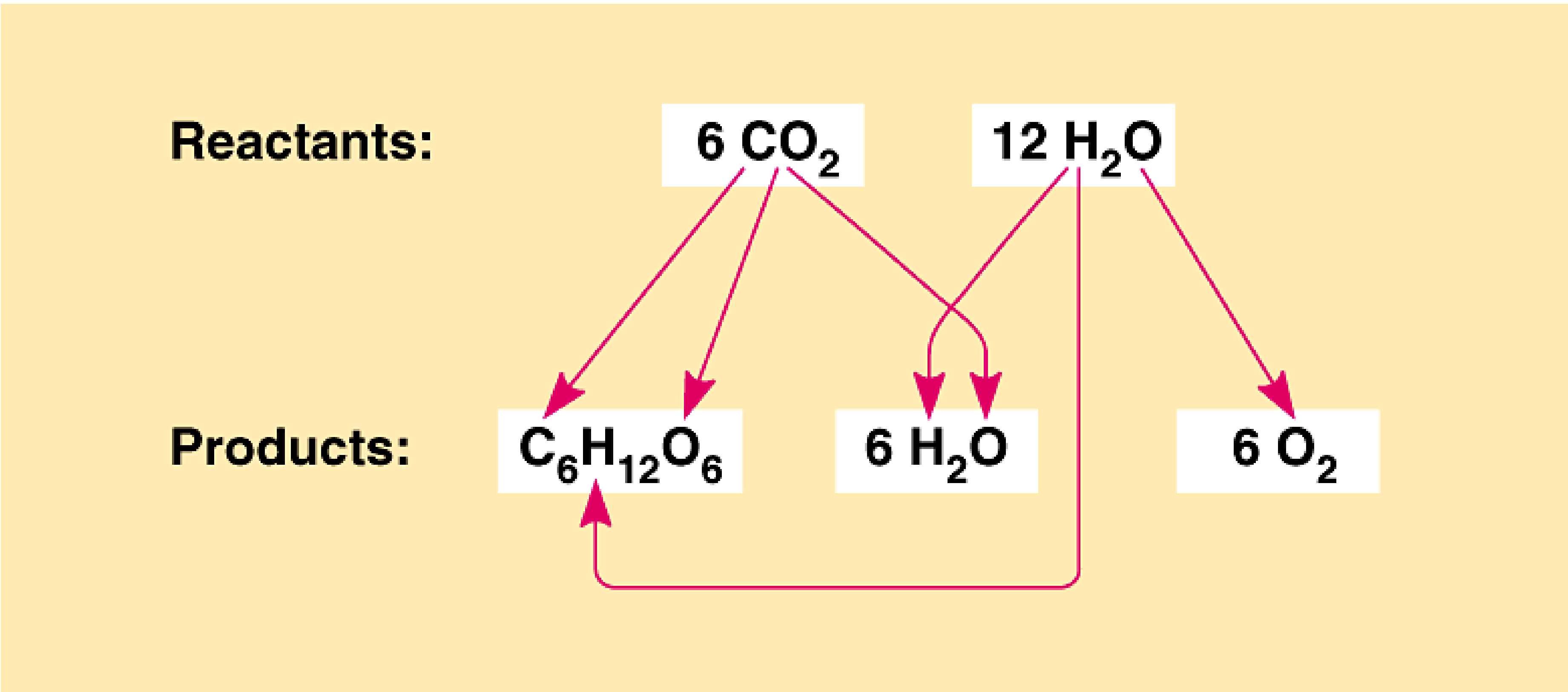
- Photosynthesizing plants take in CO_2, water, and light energy, producing O_2 and carbohydrate. The overall reaction is

$$6\ CO_2 + 12\ H_2O + \text{light} \rightarrow C_6H_{12}O_6 + 6\ O_2 + 6\ H_2O$$

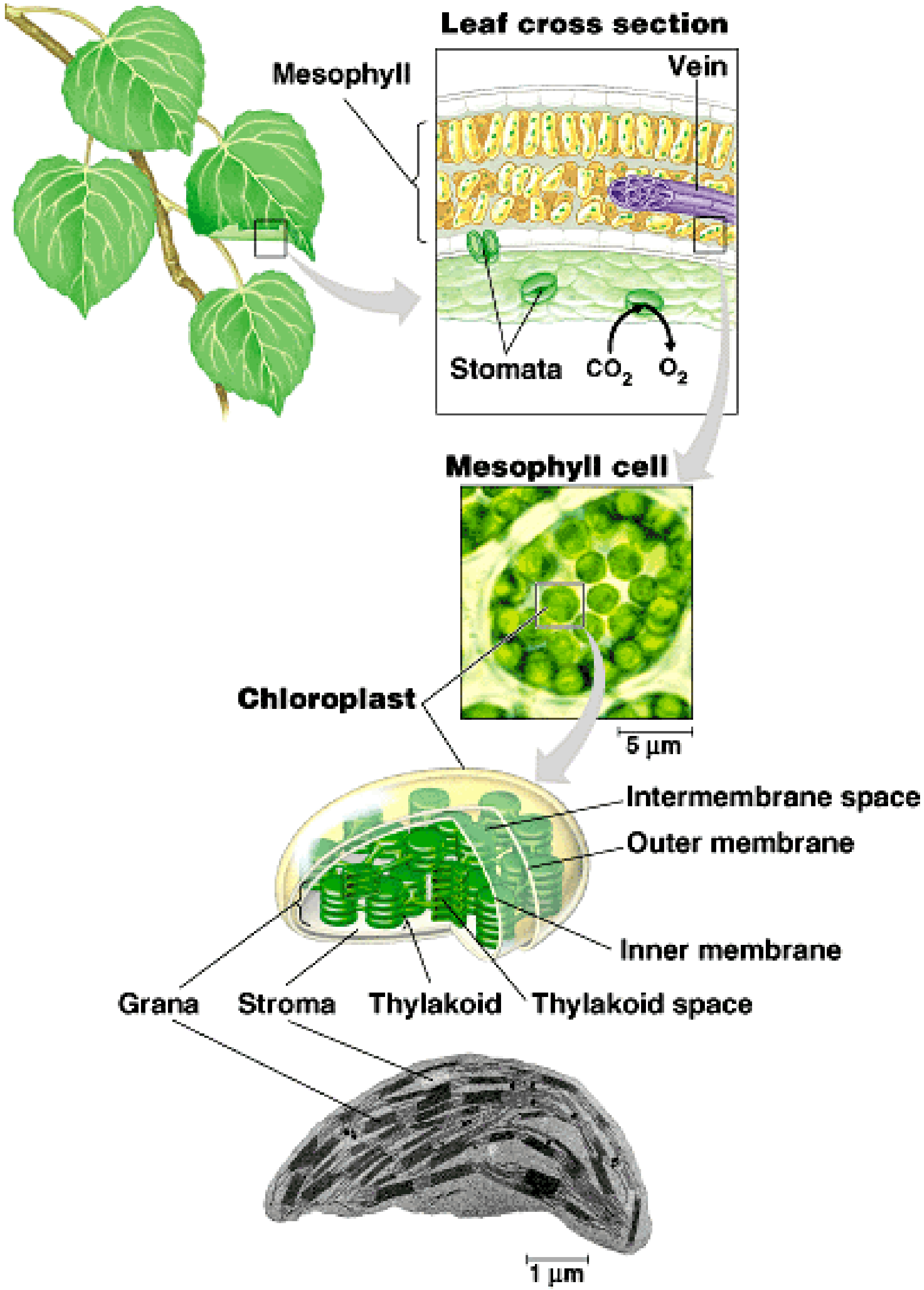
- The oxygen atoms in O_2 come from water, not from CO_2.


EXPERIMENT
Question: What is the source of the O_2 produced by photosynthesis?
Experiment 1
Experiment 2
H_2O, $C^{18}O_2$
$H_2{}^{18}O$, CO_2
METHOD
RESULTS
O_2
$^{18}O_2$
Conclusion: Water is the source of the O_2 produced by photosynthesis.

Tracking atoms through photosynthesis



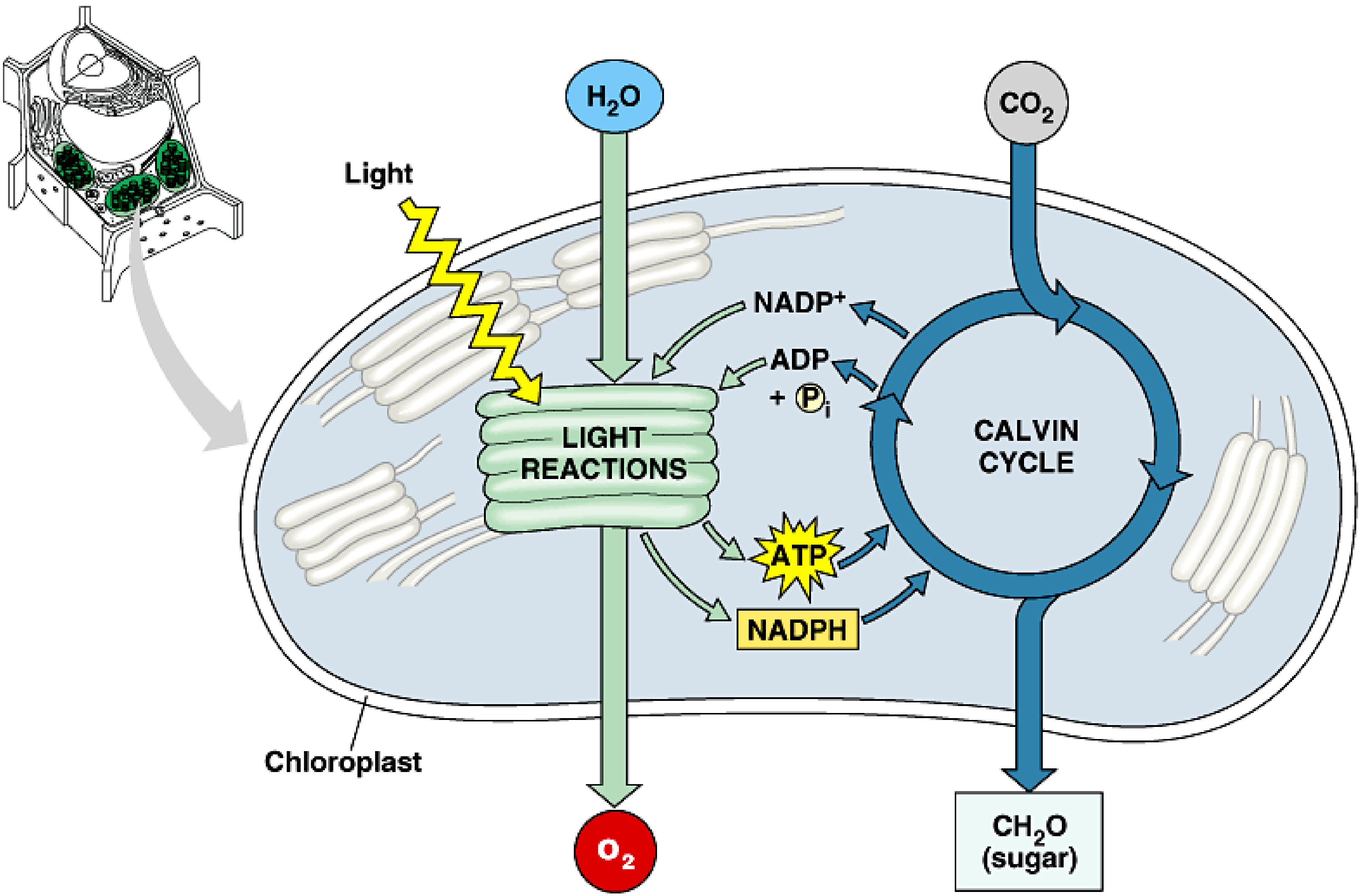
Focusing in on the location of photosynthesis in a plant



B. The Two Pathways of Photosynthesis: An Overview

- In the light reactions of photosynthesis, electron flow and photophosphorylation produce ATP and reduce $NADP^+$ to $NADPH + H^+$.
- ATP and $NADPH + H^+$ are needed for the reactions that fix and reduce CO_2 in the Calvin–Benson cycle, forming sugars. These are sometimes erroneously referred to as the dark reactions.

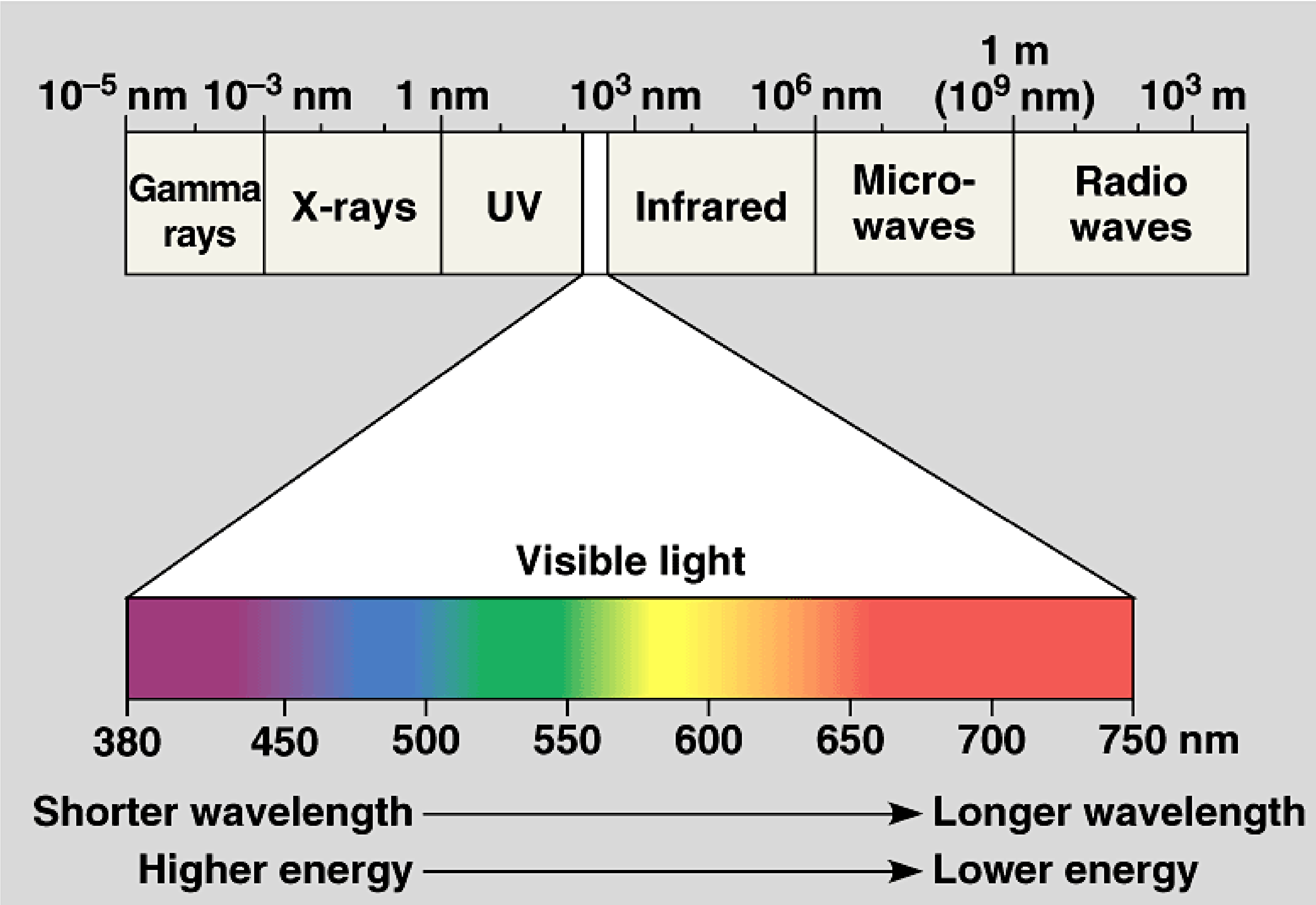
An overview of photosynthesis: cooperation of the light reactions and the Calvin cycle



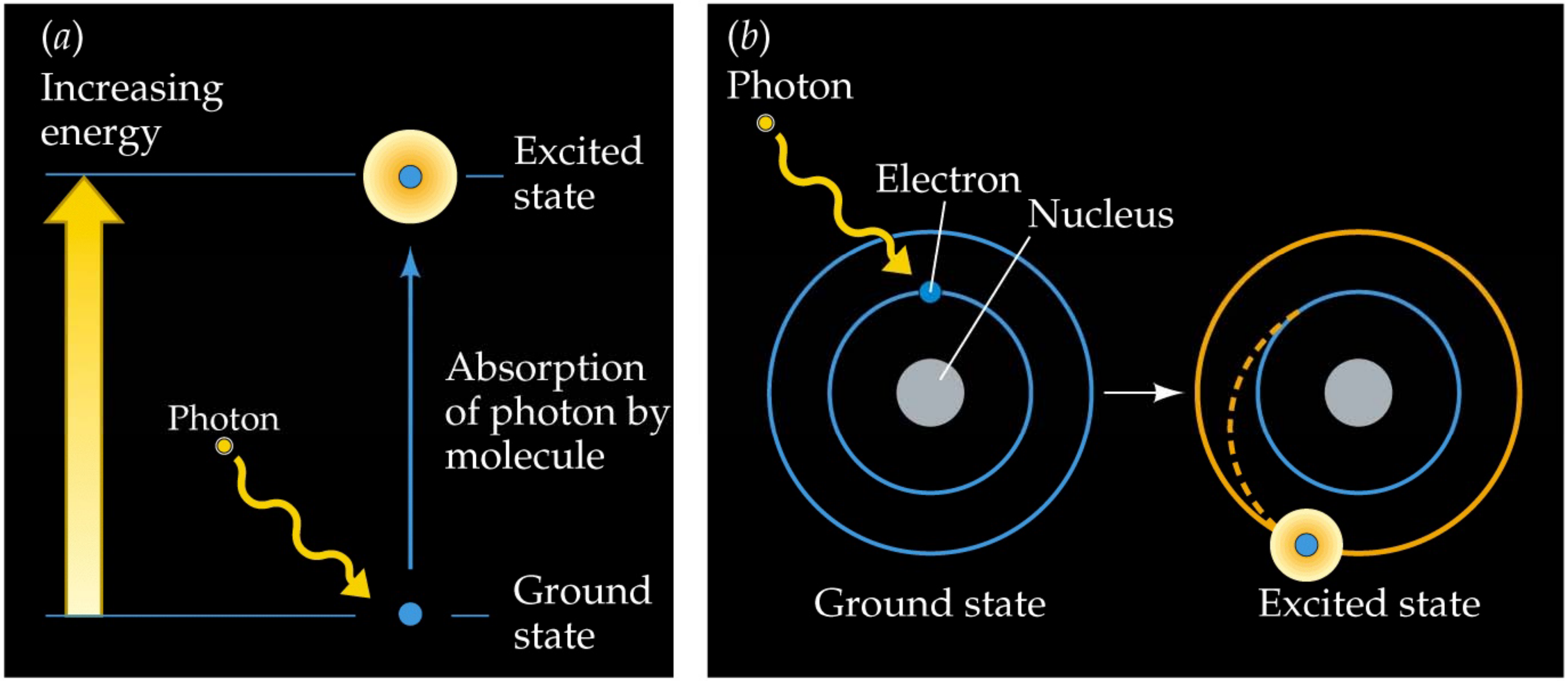
C. Properties of Light and Pigments

- 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



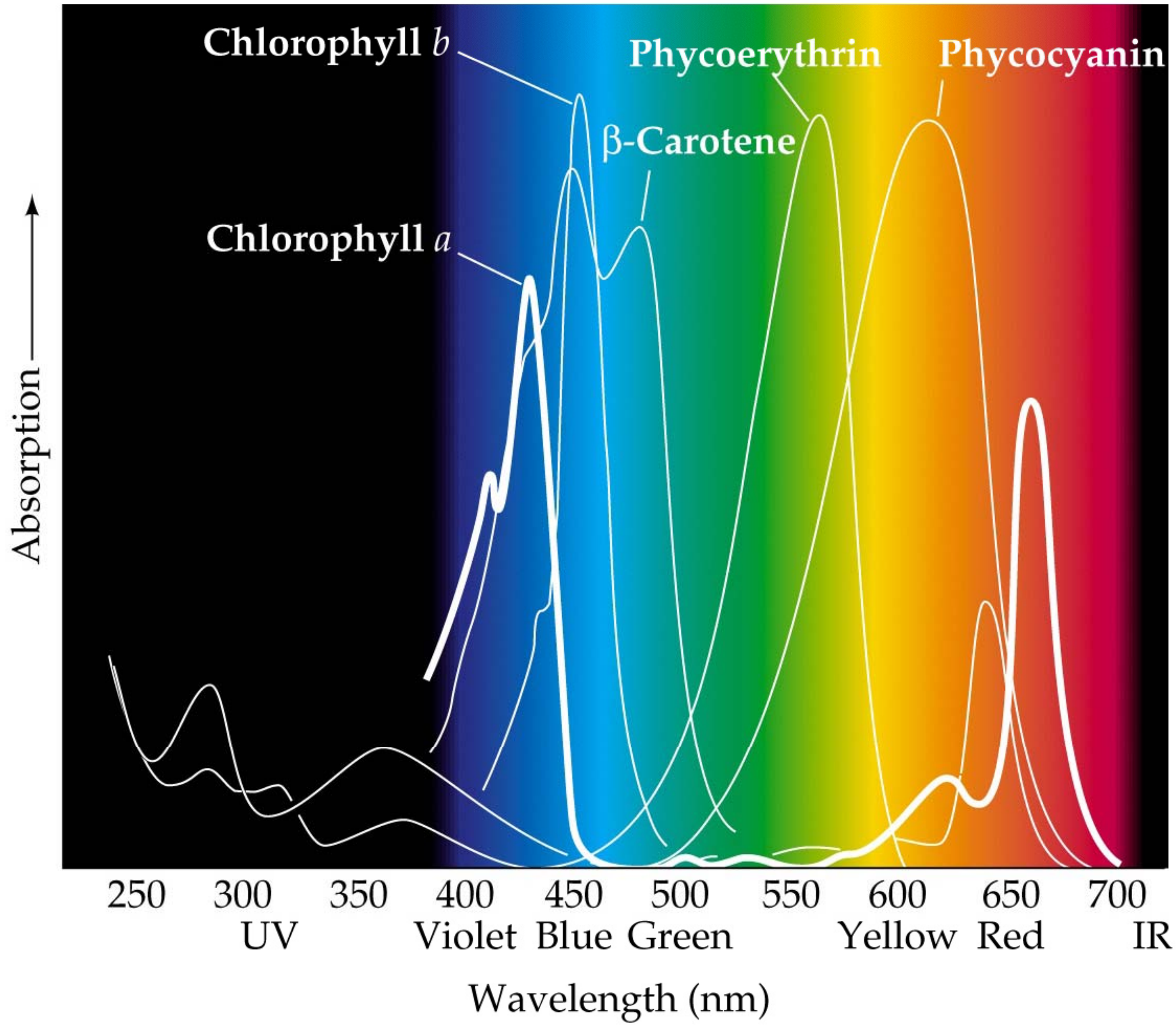
Exciting a Molecule



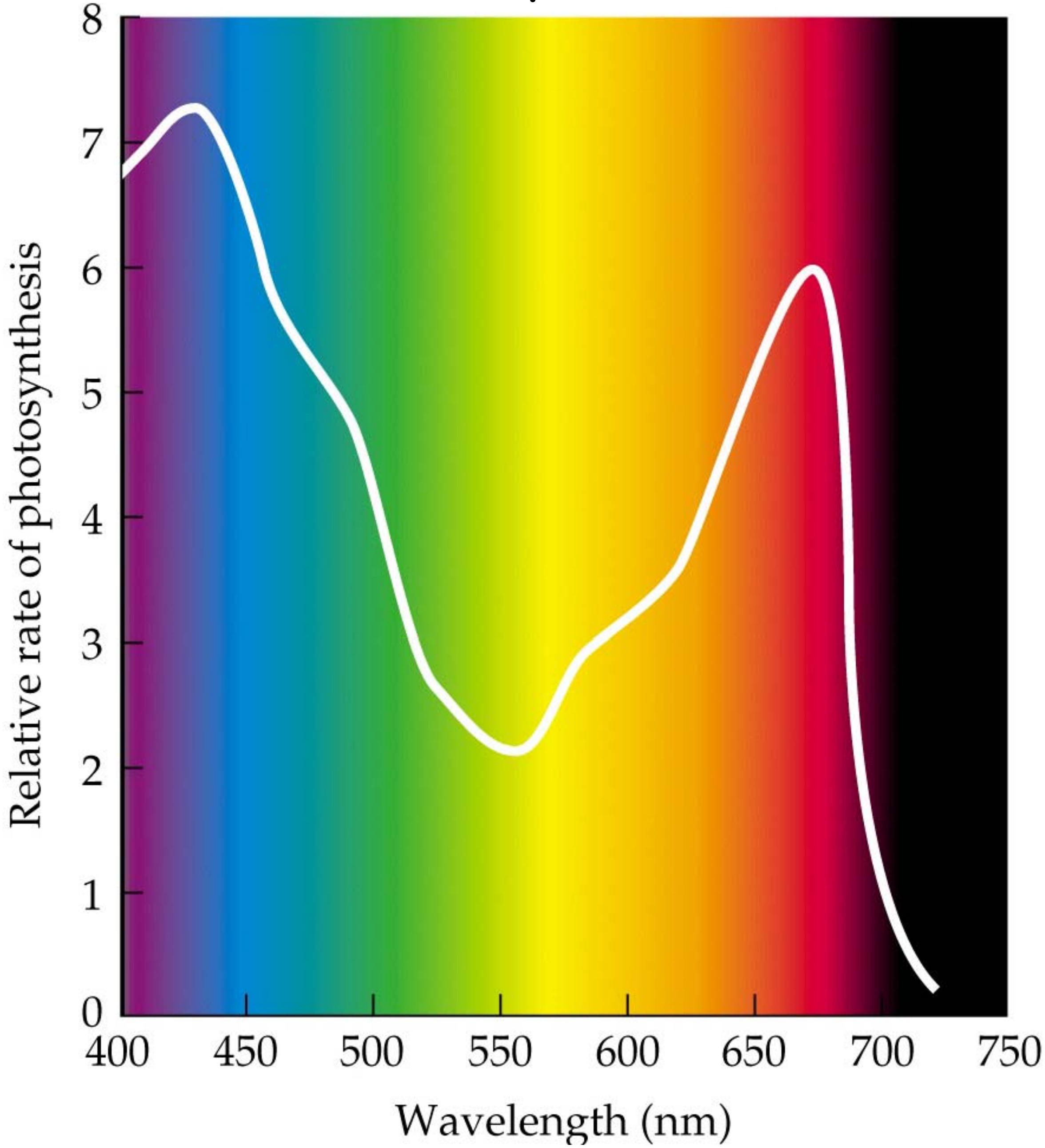
C. Properties of Light and Pigments

- 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.

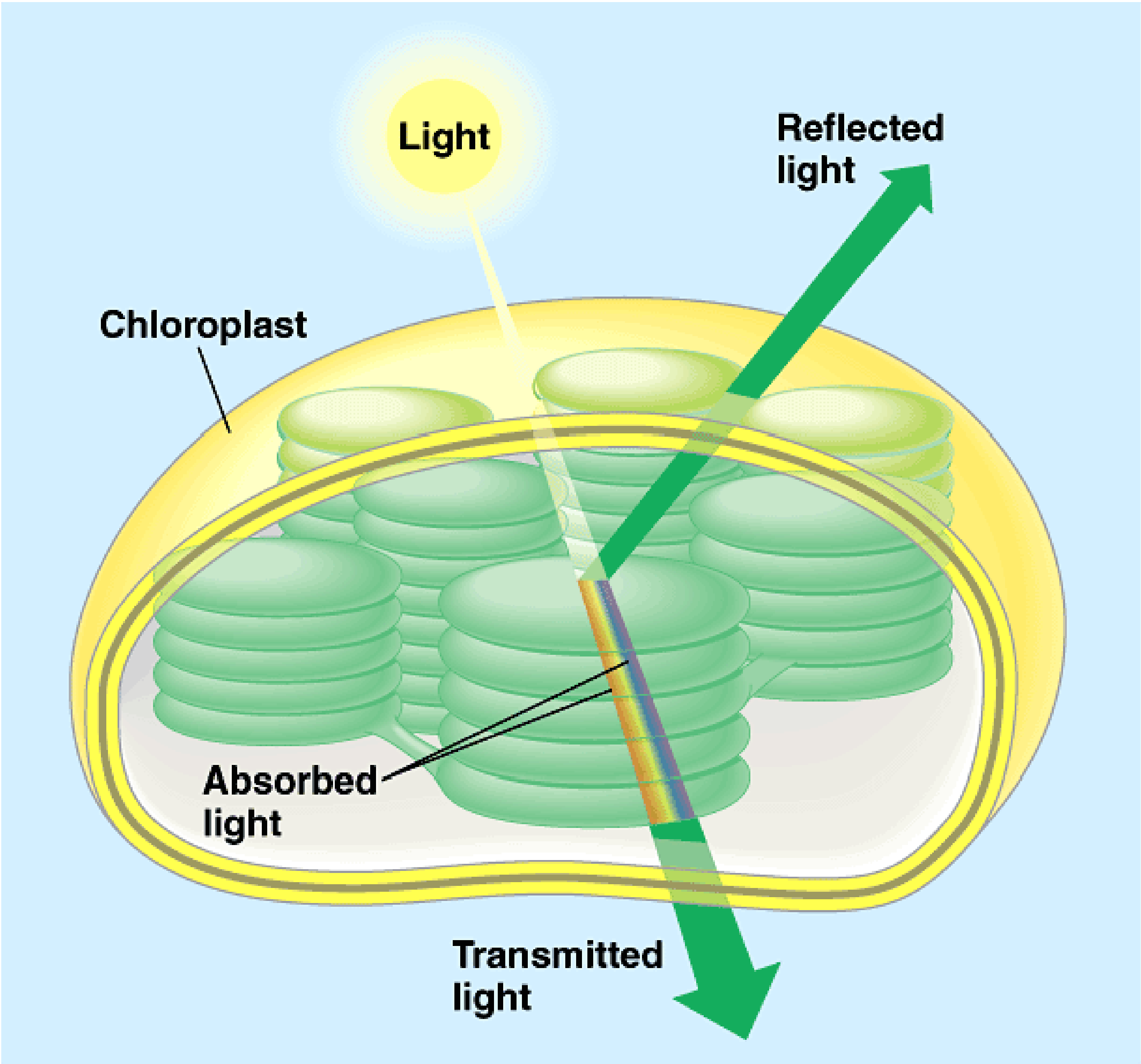
Absorption Spectra



Action Spectrum



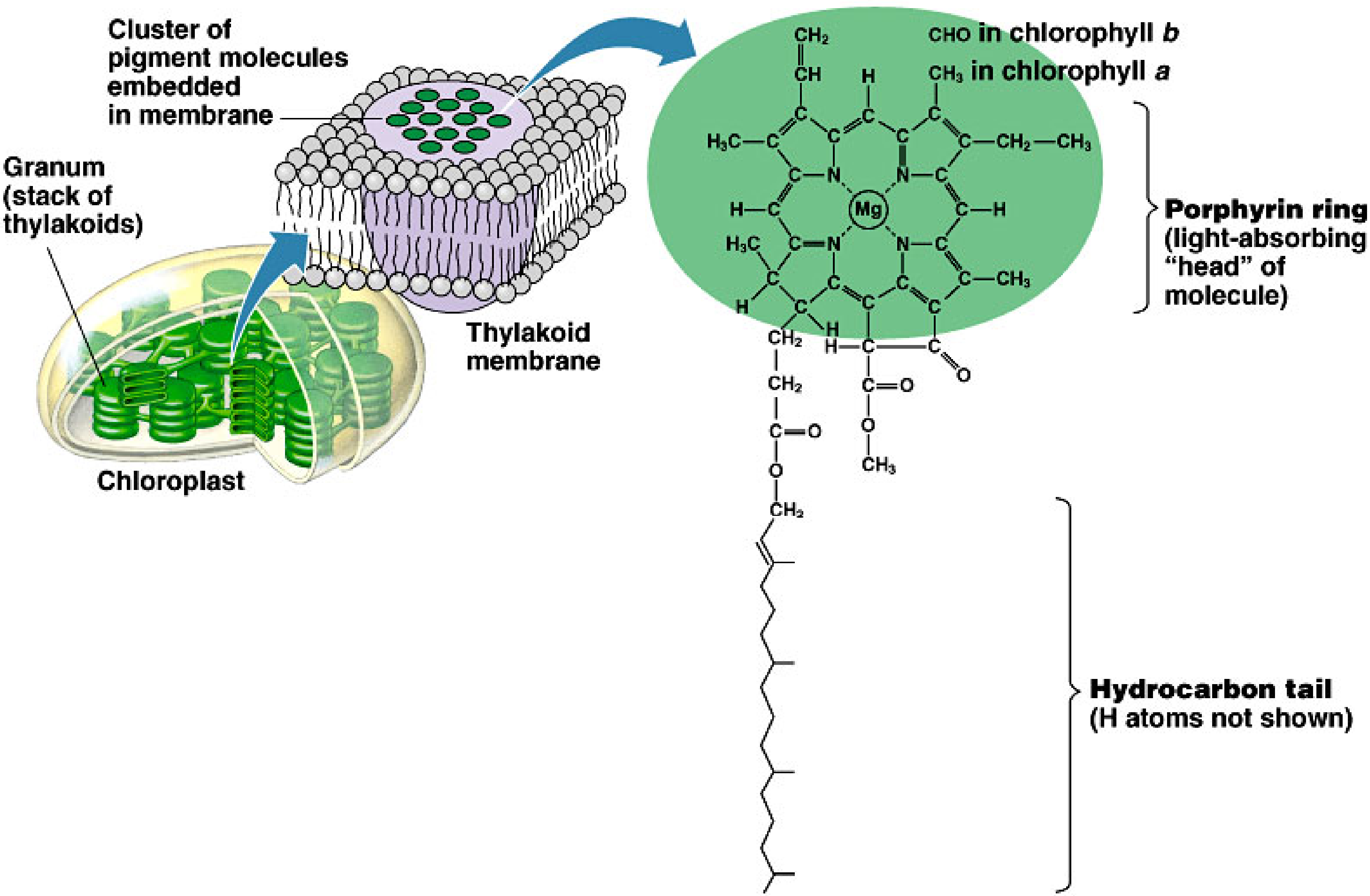
Why leaves are green: interaction of light with chloroplasts

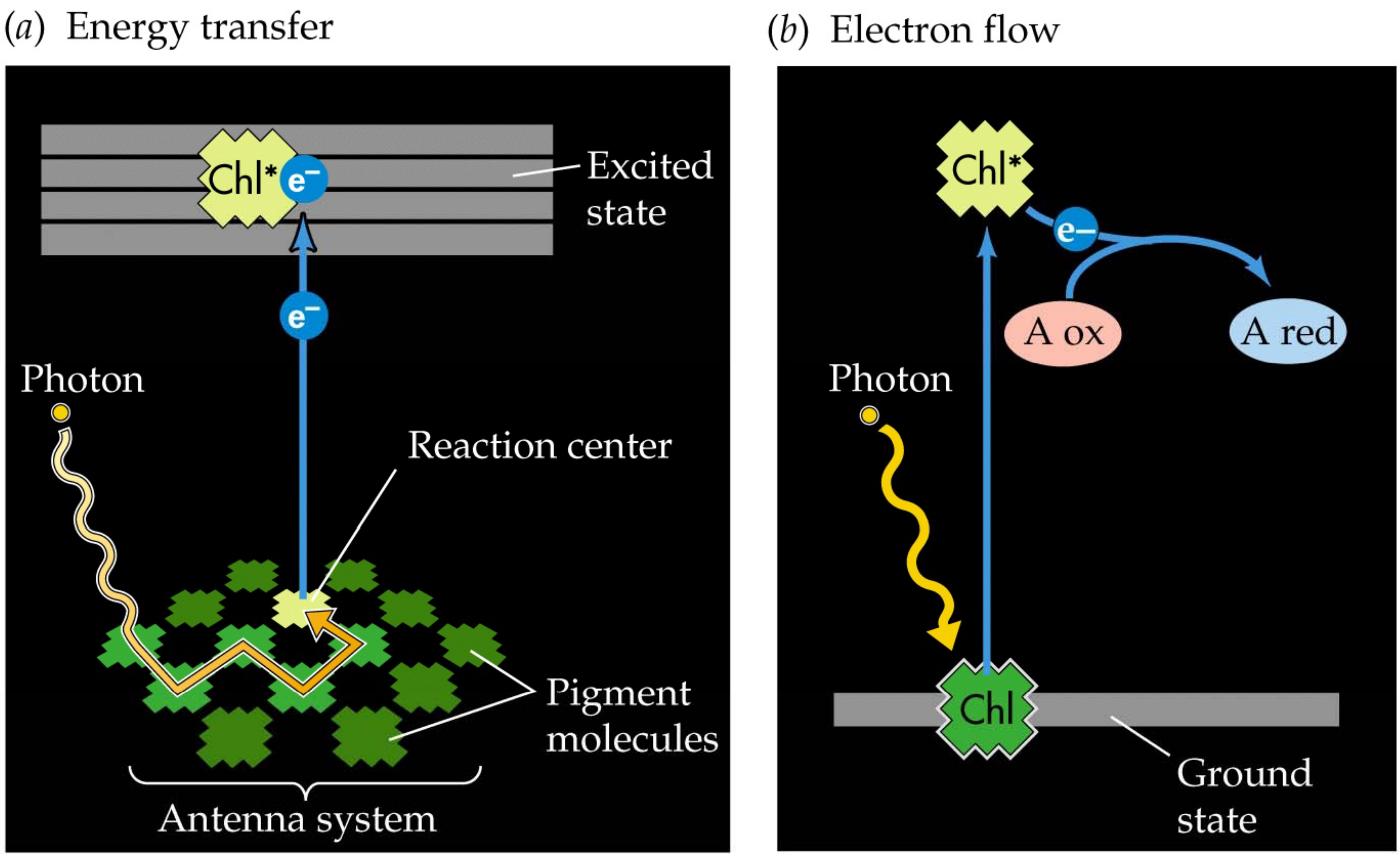


C. Properties of Light and Pigments

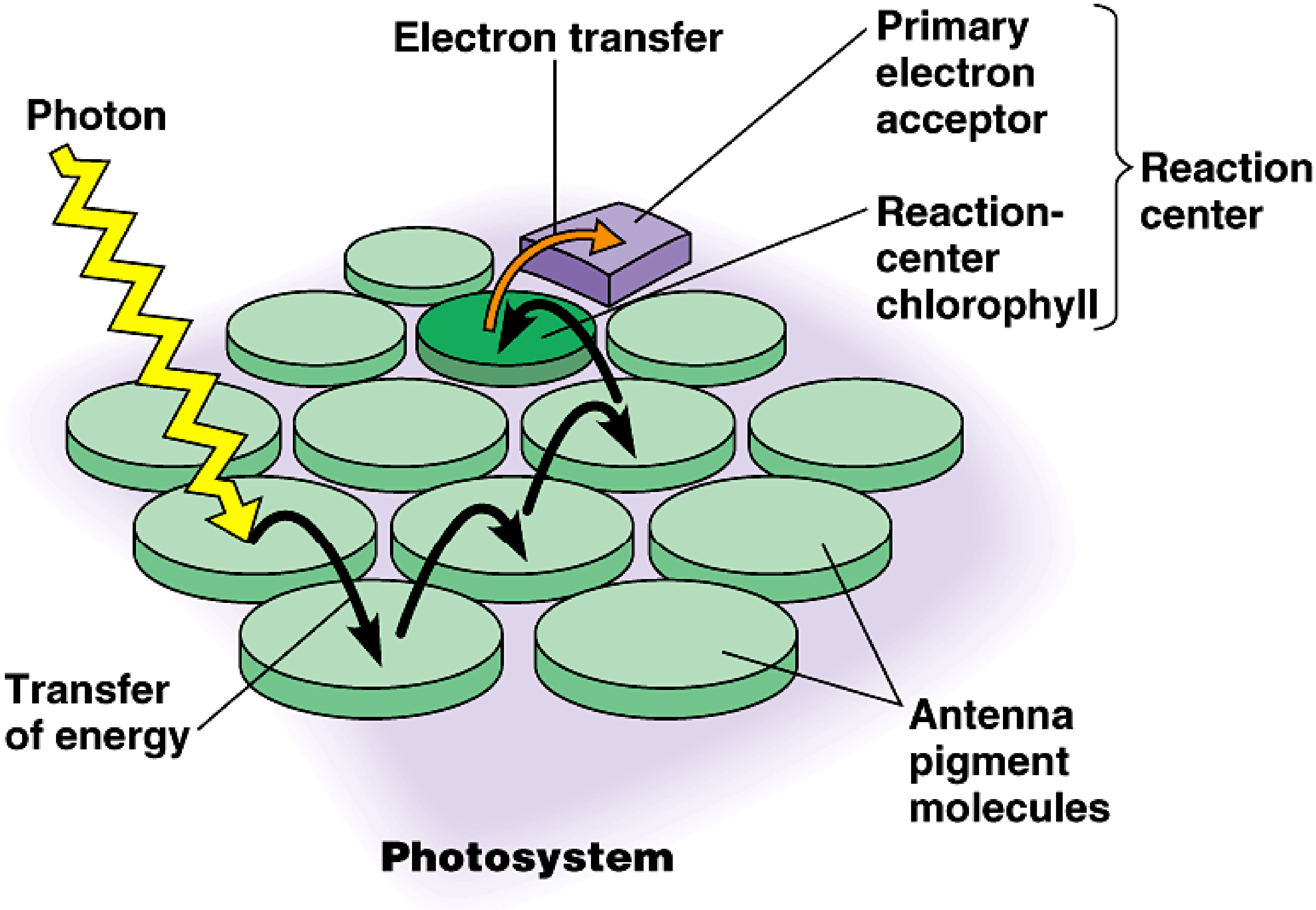
- Chlorophylls and accessory pigments form antenna systems for absorption of light energy.
- An excited pigment molecule may lose its energy by fluorescence, or by transferring it to another pigment molecule.

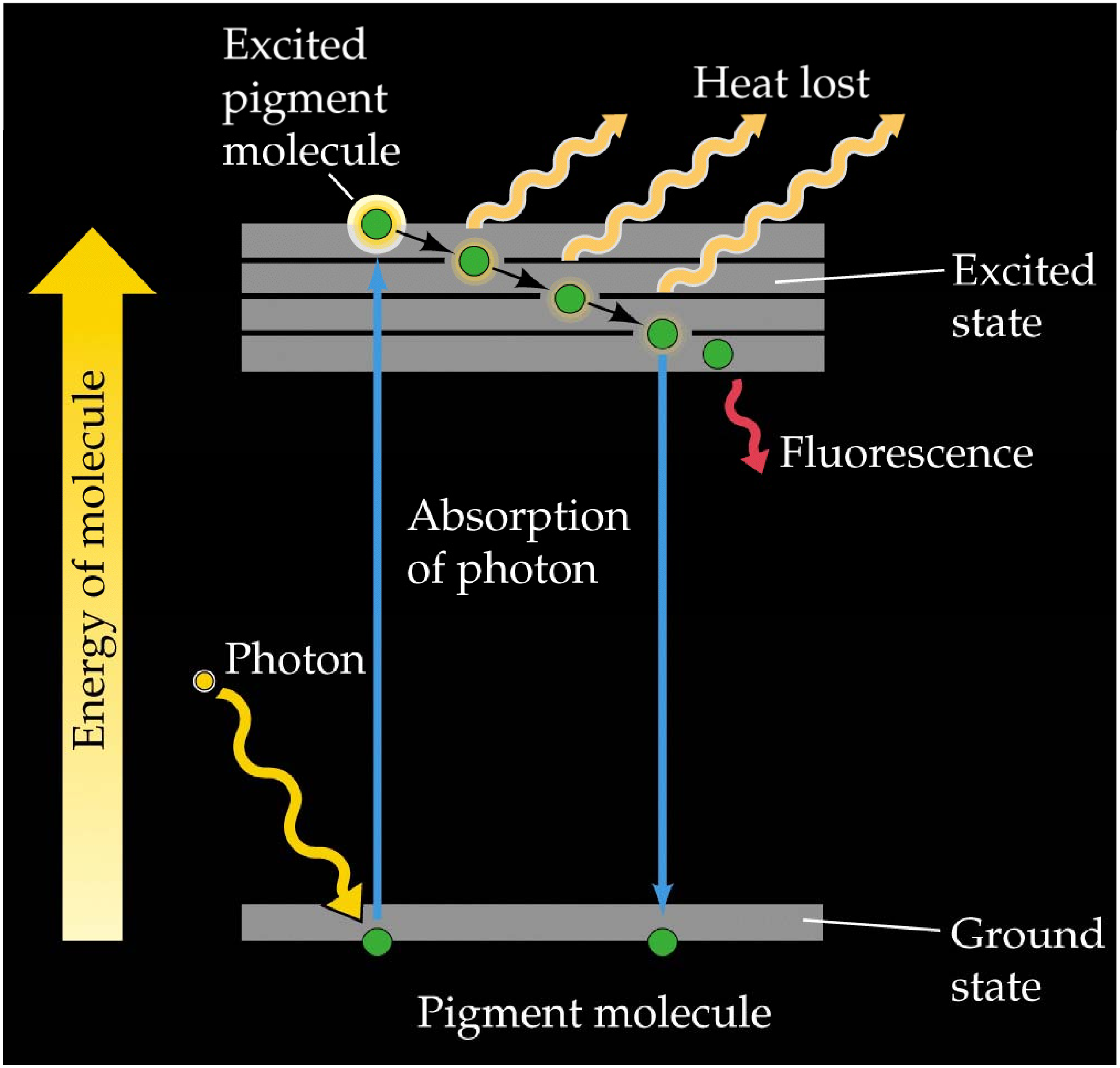
Location and structure of chlorophyll molecules in plants



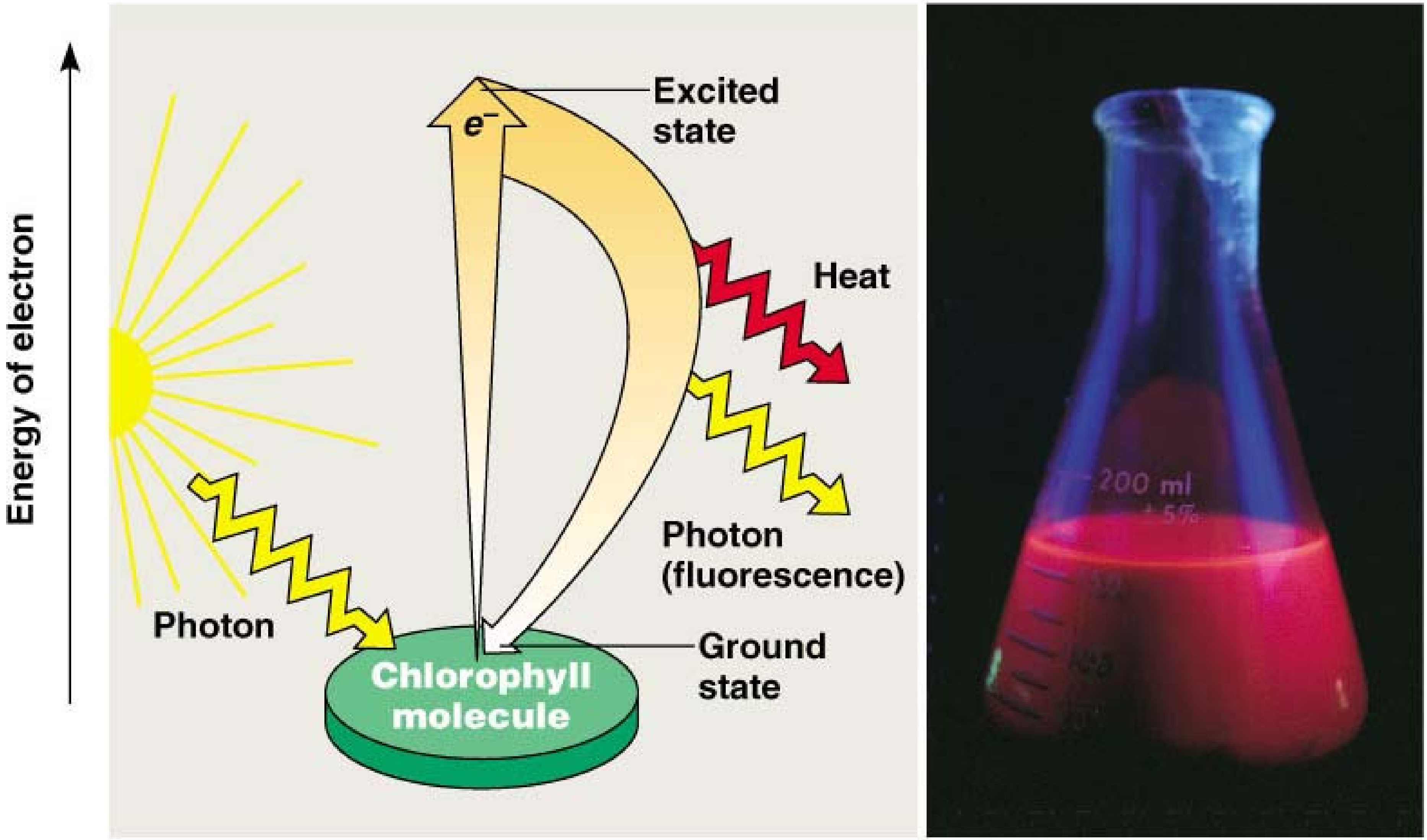

(a) Energy transfer
Chl*
e⁻
Excited state
e⁻
Photon
Reaction center
Pigment molecules
Antenna system
(b) Electron flow
Chl*
e–
A ox
A red
Photon
Chl
Ground state

How a photosystem harvests light




Excited pigment molecule
Heat lost
Excited state
Fluorescence
Absorption of photon
Energy of molecule
Photon
Ground state
Pigment molecule

Excitation of isolated chlorophyll by light

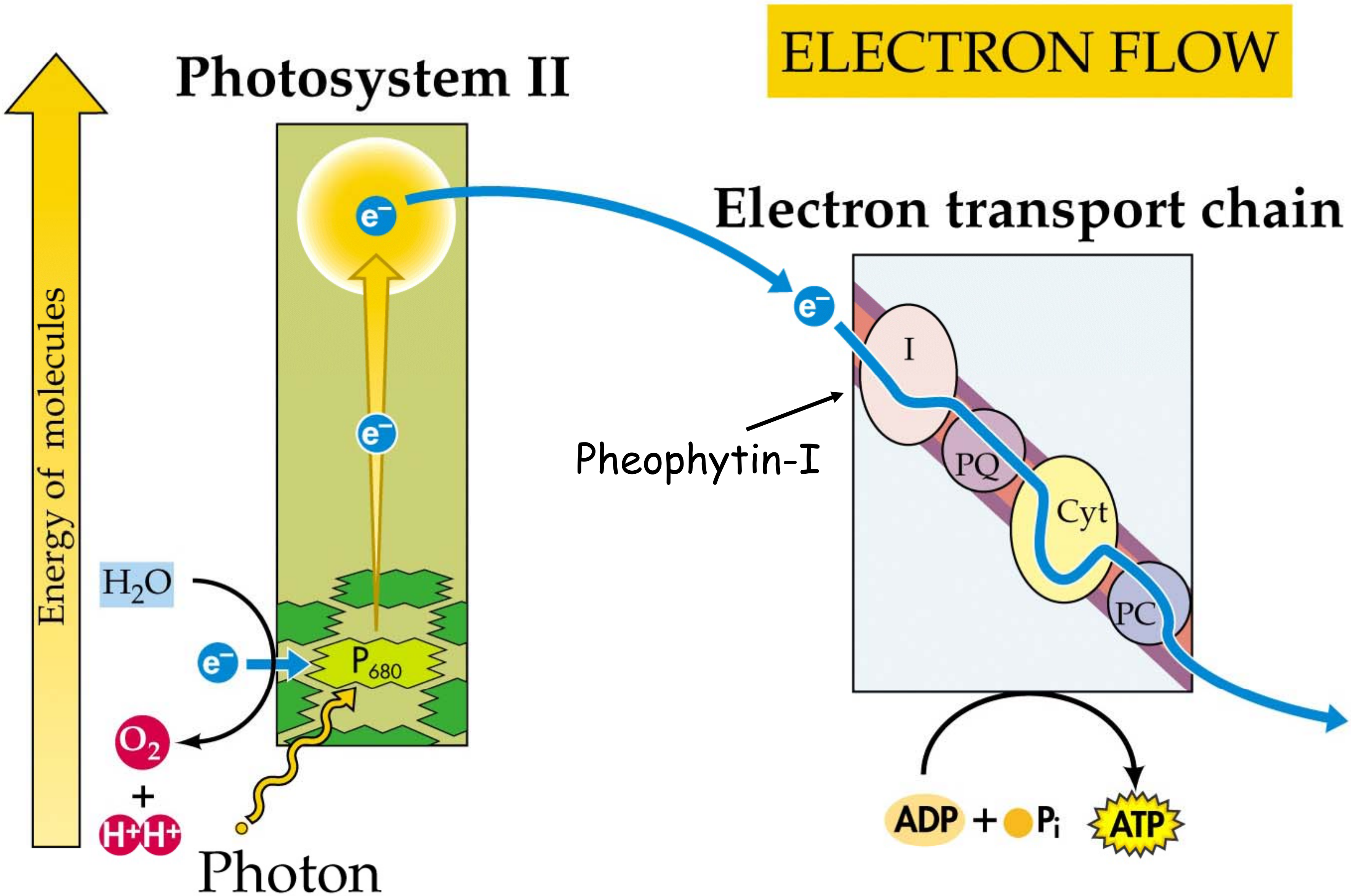


(a) Excitation of isolated chlorophyll molecule

(b) Fluorescence

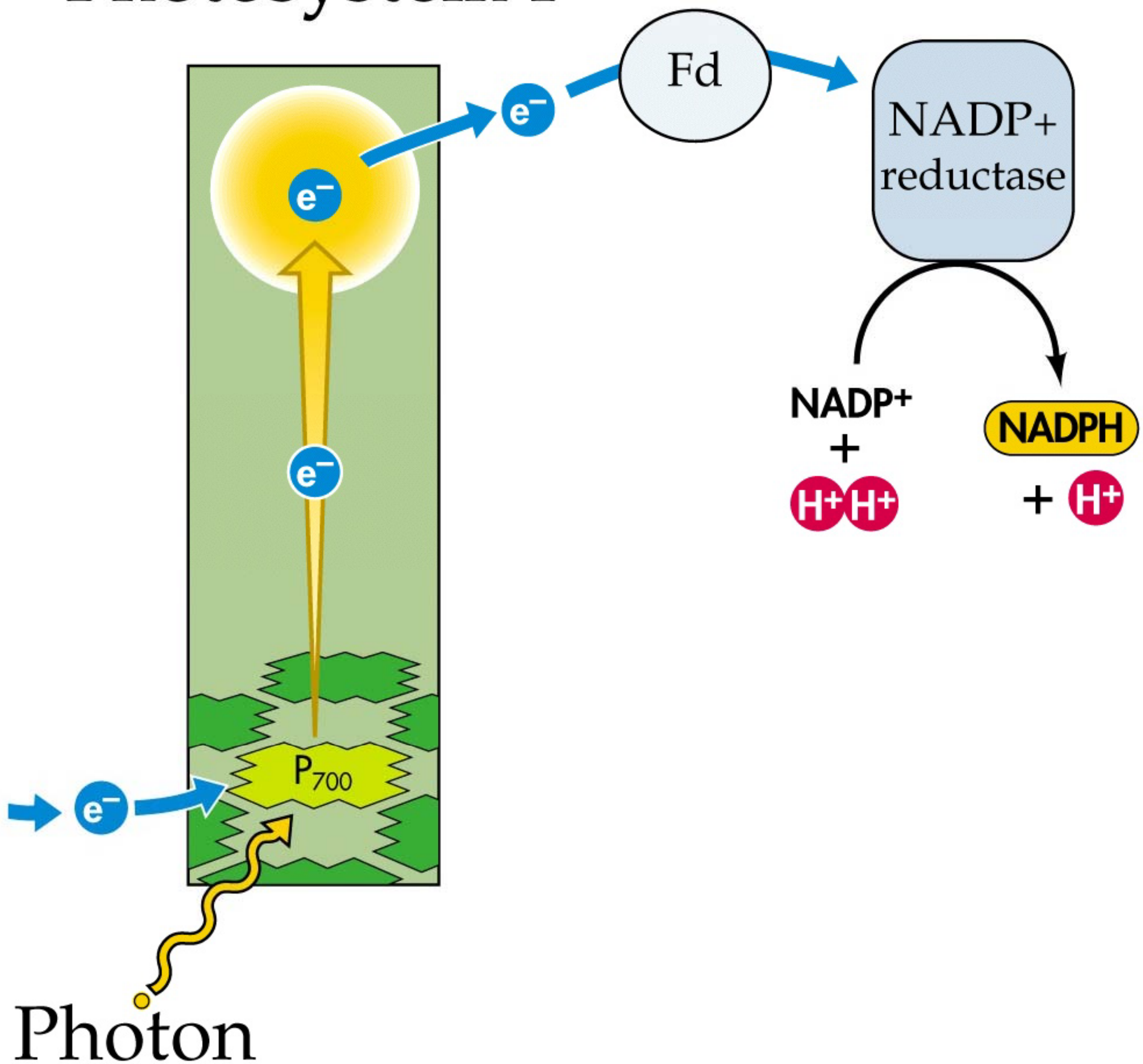
D. Electron Flow, Photophos-phorylation, and Reductions

- 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^+.

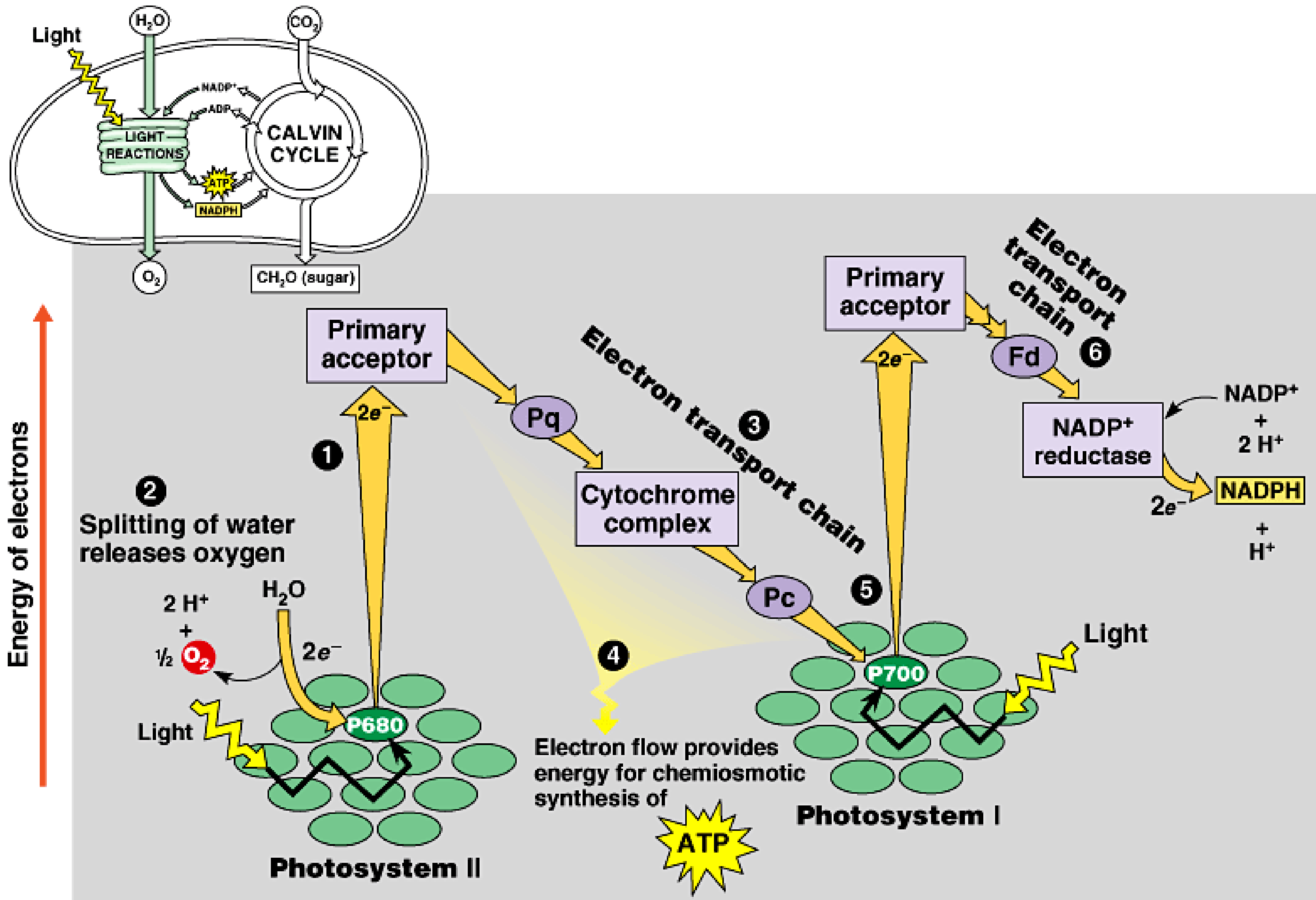


ELECTRON FLOW
Photosystem II
Energy of molecules
e⁻
e⁻
H2O
e⁻
P680
O2
+
H+ H+
Photon
Electron transport chain
e⁻
I
PQ
Cyt
PC
Pheophytin-I
ADP + Pi
ATP

Photosystem I

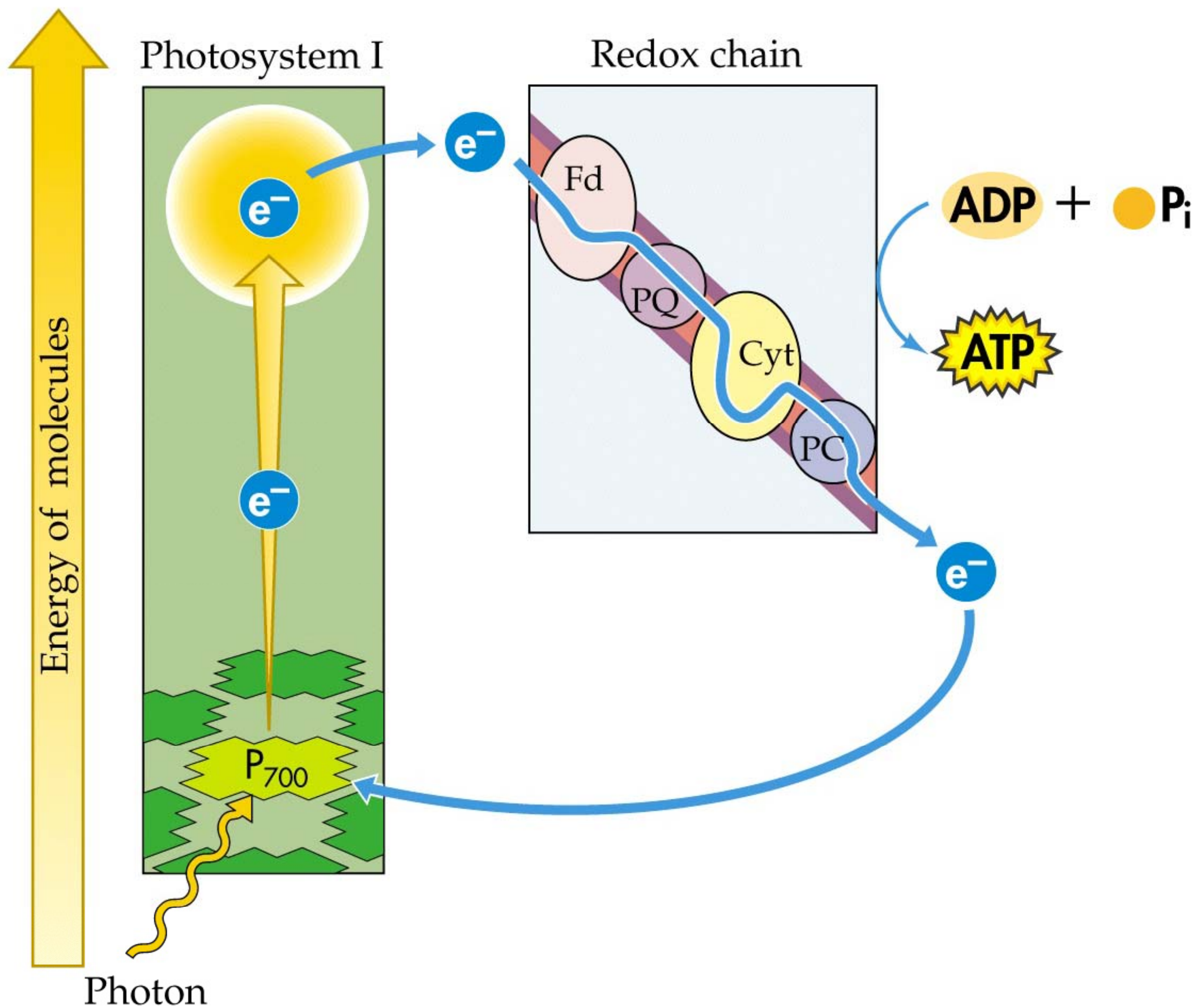


How noncyclic electron flow during the light reactions generates ATP and NADPH



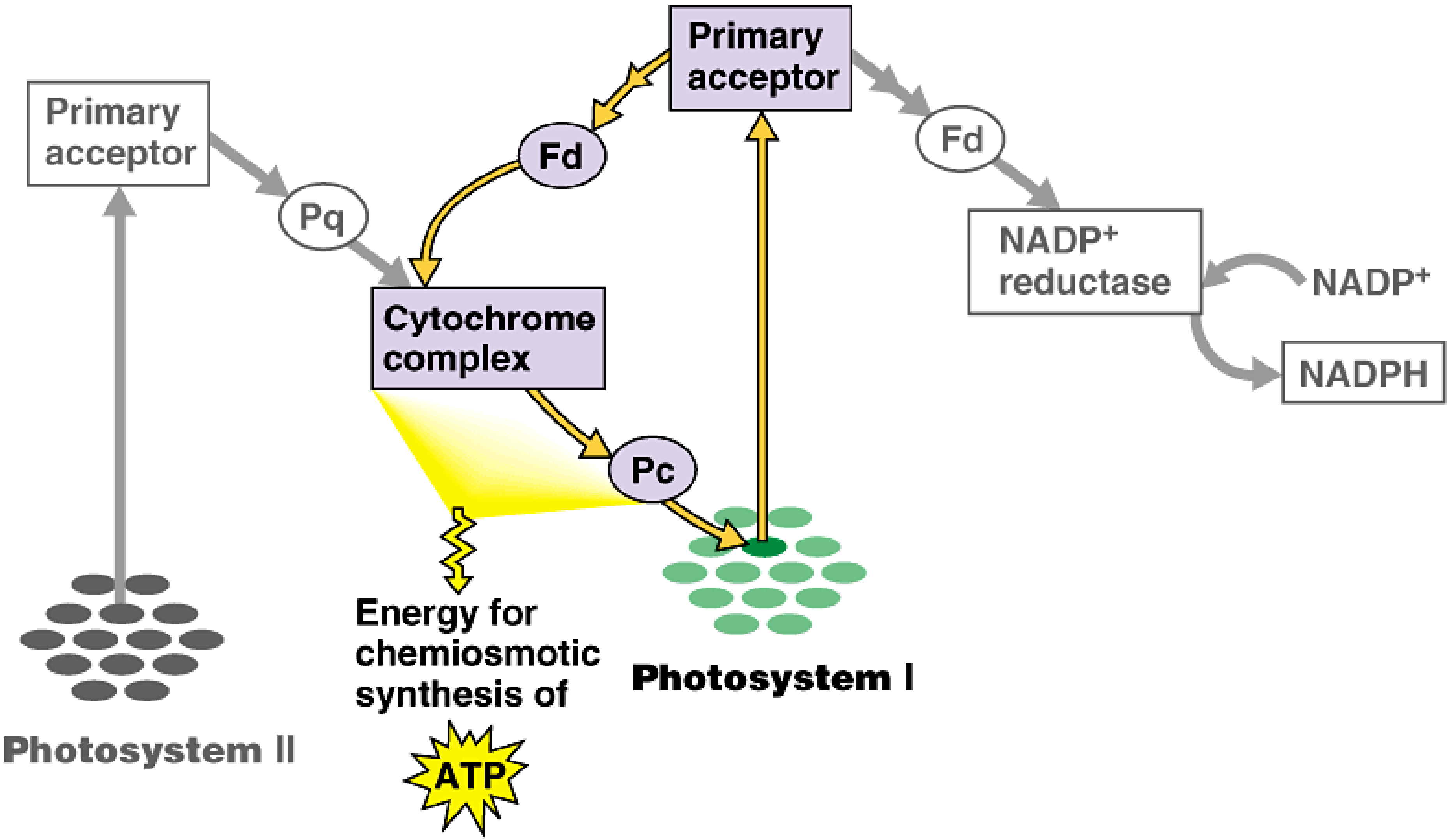
D. Electron Flow, Photophos-phorylation, and Reductions

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



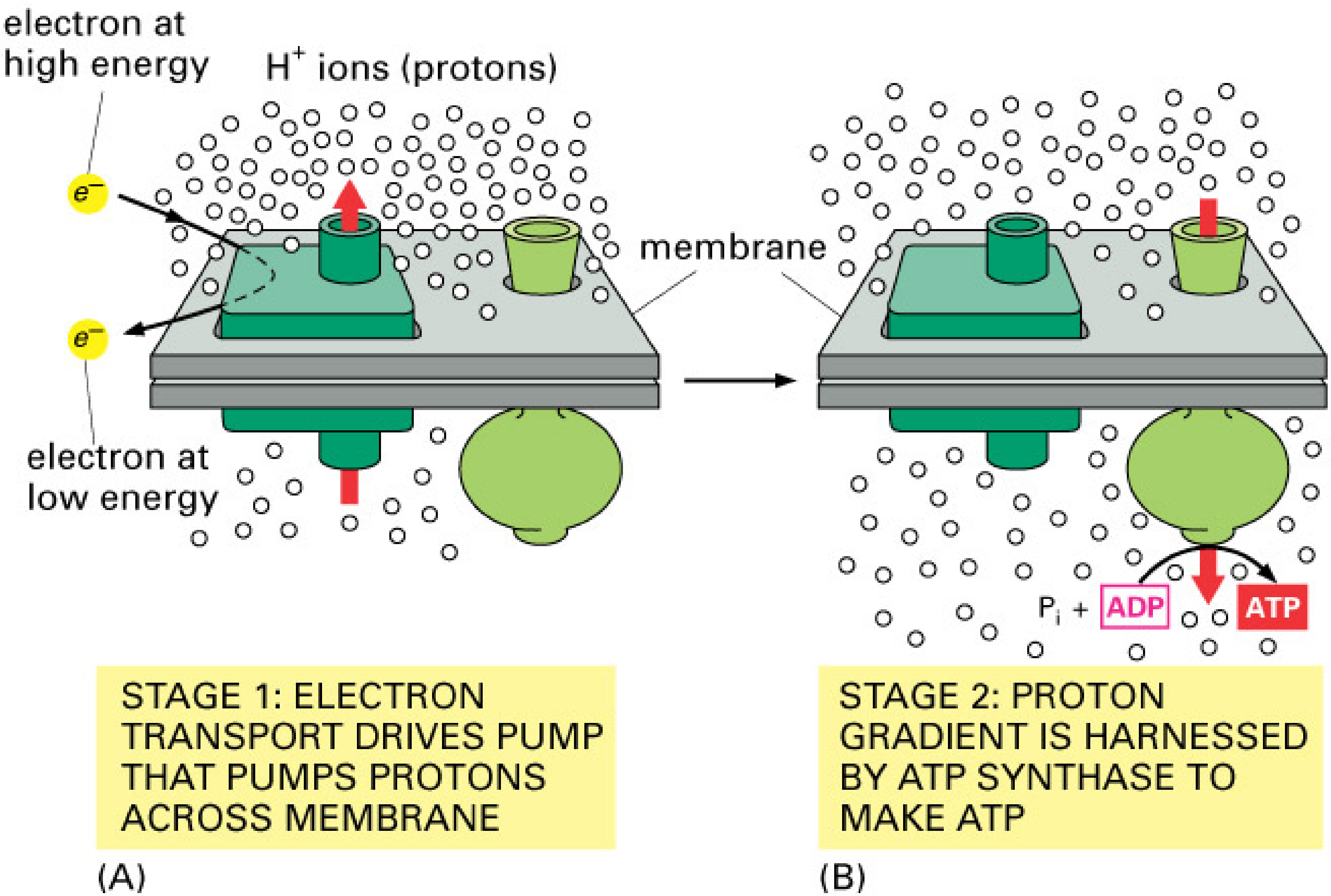
Energy of molecules
Photosystem I
Redox chain
e⁻
Fd
PQ
Cyt
PC
ADP + Pi
ATP
P700
Photon

Cyclic electron flow

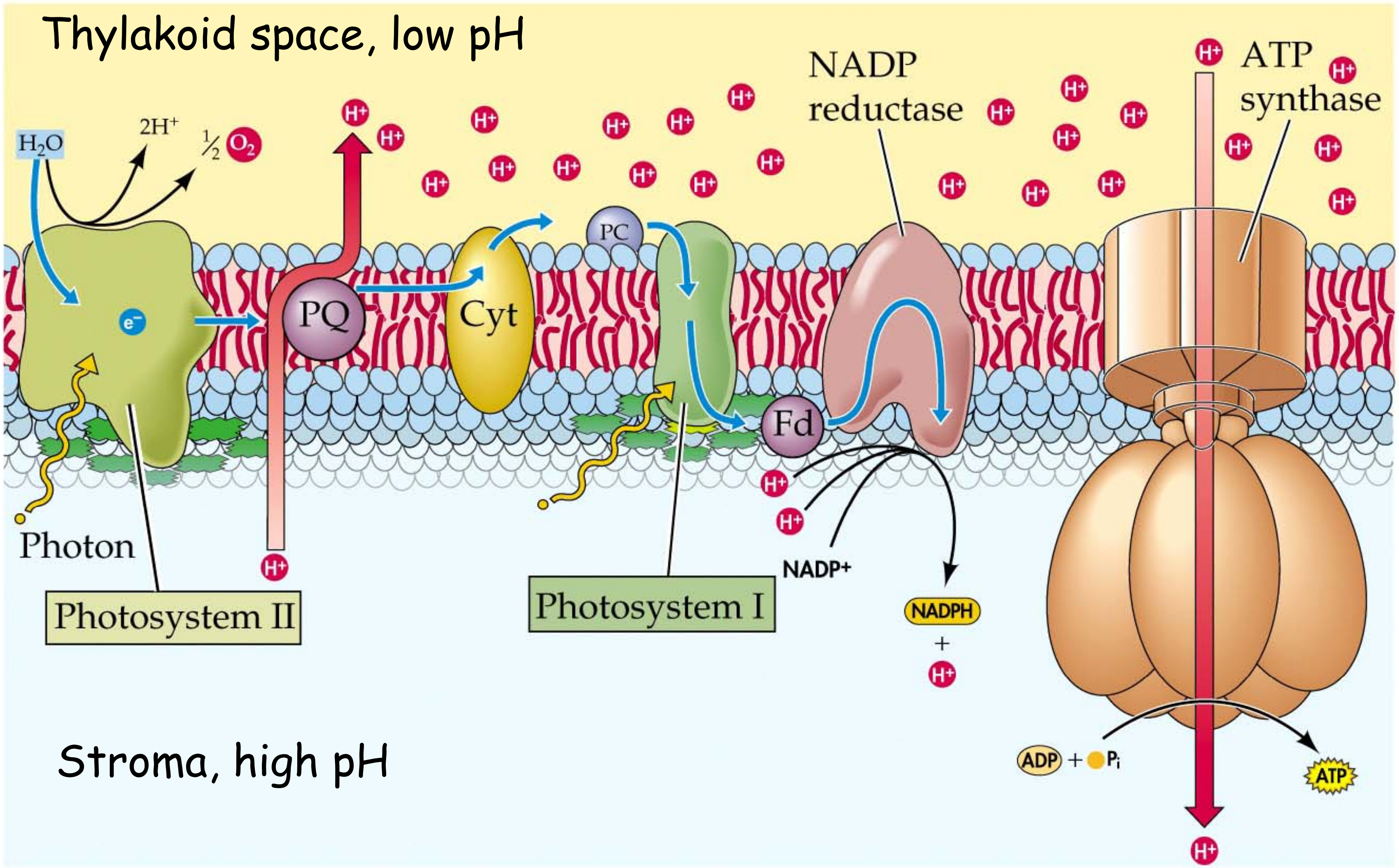


D. Electron Flow, Photophos-phorylation, and Reductions

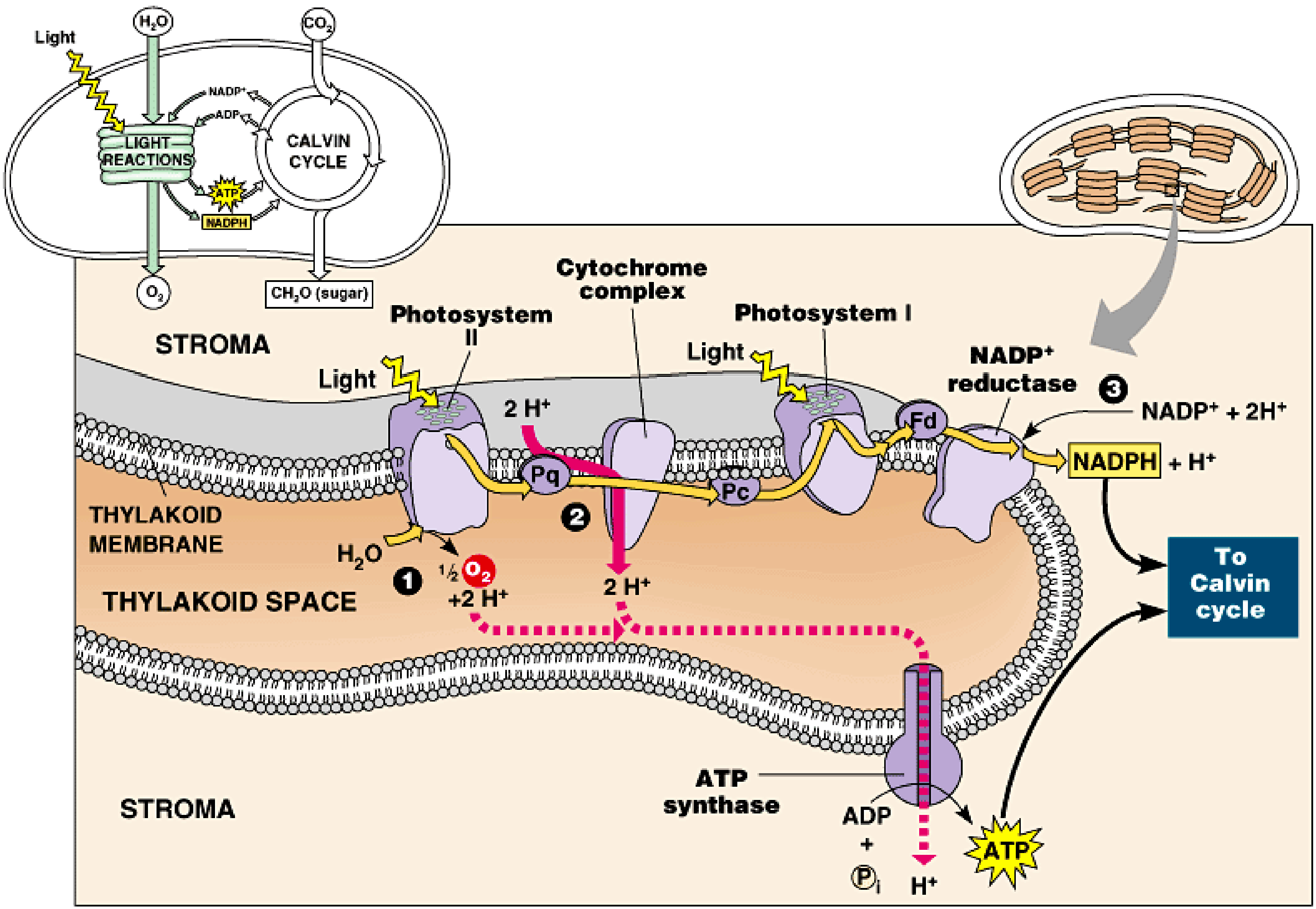
- Chemiosmosis is the source of ATP in photophosphorylation.
- Electron transport pumps protons from stroma into thylakoids, establishing a proton-motive force.
- Proton diffusion to stroma via ATP synthase channels drives ATP formation from ADP and P_i.


electron at high energy
H+ ions (protons)
e−
e−
electron at low energy
membrane
Pi + ADP
ATP
STAGE 1: ELECTRON TRANSPORT DRIVES PUMP THAT PUMPS PROTONS ACROSS MEMBRANE
(A)
STAGE 2: PROTON GRADIENT IS HARNESSED BY ATP SYNTHASE TO MAKE ATP
(B)

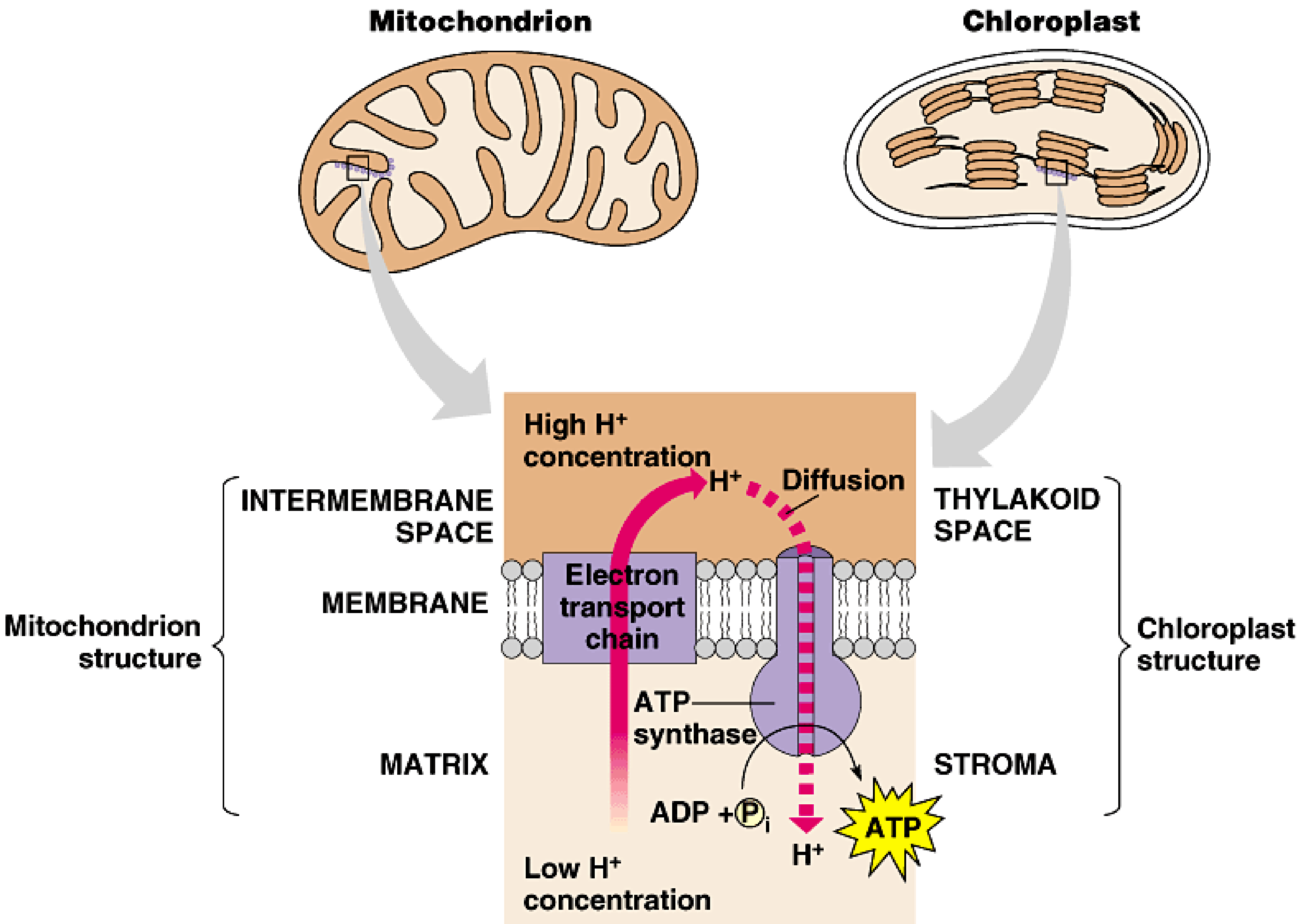
Chloroplast forms ATP Chemiosmotically



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



Comparison of chemiosmosis in mitochondria and chloroplasts

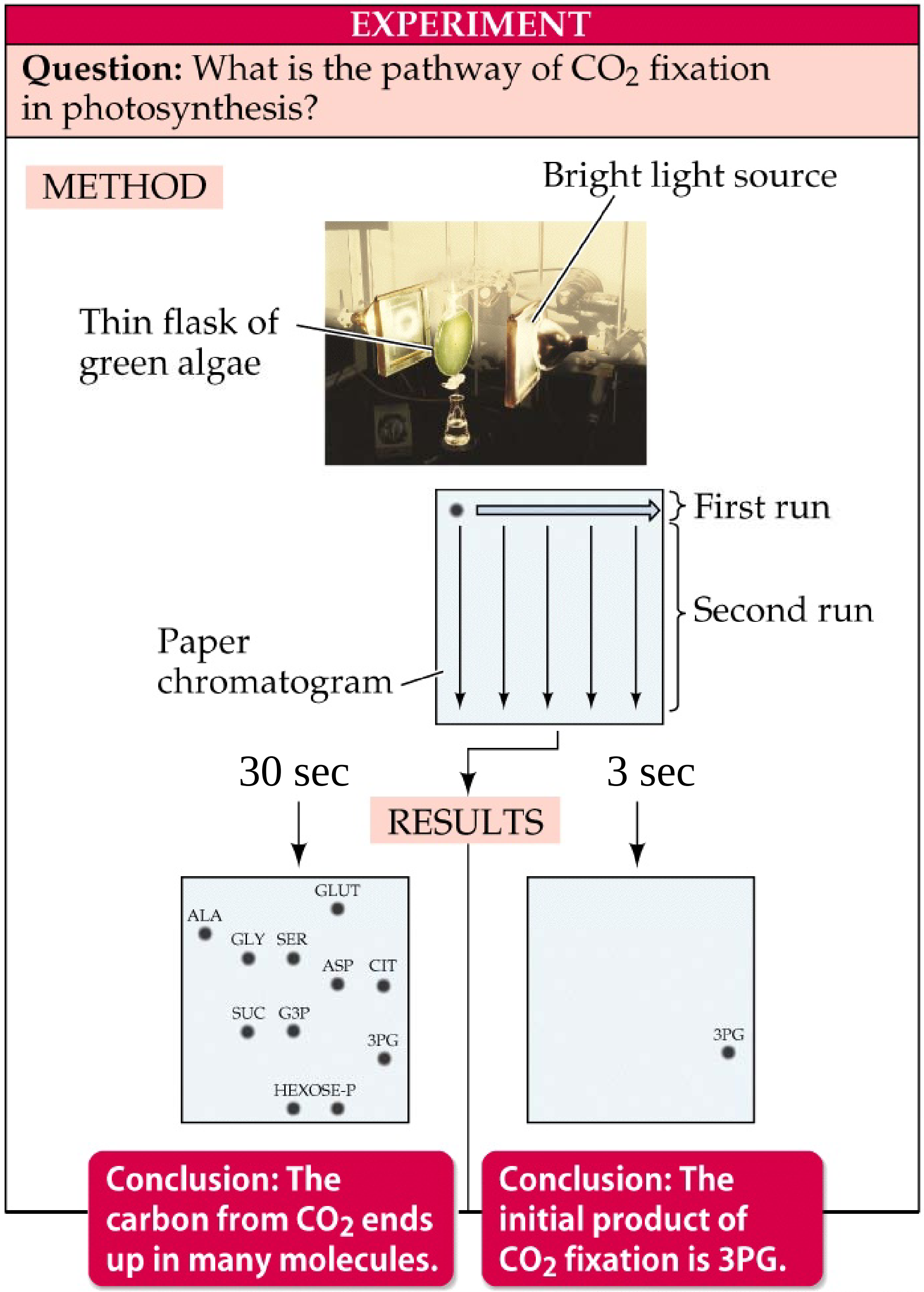


D. Electron Flow, Photophos-phorylation, and Reductions

- Photosynthesis probably originated in anaerobic bacteria that used H_2S as a source of electrons instead of H_2O.
- Oxygen production by bacteria was important in eukaryote evolution.

E. Making Sugar from CO_2: The Calvin-Benson Cycle

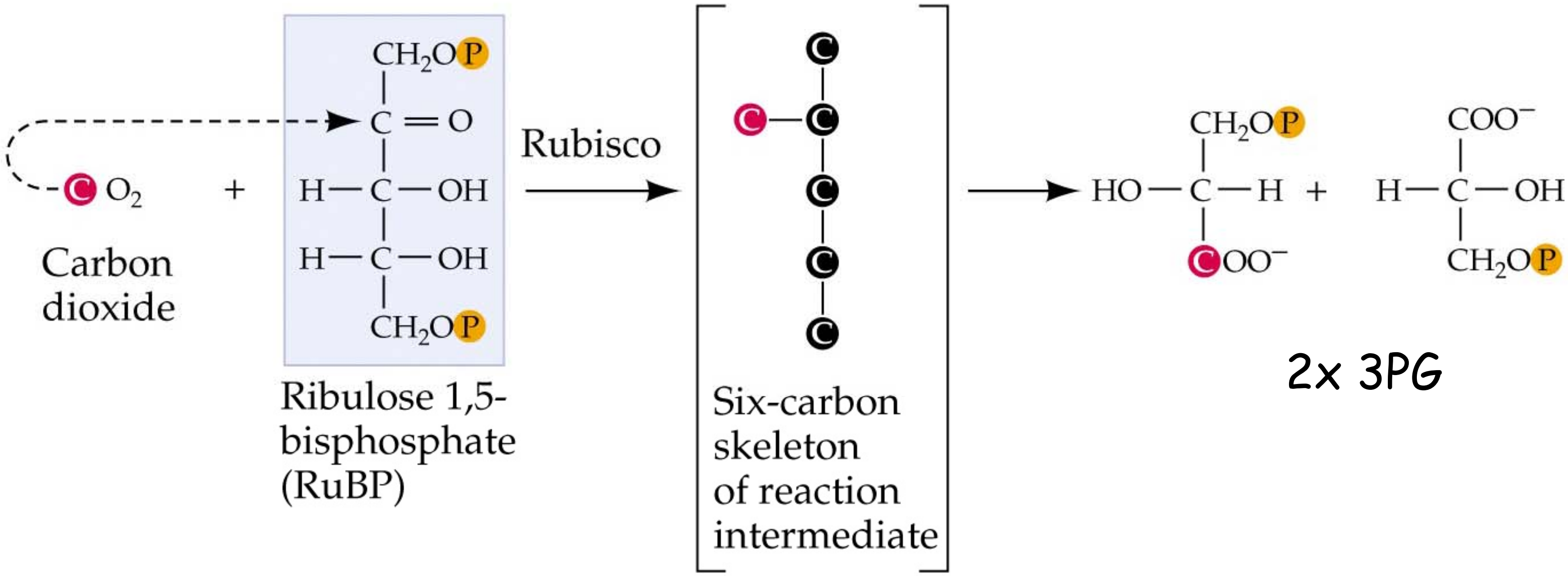
- The Calvin-Benson cycle makes sugar from CO_2. This pathway was elucidated through use of radioactive tracers.

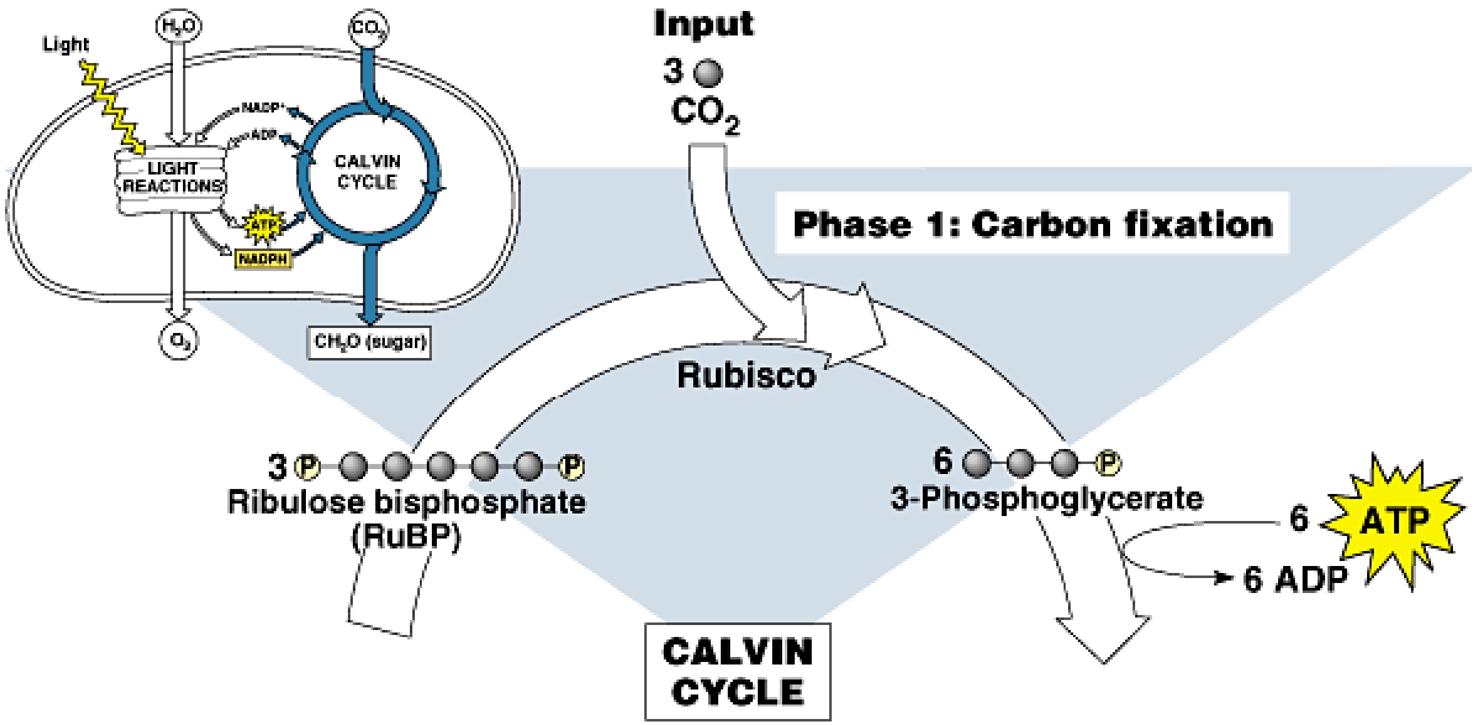

EXPERIMENT
Question: What is the pathway of CO2 fixation in photosynthesis?
METHOD
Bright light source
Thin flask of green algae
First run
Second run
Paper chromatogram
30 sec
3 sec
RESULTS
GLUT
ALA
GLY
SER
ASP
CIT
SUC
G3P
3PG
HEXOSE-P
3PG
Conclusion: The carbon from CO2 ends up in many molecules.
Conclusion: The initial product of CO2 fixation is 3PG.

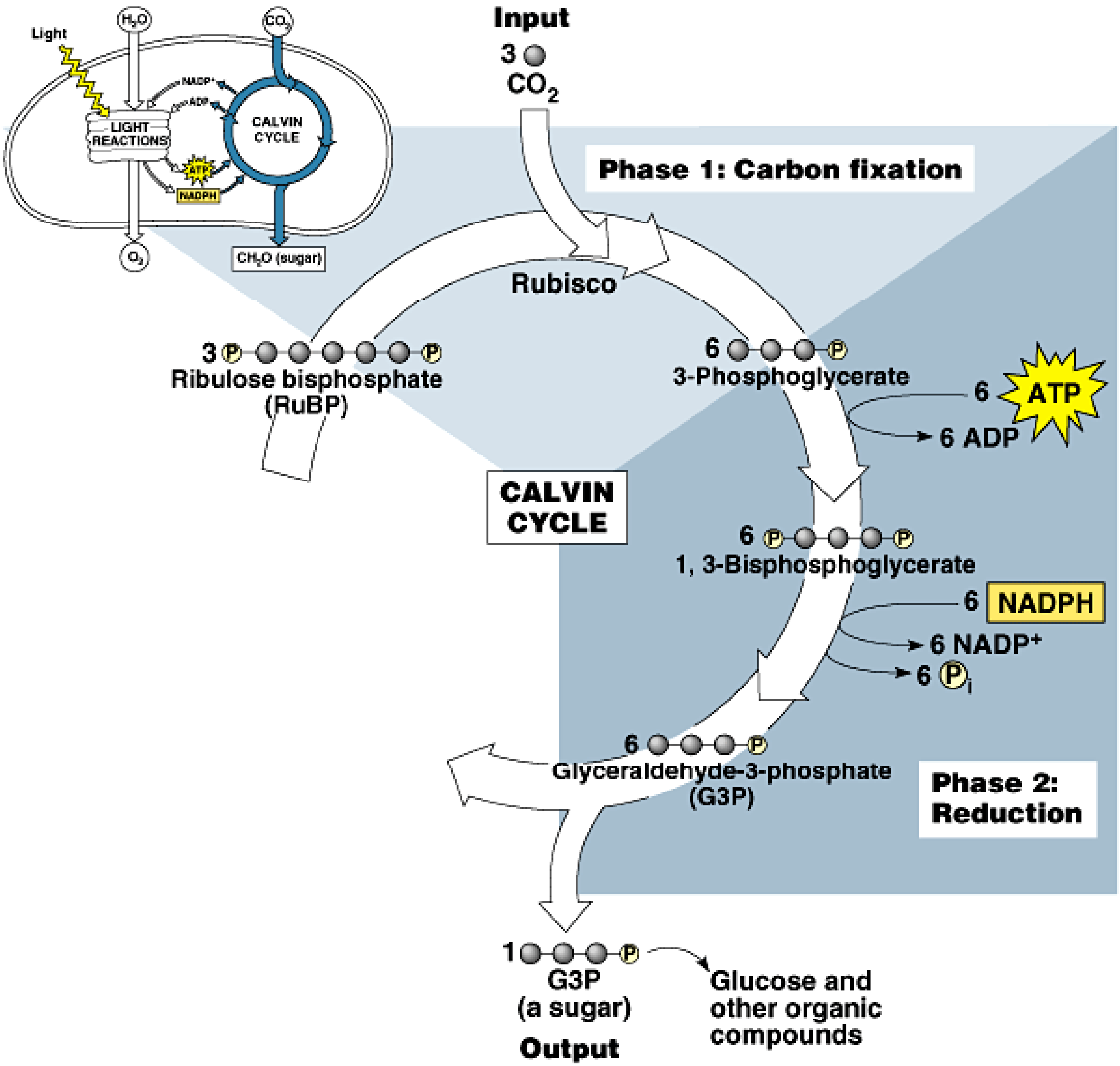
E. Making Sugar from CO_2: The Calvin-Benson Cycle

- The Calvin-Benson cycle has three phases:
- Fixation of CO_2
- Reduction (and carbohydrate production)
- Regeneration of RuBP.
- RuBP is the initial CO_2 acceptor, 3PG is the first stable product of CO_2 fixation. Rubisco catalyzes the reaction of CO_2 and RuBP to form 3PG.

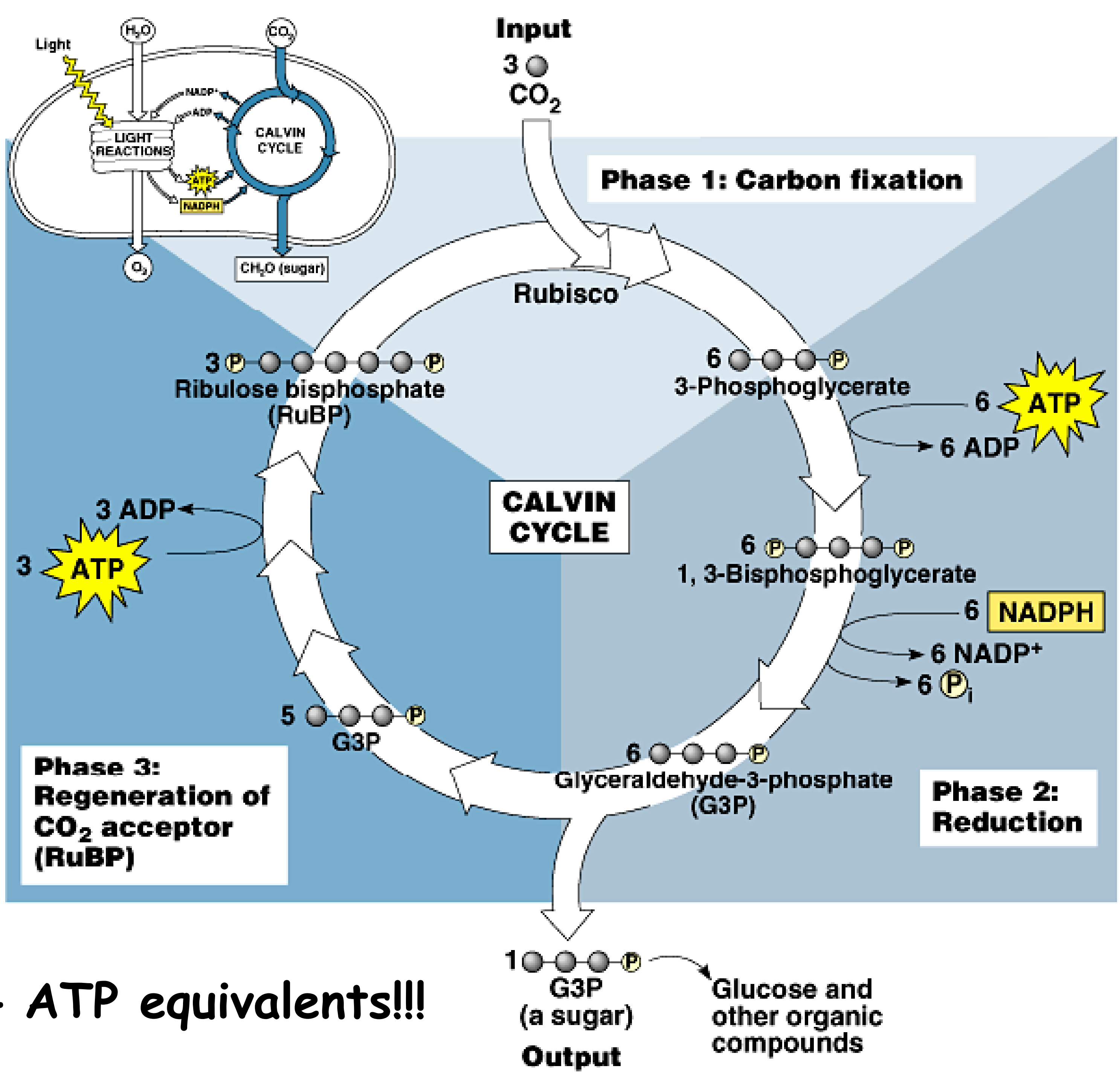
RuBP is the CO_2 Acceptor




Light
H_2O
CO_2
$NADP^+$
ADP
LIGHT REACTIONS
CALVIN CYCLE
ATP
NADPH
O_2
CH_2O (sugar)
Input
3
CO_2
Phase 1: Carbon fixation
Rubisco
3 P P
Ribulose bisphosphate (RuBP)
6 P
3-Phosphoglycerate
6 ATP
6 ADP
CALVIN CYCLE

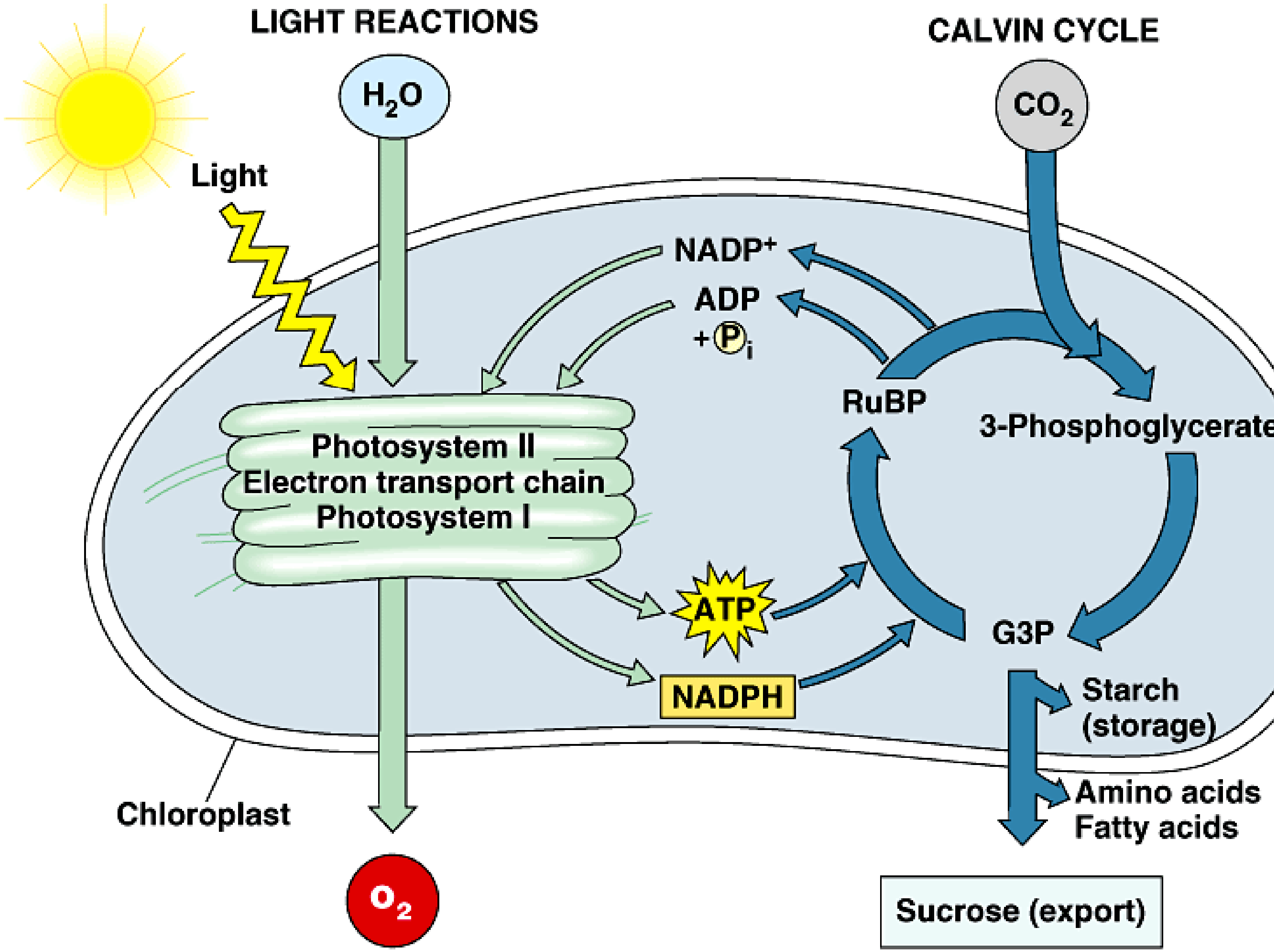


Light
H_2O
CO_2
$NADP^+$
ADP
LIGHT REACTIONS
CALVIN CYCLE
ATP
NADPH
O_2
CH_2O (sugar)
Input
3
CO_2
Phase 1: Carbon fixation
Rubisco
3 P P
Ribulose bisphosphate (RuBP)
6 P
3-Phosphoglycerate
6 ATP
6 ADP
CALVIN CYCLE
6 P P
1, 3-Bisphosphoglycerate
6 NADPH
6 $NADP^+$
6 P_i
6 P
Glyceraldehyde-3-phosphate (G3P)
Phase 2: Reduction
1 P
G3P (a sugar)
Output
Glucose and other organic compounds



54 ATP equivalents!!!

A review of photosynthesis

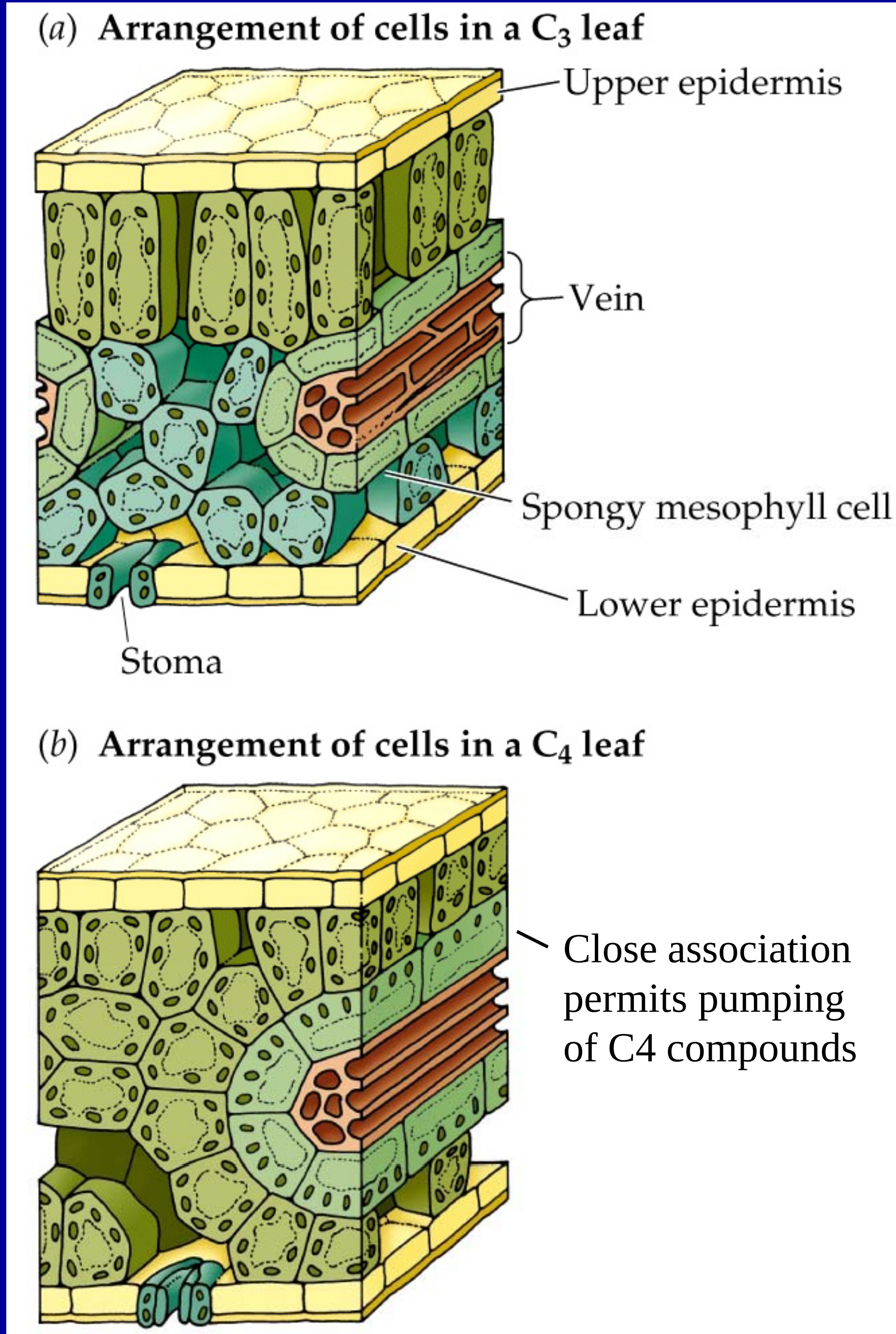


F. Photorespiration and Its Consequences

- 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.

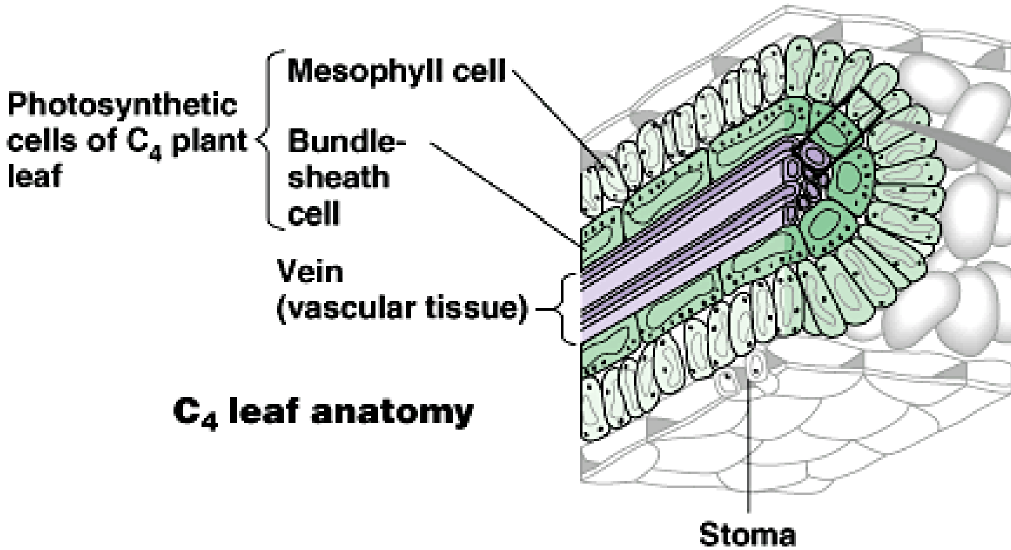
F. Photorespiration and Its Consequences

- 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.

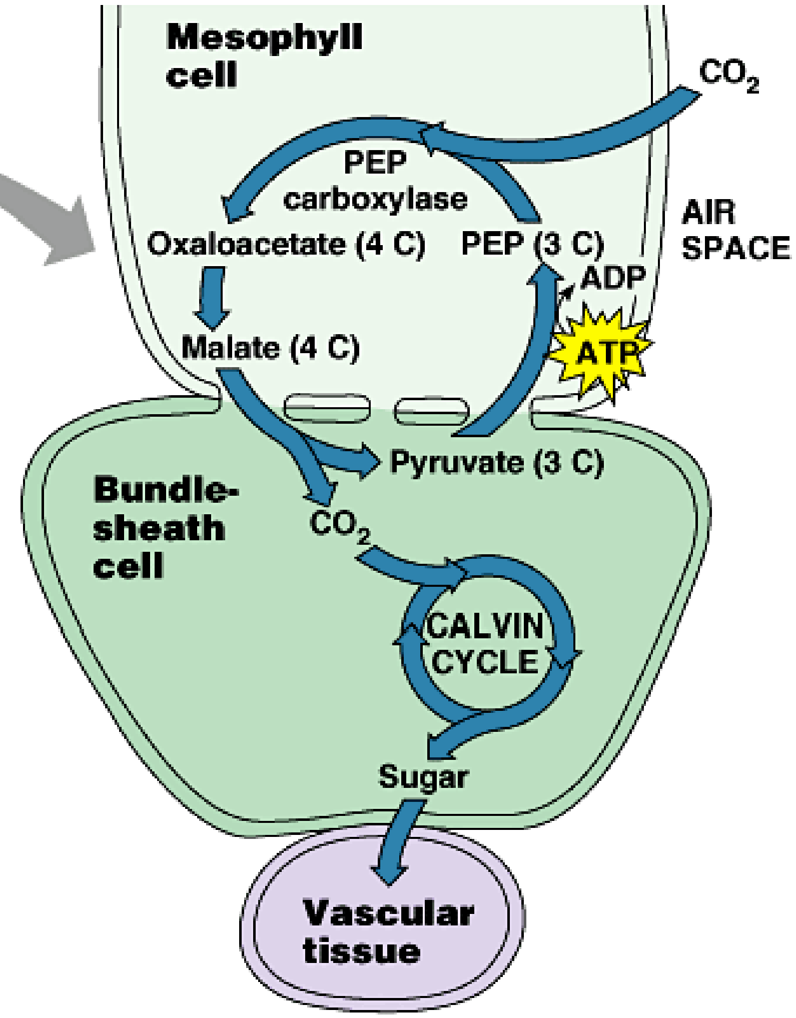


Close association permits pumping of C4 compounds

C_4 leaf anatomy and the C_4 pathway



C4 leaf anatomy

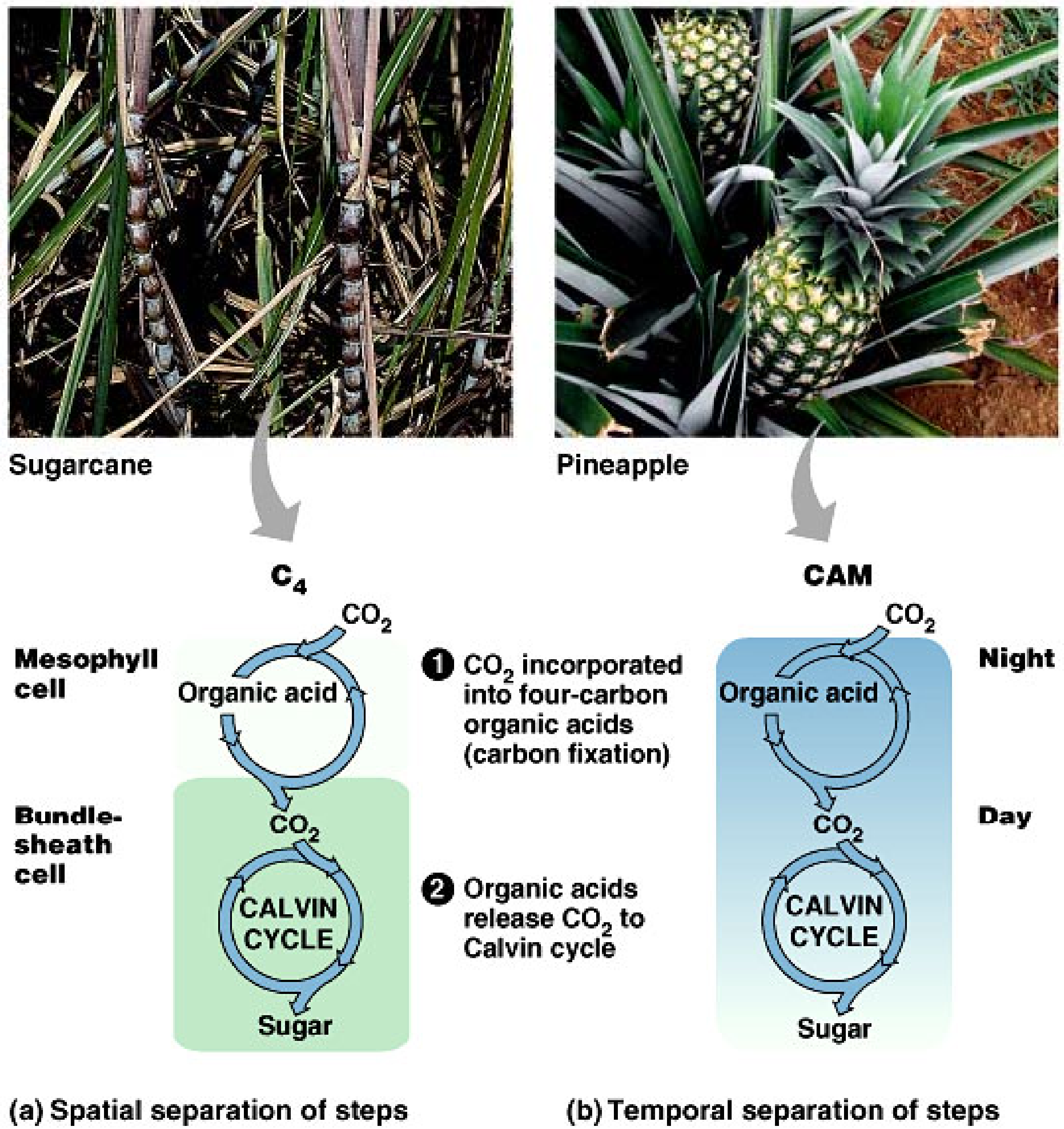


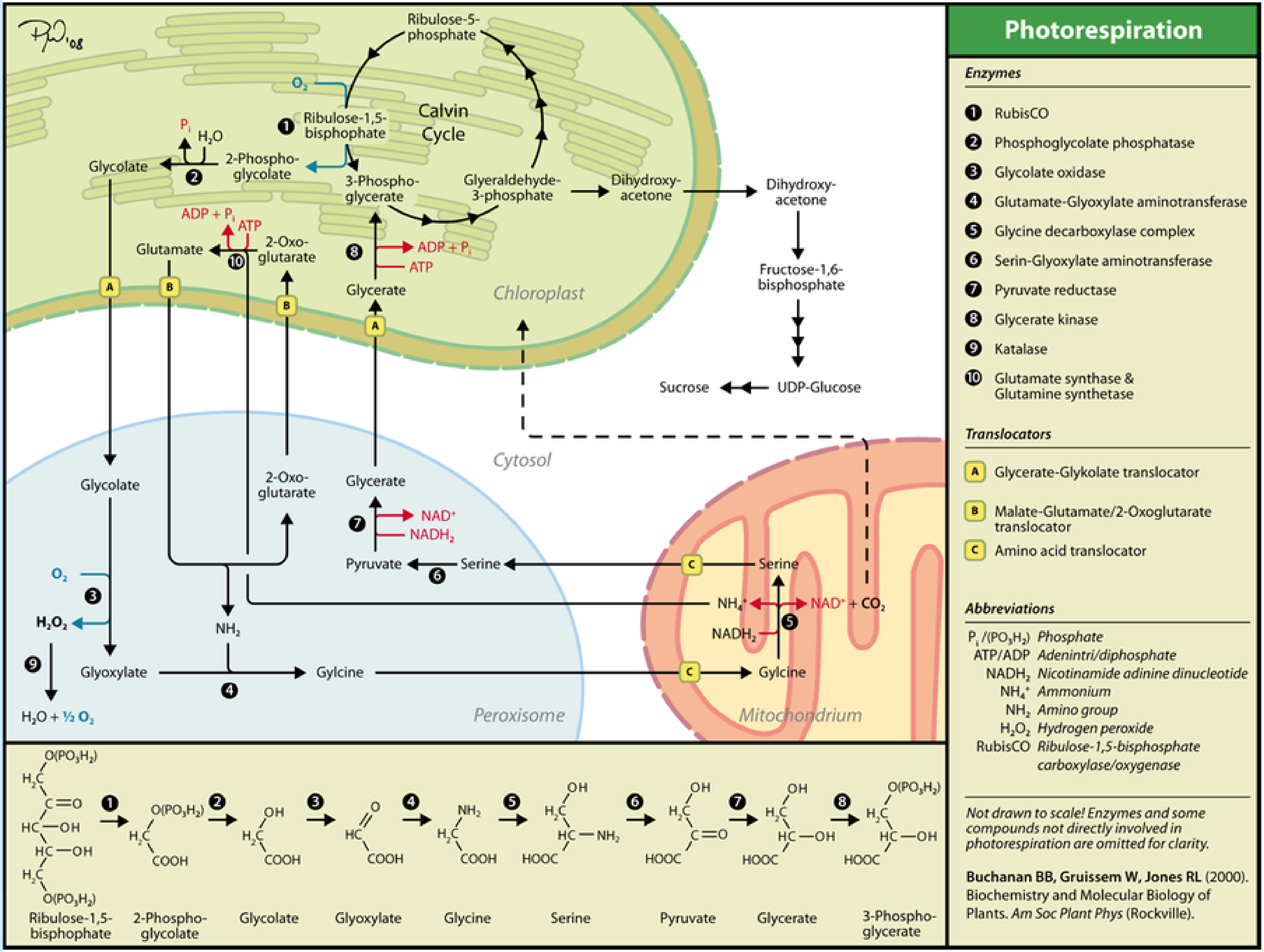
The C4 pathway

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_4 and CAM photosynthesis compared





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-Glykolate translocator
B Malate-Glutamate/2-Oxoglutarate translocator
C Amino acid translocator
Abbreviations
P_i /(PO_3H_2) Phosphate
ATP/ADP Adenintri/diphosphate
NADH_2 Nicotinamide adinine dinucleotide
NH_4^+ Ammonium
NH_2 Amino group
H_2O_2 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, Gruissem W, Jones RL (2000). Biochemistry and Molecular Biology of Plants. Am Soc Plant Phys (Rockville).
Ribulose-5-phosphate
Calvin Cycle
O2
Ribulose-1,5-bisphosphate
2-Phospho-glycolate
3-Phospho-glycerate
Glyeraldehyde-3-phosphate
Dihydroxy-acetone
Glycolate
Pi
H2O
ADP + Pi
ATP
Glutamate
2-Oxo-glutarate
Glycerate
Chloroplast
Fructose-1,6-bisphosphate
Sucrose
UDP-Glucose
Cytosol
Glycolate
2-Oxo-glutarate
Glycerate
NAD+
NADH2
Pyruvate
Serine
O2
H2O2
NH2
Glyoxylate
Gylcine
H2O + ½ O2
Peroxisome
Serine
NH4+
NAD+ + CO2
NADH2
Gylcine
Mitochondrium
Ribulose-1,5-bisphophate
2-Phospho-glycolate
Glycolate
Glyoxylate
Glycine
Serine
Pyruvate
Glycerate
3-Phospho-glycerate