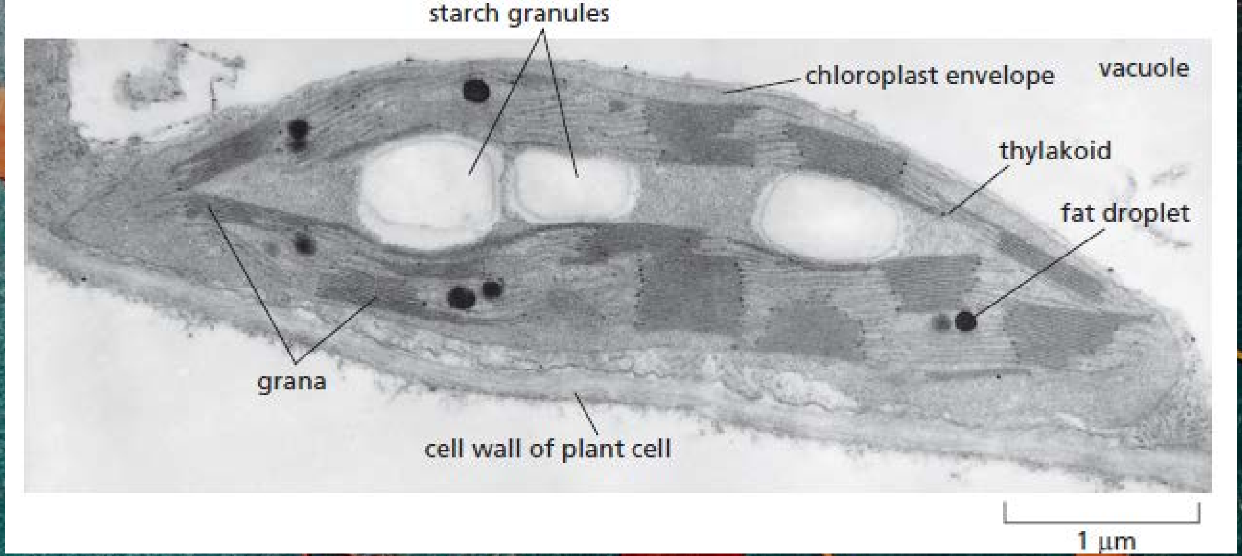
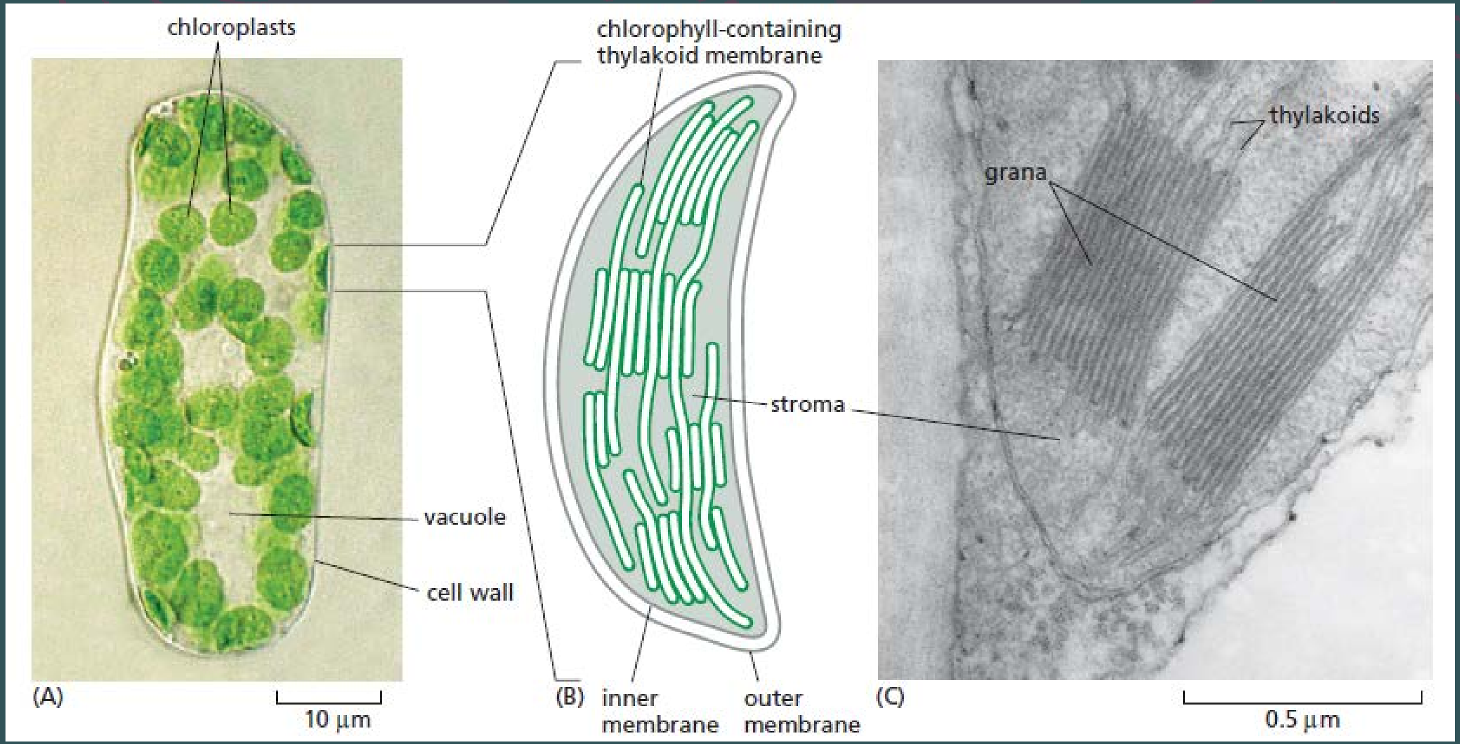
CHLOROPLAST
&
PHOTOSYNTHESIS

Virtually all the organic material in present-day cells is produced by photosynthesis—the series of light-driven reactions that creates organic molecules from atmospheric carbon dioxide (CO_2). Plants, algae, and photosynthetic bacteria such as cyanobacteria use electrons from water and the energy of sunlight to convert atmospheric CO_2 into organic compounds. In the course of these reactions, water molecules are split, releasing vast quantities of O_2 gas into the atmosphere. This oxygen in turn supports oxidative phosphorylation—not only in animals but also in plants and aerobic bacteria.



- **In plants, photosynthesis is carried out in a specialized intracellular organelle—the chloroplast, which contains light-capturing pigments such as the green pigment *chlorophyll*.**
- **For most plants, the leaves are the major sites of photosynthesis.**
- **Photosynthesis occurs only during the daylight hours, producing ATP and NADPH. These activated carriers can then be used, at any time of day, to convert CO_2 into sugar inside the chloroplast—a process called *carbon fixation*.**

CHLOROPLAST STRUCTURE



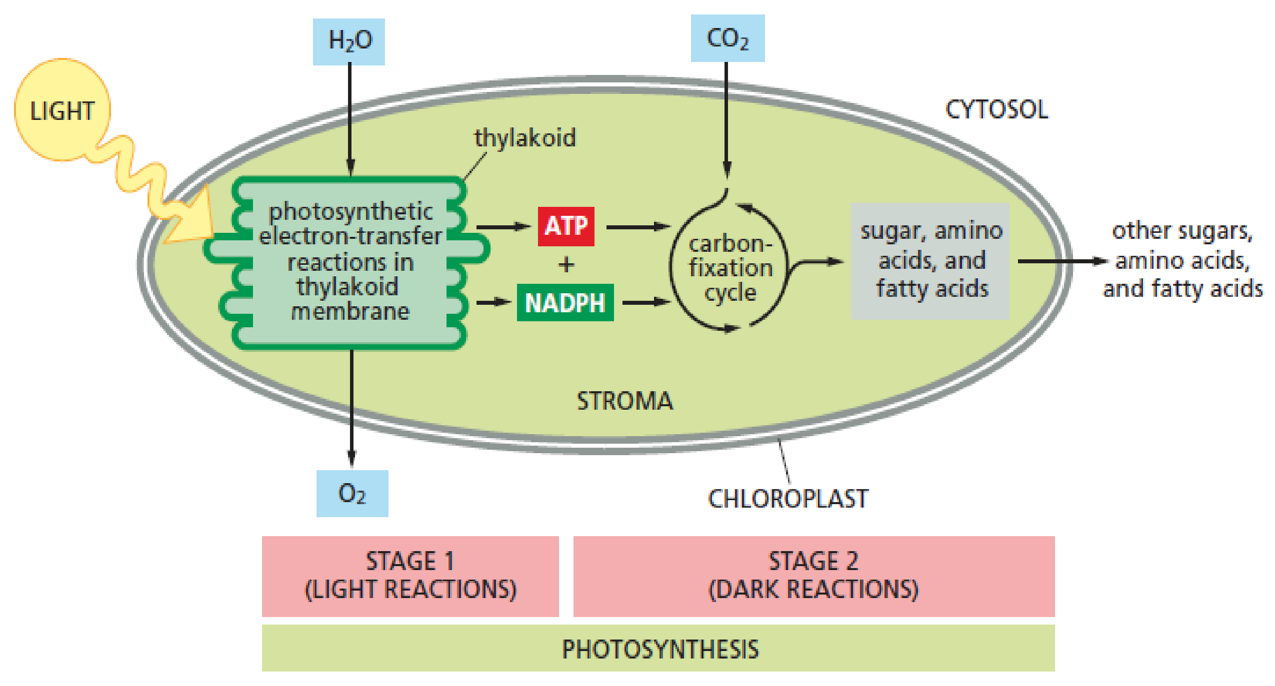
- (A) Light micrograph shows chloroplasts (*green*) in the cell of a flowering plant.
- (B) Drawing of a single chloroplast shows the organelle's three sets of membranes, including the thylakoid membrane, which contains the light-capturing and ATP -generating systems.
- (C) A high magnification view of an electron micrograph shows the thylakoids arranged in stacks called *grana*; a single thylakoid stack is called a *granum*.

(A, courtesy of Preeti Dahiya; C, courtesy of K. Plaskitt.)

- Chloroplasts have a highly permeable **outer membrane** and a much less permeable **inner membrane**, in which various membrane transport proteins are embedded.
- Together, these two membranes—and the narrow, intermembrane space that separates them—form the **chloroplast envelope**.
- The inner membrane surrounds a large space called the **stroma**, which is analogous to the mitochondrial matrix and contains many metabolic enzymes.

- There is, however, one important difference between the organization of mitochondria and that of chloroplasts. The inner membrane of the chloroplast does not contain the photosynthetic machinery. Instead, the light-capturing systems, electron-transport chain, and ATP synthase that produce ATP during photosynthesis are all contained in the **thylakoid membrane**.
- This third membrane is folded to form a set of flattened, disc like sacs, called the **thylakoids**, which are arranged in stacks called **grana**.
- The space inside each thylakoid is thought to be connected with that of other thylakoids, creating a third internal compartment, the **thylakoid space**, which is separate from the stroma.

Stages of photosynthesis

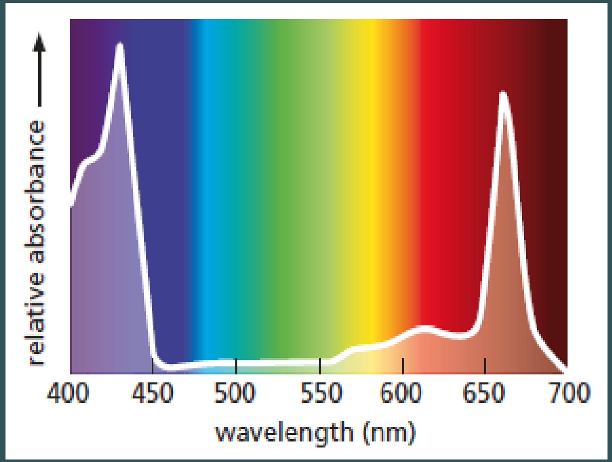


- ❑ **Both stages of photosynthesis depend on the chloroplast.**
- ❑ In stage 1, a series of photosynthetic electron transfer reactions produce ATP and NADPH; in the process, electrons are extracted from water and oxygen is released as a by-product.
- ❑ In stage 2, carbon dioxide is assimilated (fixed) to produce sugars and a variety of other organic molecules.
- ❑ Stage 1 occurs in the thylakoid membrane, whereas stage 2 begins in the chloroplast stroma and continues in the cytosol.

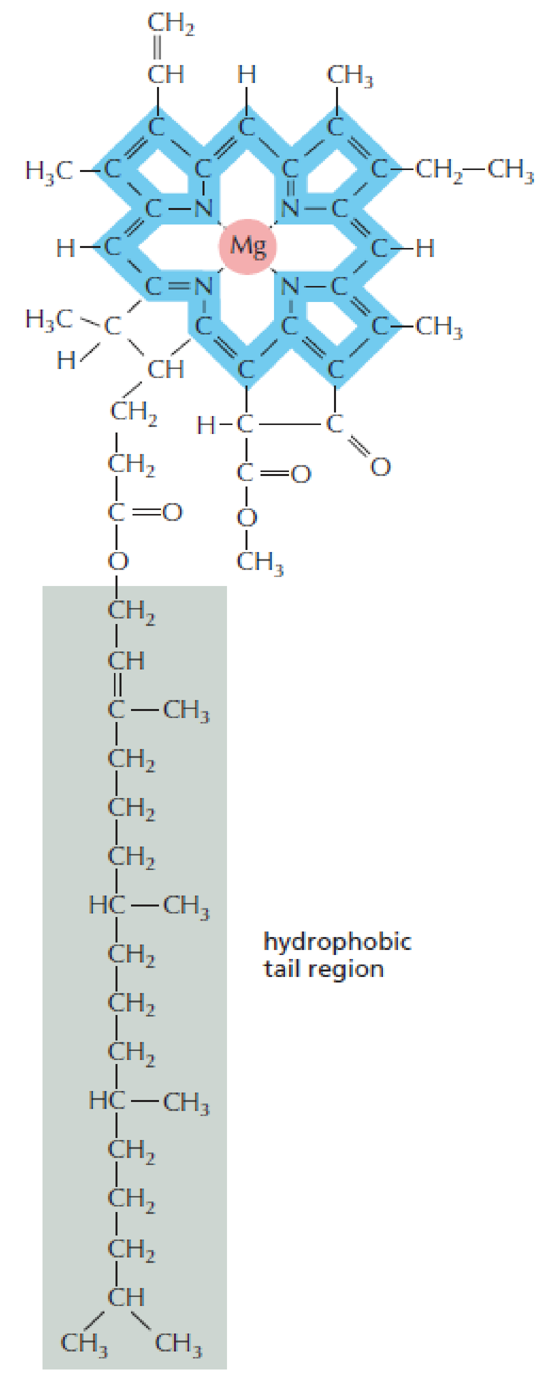
Chlorophyll- structure and light absorption

- Chlorophyll's ability to harness energy derived from sunlight stems from its unique structure. The electrons in a chlorophyll molecule are distributed in a decentralized cloud around the molecule's light-absorbing porphyrin ring. When light of an appropriate wavelength hits a molecule of chlorophyll, it excites electrons in this diffuse network, perturbing the way the electrons are distributed. This perturbed high-energy state is unstable, and an excited chlorophyll molecule will seek to get rid of this excess energy so it can return to its more stable, unexcited state.

- ❑ Each chlorophyll molecule contains a porphyrin ring with a magnesium atom (*pink*) at its center. This porphyrin ring is structurally similar to the one that binds iron in heme. Light is absorbed by electrons within the bond network shown in *blue*, while the long, hydrophobic tail (*gray*) helps hold the chlorophyll in the thylakoid membrane.

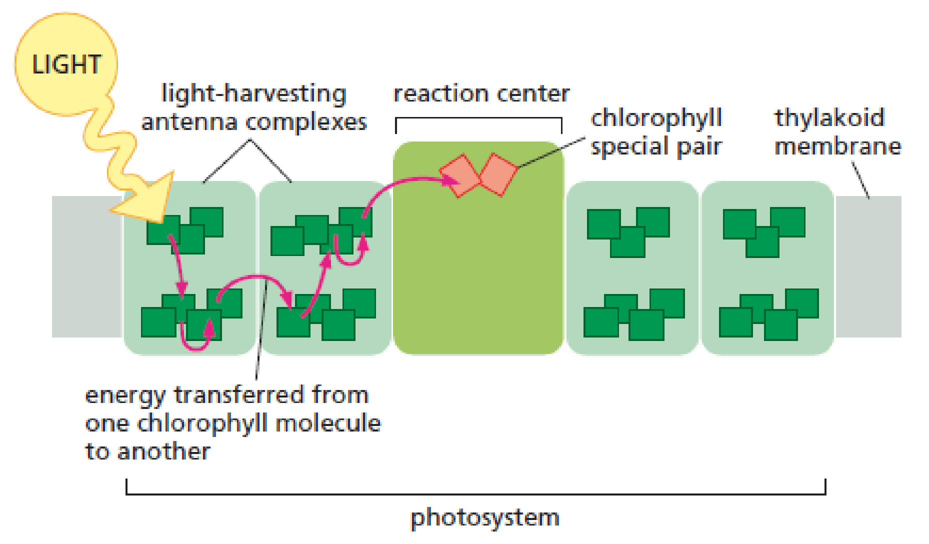


- ❑ Chlorophylls absorb light of blue and red wavelengths. As shown in this absorption spectrum, one form of chlorophyll preferentially absorbs light around wavelengths of 430 nm (*blue*) and 660 nm (*red*). Green light, in contrast, is absorbed poorly by this pigment. Other chlorophylls can absorb light of slightly different wavelengths.

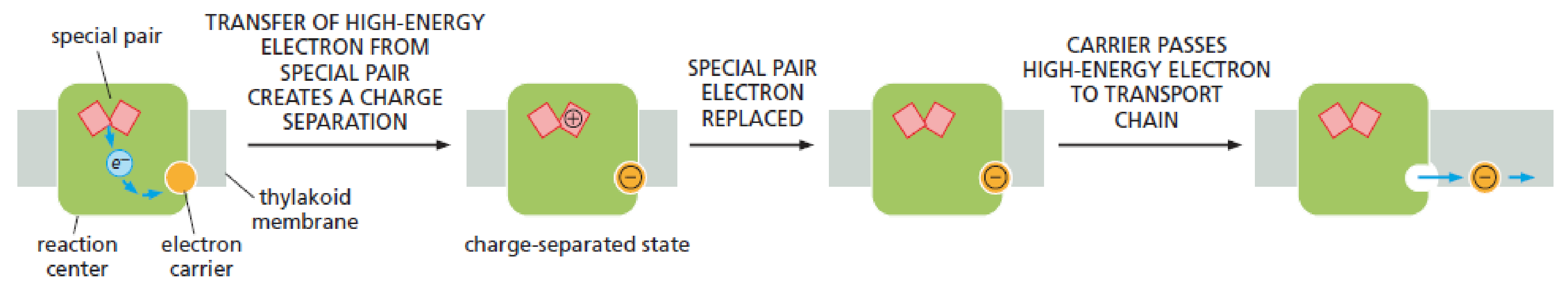


Photosystems & Reaction Center

- A photosystem consists of a reaction center surrounded by chlorophyll-containing **antenna complexes**.
- Once light energy has been captured by a chlorophyll molecule in an antenna complex, it will pass randomly from one chlorophyll molecule to another (*red lines*), until it gets trapped by a chlorophyll dimer called the **special pair**, located in the **reaction center**.
- The chlorophyll special pair holds its electrons at a lower energy than the antenna chlorophylls, so the energy transferred to it from the antenna gets trapped there. Note that in the antenna complex only energy moves from one chlorophyll molecule to another, not electrons.

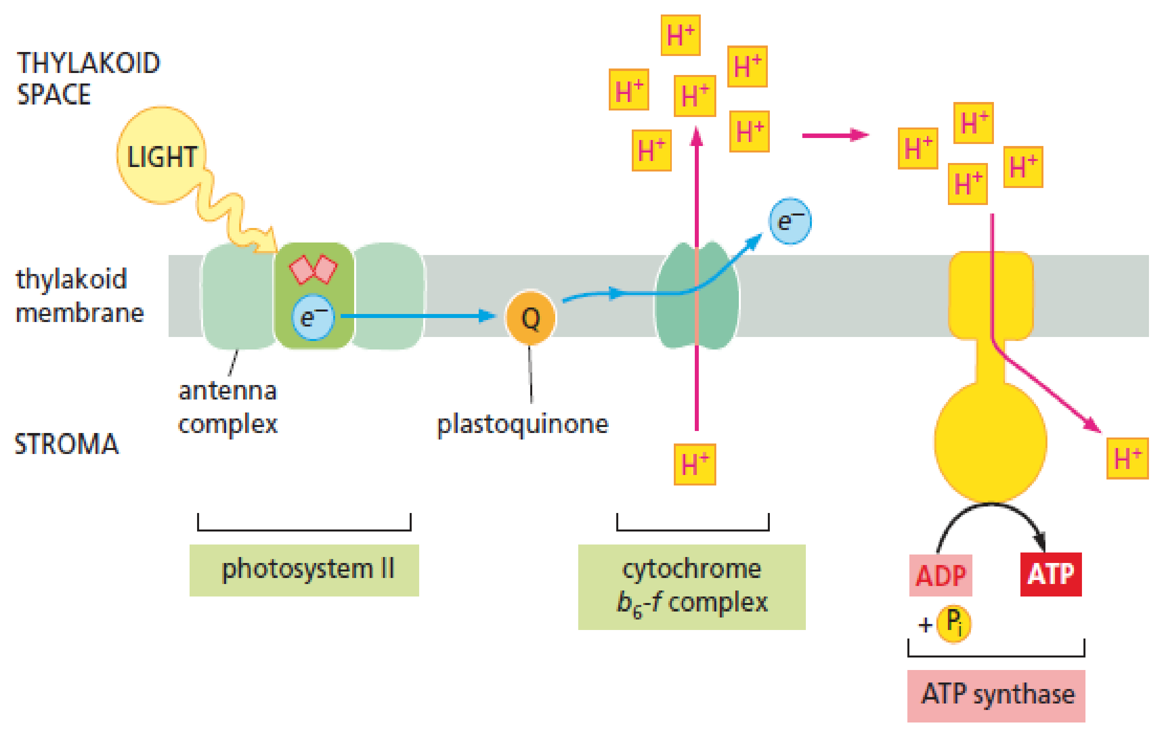


- In a reaction center, a high energy electron is transferred from the special pair to a carrier that becomes part of an electron-transport chain. Not shown is a set of intermediary carriers embedded in the reaction center that provide the path from the special pair to this carrier (*orange*). The transfer of the high energy electron from the excited chlorophyll special pair leaves behind a positive charge that creates a charge-separated state, thereby converting light energy to chemical energy. Once the electron in the special pair has been replaced, the carrier diffuses away from the reaction center, transferring the high-energy electron to the transport chain.

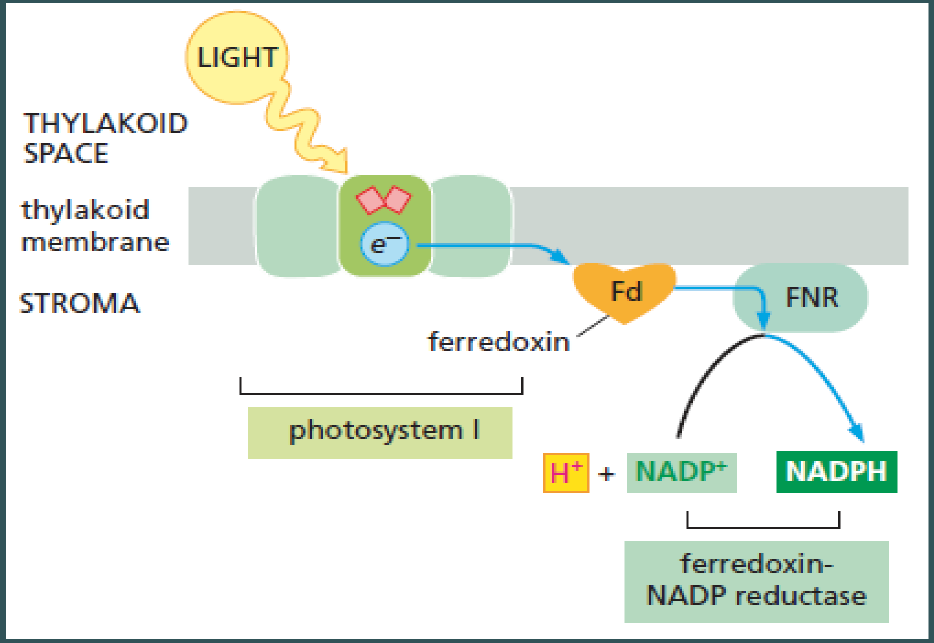


Photosystem II & I

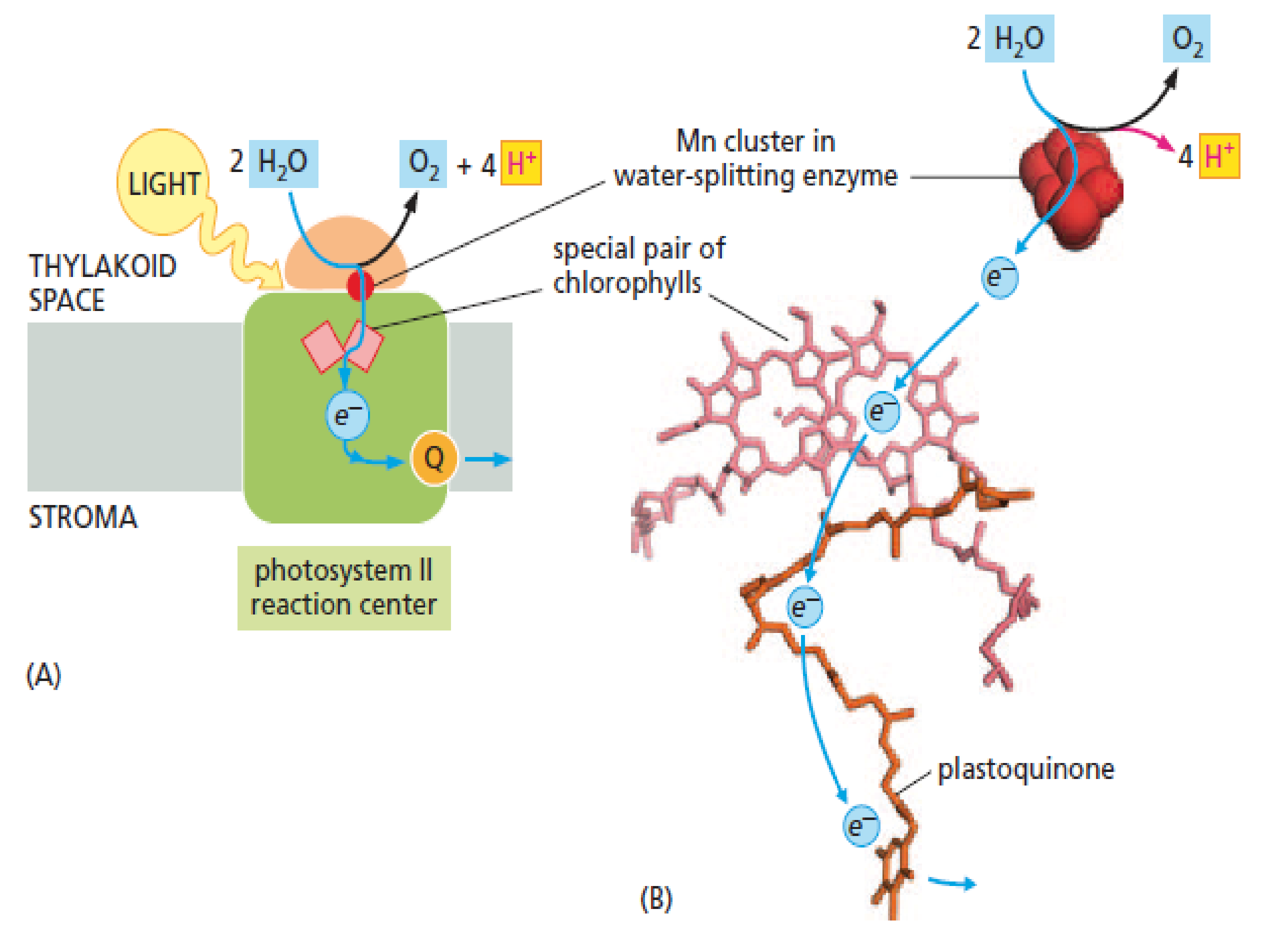
- Photosystem II feeds electrons to a photosynthetic proton pump, leading to ATP synthesis by ATP synthase. When light energy is captured by photosystem II, a high-energy electron is transferred to a mobile electron carrier called plastoquinone (Q), which closely resembles the ubiquinone of mitochondria. This carrier transfers its electrons to a proton pump called the cytochrome *b6-f* complex, which resembles the cytochrome *c* reductase complex of mitochondria and is the sole site of active proton pumping in the chloroplast electron-transport chain. As in mitochondria, an ATP synthase embedded in the membrane then uses the energy of the electrochemical proton gradient to produce ATP .



- Photosystem I transfers high-energy electrons to an enzyme that produces NADPH. When light energy is captured by photosystem I, a high energy electron is passed to a mobile electron carrier called ferredoxin (Fd), a small protein that contains an iron–sulfur center. Ferredoxin carries its electrons to ferredoxin-NADP reductase (FNR), the final protein in the electron-transport chain that generates NADPH.

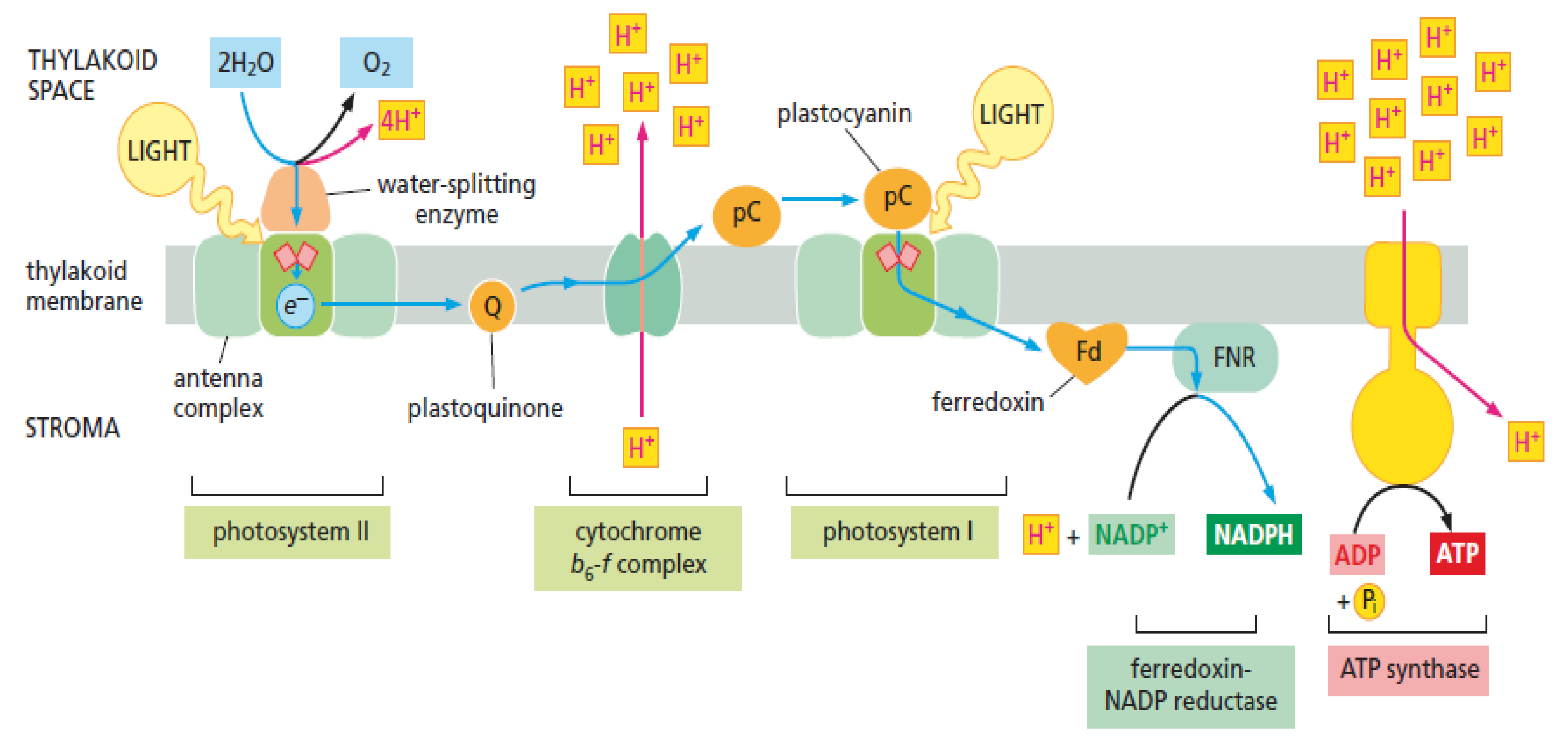


The Reaction Center



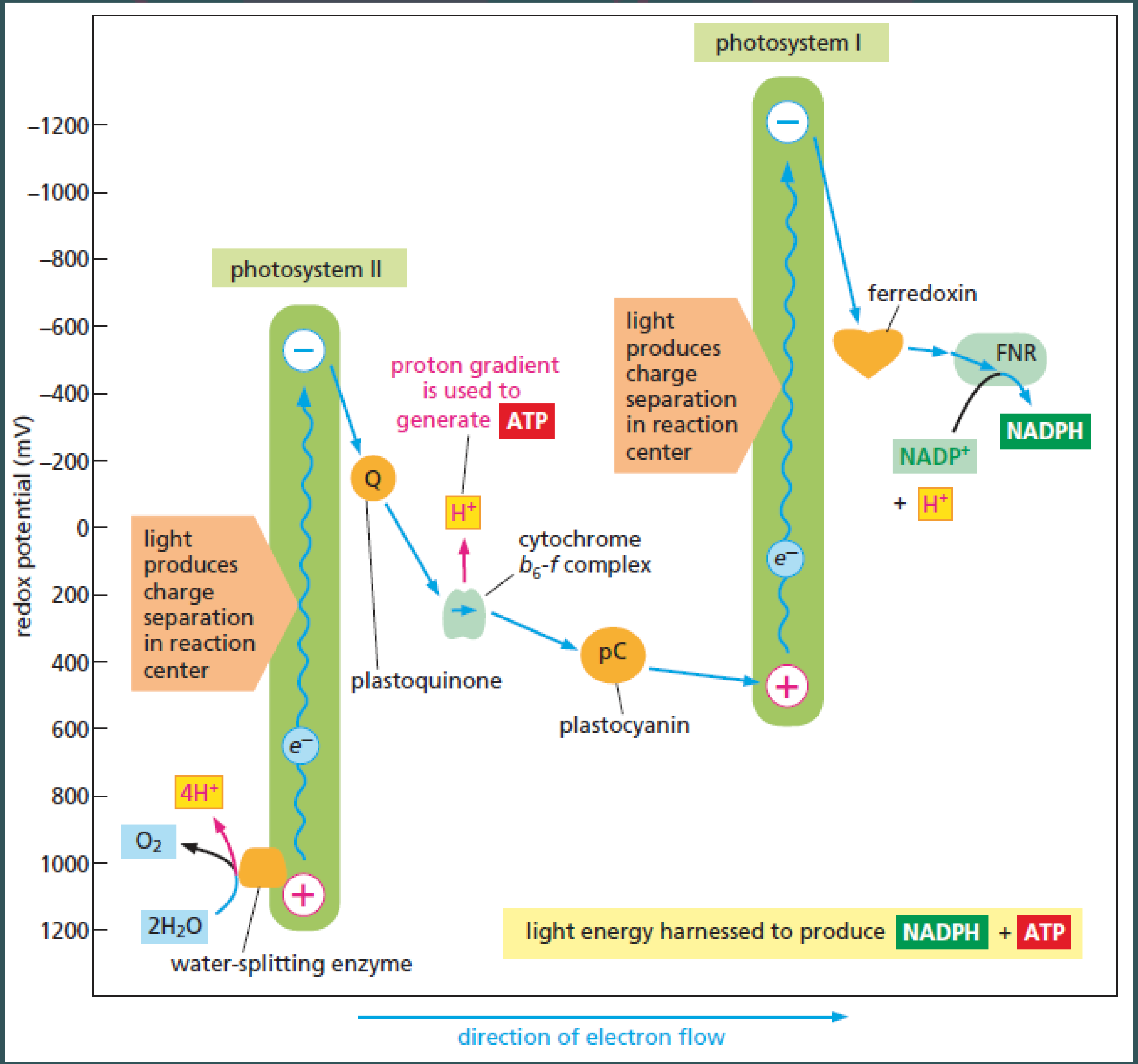
- **The reaction center of photosystem II includes an enzyme that catalyzes the extraction of electrons from water**
- (A) Schematic diagram shows the flow of electrons through the reaction center of photosystem II. When light energy excites the chlorophyll special pair, an electron is passed to the mobile electron carrier plastoquinone (Q). An electron is then returned to the special pair by a water splitting enzyme that extracts electrons from water. The Mn cluster that participates in the electron extraction is shown as a *red spot*. Once four electrons have been withdrawn from two water molecules, O_2 is released into the atmosphere.
- (B) The structure and position of some of the electron carriers involved.

Photosynthetic electron transport



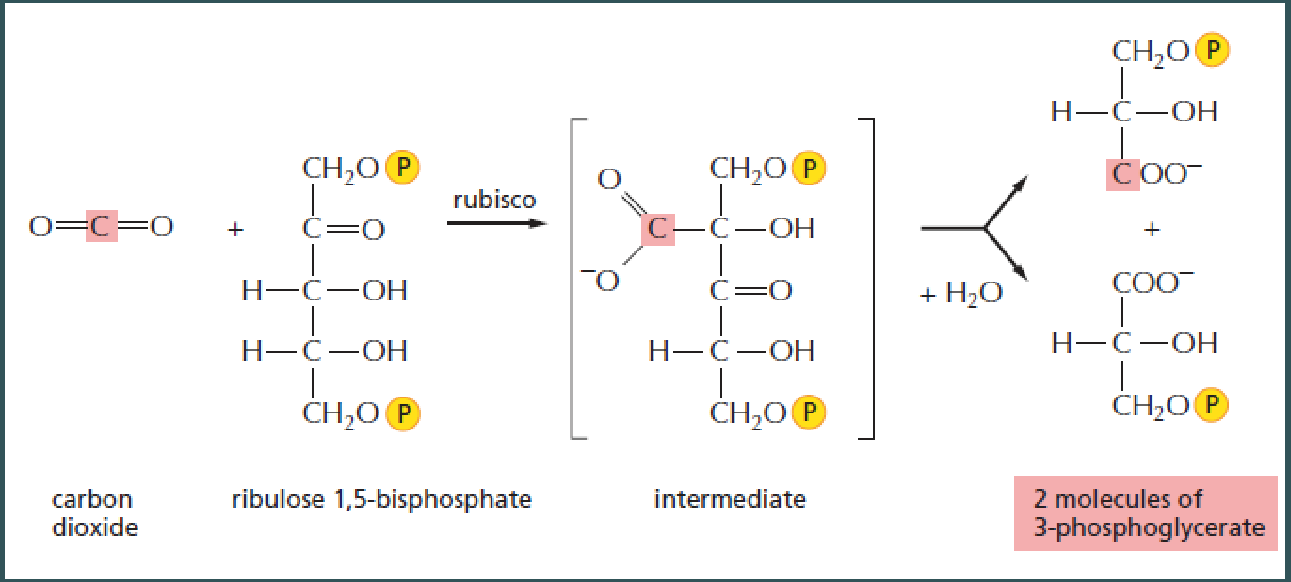
- The movement of electrons along the photosynthetic electron transport chain powers the production of both ATP and NADPH. Electrons are supplied to photosystem II by a water splitting complex that extracts four electrons from two molecules of water, producing O_2 as a by-product. After their energy is raised by the absorption of light, these electrons power the pumping of protons by the cytochrome *b6-f* complex. Electrons that pass through this complex are then donated to a copper-containing protein, the mobile electron carrier plastocyanin (pC), which ferries them to the reaction center of photosystem I. After an additional energy boost from light, these electrons are used to generate NADPH.

The Z scheme of photosynthetic light reaction



- ❑ The combined actions of photosystems I and II boost electrons to the energy level needed to produce both ATP and NADPH. The redox potential for each molecule is indicated by its position on the vertical axis. Electron transfers are shown with non-wavy *blue arrows*.
- ❑ Photosystem II passes electrons from its excited chlorophyll special pair to an electron-transport chain in the thylakoid membrane that leads to photosystem I. The net electron flow through the two photosystems linked in series is from water to NADP+, to form NADPH.

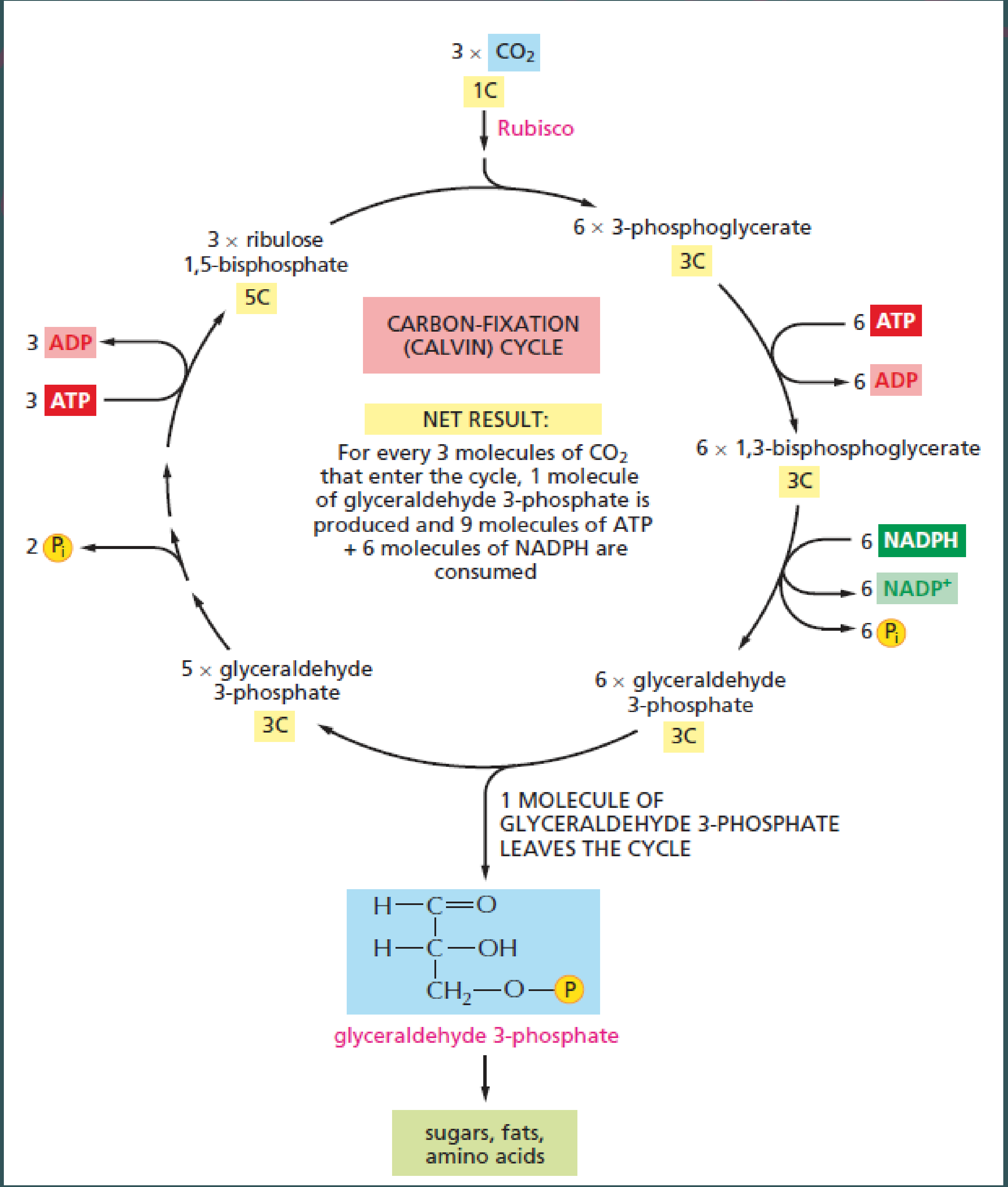
Photosynthetic Carbon Fixation



Carbon fixation involves the formation of a covalent bond that attaches carbon dioxide to ribulose 1,5-bisphosphate. The reaction is catalyzed in the chloroplast stroma by the abundant enzyme ribulose bisphosphate carboxylase, or Rubisco. The product is two molecules of 3-phosphoglycerate.

The Calvin Cycle/Carbon-fixation Cycle

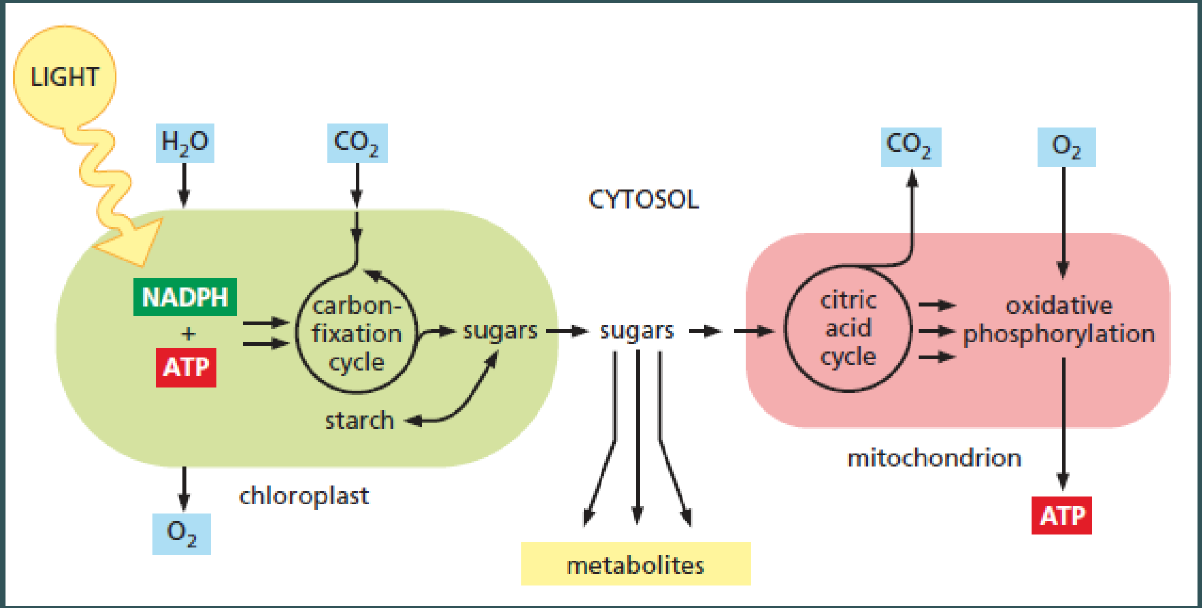
- **The carbon-fixation cycle consumes ATP and NADPH to form glyceraldehyde 3-phosphate from CO_2 and H_2O.**
- In the first stage of the cycle, CO_2 is added to ribulose 1,5-bisphosphate.
- In the second stage, ATP and NADPH are consumed to produce glyceraldehyde 3-phosphate.
- In the final stage, some of the glyceraldehyde 3-phosphate produced is used to regenerate ribulose 1,5-bisphosphate; the rest is transported out of the chloroplast stroma into the cytosol. The number of carbon atoms in each type of molecule is indicated in *yellow*. There are many intermediates between glyceraldehyde 3-phosphate and ribulose 5-phosphate, but they have been omitted here for clarity. The entry of water into the cycle is also not shown.



NET RESULT:

For every 3 molecules of CO_2 that enter the cycle, 1 molecule of glyceraldehyde 3-phosphate is produced and 9 molecules of ATP + 6 molecules of NADPH are consumed

Chloroplasts and Mitochondria collaborate



☐ **In plants, the chloroplasts and mitochondria collaborate to supply cells with metabolites and ATP.**

- The chloroplast's inner membrane is impermeable to the ATP and NADPH that are produced in the stroma during the light reactions of photosynthesis.
- These molecules are therefore funneled into the carbon-fixation cycle, where they are used to make sugars.
- The resulting sugars and their metabolites are either stored within the chloroplast–in the form of starch or fat–or exported to the rest of the plant cell.
- There, they can enter the energy-generating pathway that ends in ATP synthesis in the mitochondria.
- Mitochondrial membranes are permeable to ATP. The O_2 released to the atmosphere by photosynthesis in chloroplasts is used for oxidative phosphorylation in mitochondria.
- Similarly, the CO_2 released by the citric acid cycle in mitochondria is used for carbon fixation in chloroplasts.