PHOTOSYNTHESIS

PREFACE

- The sun is the ultimate source of energy.
- The sun powers nearly all life forms.
- Photosynthesis converts solar energy into chemical energy.
- Photoautotrophs use solar energy to synthesize organic compounds from carbon dioxide and water.
  - They include plants, algae and some prokaryotes
  - They form the base of almost every food chain/web
- Fossil fuels represent stored solar energy from the past.

RECALL

- Phototrophs: obtain energy from light
- Chemotrophs: obtain energy from chemicals
- Autotrophs: obtain carbon from CO_2
- Heterotrophs: obtain carbon from organic sources

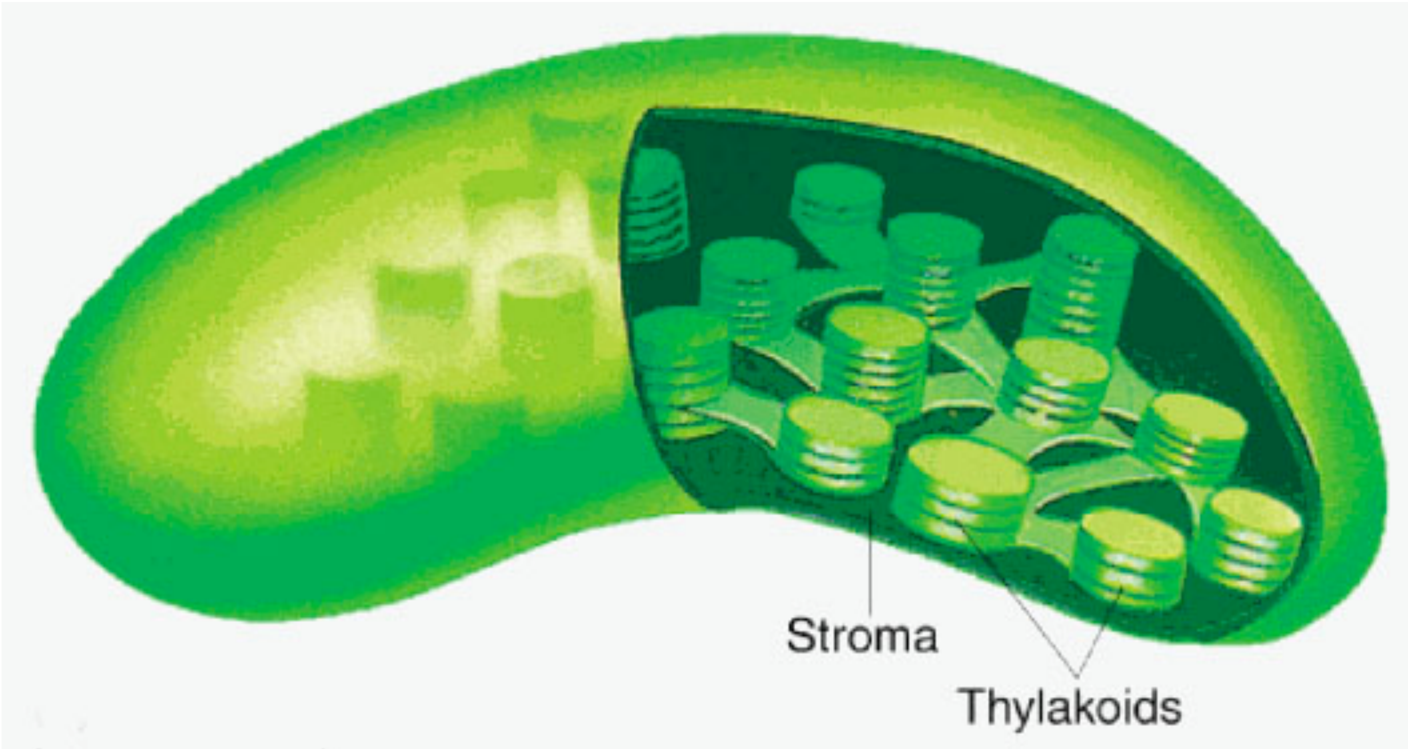
Photosynthesis

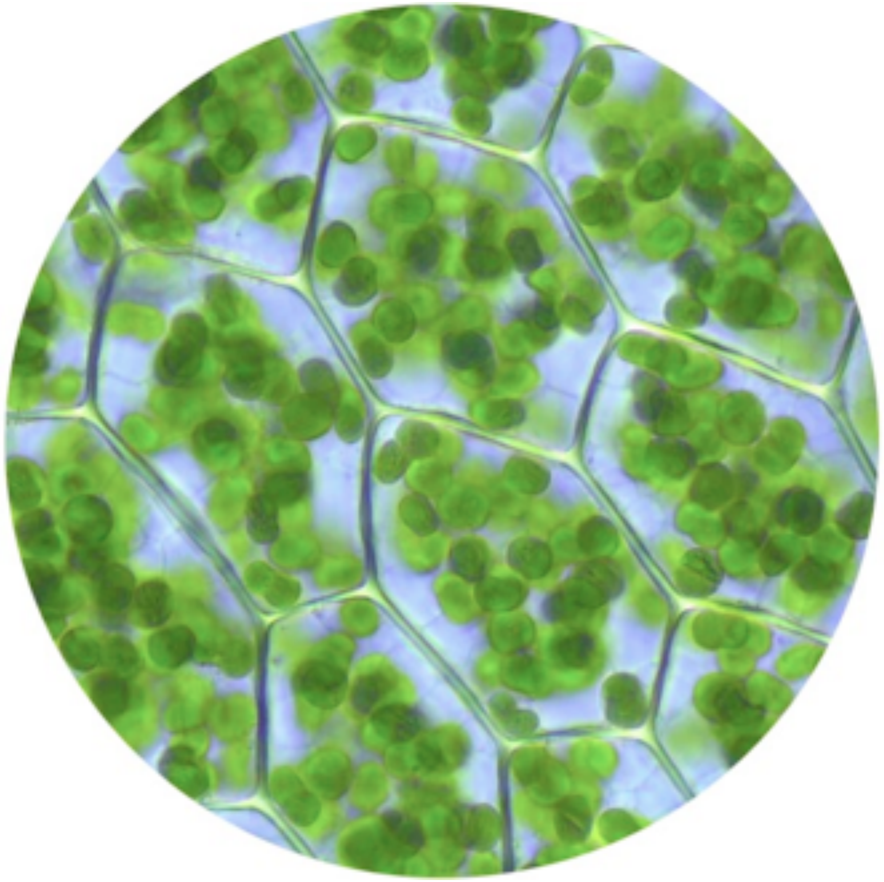
I.

Main Idea: A series of enzymatic reactions use solar energy to produce large organic compounds from smaller inorganic compounds.

Solar Energy to Chemical Energy

- Photosynthesis likely evolved in prokaryotes which possessed infolded membranes with enzymes and other molecules that could harness solar energy to produce organic compounds
  - The site of photosynthesis in modern photoautotrophs is the chloroplasts
  - The endosymbiotic theory explains how chloroplasts may have evolved



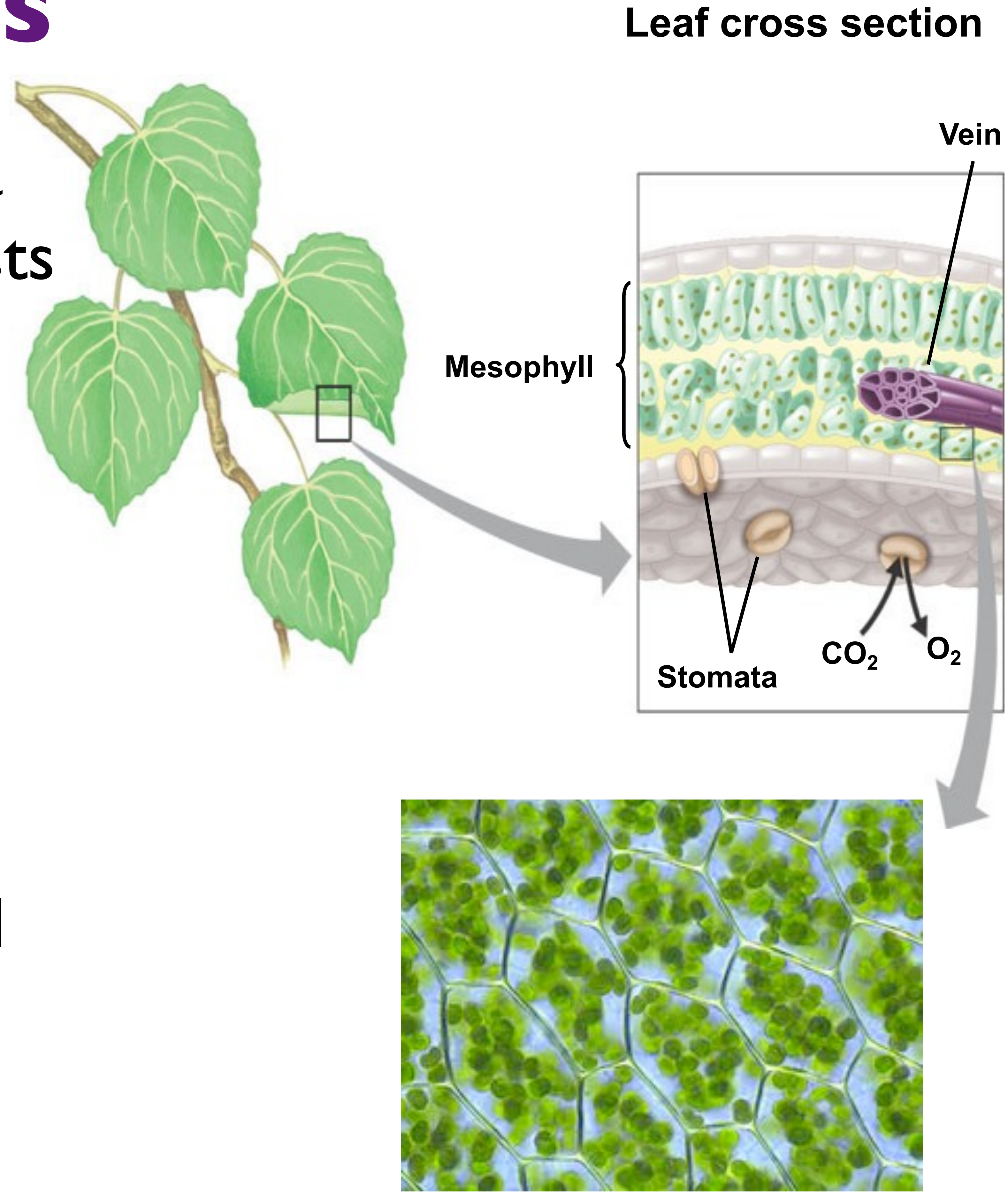


Chloroplasts

All green parts of a plant have chloroplasts

There are millions of chloroplasts in a single leaf

A typical mesophyll cell contains 30-40 chloroplasts



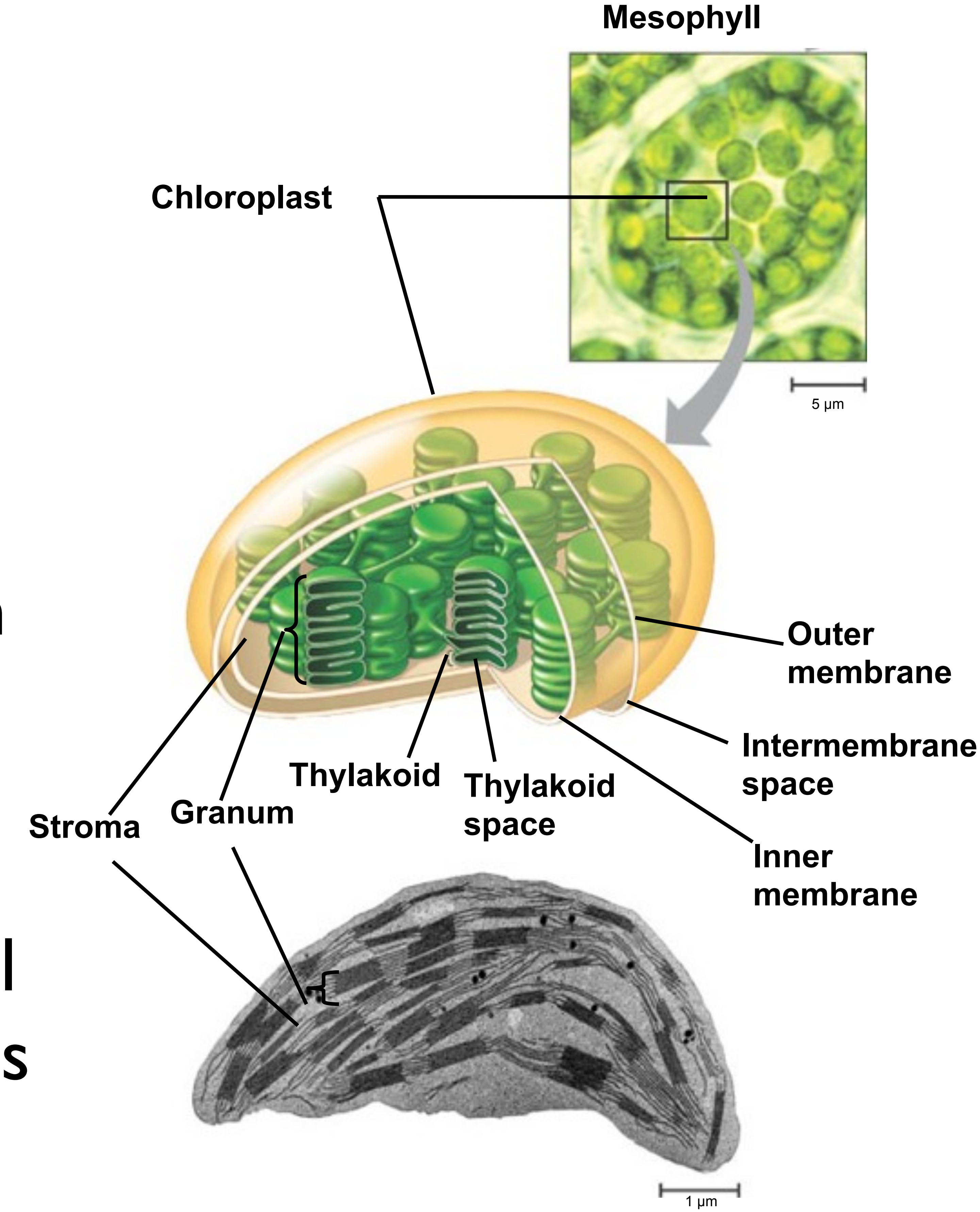
Chloroplasts

Double outer membrane

Chloroplasts filled with a dense fluid

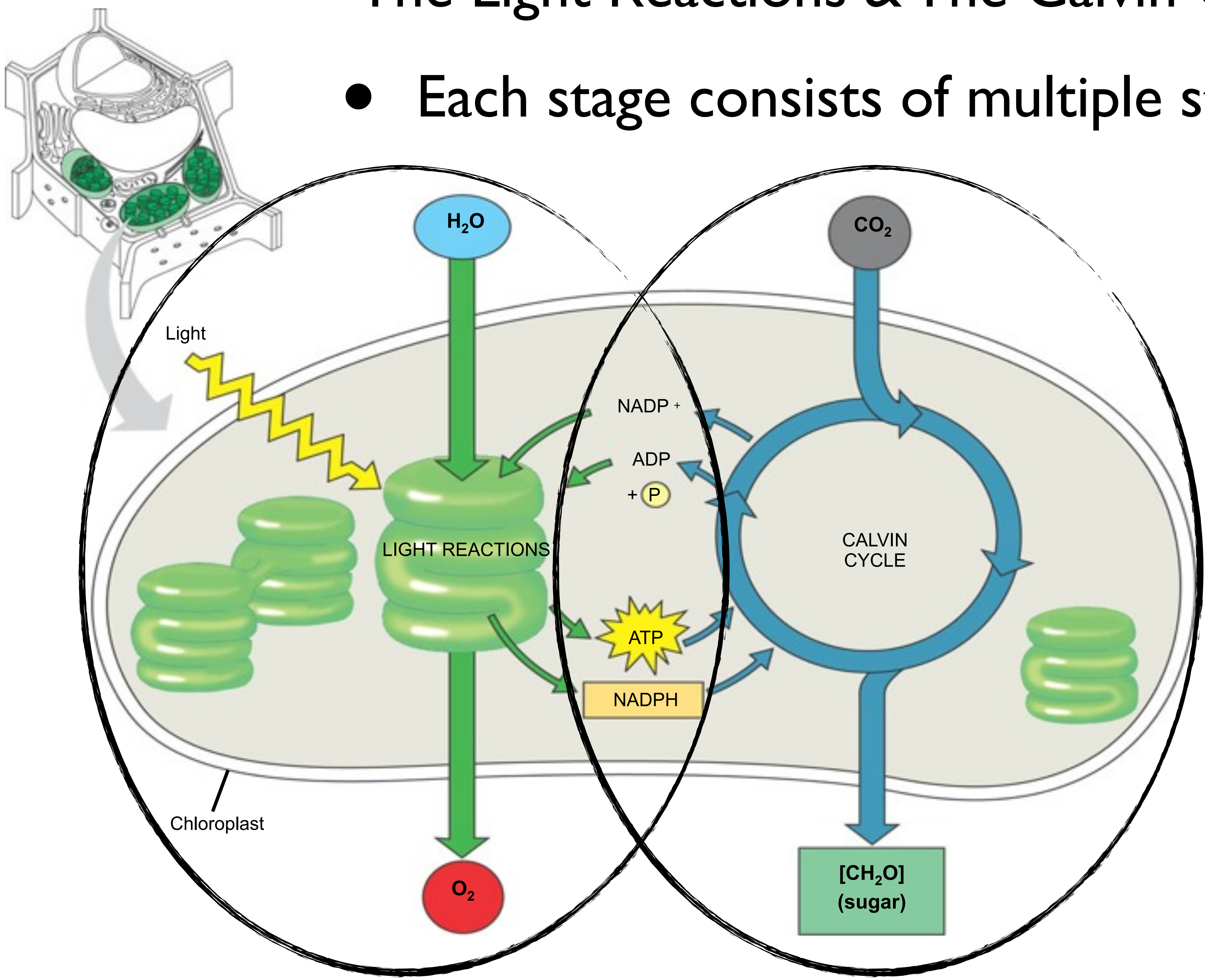
A third membrane system made of stacks called thylakoids

Green pigment chlorophyll found thylakoid membranes

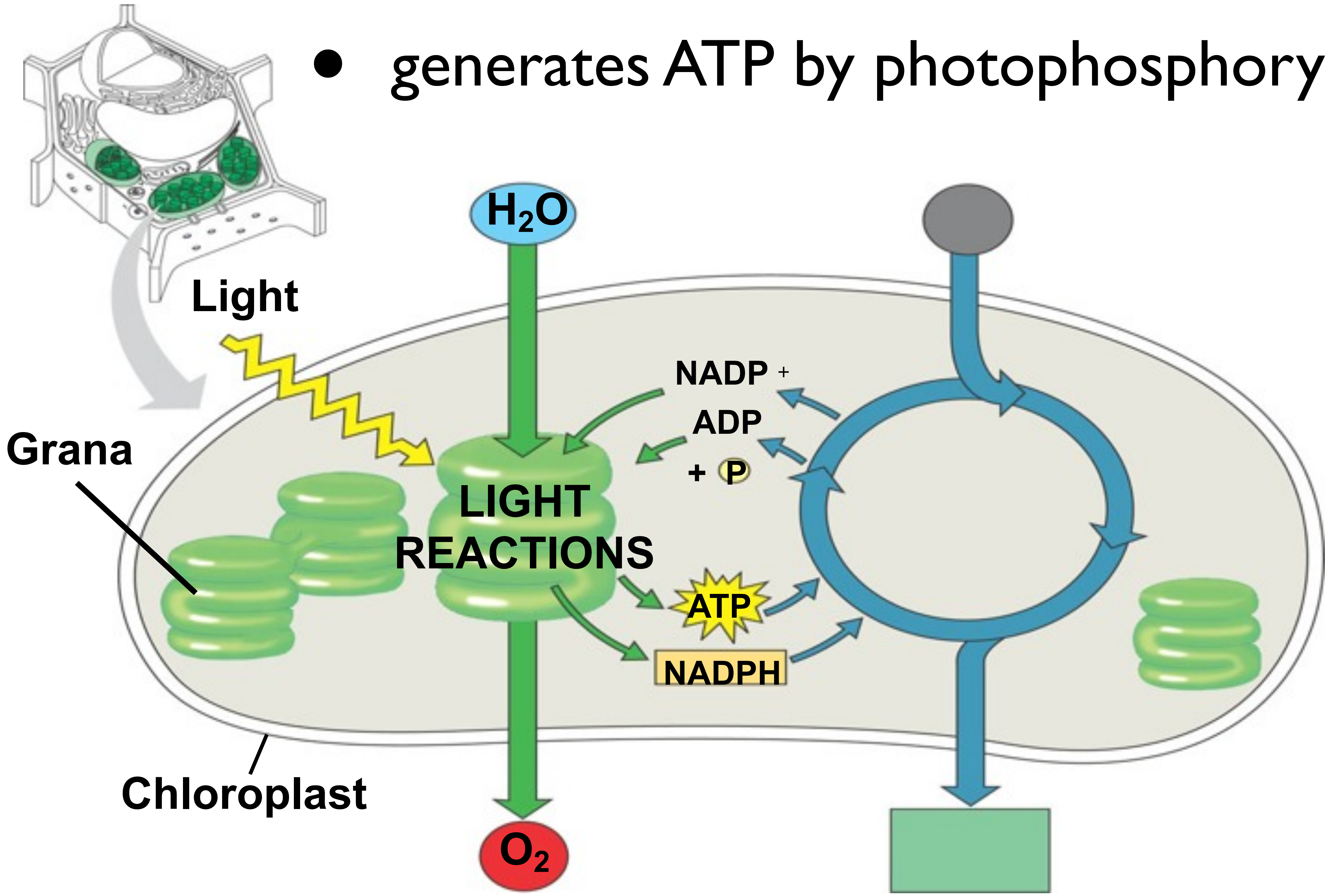


Photosynthesis: Occurs in Two Stages

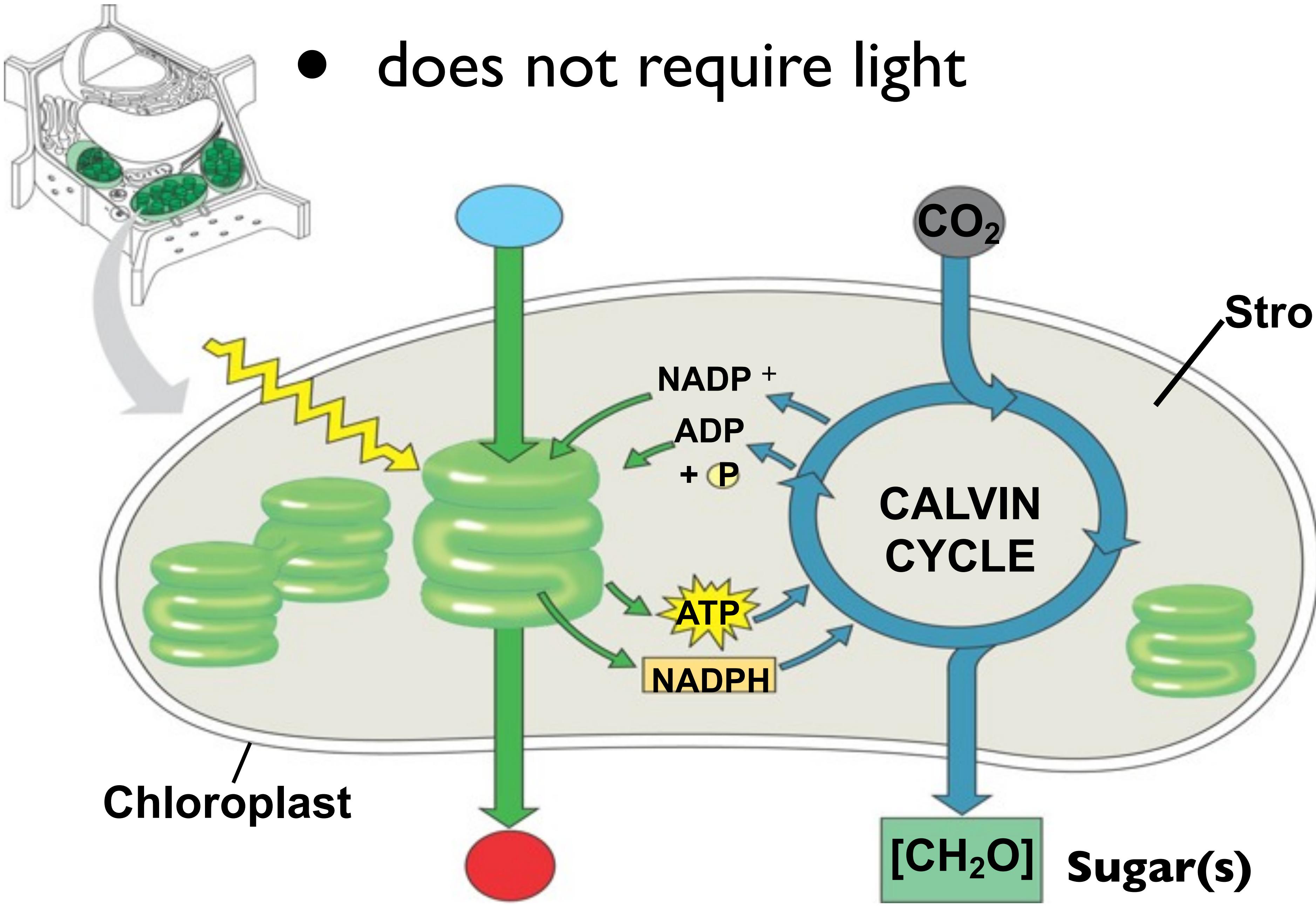
- Photosynthesis takes place in two stages:
  - The Light Reactions & The Calvin Cycle
    - Each stage consists of multiple steps



- **Light Reactions**
  - occurs in the grana (thylakoid membranes)
    - converts solar to chemical energy (NADPH & ATP)
      - harvests electrons and hydrogens from water
        - generates ATP by photophosphorylation



- **Calvin Cycle**
  - occurs in the stroma
    - uses chemical energy (NADPH & ATP) to make sugar
      - builds sugars using carbon from CO_2
        - does not require light



this step is the carbon fixation portion of photosynthesis

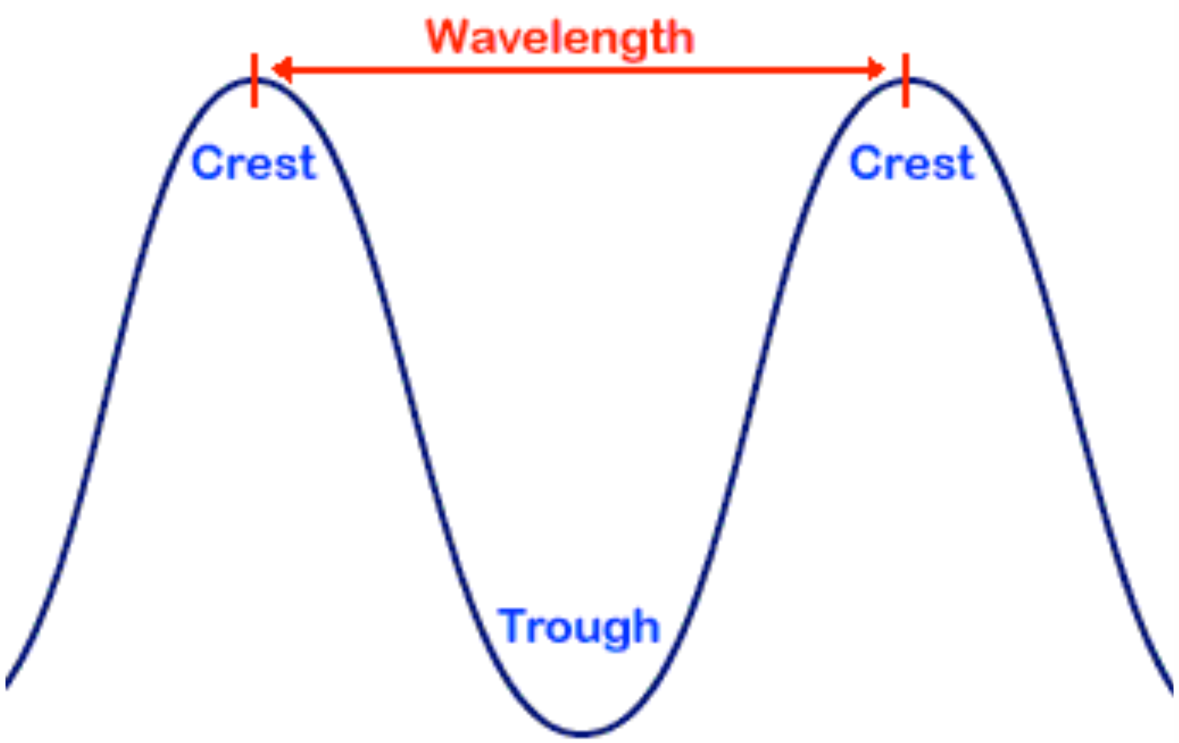
Photosynthesis

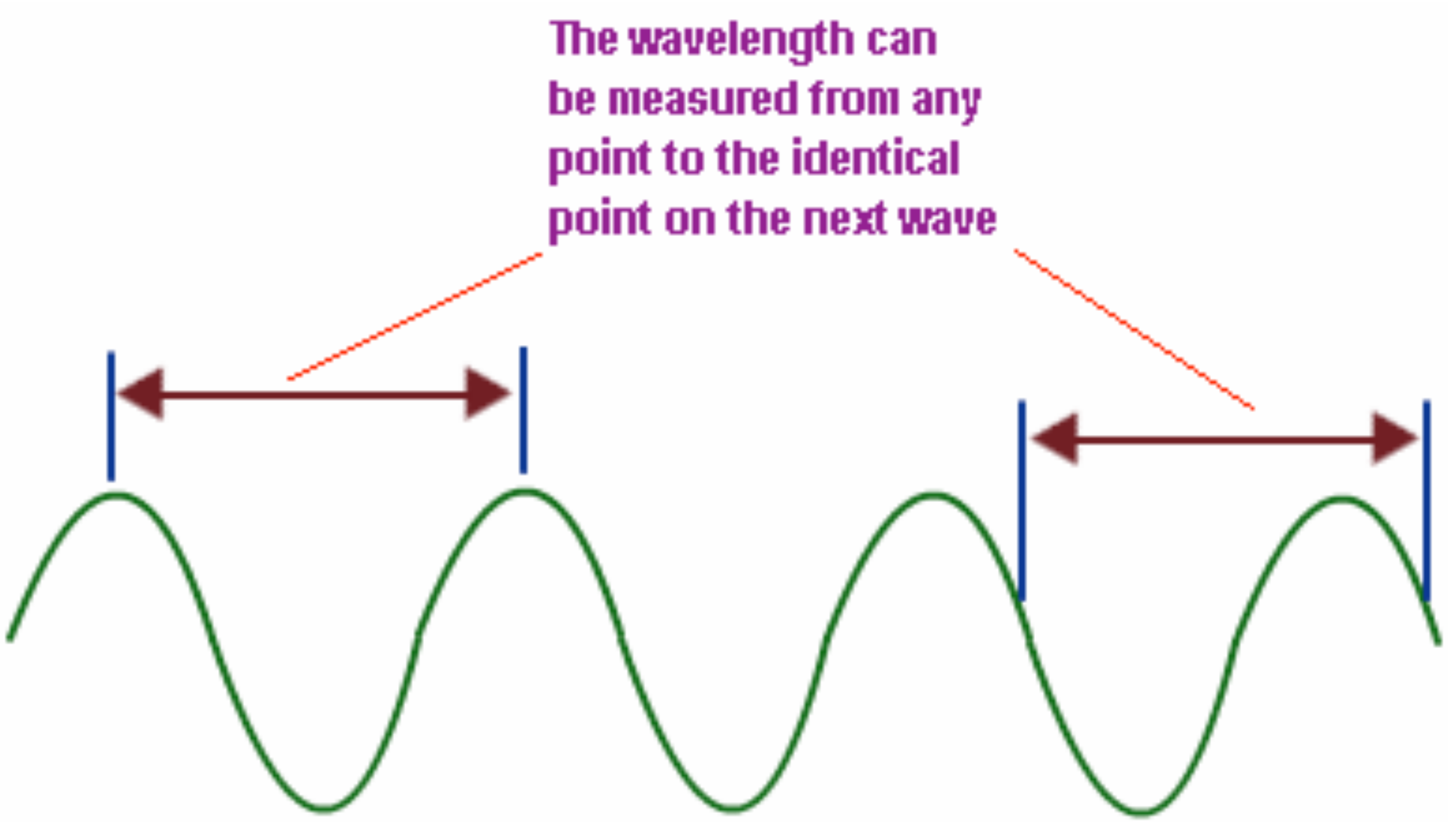
II.

Main Idea: Comprehending photosynthesis requires knowledge of about the nature of light and pigments.

Nature of Sunlight

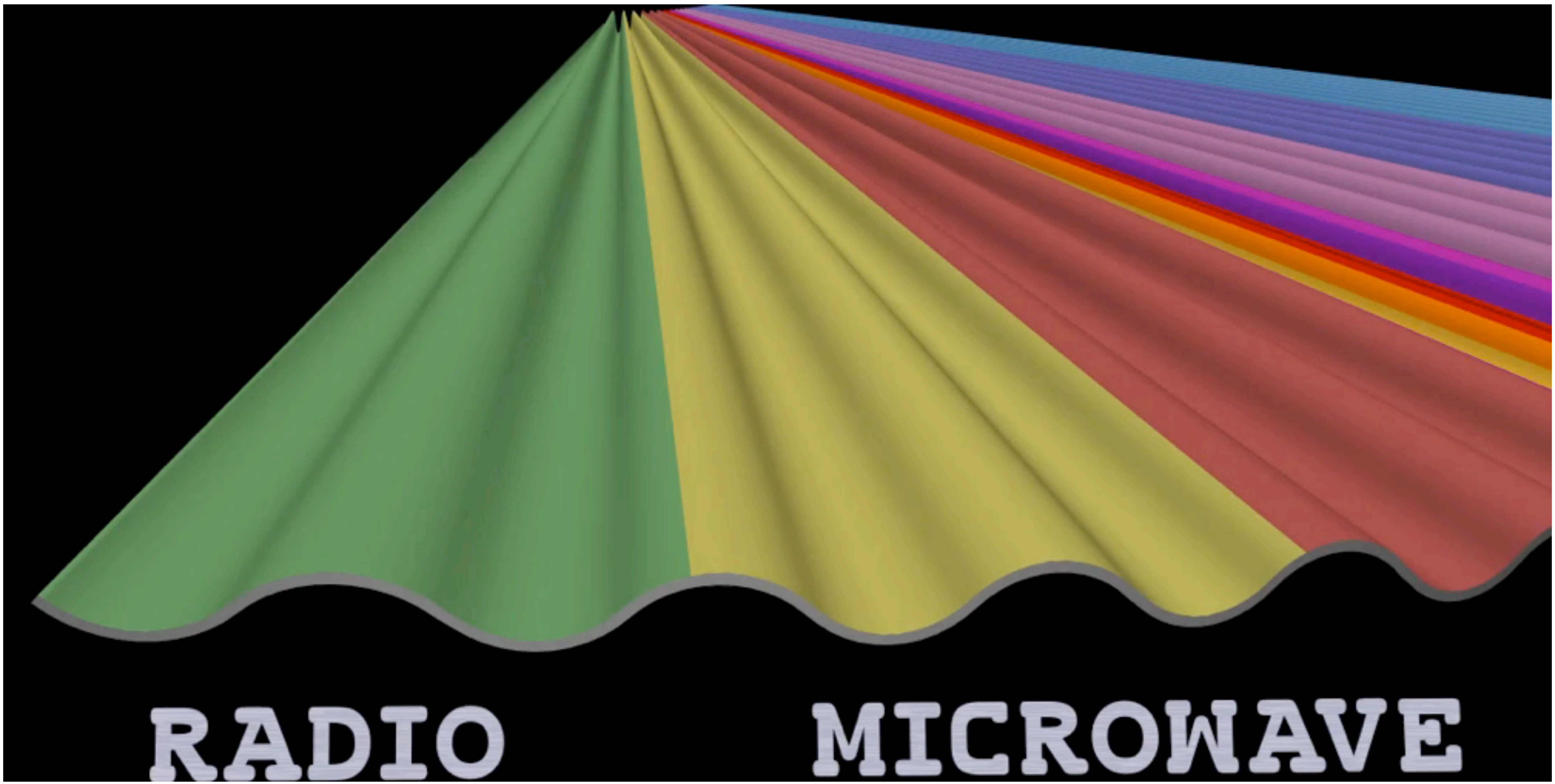
- Light is a type of energy called electromagnetic radiation.
  - Light travels as waves or particles.
  - Light waves are rhythmic disturbances in electric or magnetic fields.
    - The distance between the crests of these waves are called *wavelengths*, the amount of energy in this electromagnetic radiation is indirectly correlated with wavelength.





Nature of Sunlight

- The entire range of wavelengths of radiation is called *electromagnetic spectrum*.
    - Shorter wavelengths are the most energetic!



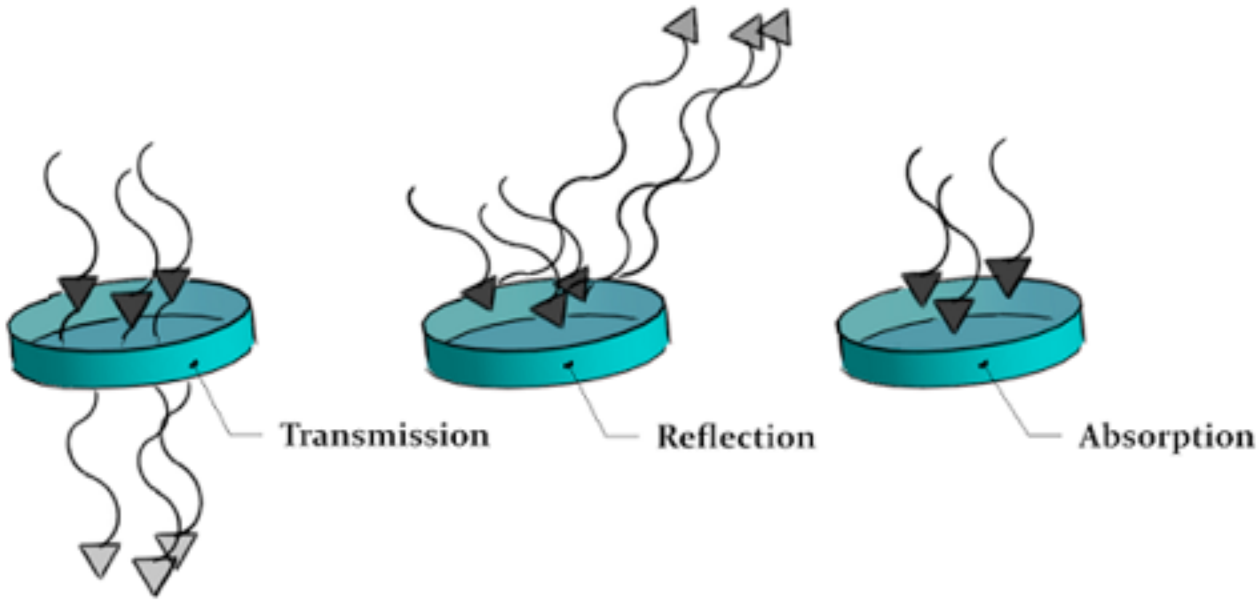
Nature of Sunlight

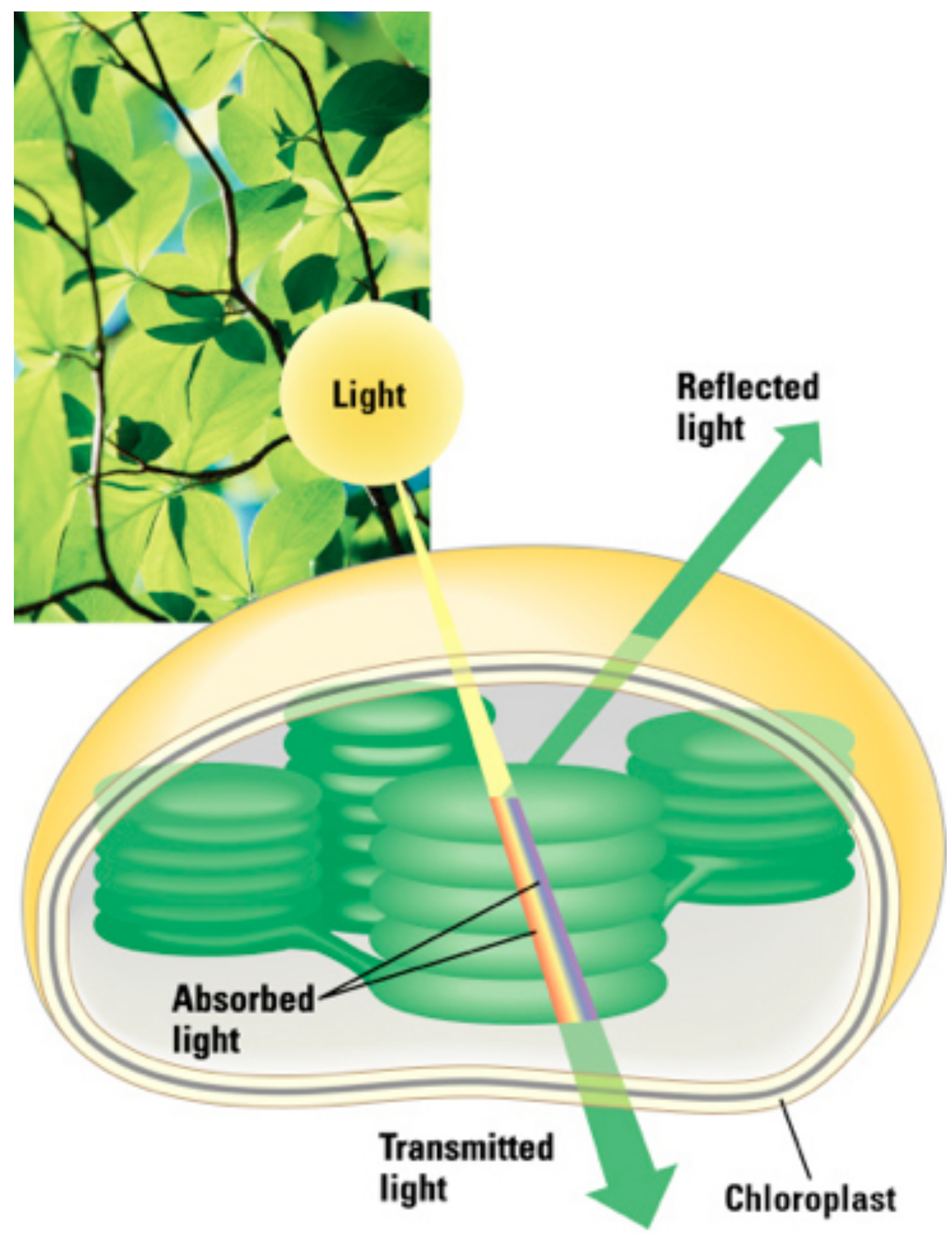
- Light also acts like a particles at times.
  - Light particles are called *photons*.
  - Each photon has a fixed amount of energy.
    - The amount of energy is inversely proportional to wavelength.
      - Violet light has almost 2X the energy of red light

ROY G BIV

Photosynthetic Pigments

- When light hits matter it can be reflected, absorbed or transmitted.

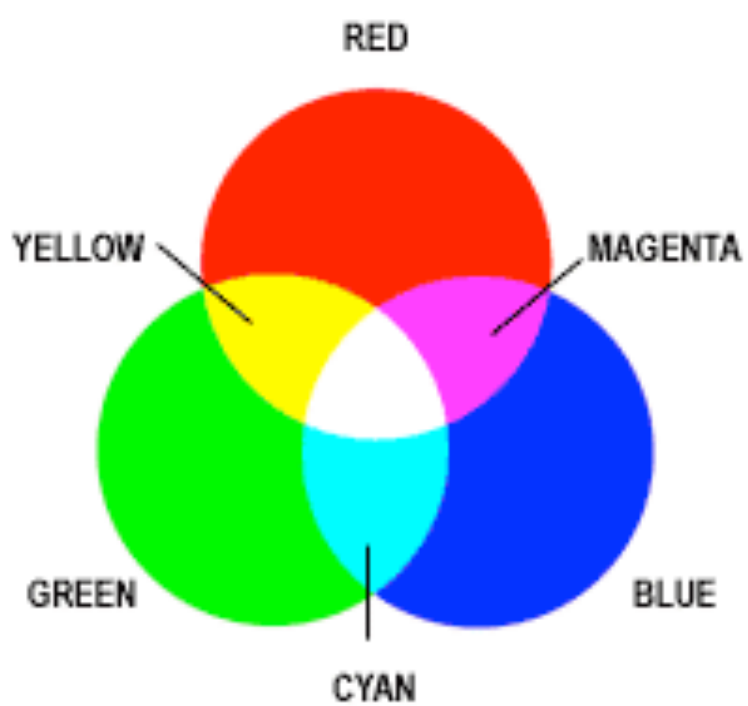


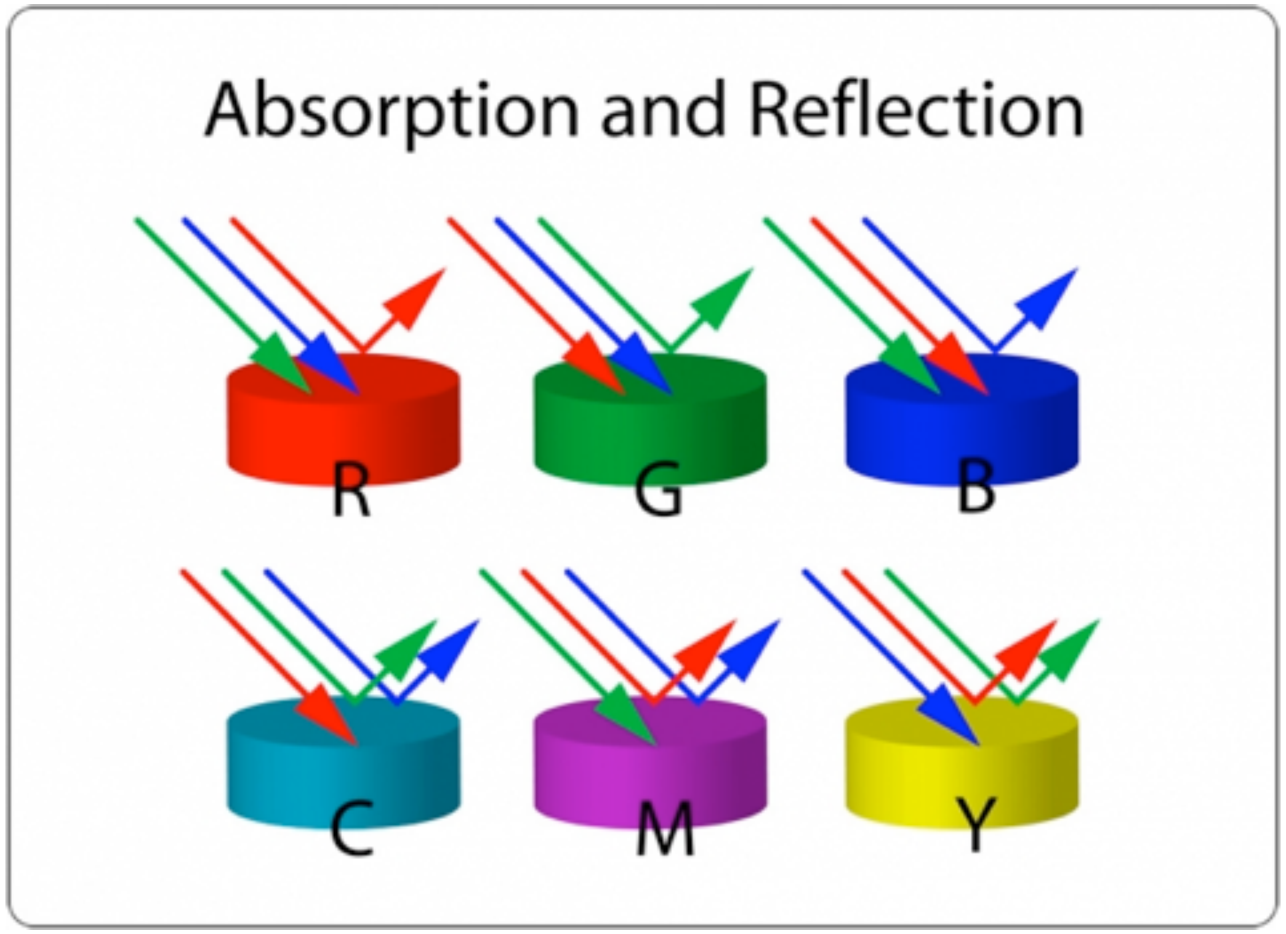


- Pigments are molecules that absorb light.
- Different pigments absorb different wavelengths of light.

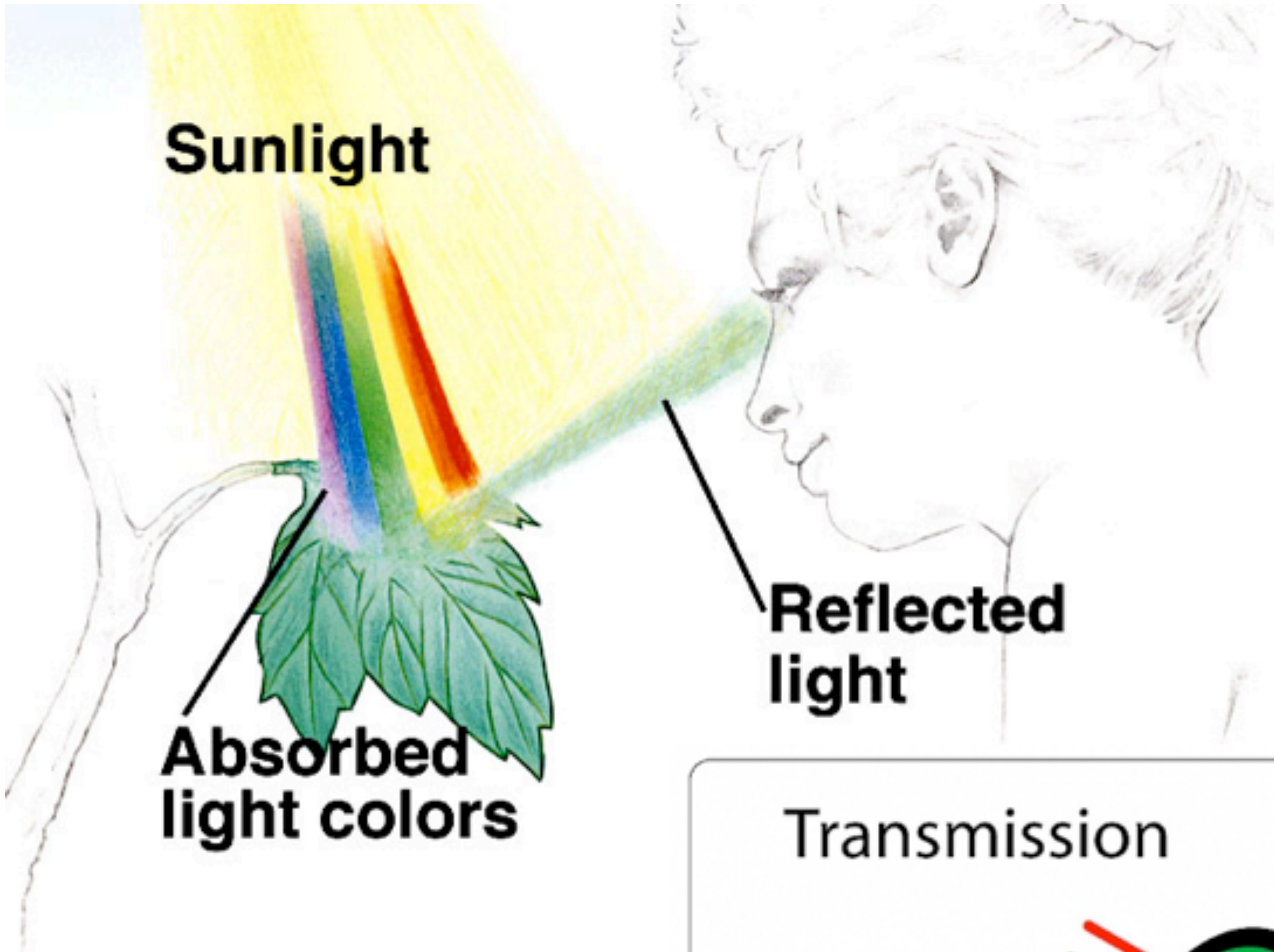
Photosynthetic Pigments

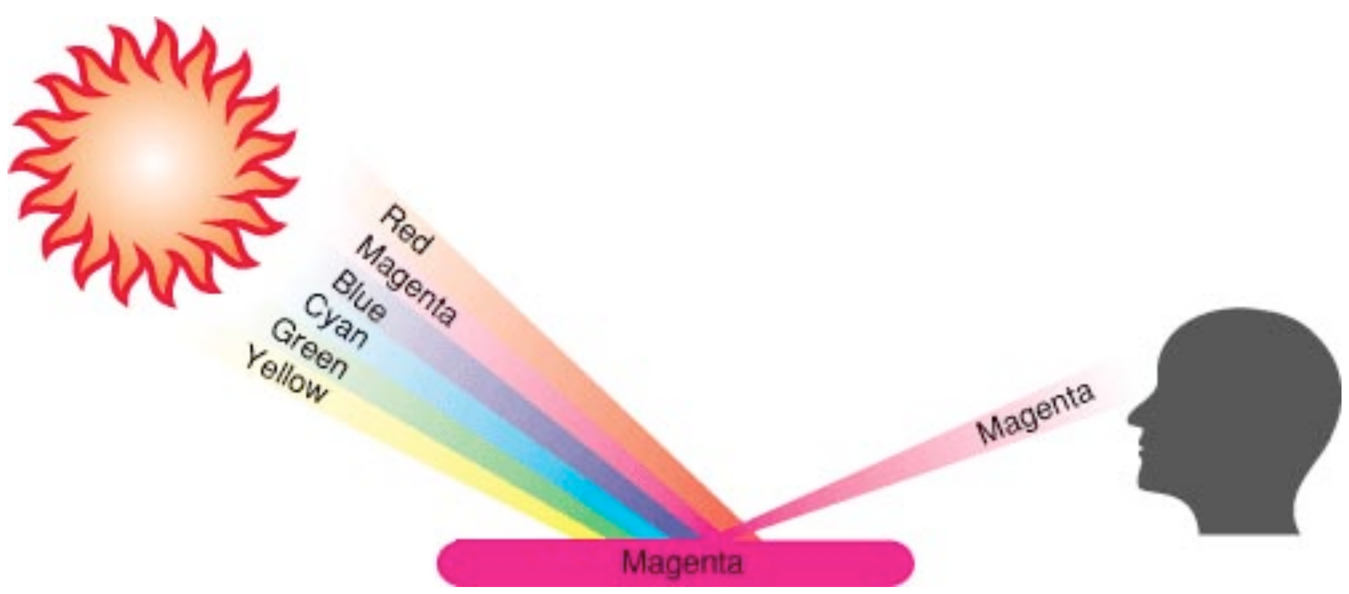
- When white light strikes pigment the color we see, is the color that is reflected or transmitted.
  - White color / light = no pigments present in matter
  - Black color / no light = pigments absorb all wavelengths
  - Green color (etc) / green light = pigments absorb all wavelengths of light except green

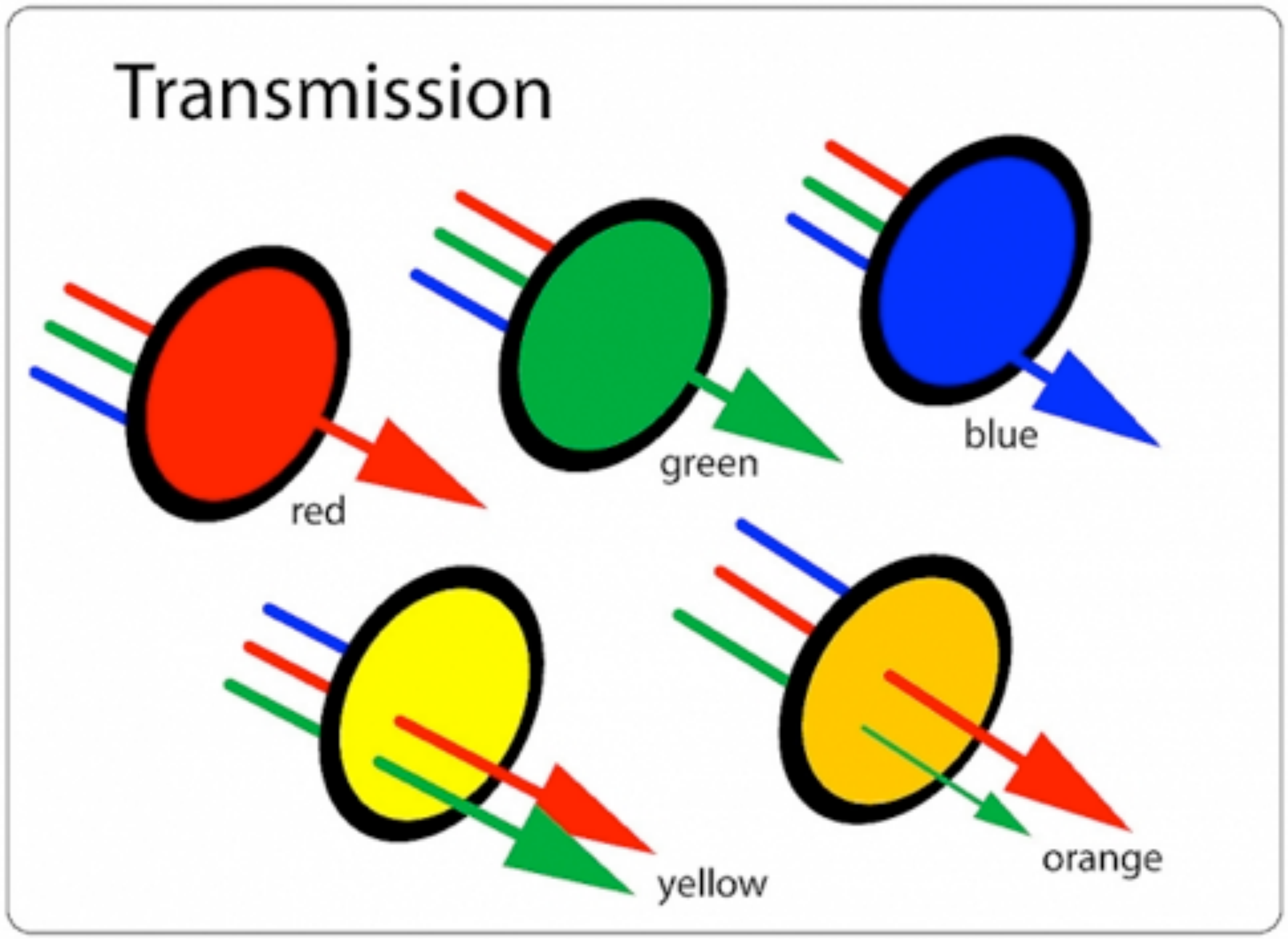




Photosynthetic Pigments

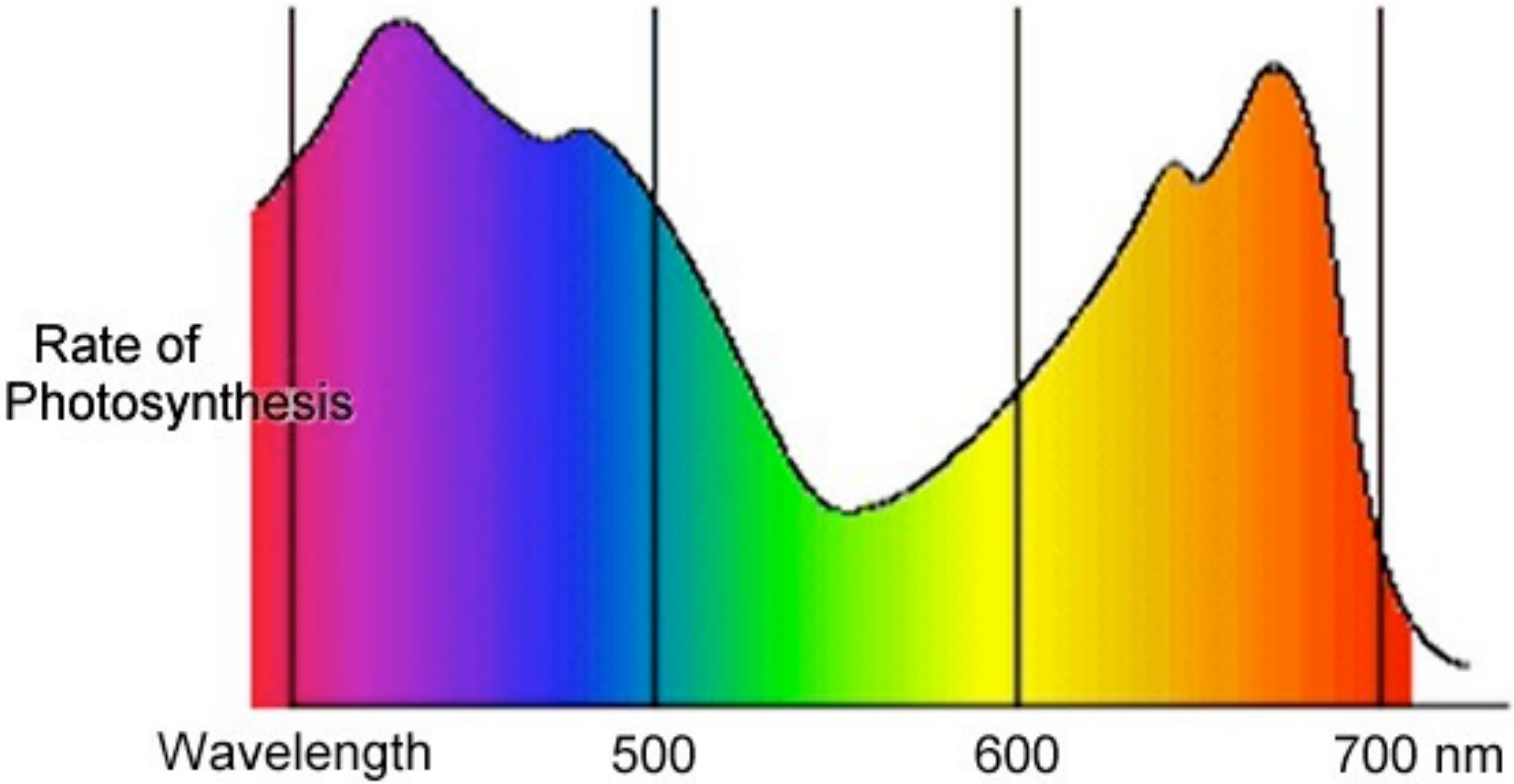






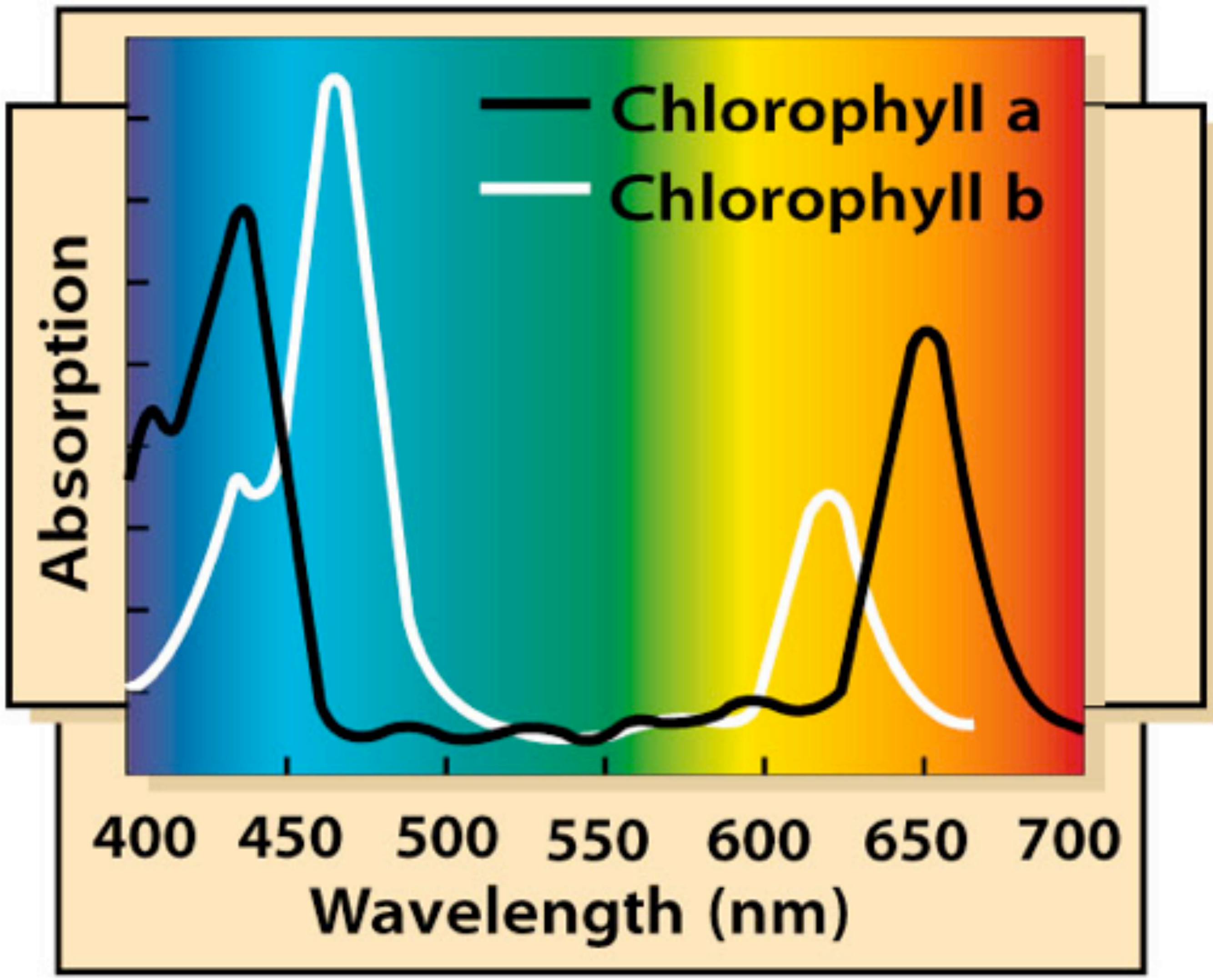
Action Spectrum

- The action spectrum profiles the relative effectiveness of each wavelength in driving photosynthesis.



Photosynthetic Pigments

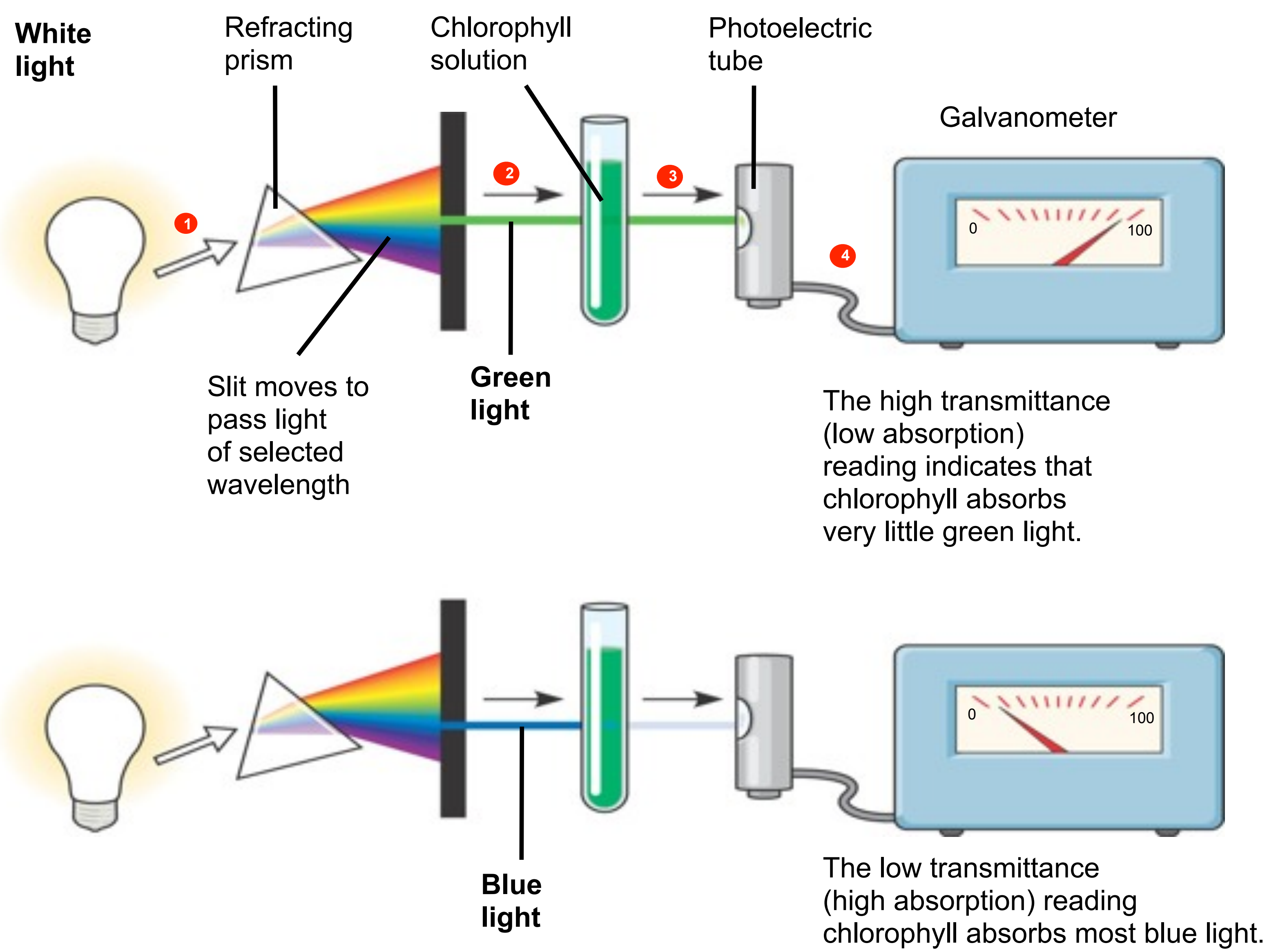
- An graph plotting a pigment's light absorption versus wavelength is called an ***absorption spectrum***.
- The absorption spectrum of chlorophyll provides evidence to which wavelength(s) are driving photosynthesis.



How did we determine this absorption spectrum?

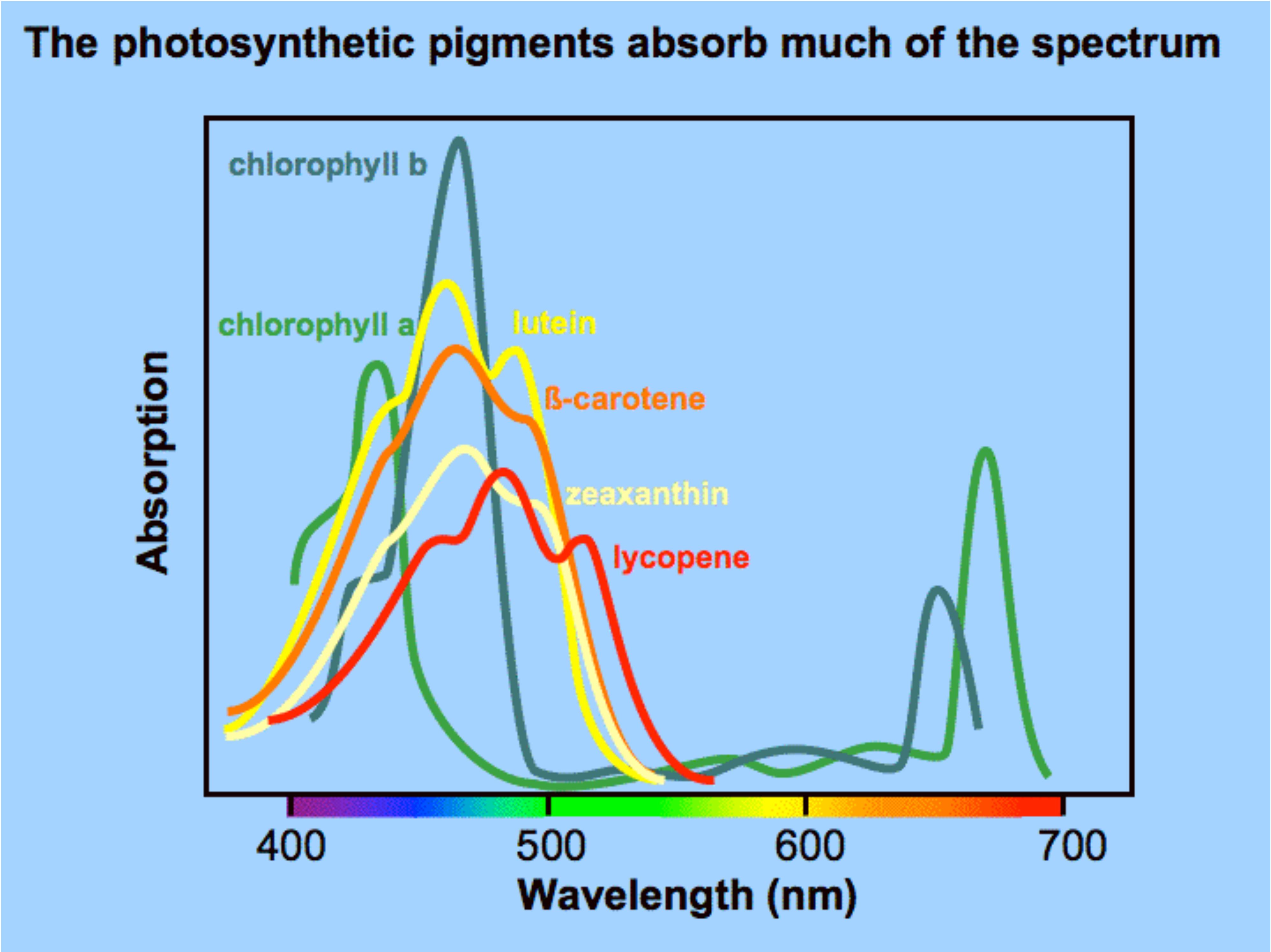
Absorption Spectrum of Chlorophyll

- Today we can determine absorption spectrums using ***spectrophotometers***.
- A ***spectrophotometer*** measures the amounts of light of different wavelengths absorbed and transmitted by a pigment solution.



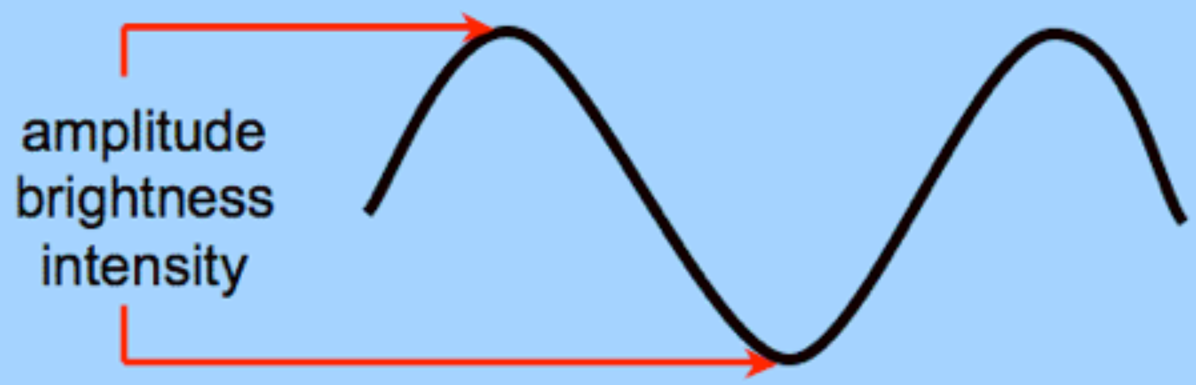
Absorption Spectrum

- Today, spectrophotometers can measure the absorption of certain wavelengths by individual pigments .



Light Intensities

- Light waves not only vary in wavelength but they can vary in ***amplitude*** as well.
- The amplitude is the height of each wave.
- Light with higher amplitudes are brighter or more intense



Many metric units for different purposes
We will use an easy-to-remember English unit: foot-candle

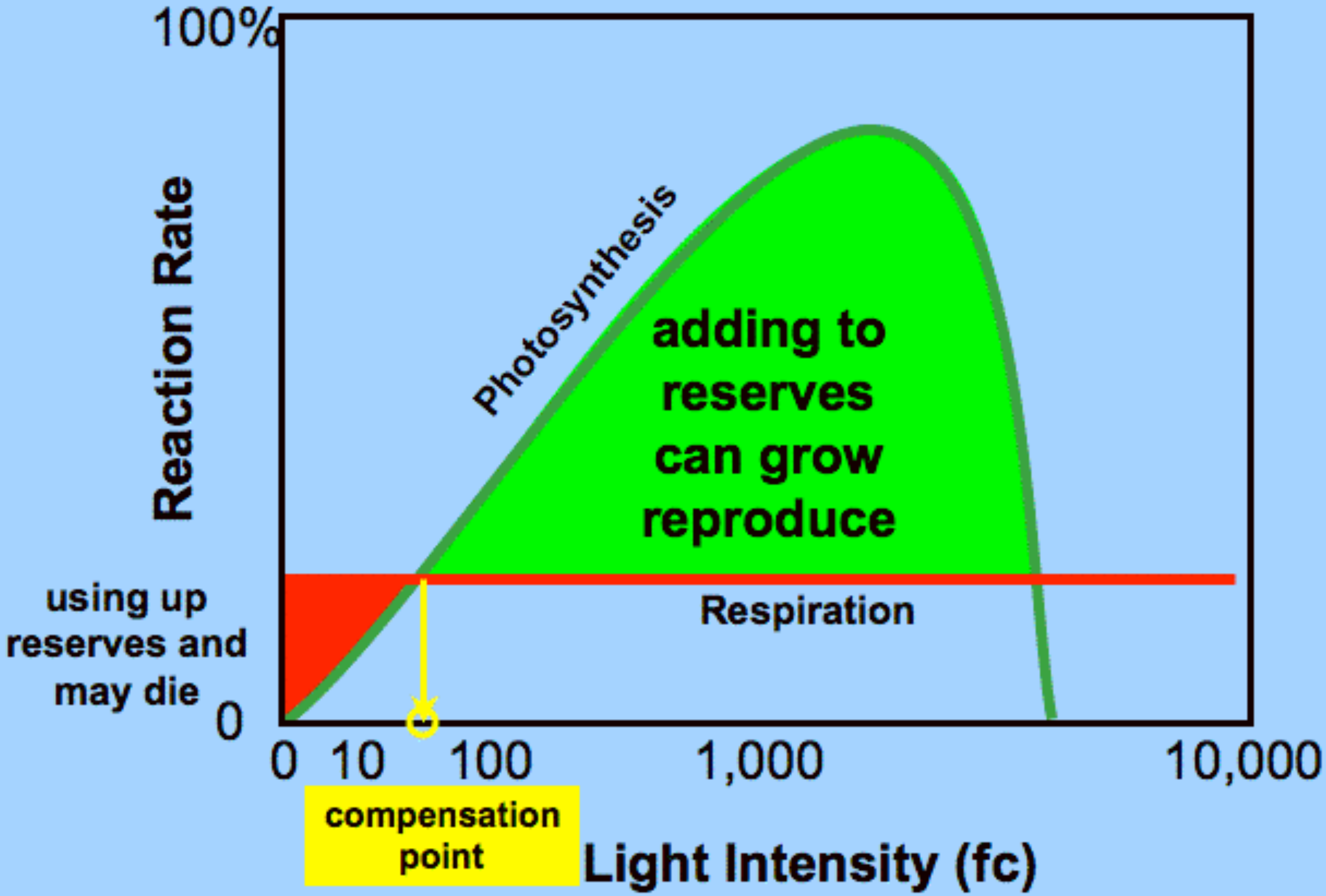
0 fc = darkness

100 fc = living room

1,000 fc = CT winter day

10,000 fc = June 21, noon, equator, 0 humidity

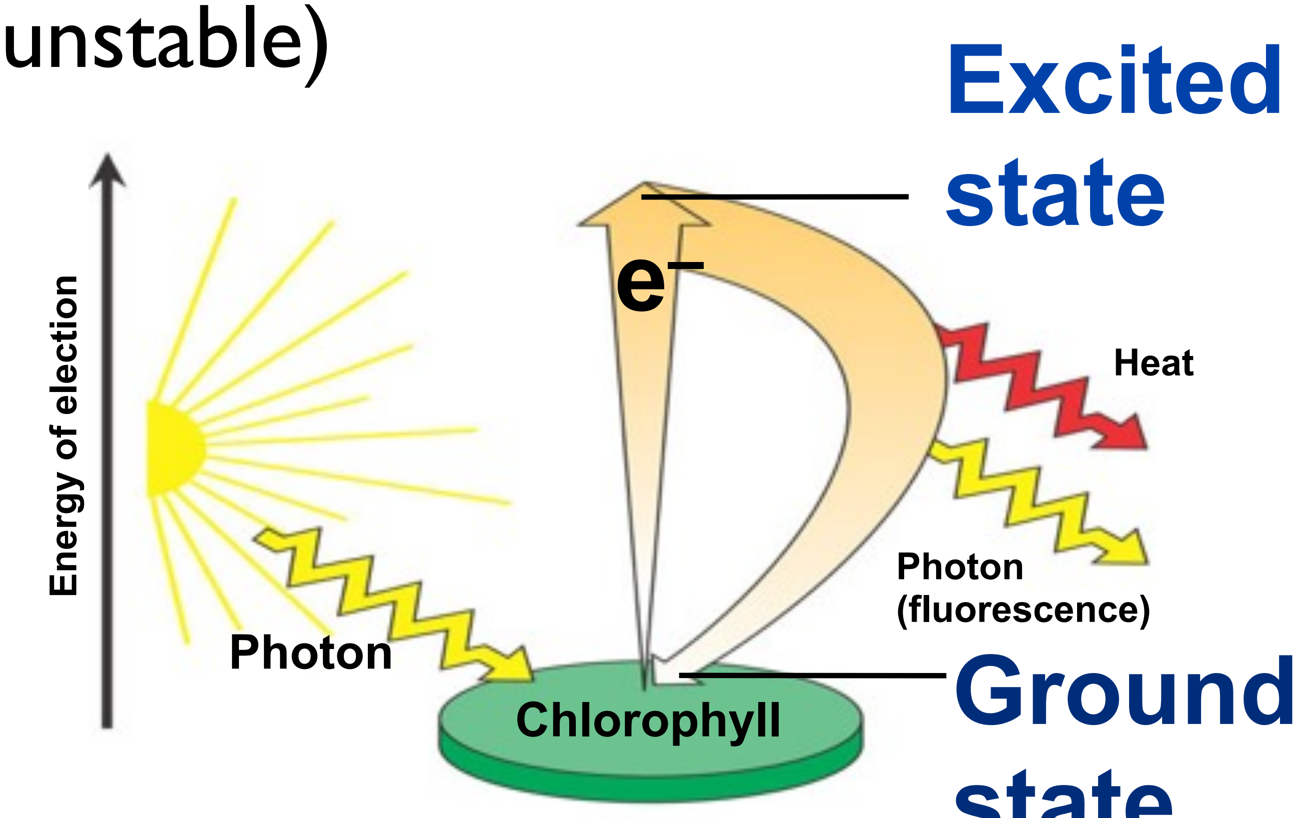
What intensities of light drive photosynthesis?



The example plant shown here "breaks even" at an intensity we have in our homes…a house plant!

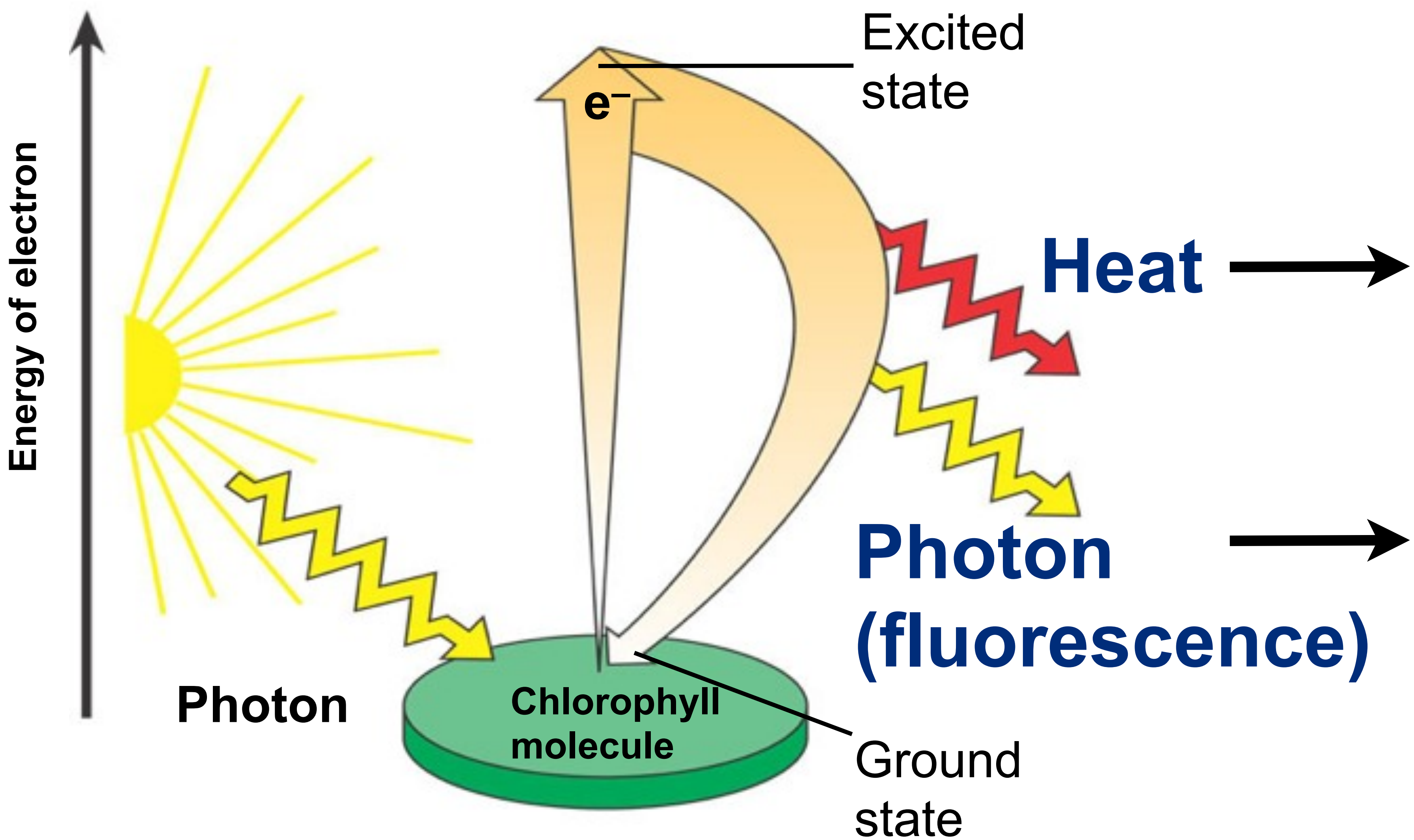
Exciting Chlorophyll by Light

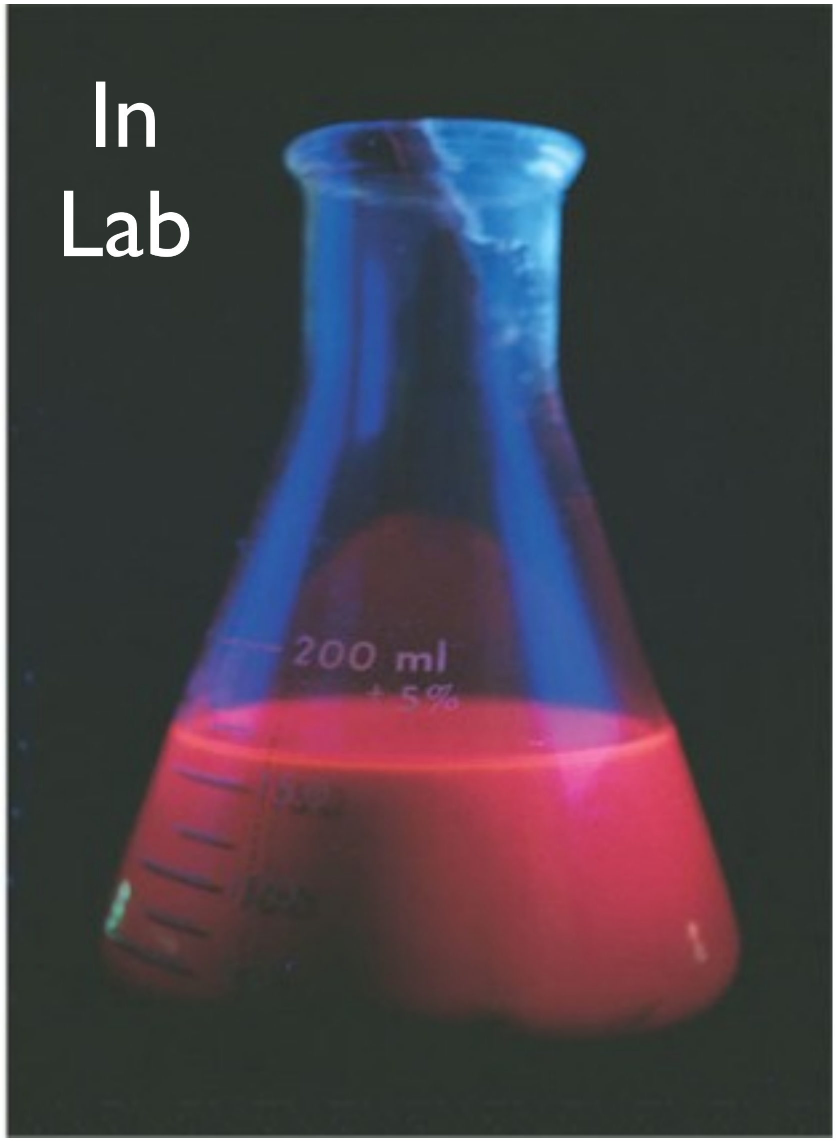
- When a pigment absorbs a wavelength(s) of light that wavelength disappears but the energy can not!
- Remember light also acts as particles, when *photons* hit molecules they impact can send "electrons flying"
- Electrons in their normal energy level are said to be in their ***ground state***. (they are stable)
- Photons can boost electrons to higher energy levels called their ***excited state***. (they are unstable)



Exciting Chlorophyll by Light

- An electron can not stay in the unstable, excited state.
  - In a billionth of second it falls back to the ground state
    - releasing the excess energy as heat and sometimes light
- In isolation chlorophyll releases heat and light (fluorescence).





Photosynthesis

III.

Main Idea: Light and an array of molecules found in the thylakoid membranes convert solar energy into chemical.

Light Reactions

- We know that light reactions convert solar energy into chemical energy
- We know that light reactions occur in the thylakoid membranes of the chloroplasts
- We know that only certain wavelengths power photosynthesis
- We know that certain light intensities are also necessary
- We know that pigments absorb light
- We know that electrons are excited in pigment molecules when a photon of light strikes them

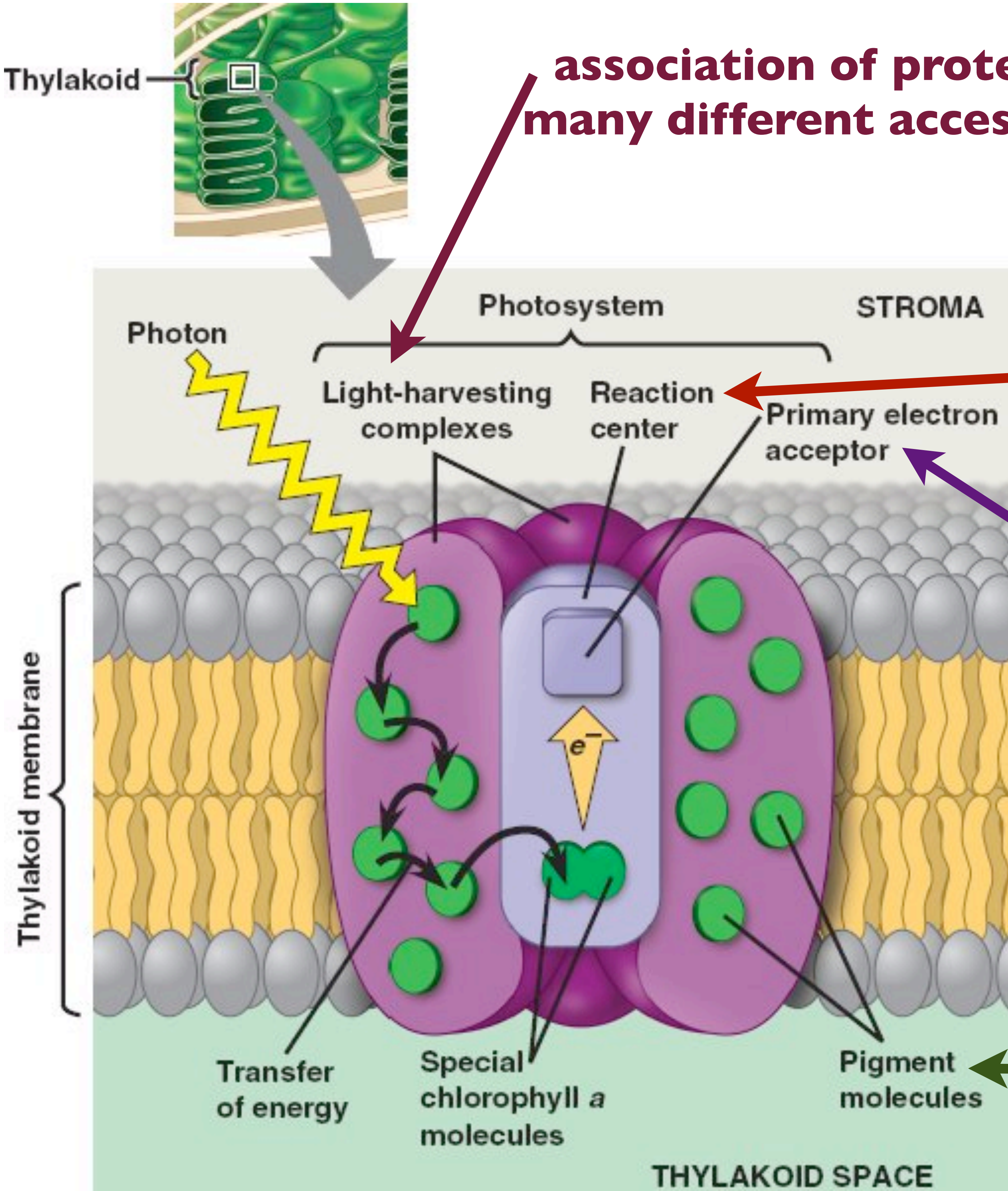
But we do not YET know...HOW

Photosystems

- Needless to say excited chlorophyll molecules act very differently in when they are intact in their chloroplasts compared to when we isolate them in a flask.
  - After all, leaves are not warm and fluorescent red in nature!

- To understand the mechanism of of the light reactions, the first of stages in photosynthesis we need to understand the structure of photosystems.

General Photosystem



association of proteins holding a many different accessory pigments

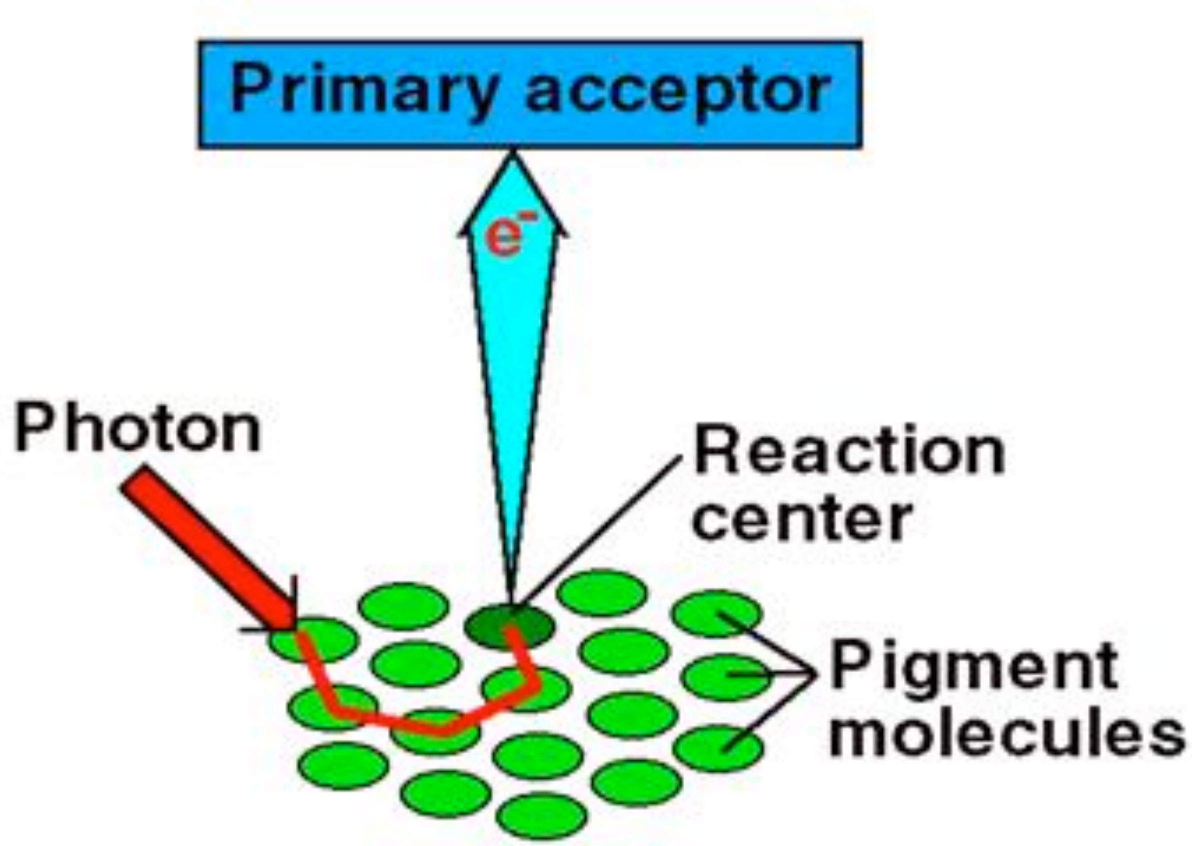
association of proteins holding chlorophyll *a* pigments

a molecule (similar to chlorophyll) that captures an electron, it is "reduced"

accessory or antennae pigments which transfer energy to special chlorophyll *a* pigments

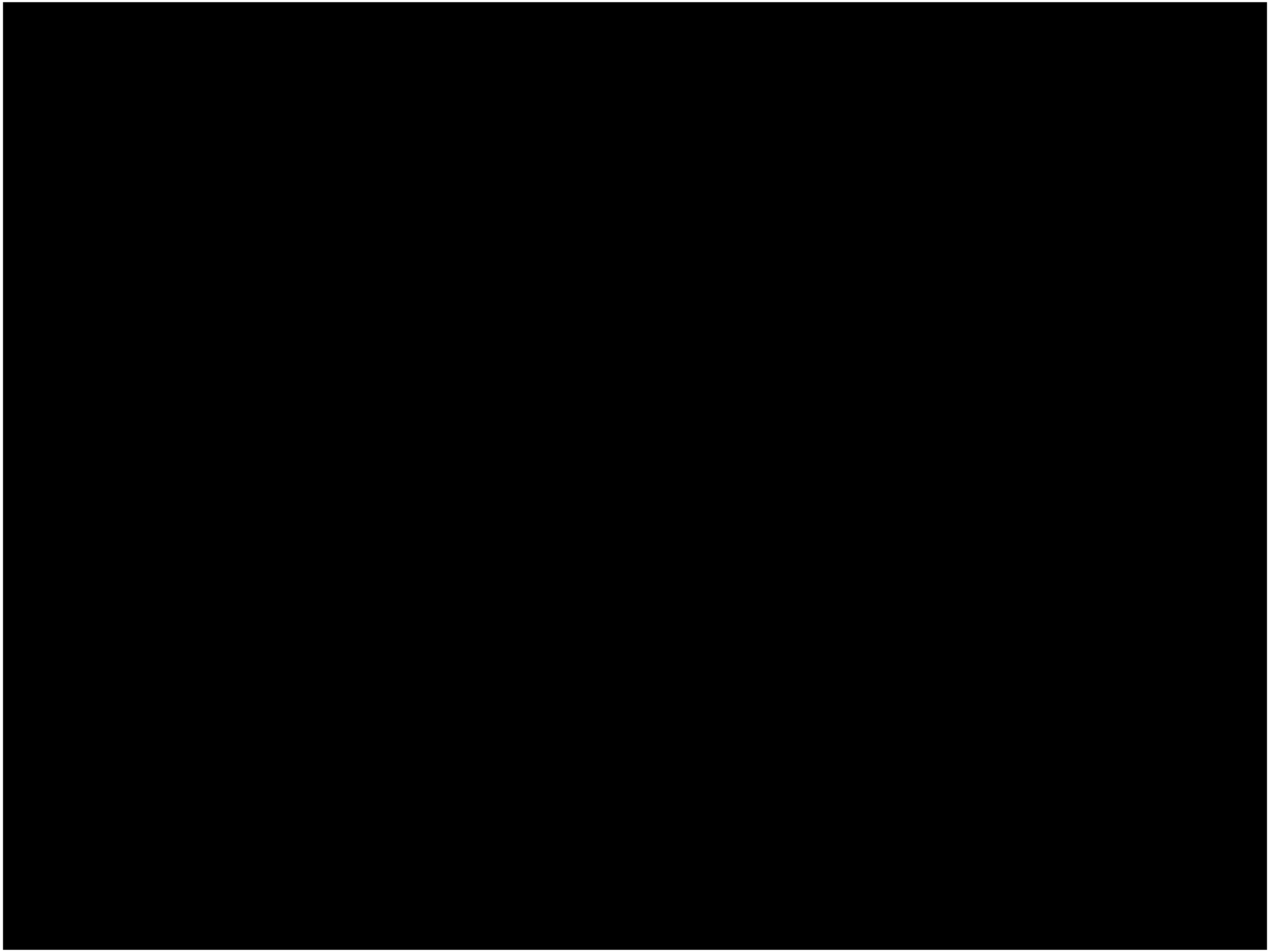
Side Bar...

- Remember "leaves are not warm and fluorescent red in nature!"



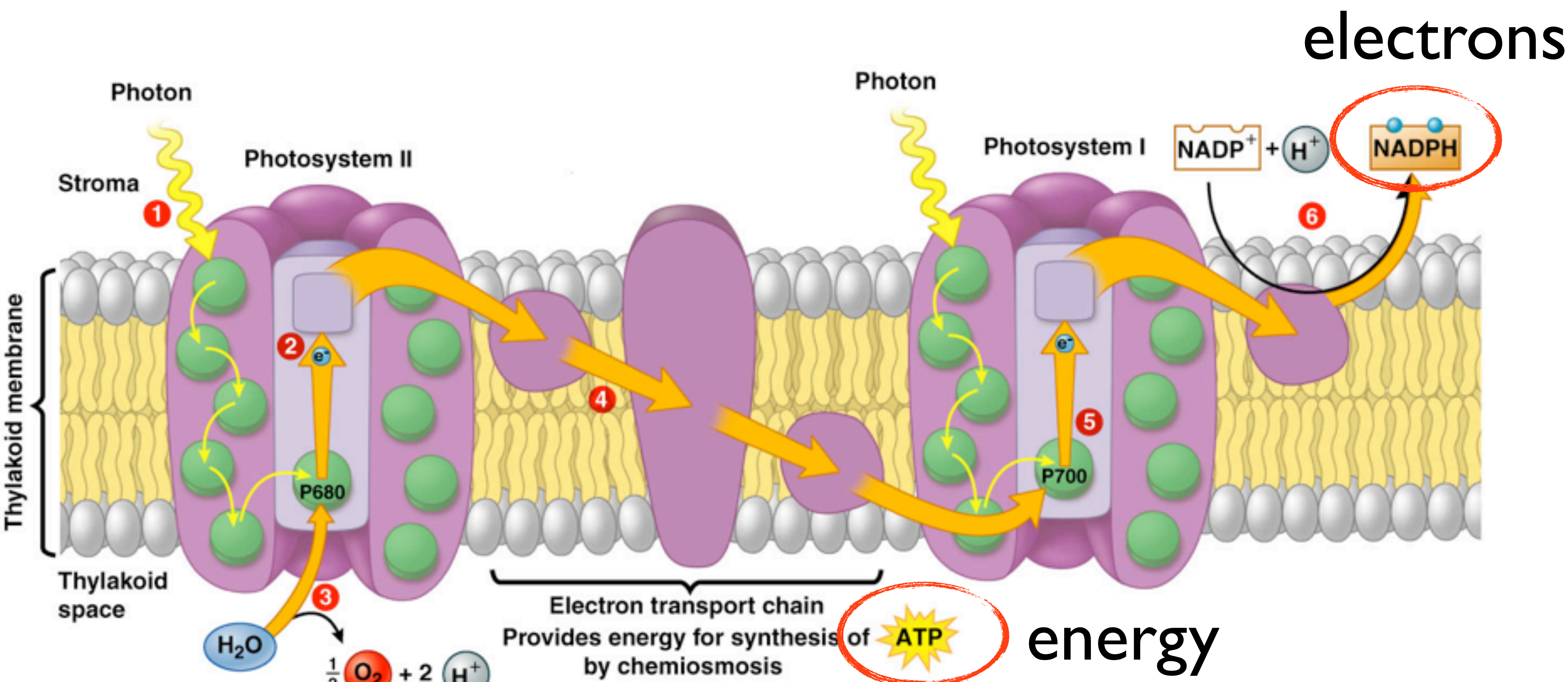
- When the pigment is excited in isolation the electrons fall back to the ground state, releasing energy as heat and light but in plants the primary acceptor does not allow the electron to fall back down and thus "keeps" that potential energy to do work we will see later.

Photosystem II



Photosystem I and II

- To complete the light reactions plants require 2 different photosystems working together to harvest the energy and electrons needed to build sugar.
  - Photosystem I was the first one discovered but it turns out that it the second photosystem used in the light reactions.



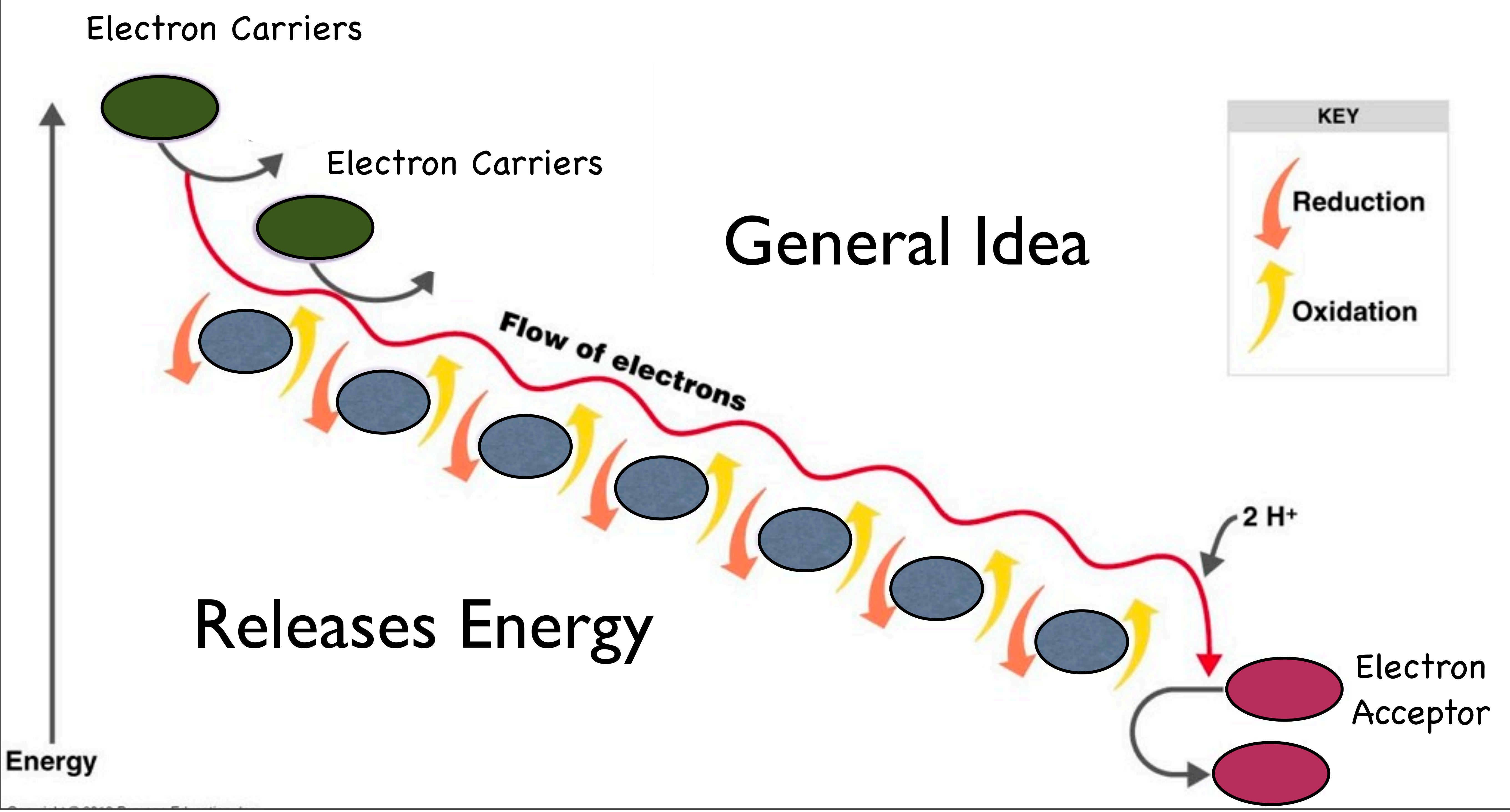
E.T.C. Establishes a H^+ ion Gradient

- The ***electron transport chain*** makes no ATP.
- The e^- transfer releases energy as the electron moves through the chain, this energy is used to pump H^+ ions through a membrane.
  - *This generates a electrochemical gradient with great potential energy*

E.T.C. and Chemiosmosis

- Stored energy in the form a H^+ ion gradient across a membrane is called the ***proton motive force,*** it is used to produce ATP (or drive other cellular work), which is called ***chemiosmosis***.
- ***Chemiosmosis*** *is an energy coupling mechanism that uses energy stored in in the form of H+ ion gradients across membranes to drive cellular work*
  - *Osmosis is the diffusion of water*
  - *Chemiosmosis is the diffusion of H^+ ions*
- Specifically an enzyme ATP synthase uses the energy to produce ATP from ADP

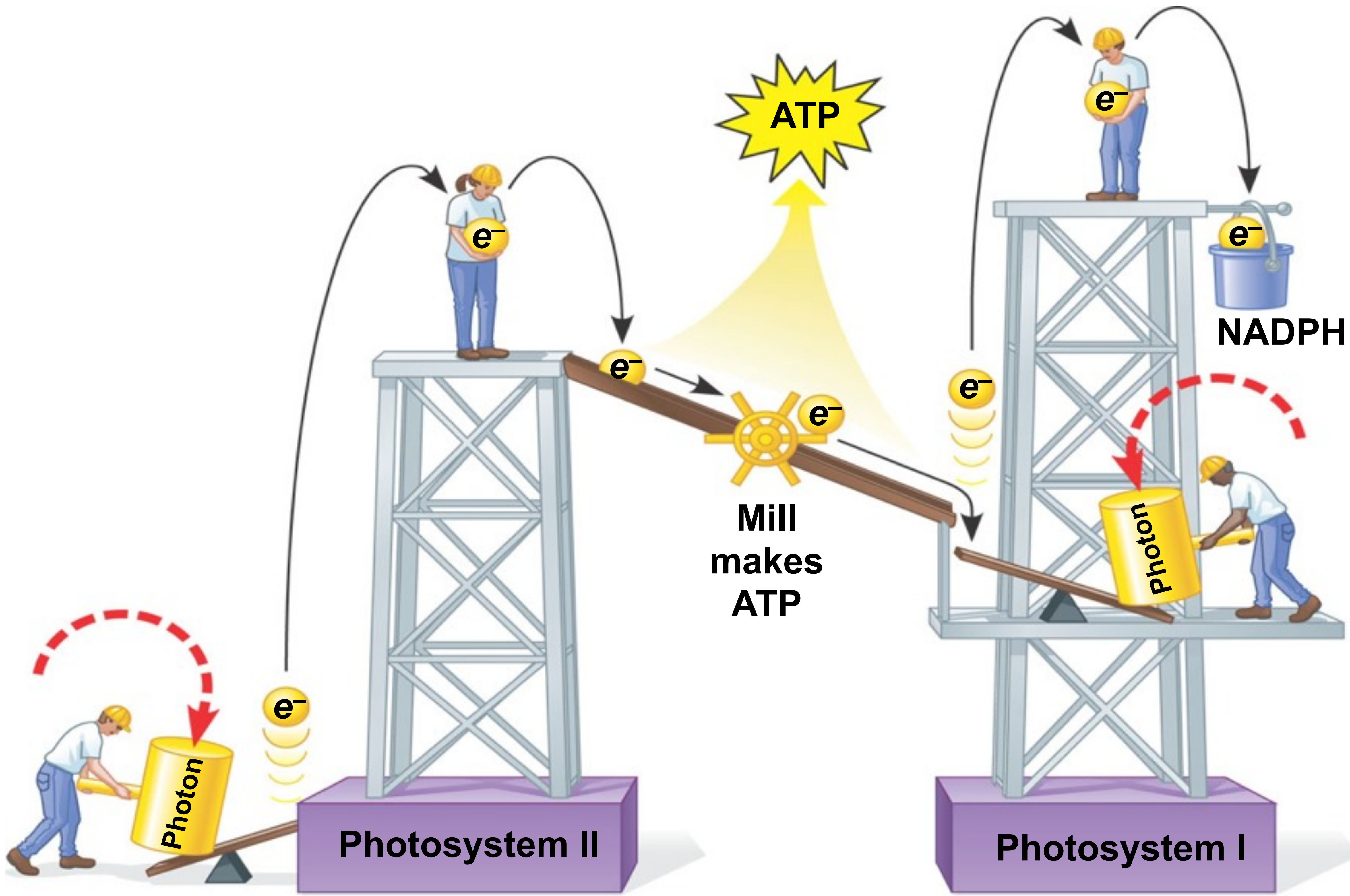
Electron Acceptors & Transport



“The Big Picture Before We Continue”

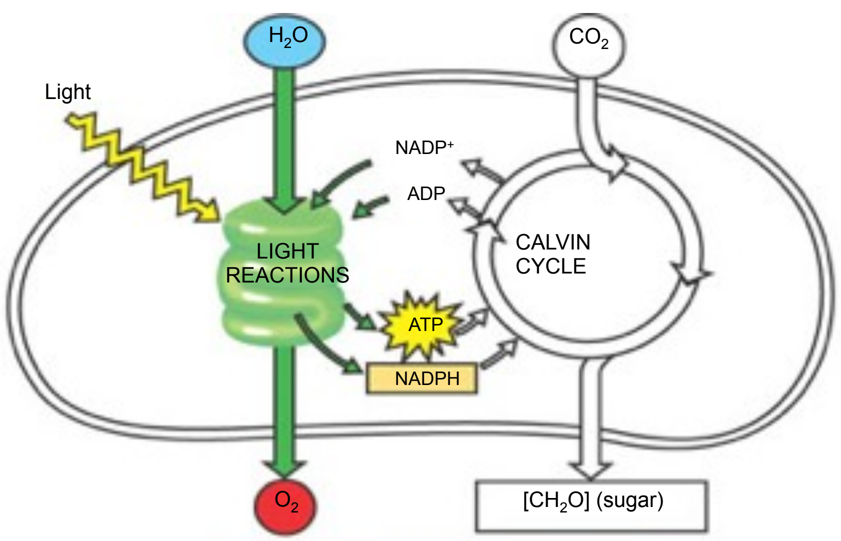
- **Building sugar in stage 2 of photosynthesis (Calvin Cycle) requires:**
  - **building blocks,**
  - **electrons,**
  - **energy**
- The building blocks (carbon) simply come from atmosphere via carbon dioxide.
- But the electrons (carried by NADPH) have to come from the light reactions via water
- And the energy (ATP) has to also come from the light reactions

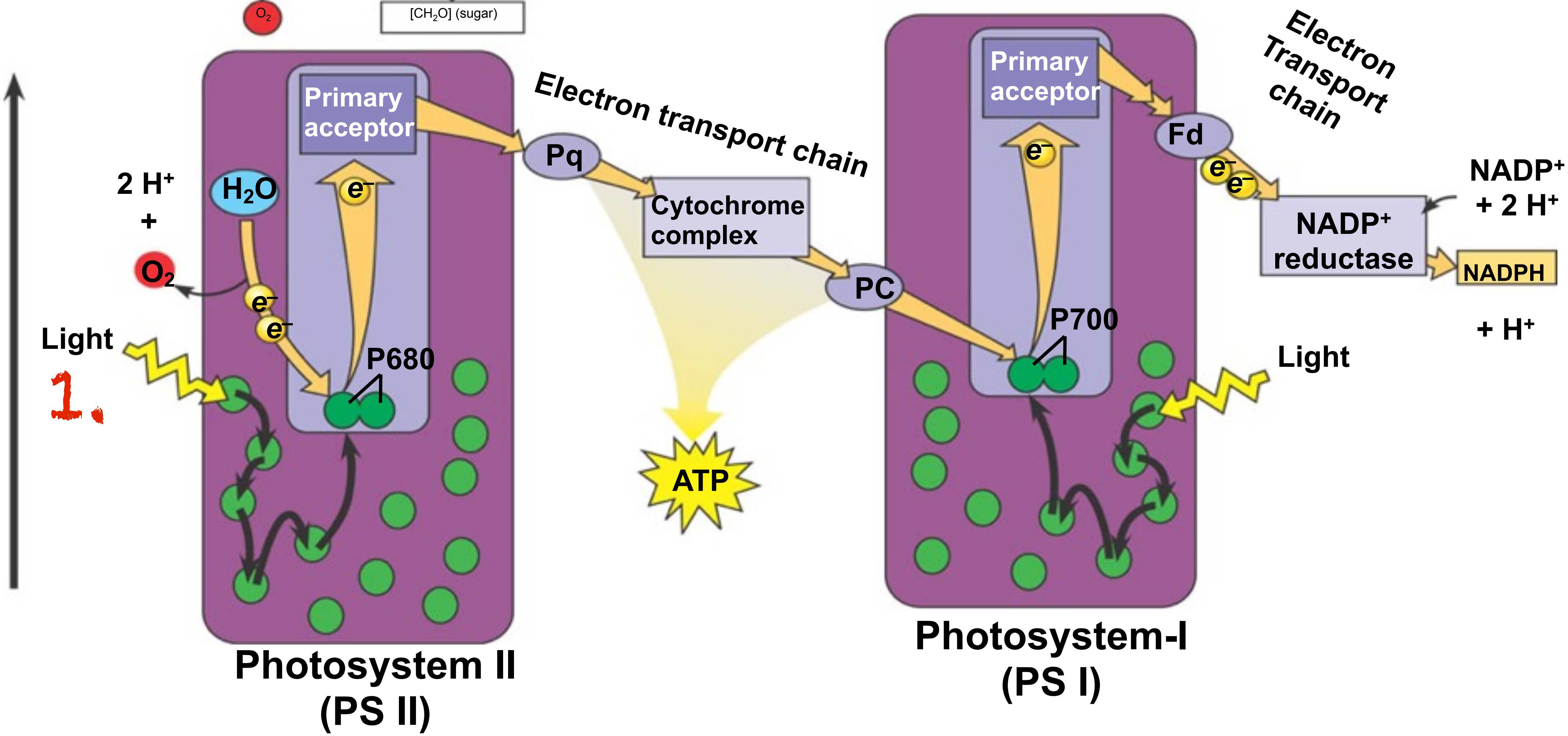
Light Reactions- Mechanical Analogy



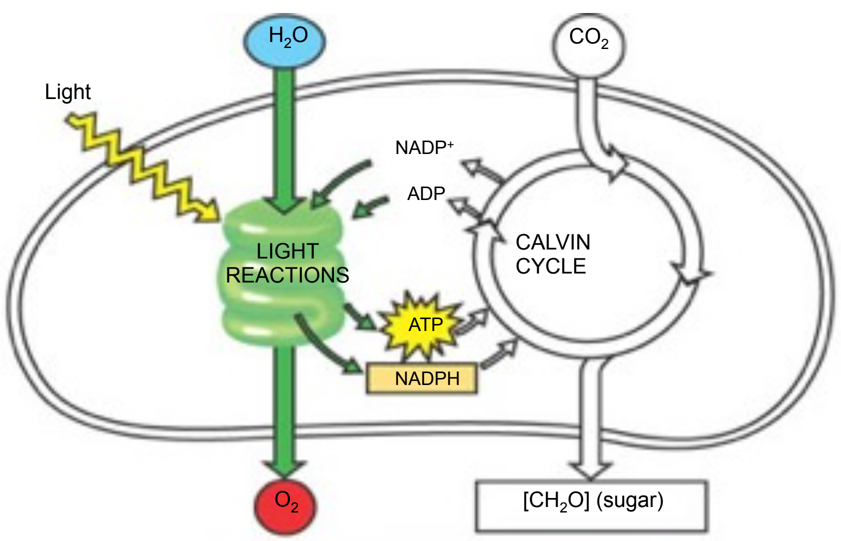
Linear Electron Flow

1. Photon of light strikes pigments in PSII, excites electron, electron falls and energy excites electron of nearby pigment, this continues until the electrons of the P680 chlorophyll are excited

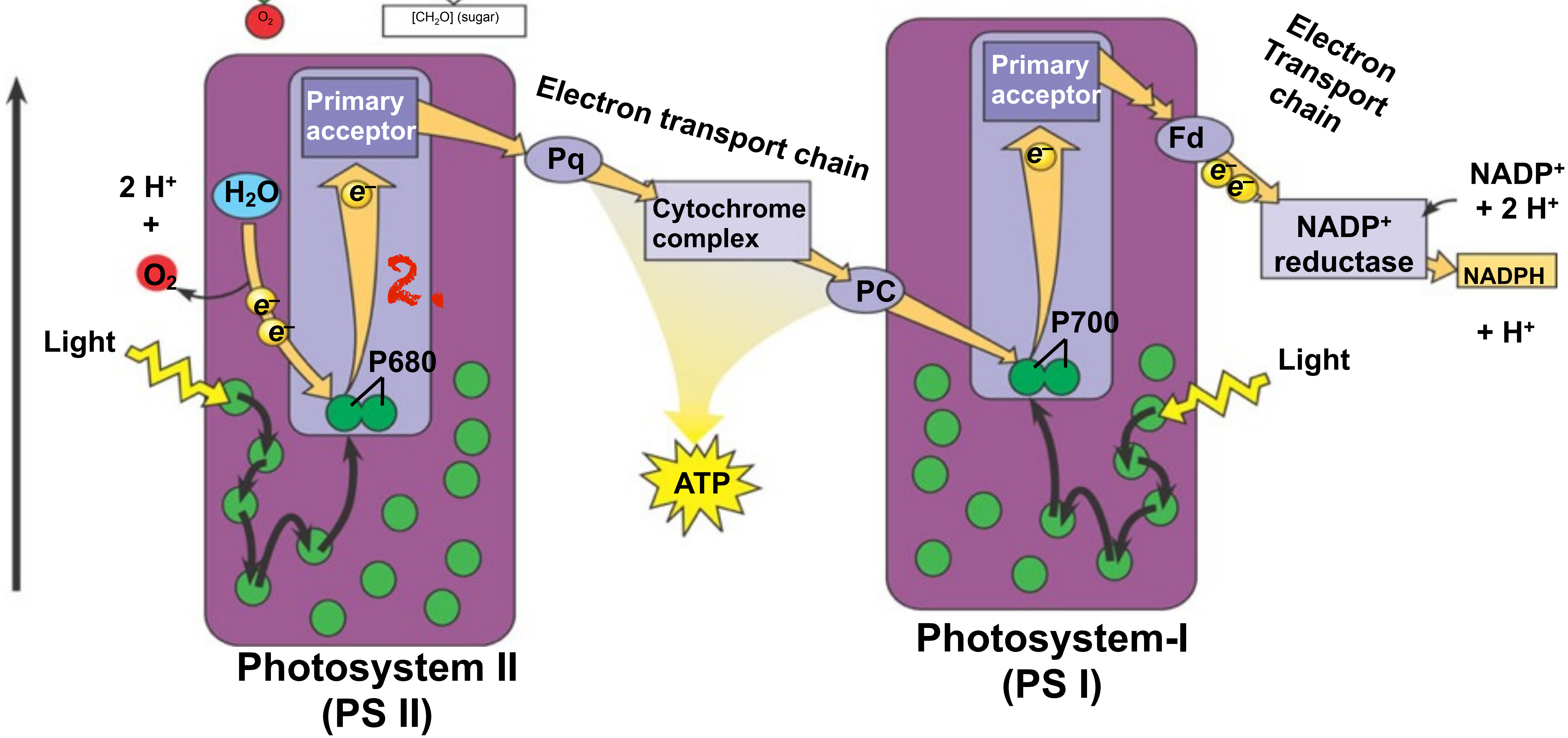




Linear Electron Flow

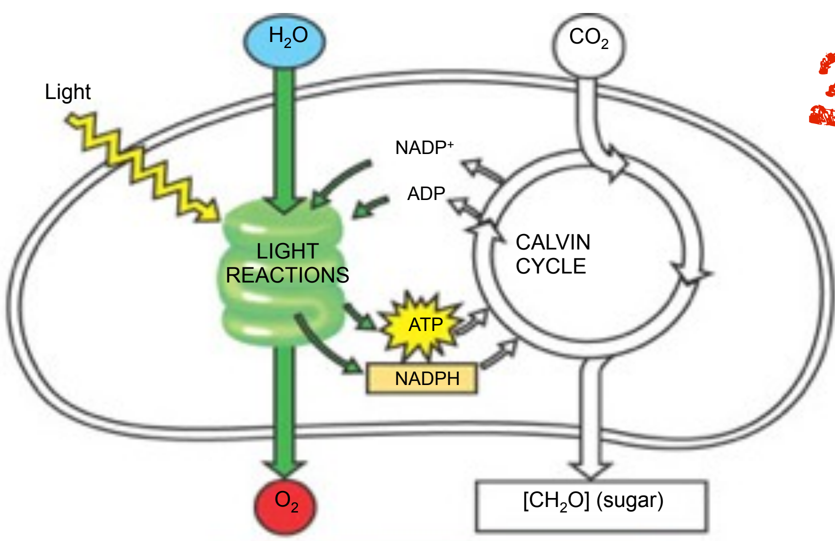


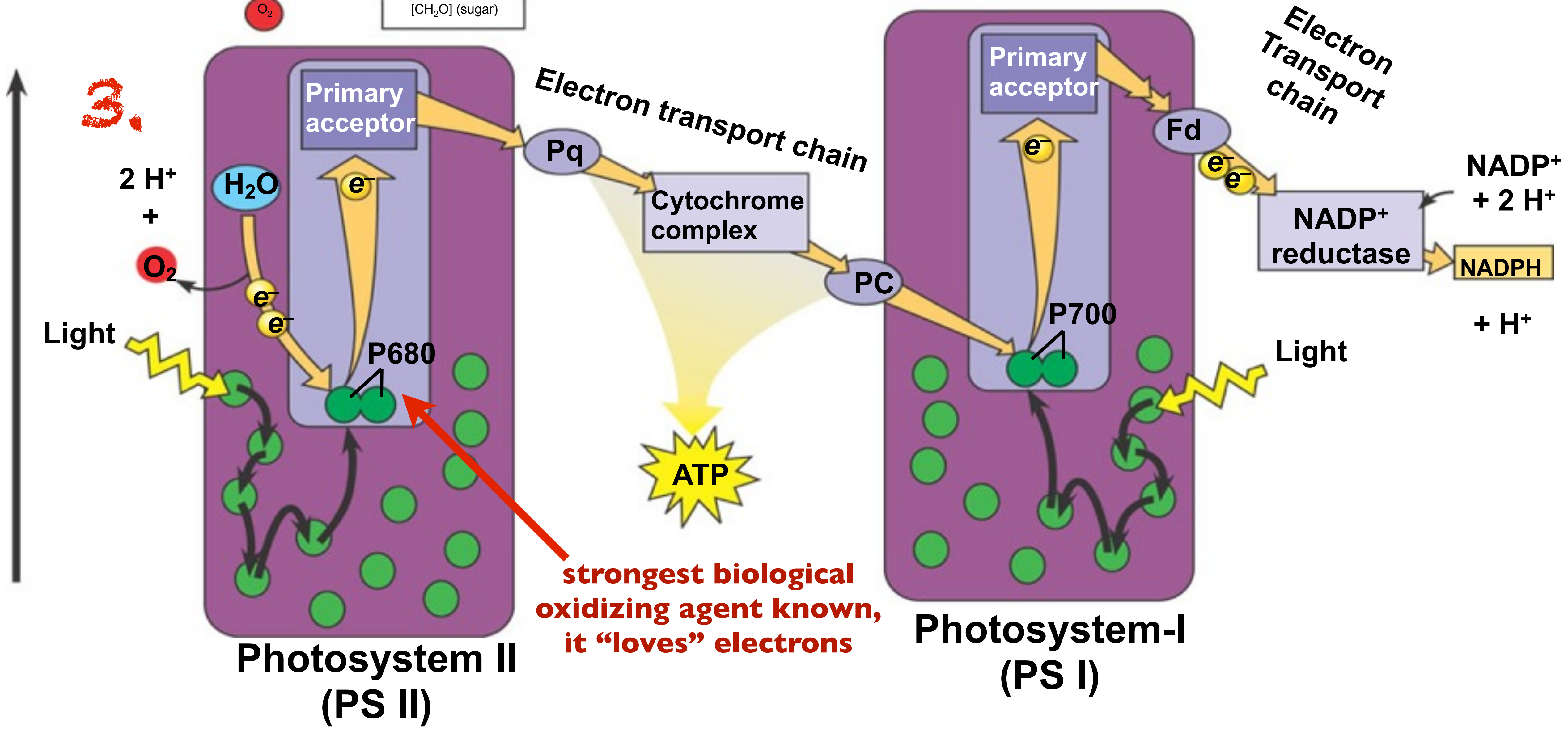
2. P680 chlorophyll is excited and loses its electron to the primary acceptor in PSII



Linear Electron Flow

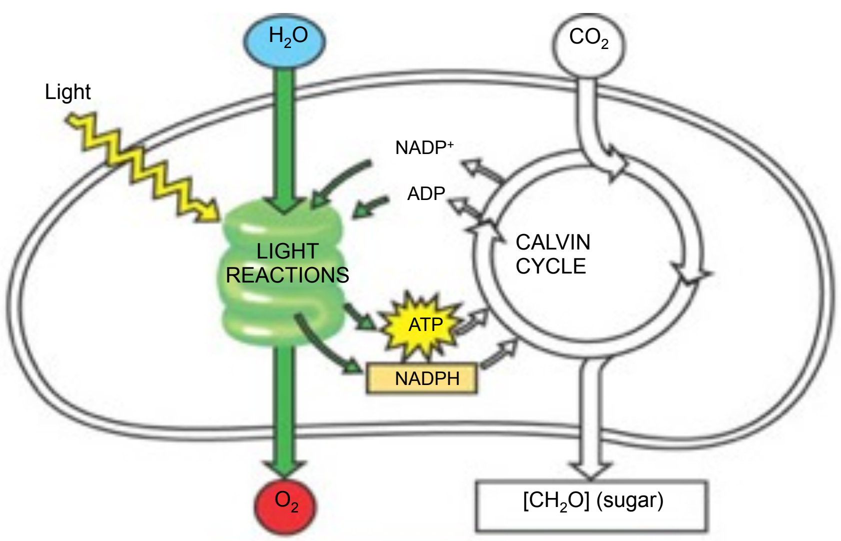
3. An enzyme catalyzes the splitting of water, thus removing its electrons, transferring and replacing them to the P680 pigment, meanwhile two oxygen atoms combine to form water and the hydrogen ions are released into thylakoid lumen

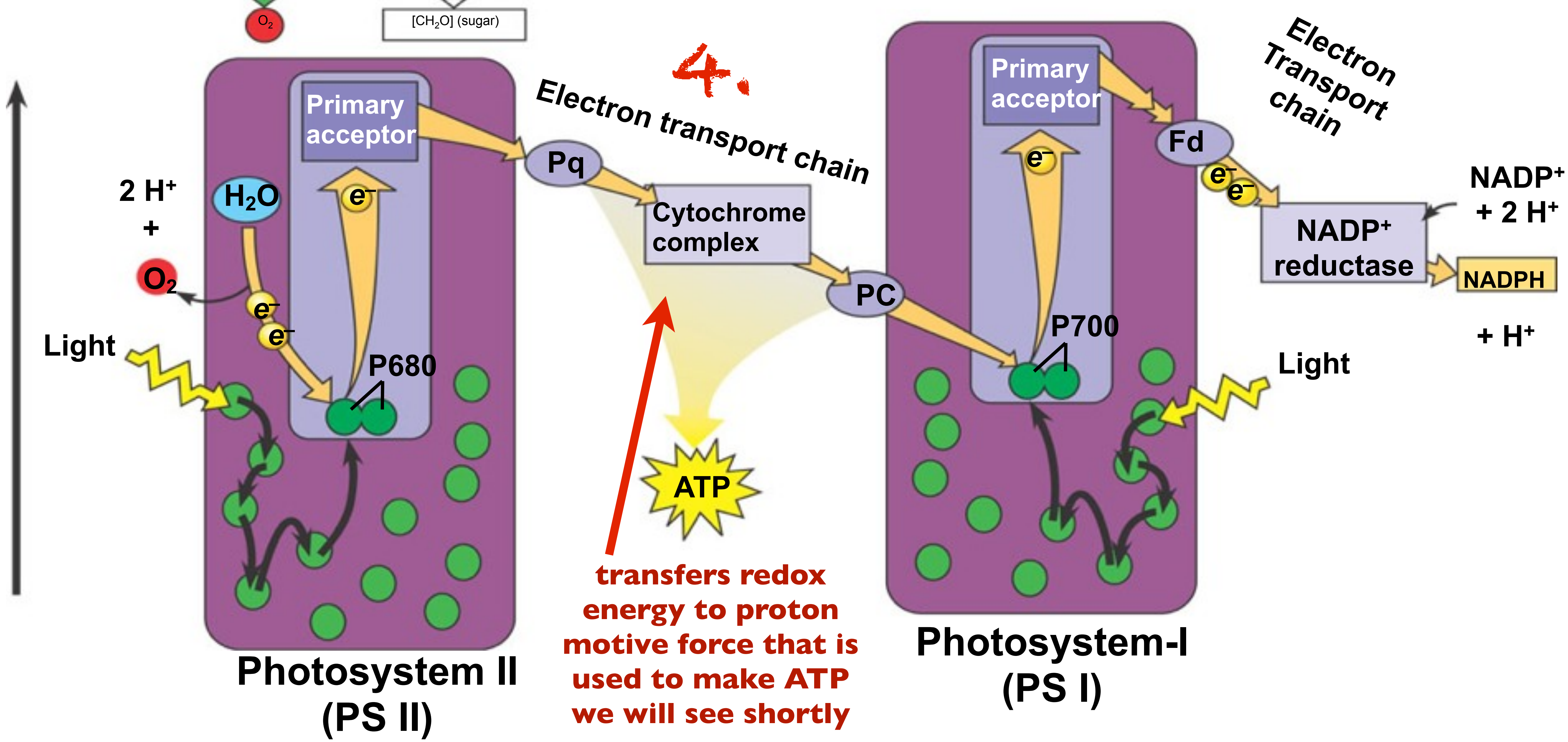




Linear Electron Flow

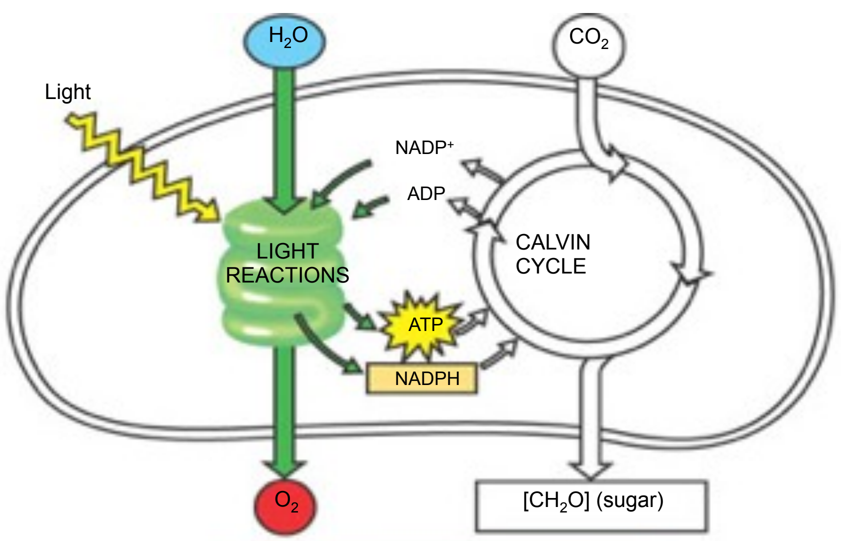
4. Each electron moves from PSII to the P700 chlorophyll pigment in the PSI via of an electron transport chain, a series of molecules each with a slightly higher electronegativity

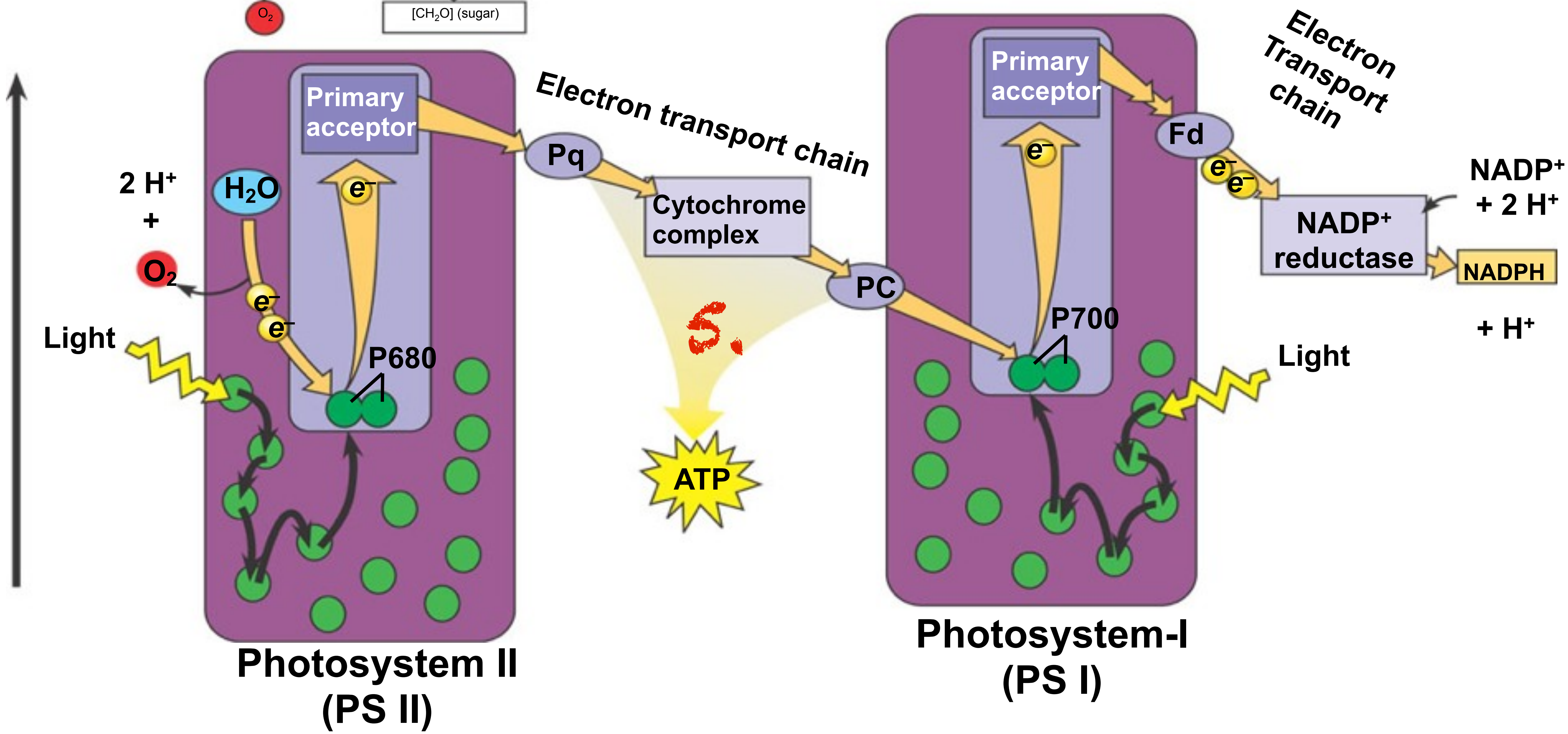




Linear Electron Flow

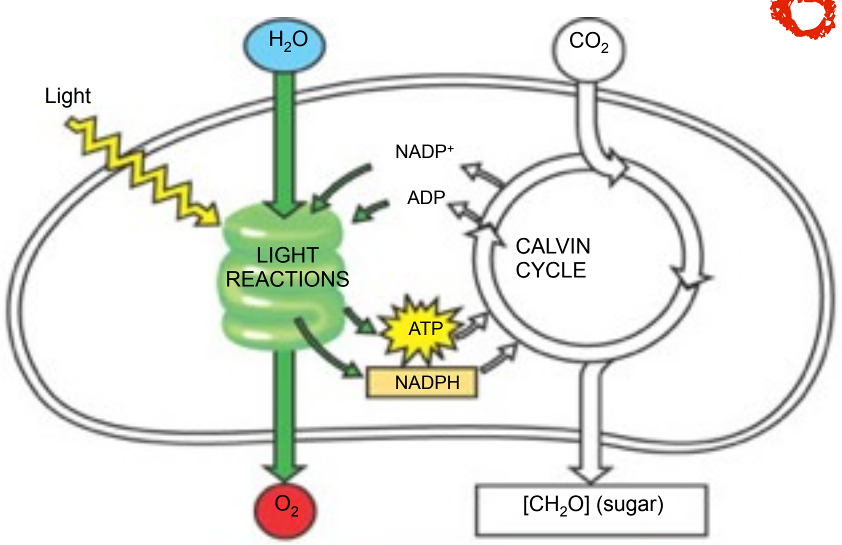
5. The energy released from the electrons "fall" is used to pump H^+ into thylakoid lumen, creating a H^+ (proton) gradient

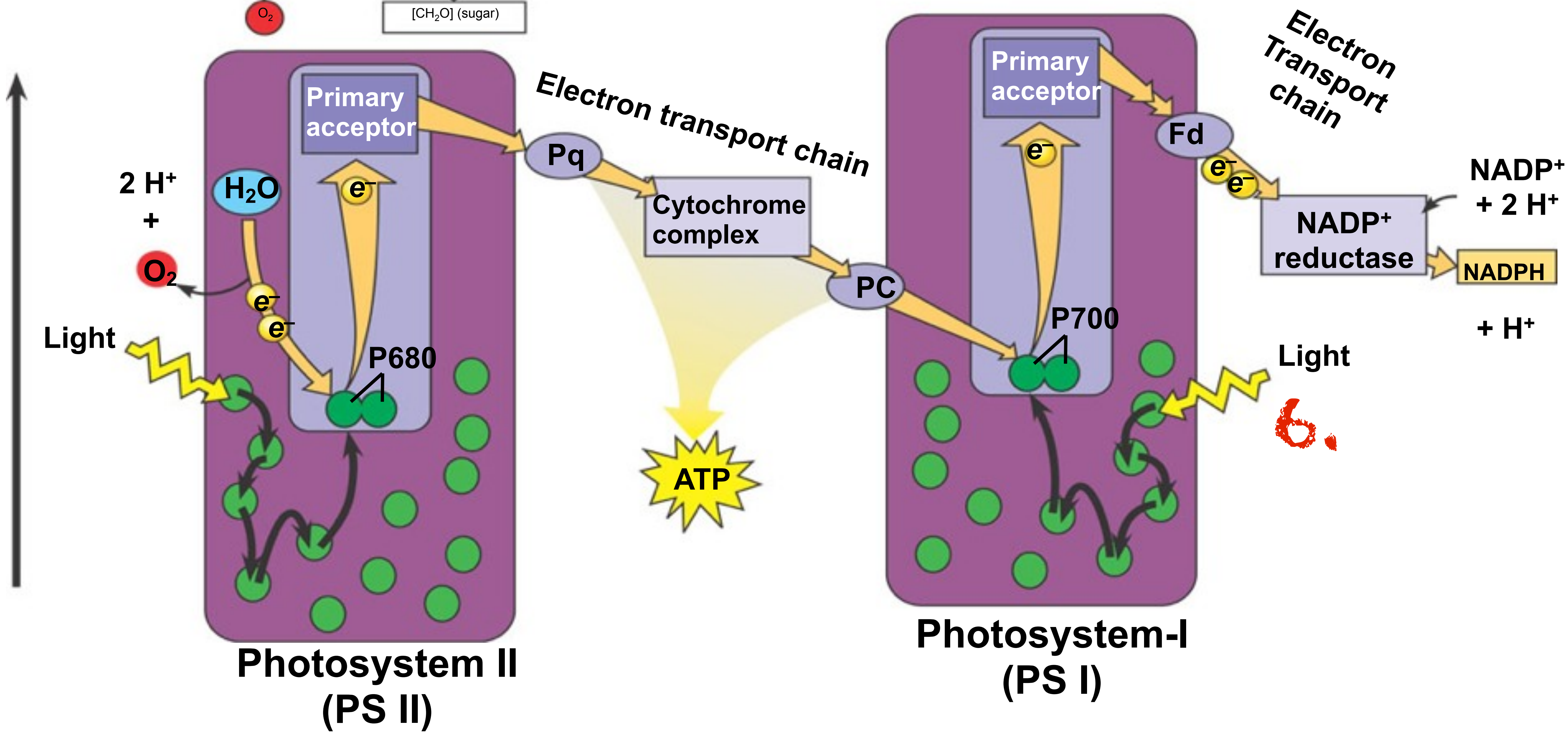




Linear Electron Flow

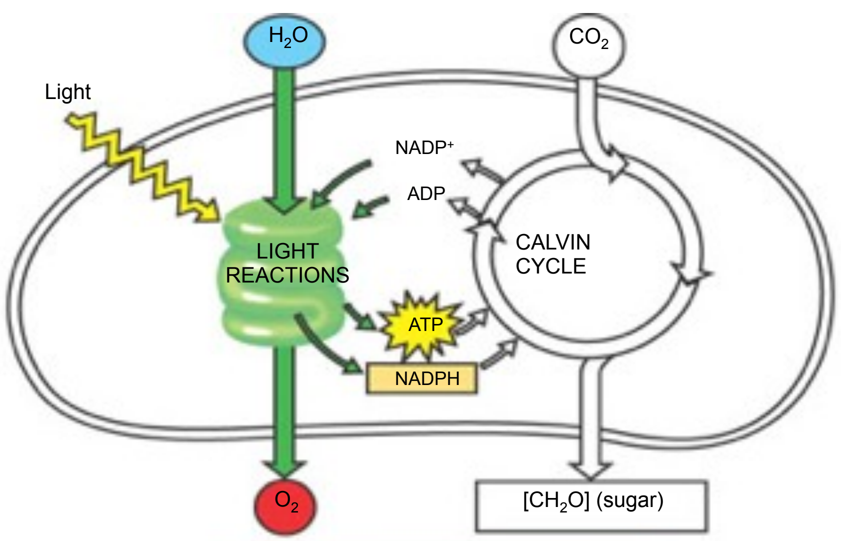
6. Photon of light strikes pigments in PSI, excites electron, electron falls and energy excites electron of nearby pigment, this continues until P700 chlorophyll is excited and loses its electron to the acceptor, the electrons are continuously replaced by incoming electron from from PSII

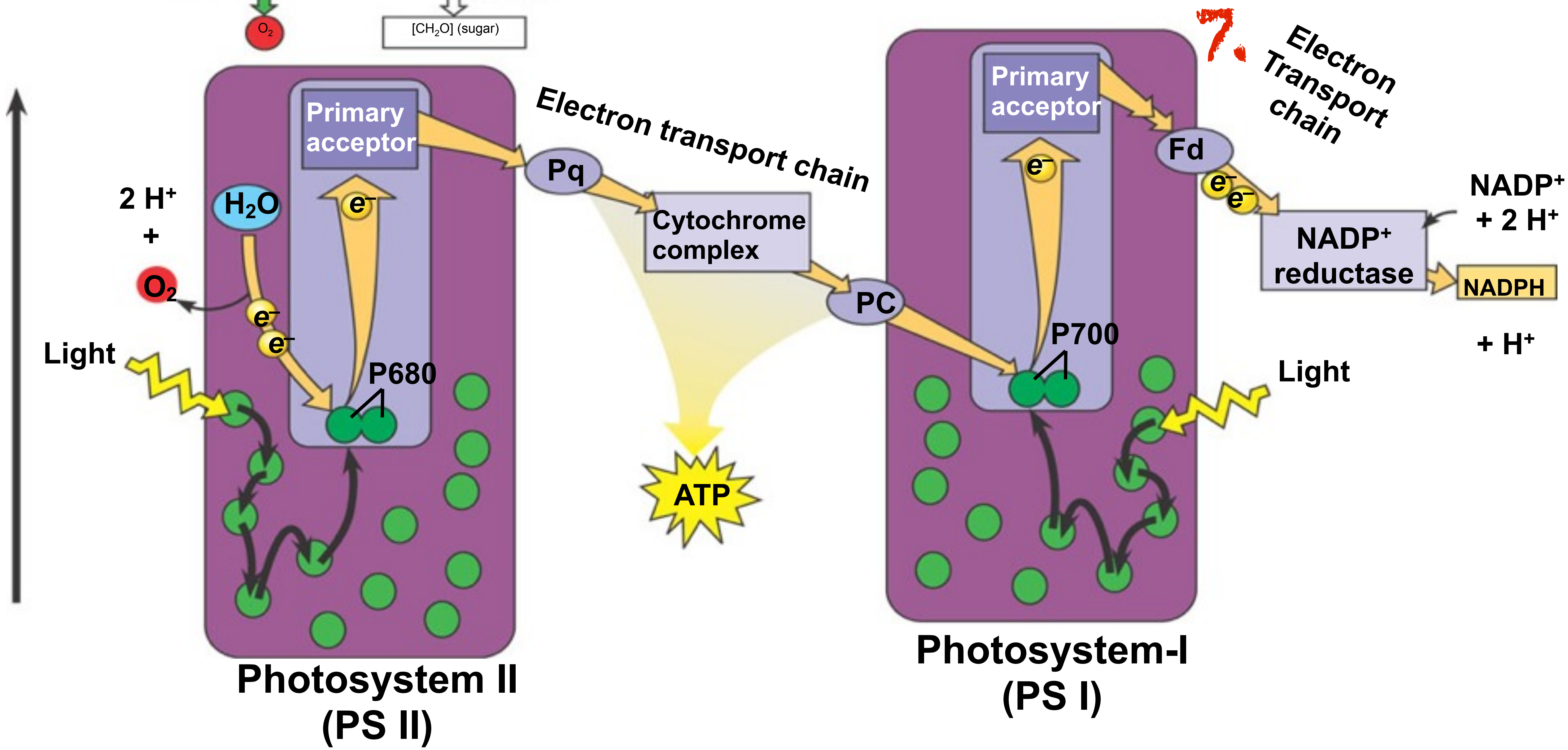




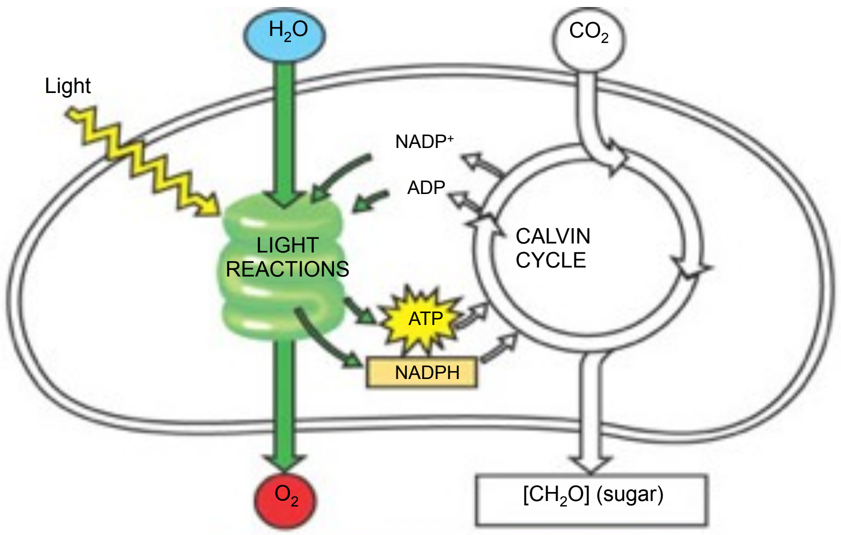
Linear Electron Flow

7. Each electron moves from PSI to $NADP^+$ via of an electron transport chain, but proton a gradient is not produced and thus no ATP is produced

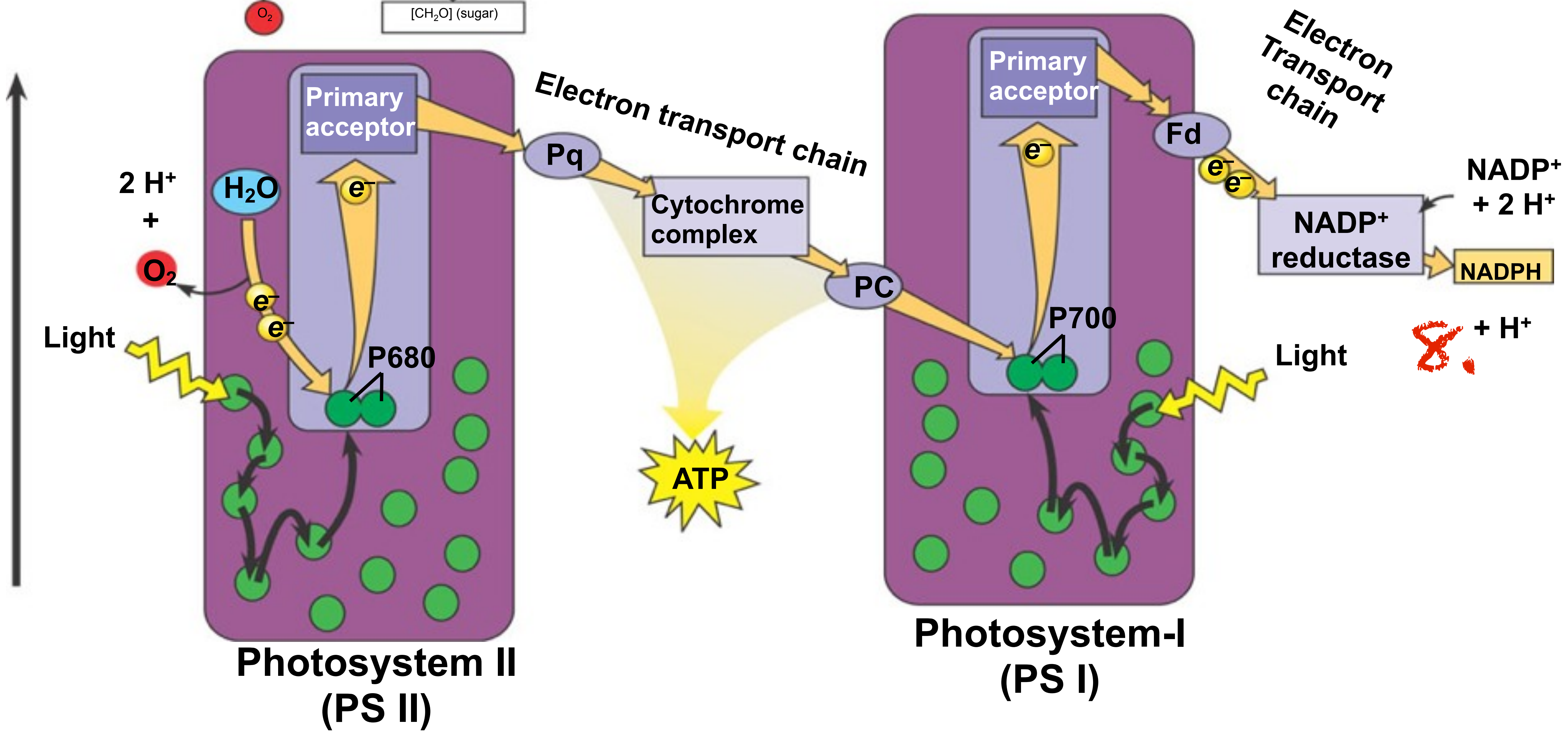




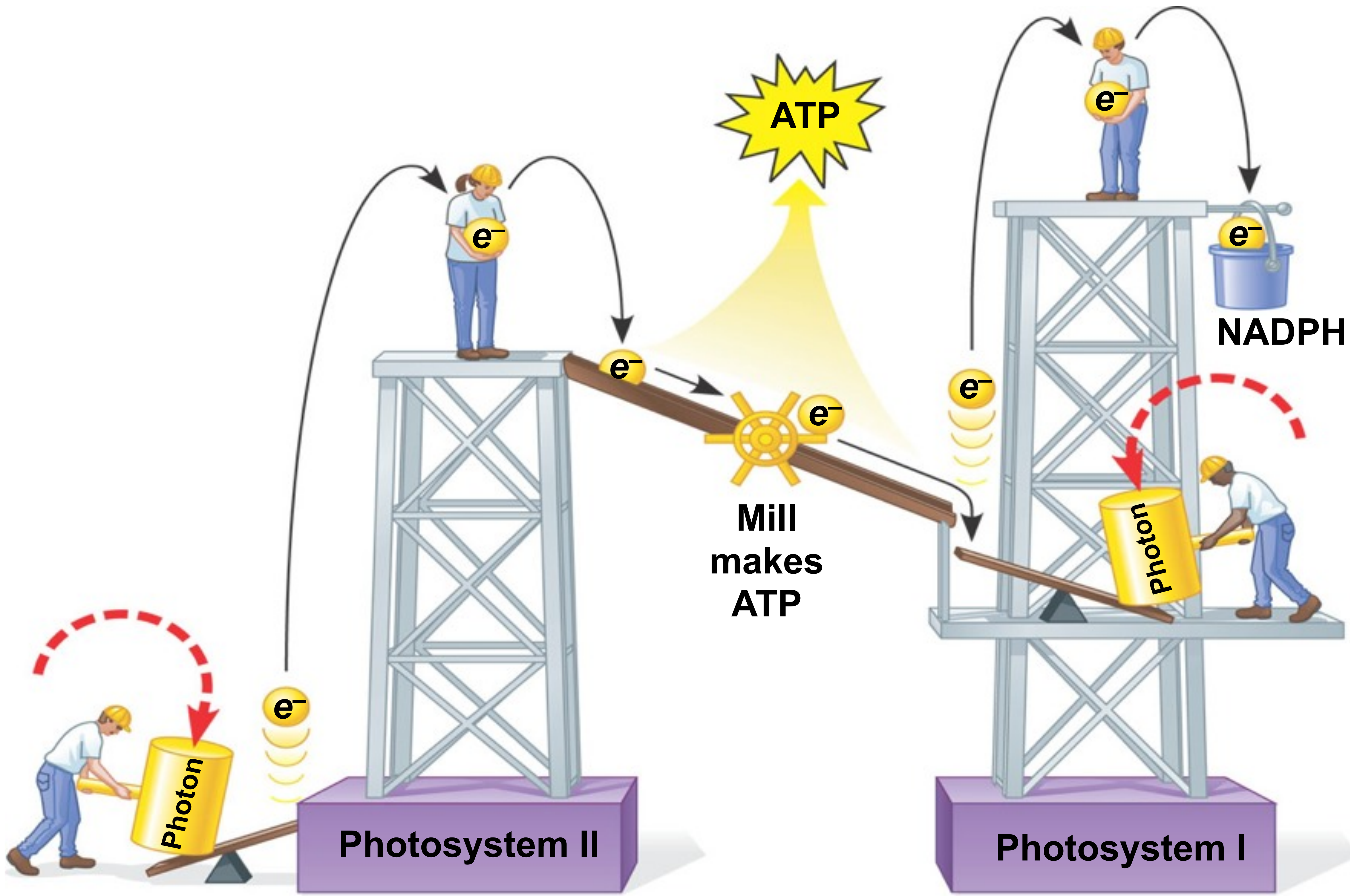
Linear Electron Flow



8. An enzyme transfers 2 electrons to $NADP^+$ thus reducing it to NADPH, the H^+ come from the stroma, the electrons in NADPH are at a higher energy level then water and thus easier to use in the Calvin Cycle

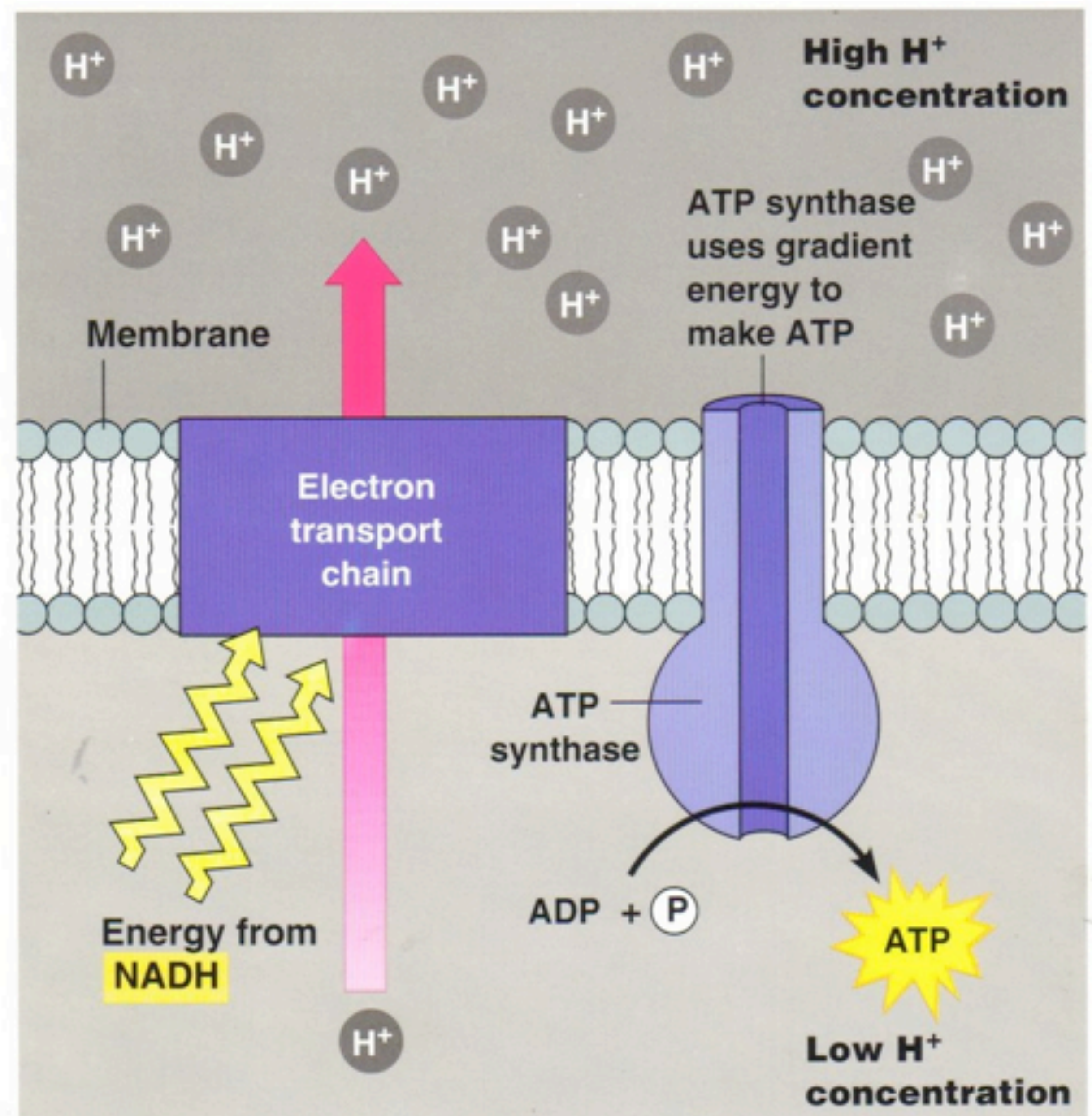


Light Reactions- Mechanical Analogy

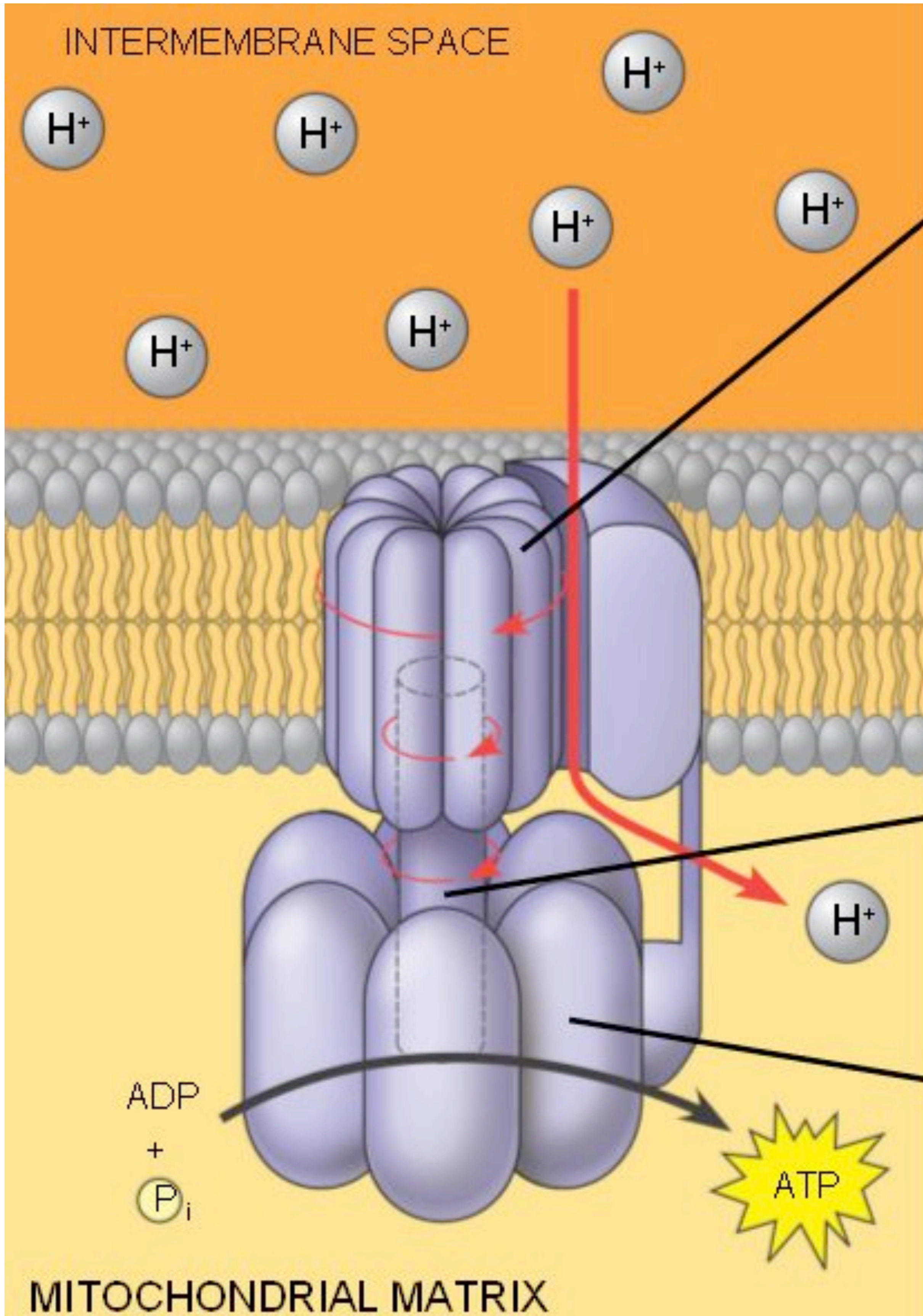


Chemiosmosis

- Chemiosmosis is an energy coupling mechanism that uses energy stored in the form of an H^+ gradient across a membrane to drive cellular work
  - it employs an electron transport chain & ATP synthase
  - it can be found in prokaryotes & eukaryotes
  - it is used in photosynthesis & cell respiration (as well as other cellular processes)



ATP Synthase



A **rotor** within the membrane spins clockwise when H^+ flows past it down the H^+ gradient.

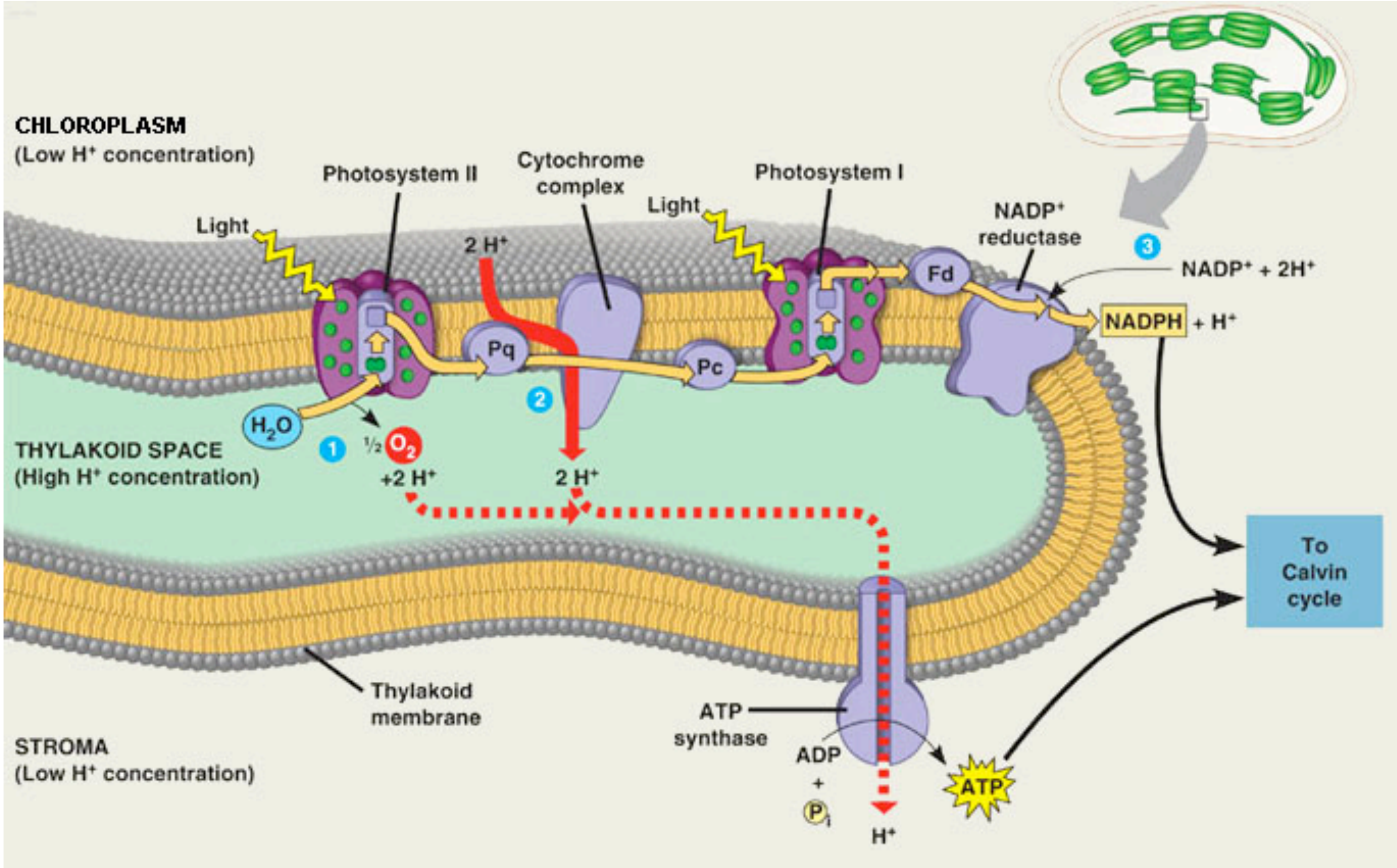
A **stator** anchored in the membrane holds the knob stationary.

A **rod** (or "stalk") extending into the knob also spins, activating catalytic sites in the knob.

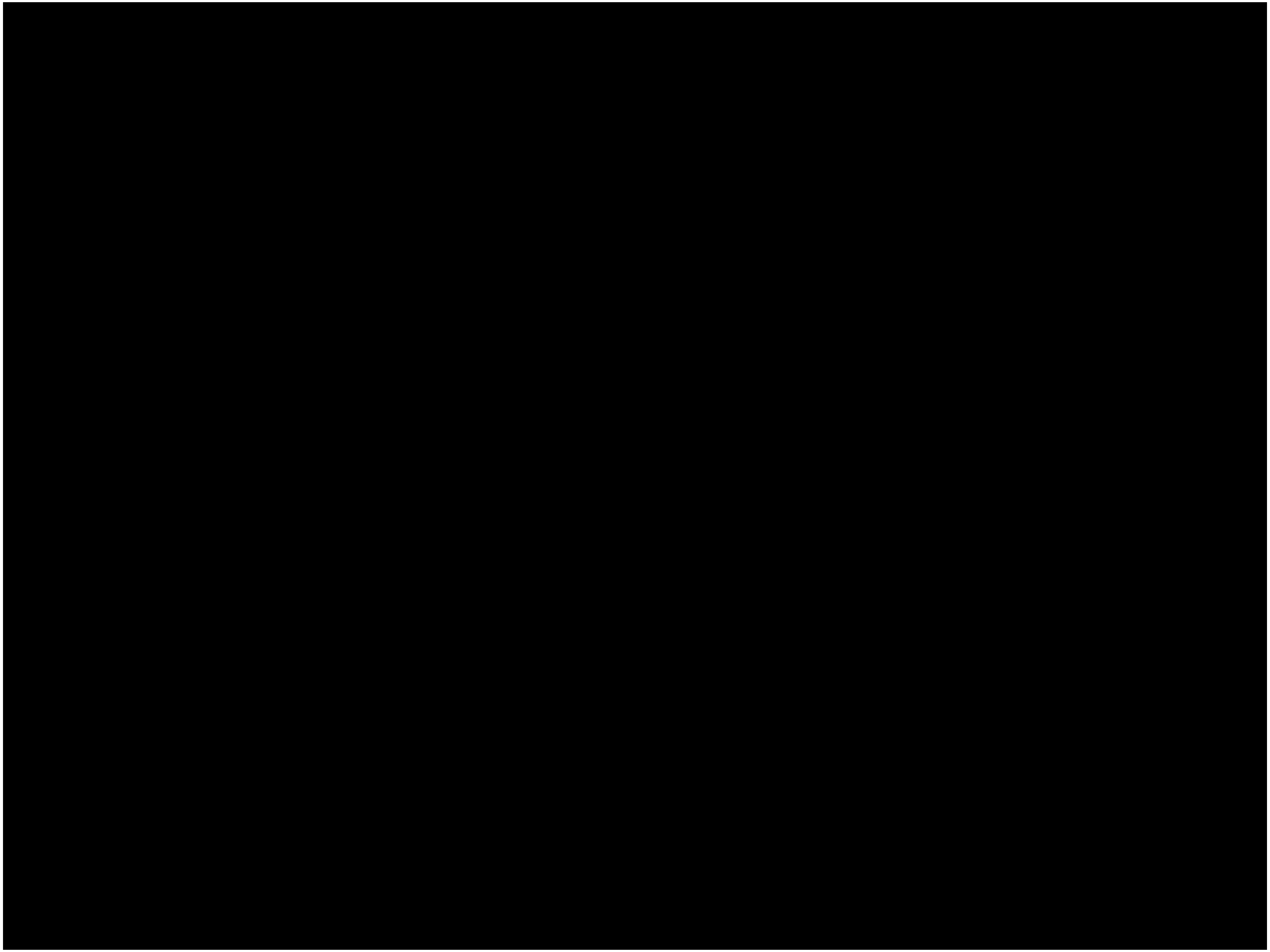
Three catalytic sites in the stationary **knob** join inorganic Phosphate to ADP to make ATP.

Photophosphorylation

- Chloroplasts are able harness solar energy (photo) to produce ATP (ADP + P = phosphorylation)
  - it does so through chemiosmosis



Photosynthesis



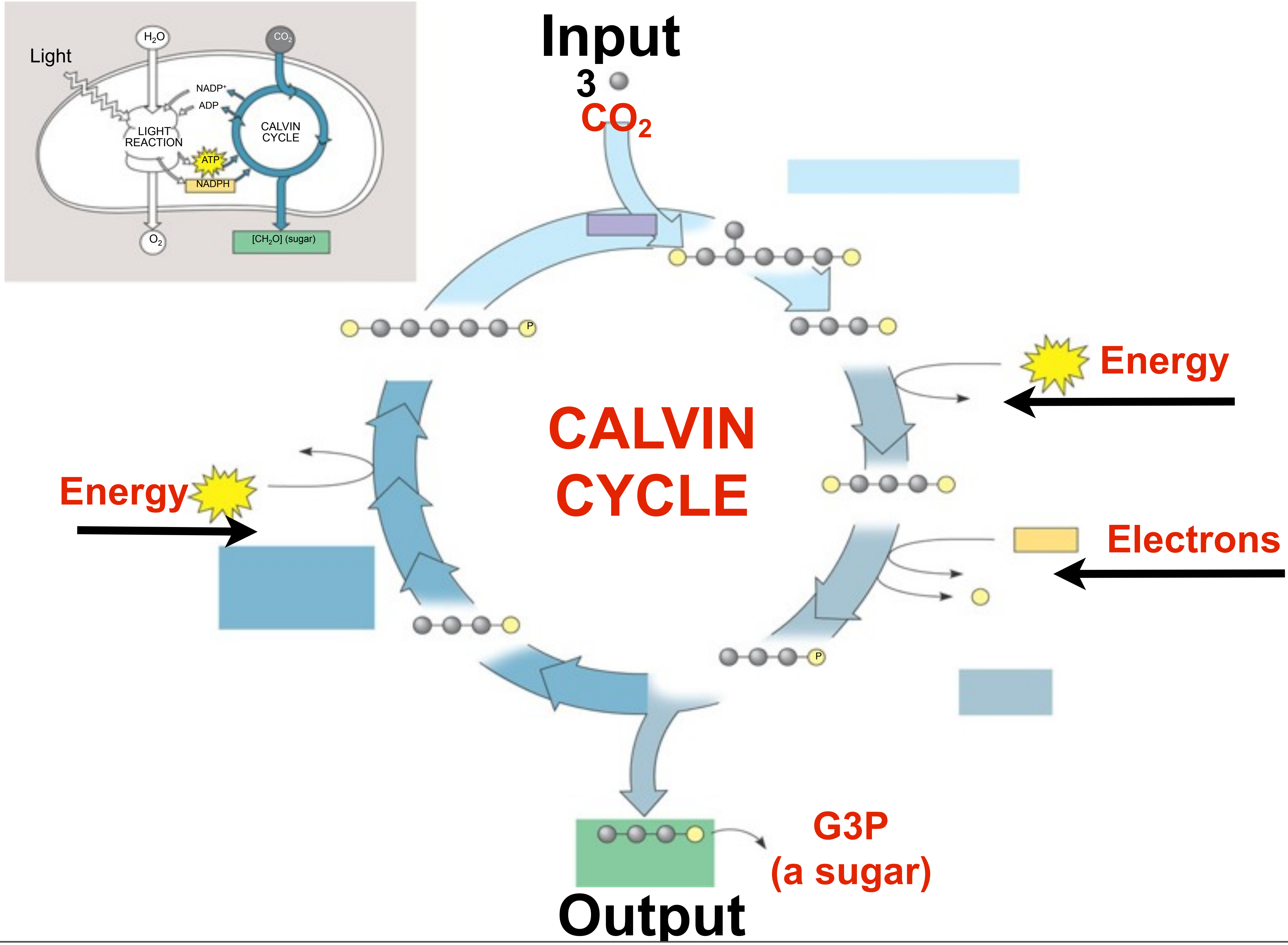
C_3 Photosynthesis

IV.

Main Idea: The Calvin Cycle builds sugars from carbon dioxide using energy from ATP and electrons from NADPH.

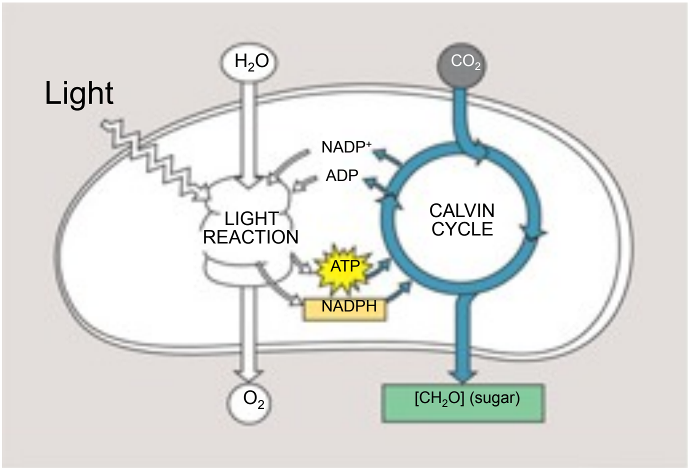
The Calvin Cycle (C_3 photosynthesis)

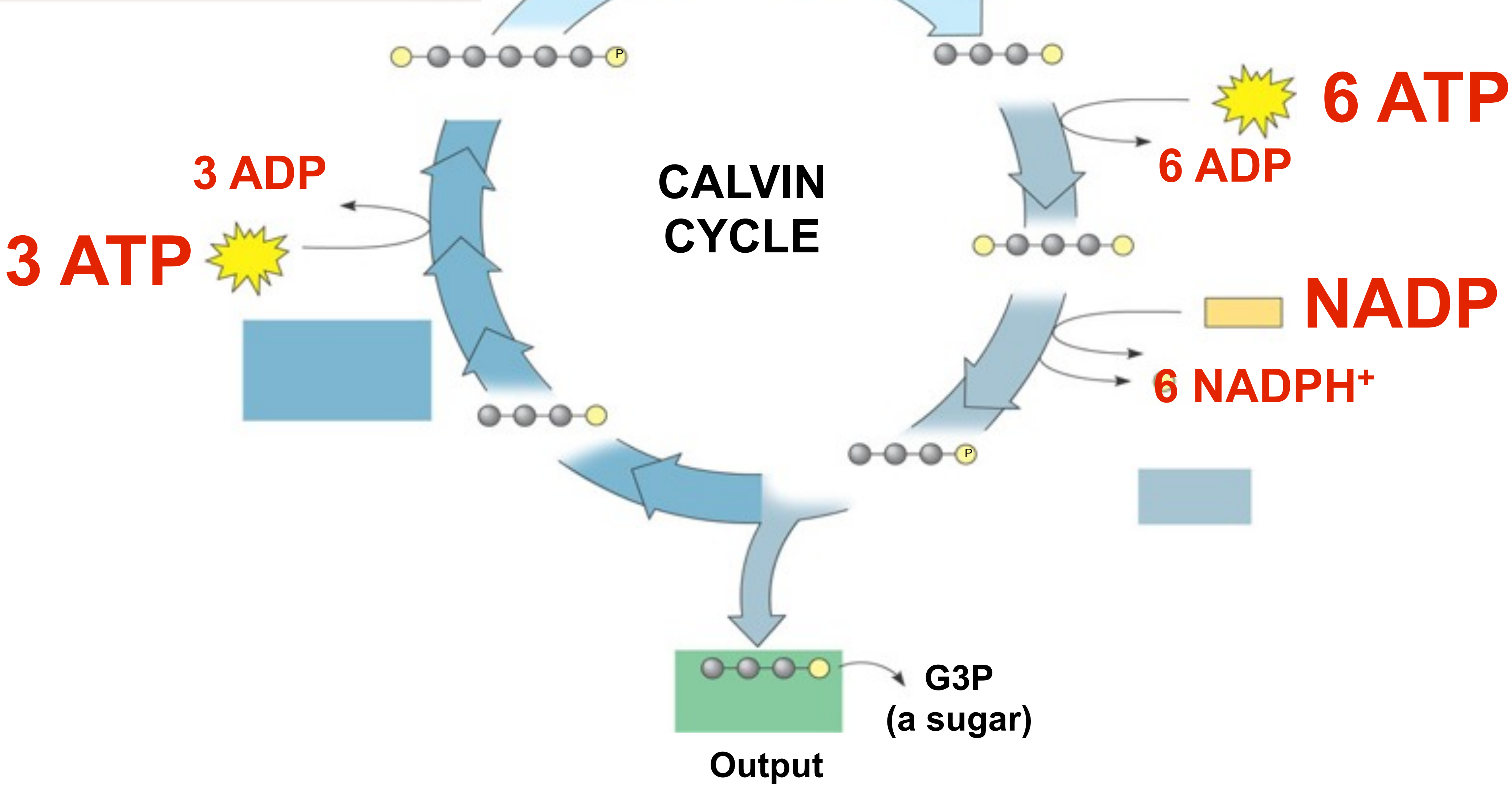
- The Calvin Cycle is an anabolic, energy consuming pathway of reactions that produce sugar form carbon dioxide



The Calvin Cycle (C₃ photosynthesis)

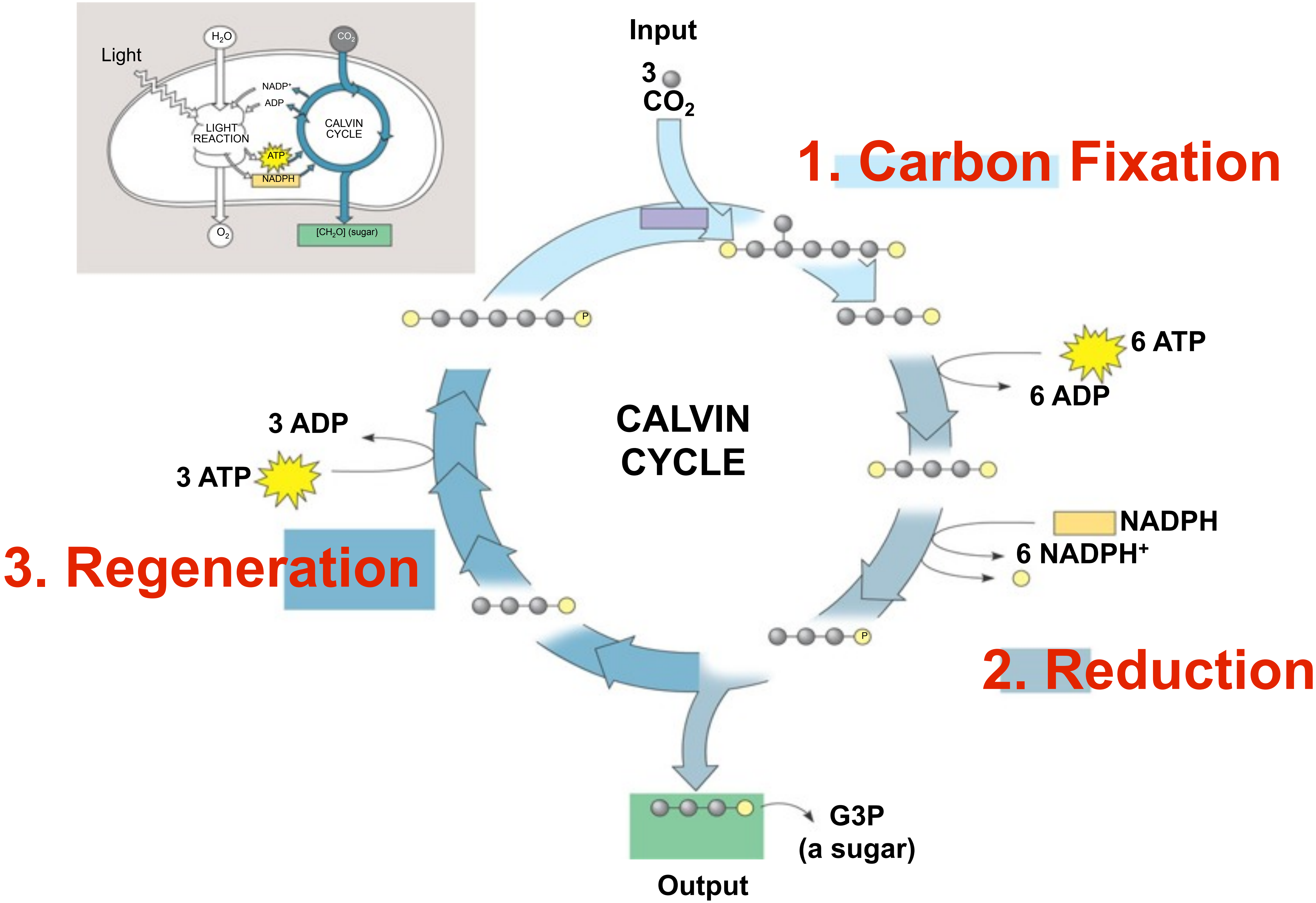
- The Calvin Cycle uses ATP and NADPH from the light reactions





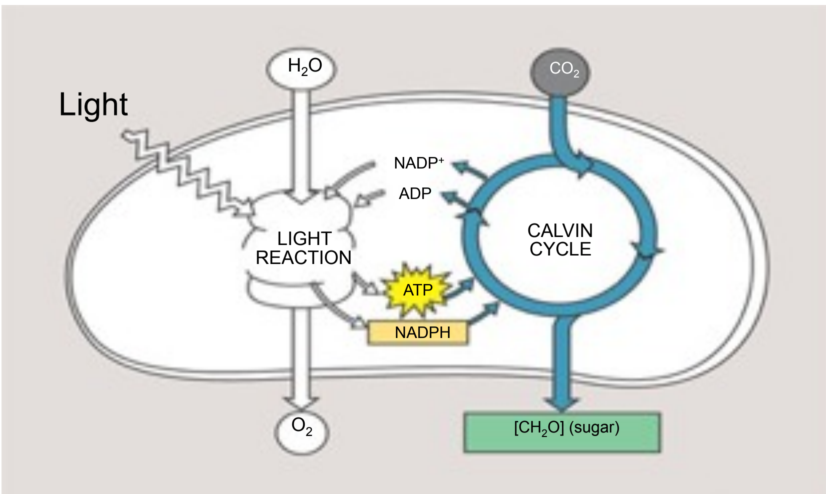
The Calvin Cycle (C3 photosynthesis)

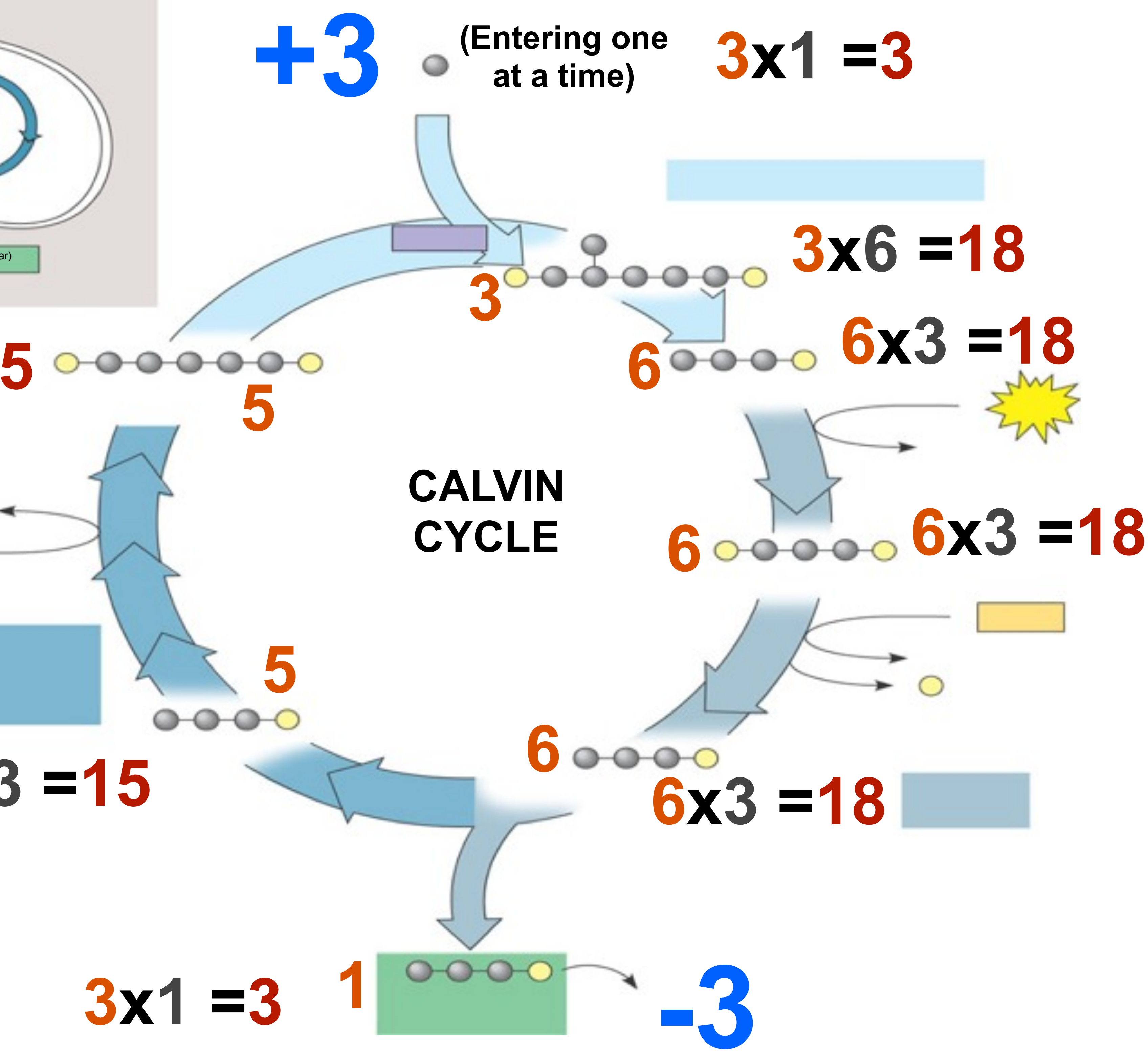
- The Calvin Cycle can be divided into three phases.



The Calvin Cycle (C_3 photosynthesis)

- Do some accounting work! (Track the number of carbon atoms)





The Calvin Cycle

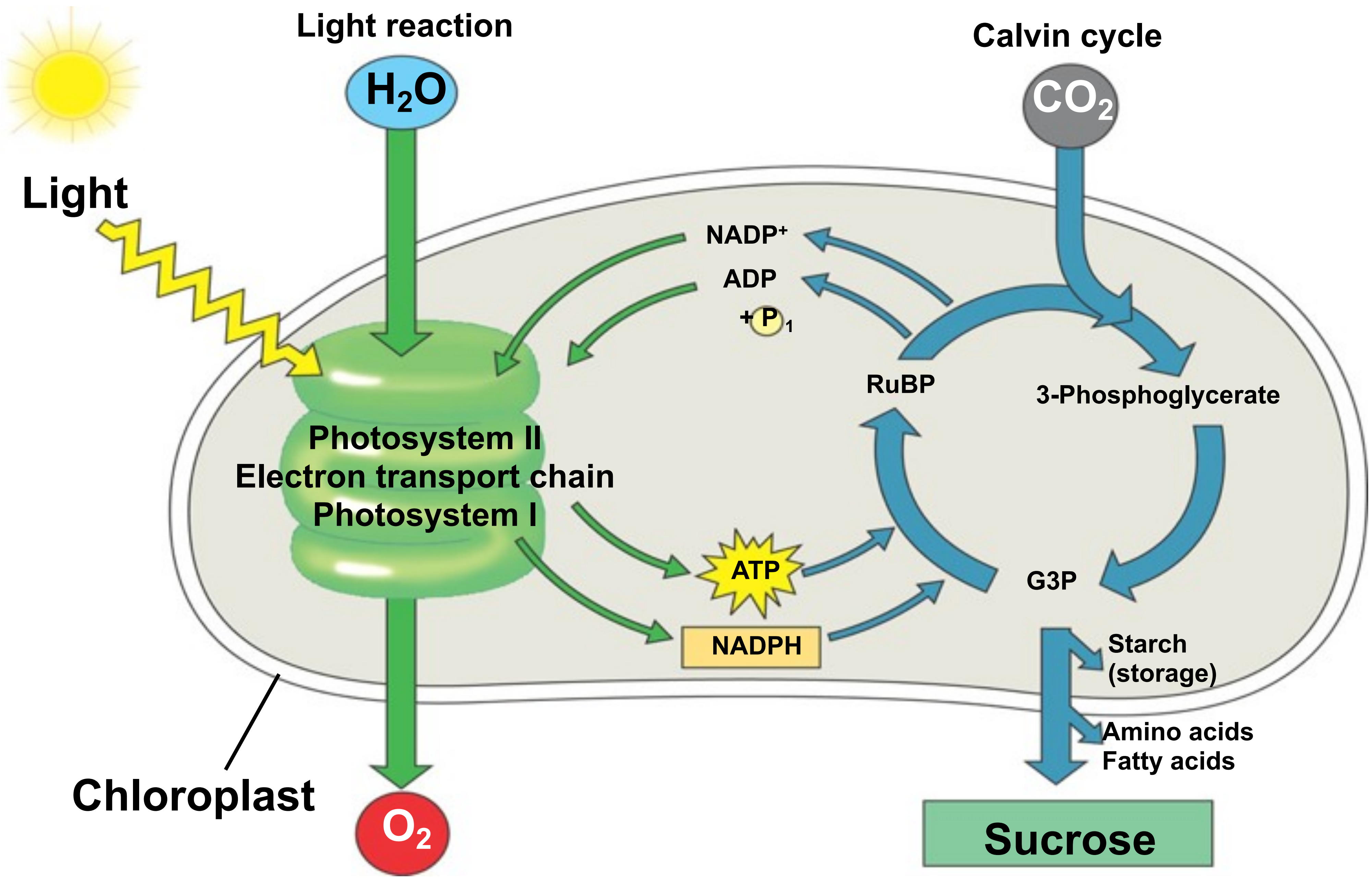
Maximum Photosynthetic Production

- There are two in which plants can increase there photosynthetic output or production.
  - Increase the rate of CO_2 into the leaf (could be accomplished by opening more and more stomata).
  - Increase the rate of carbon fixation (could be accomplished by using nitrogen and other nutrients to build more enzymes).

Why do you suppose that actual plant production is much lower than its theoretical maximum?

Because life is all about trade-offs, open too many stomates plant dehydrates, build too many enzymes plant depletes its nitrogen stores which are usually limited to begin with

Photosynthesis in Review



Light reactions:

- Are carried out by molecules in the thylakoid membranes
- Convert light energy to the chemical energy of ATP and NADPH
- Split H_2O and release O_2 to the atmosphere

Calvin cycle reactions:

- Take place in the stroma
- Use ATP and NADPH to convert CO_2 to the sugar G3P
- Return ADP, inorganic phosphate, and NADP+ to the light reactions

Importance of Photosynthesis

- 100% of the sugar made by photosynthesis provides the entire plant with carbon building blocks and energy.
- 50% of the sugar is used by the mitochondria for fuel.
  - Sugar leaves the "photosynthetic cells" as sucrose, the other cells use this for energy or to build a variety of other molecules
- Most plants, most of the time produce more sugar than they use per day.
  - The sugar is stored in chloroplasts, roots, tubers, seeds and fruits.

Importance of Photosynthesis

- On a global scale photosynthesis is responsible for our oxygen rich atmosphere.
- Photosynthesis collectively produces 160 billion metric tons of carbohydrate per year.
    - *mass equivalent to17 stacks of your textbook from here to the sun.*
- No other chemical process on earth can match this output!
- No other chemical process is more important to the welfare of life on earth.