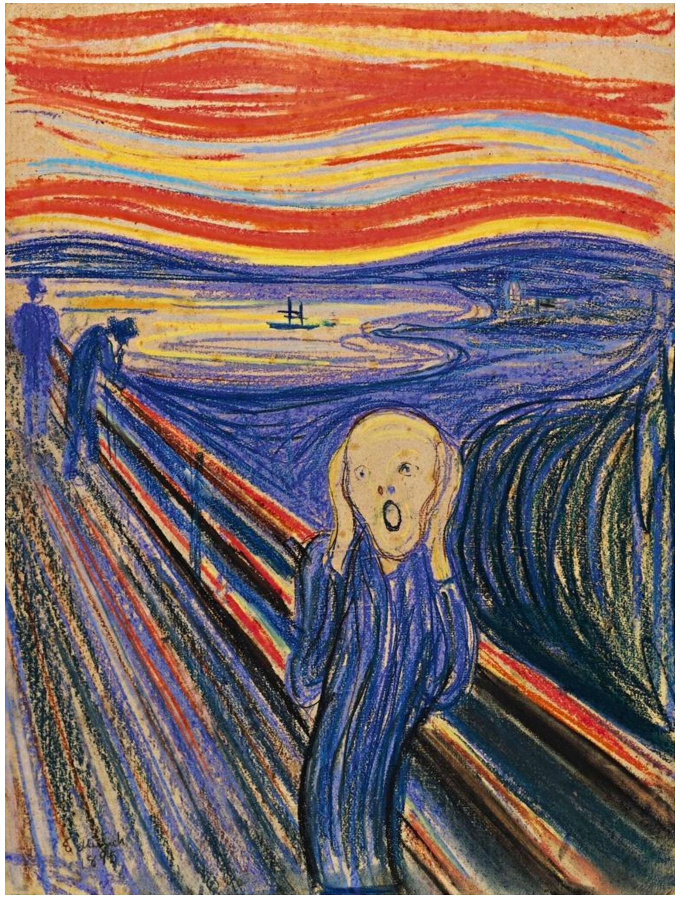

Introduction to
photosynthesis

Why Should Environmental Engineering Students Care About … Photosynthesis?



1. Photosynthesis and Climate Change

- It removes carbon dioxide from the atmosphere, playing a vital role in the carbon cycle.
- Understanding photosynthesis helps engineers design solutions for carbon sequestration and climate change mitigation.

2. Renewable Energy and Sustainability

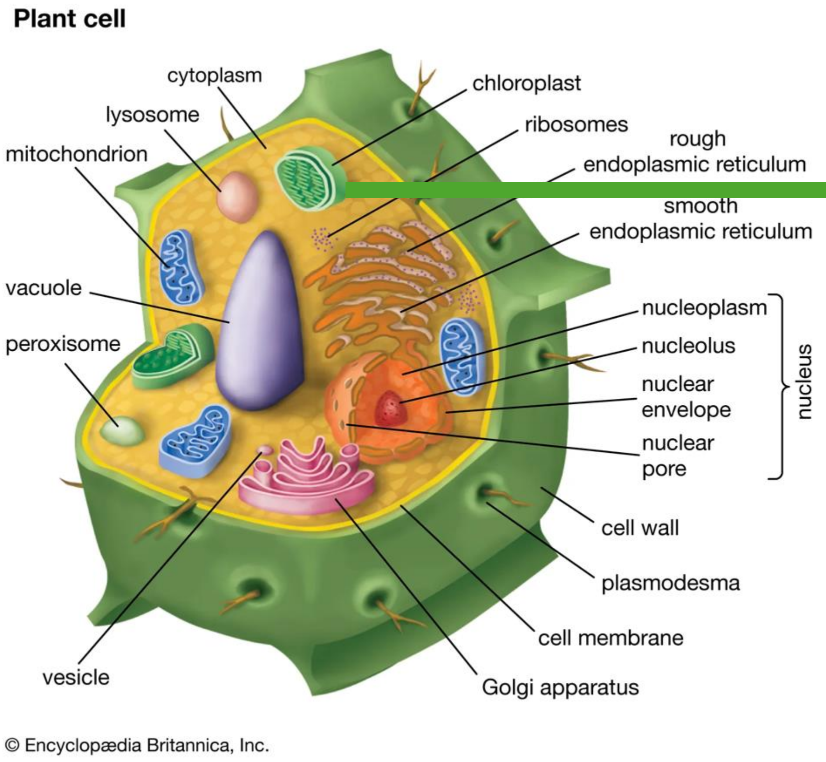
- Photosynthesis powers biofuels, converting solar energy into chemical energy.
- Development of sustainable energy sources like bioenergy.

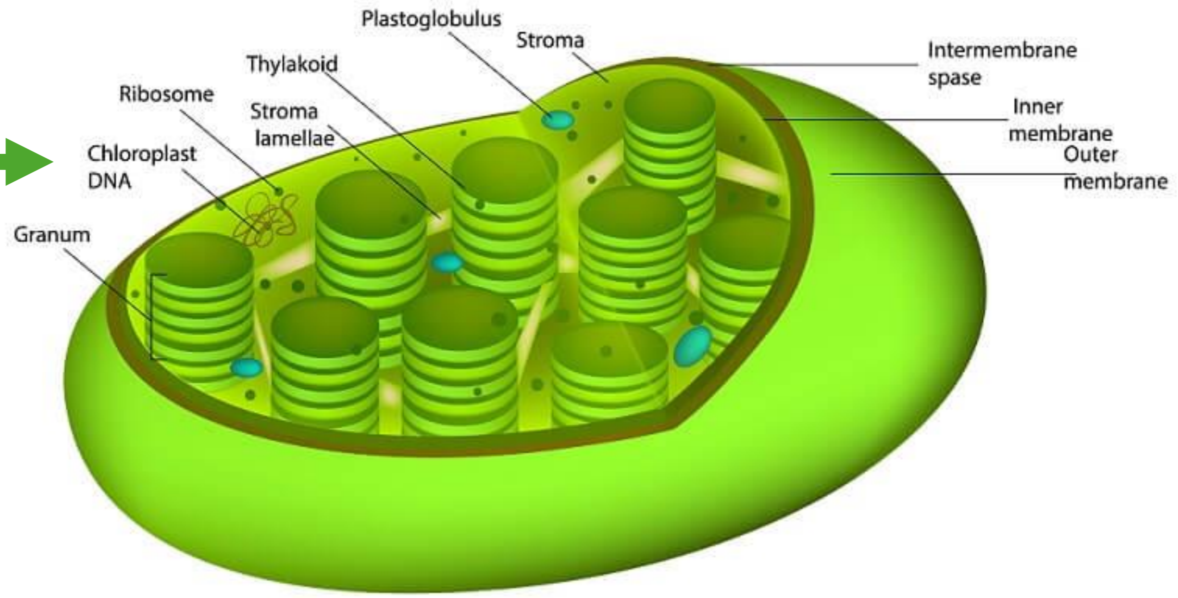
3. Pollution Control and Ecosystem Restoration

- Plants use photosynthesis in phytoremediation, absorbing pollutants from soil and water.
- Engineers can leverage this process to clean up contaminated environments and improve ecosystem health.

Photosynthesis feeds the biosphere

- **Photosynthesis** is the process that converts solar energy into chemical energy within chloroplasts
- **Photosynthesis** nourishes almost the entire living world directly or indirectly



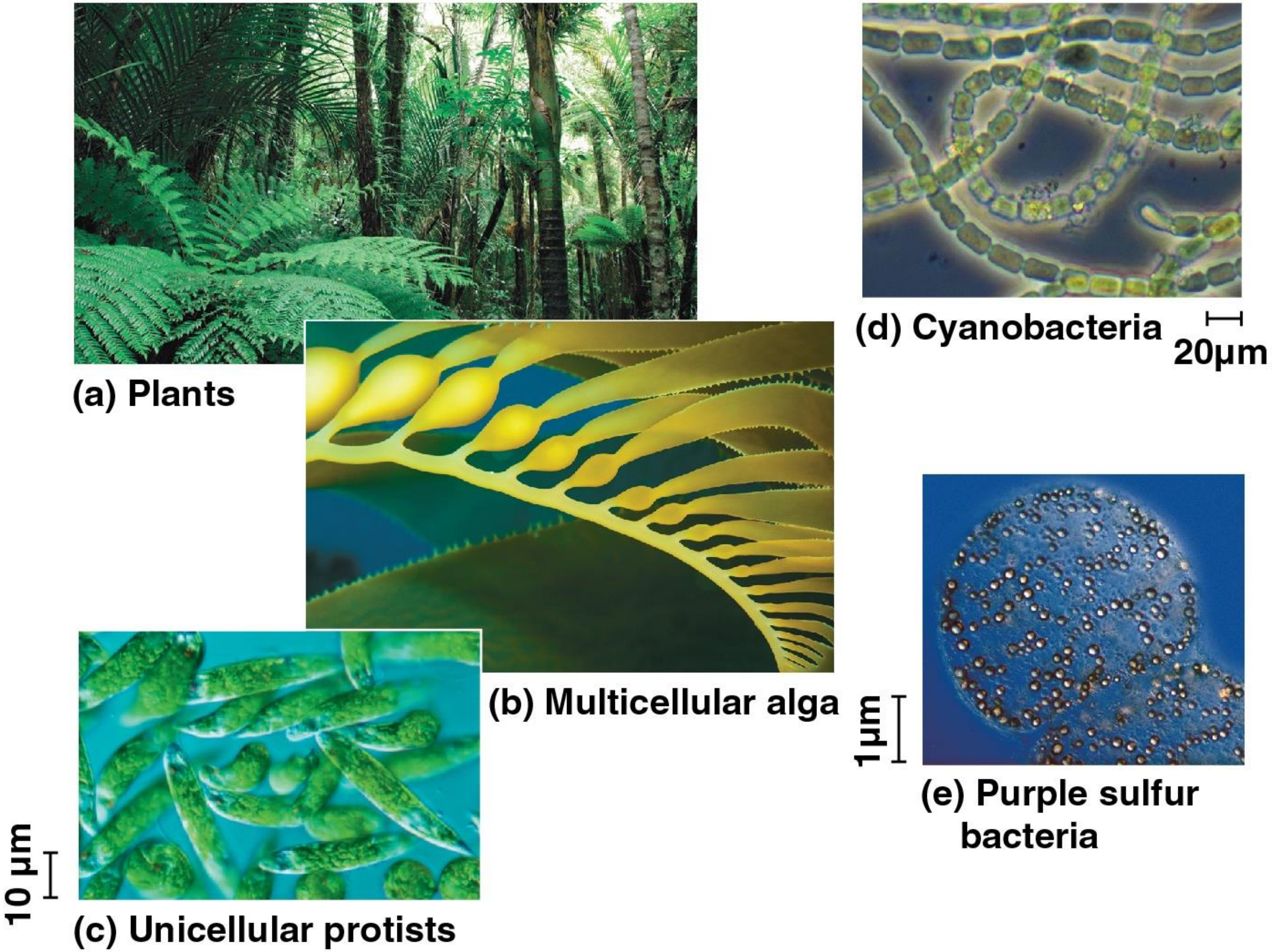


Photosynthesis Powers Most Life on Earth

- Plants, algae, and some photosynthetic protists and bacteria are **photoautotrophs**, the producers of food consumed by heterotrophic organisms.
- **Heterotrophs** are consumers that feed on plants or animals or decompose organic material.

Examples photosynthethic organisms

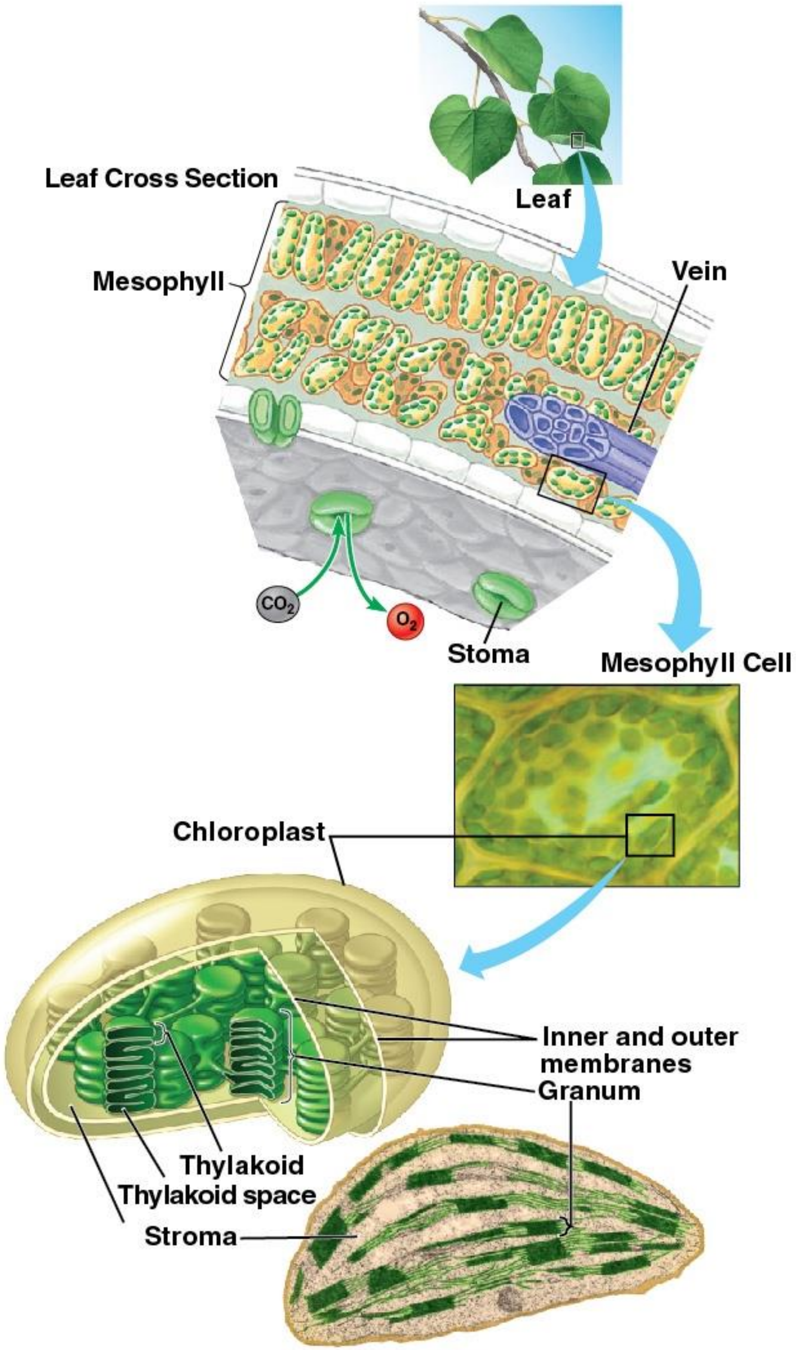
- Almost all plants are photoautotrophs, that is, they use the energy of sunlight to make organic molecules
- **Photosynthesis also occurs in algae, certain other protists, and some prokaryotes**

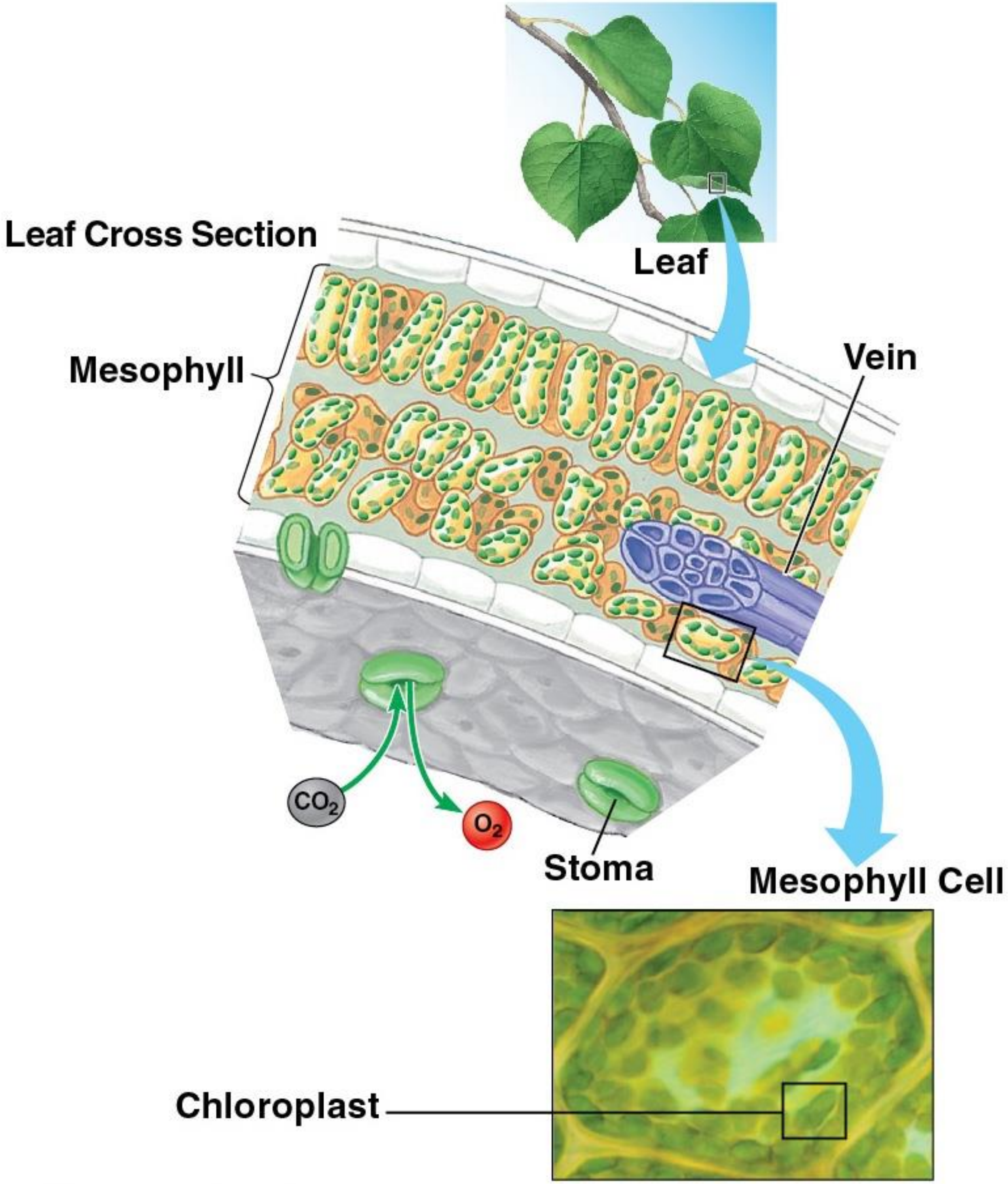


Photosynthesis Occurs in Chloroplasts in Plant Cells

- Chloroplasts are surrounded by a double membrane and contain stacks of **thylakoids** and a thick fluid called **stroma**.
- **Chlorophyll** is a light-absorbing pigment in the chloroplasts that plays a central role in converting solar energy to chemical energy.

Checkpoint question How do the reactant molecules of photosynthesis (CO2 and H2O) reach the chloroplasts in leaves?


Leaf Cross Section
Leaf
Mesophyll
Vein
CO_2
O_2
Stoma
Mesophyll Cell
Chloroplast
Inner and outer membranes
Granum
Thylakoid
Thylakoid space
Stroma


Leaf Cross Section
Leaf
Mesophyll
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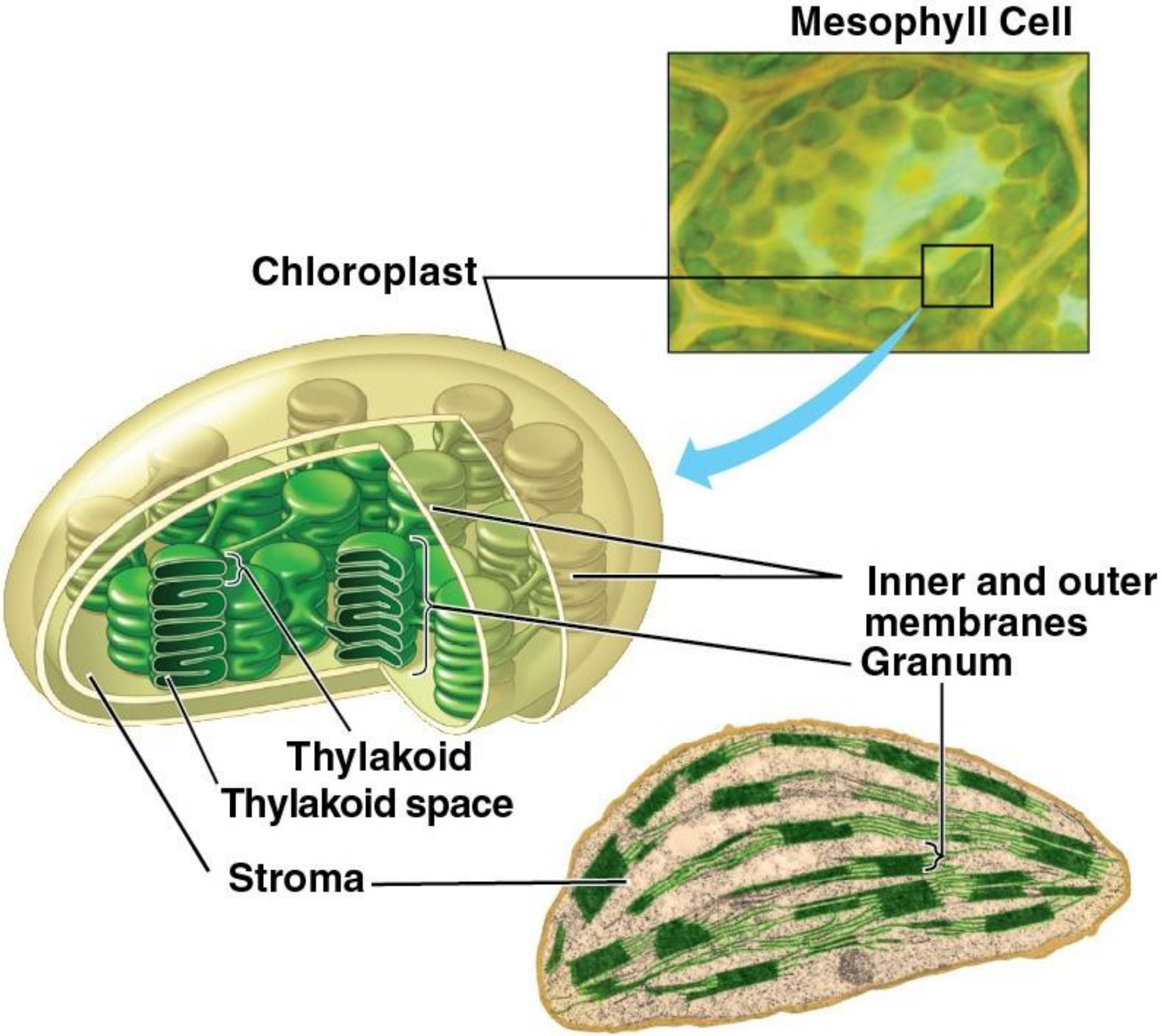
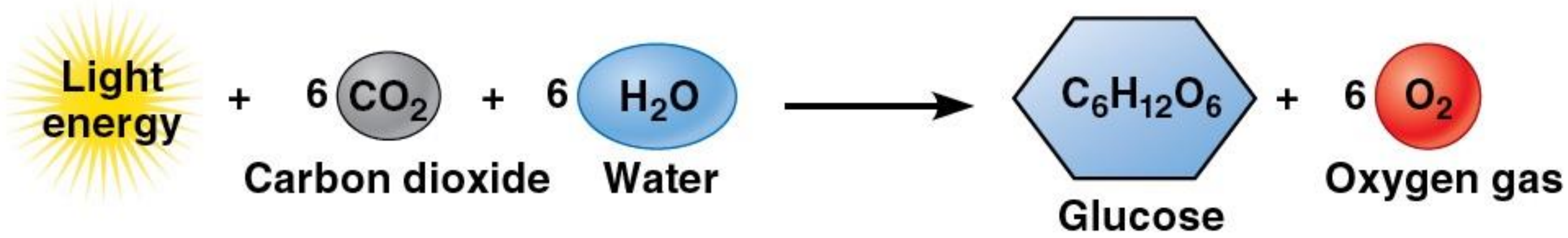
Mesophyll Cell
Chloroplast

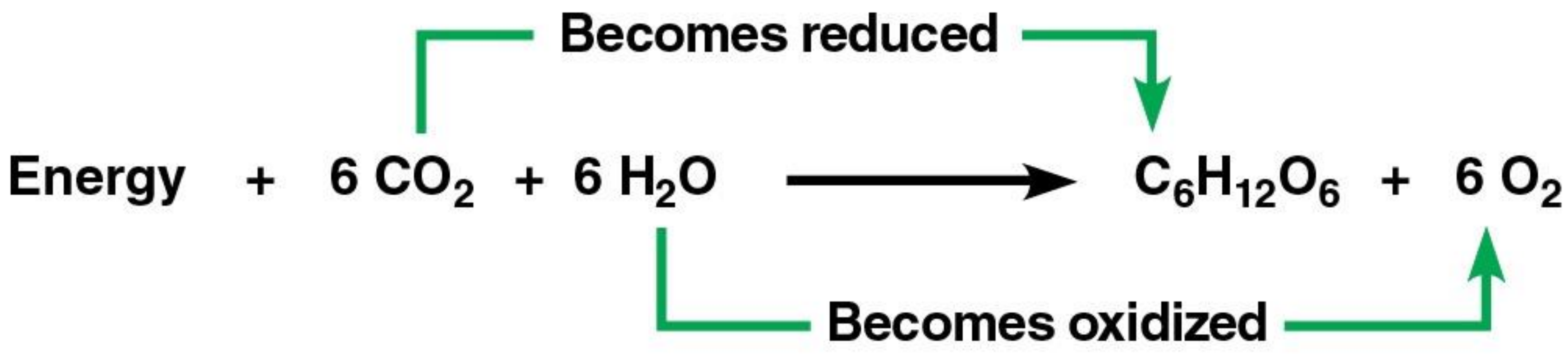


Mesophyll Cell
Chloroplast
Inner and outer membranes
Granum
Thylakoid
Thylakoid space
Stroma

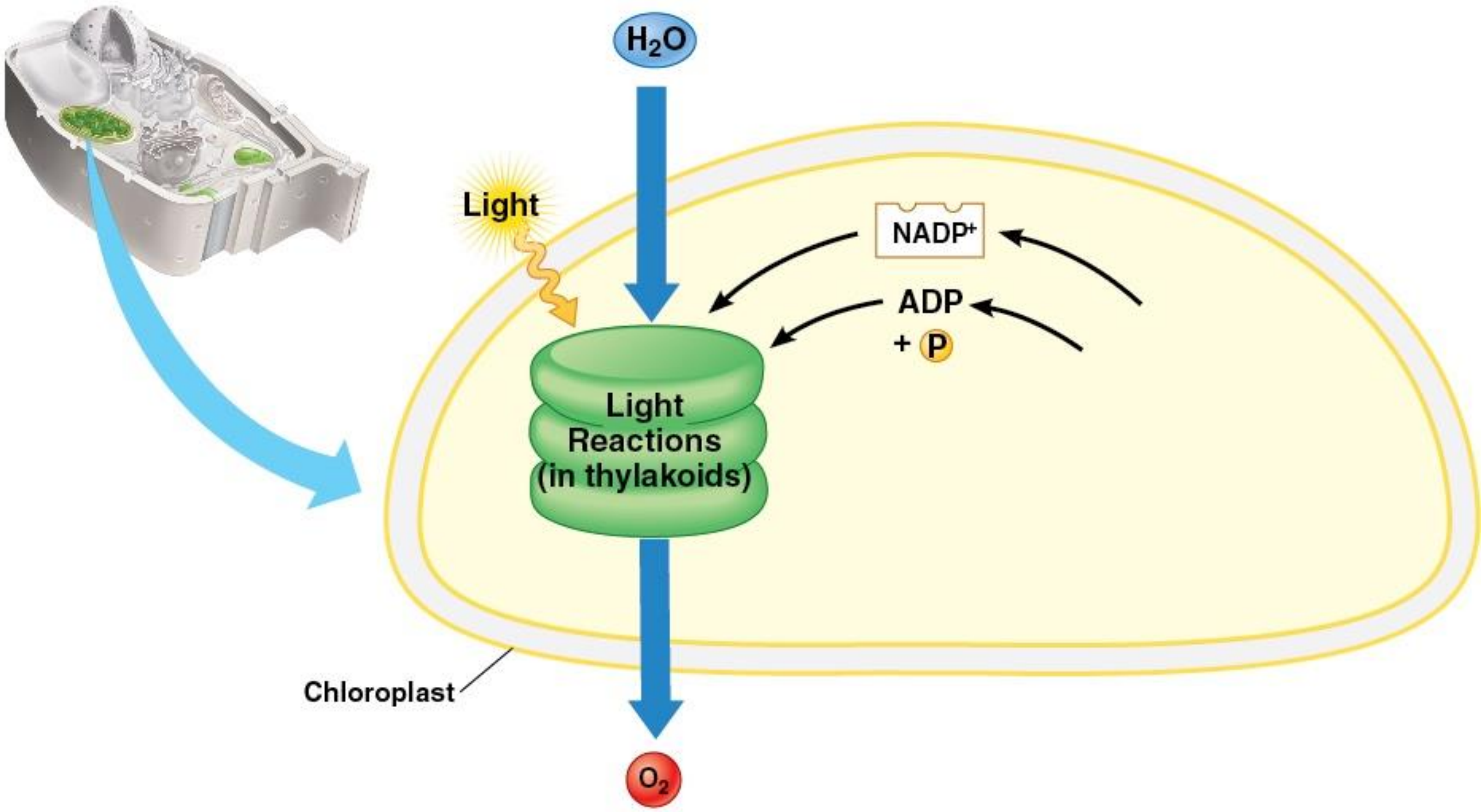

Light energy
+
6 CO_2
Carbon dioxide
+
6 H_2O
Water
$C_6H_{12}O_6$
Glucose
+
6 O_2
Oxygen gas

Photosynthesis Is a Redox Process

- Photosynthesis, like respiration, is a redox (oxidation-reduction) process.
  - In photosynthesis, H_2O is oxidized and CO_2 is reduced.
  - Cellular respiration uses redox reactions to harvest the chemical energy stored in a glucose molecule.



Photosynthesis Occurs in Two Stages, linked by ATP and NADPH



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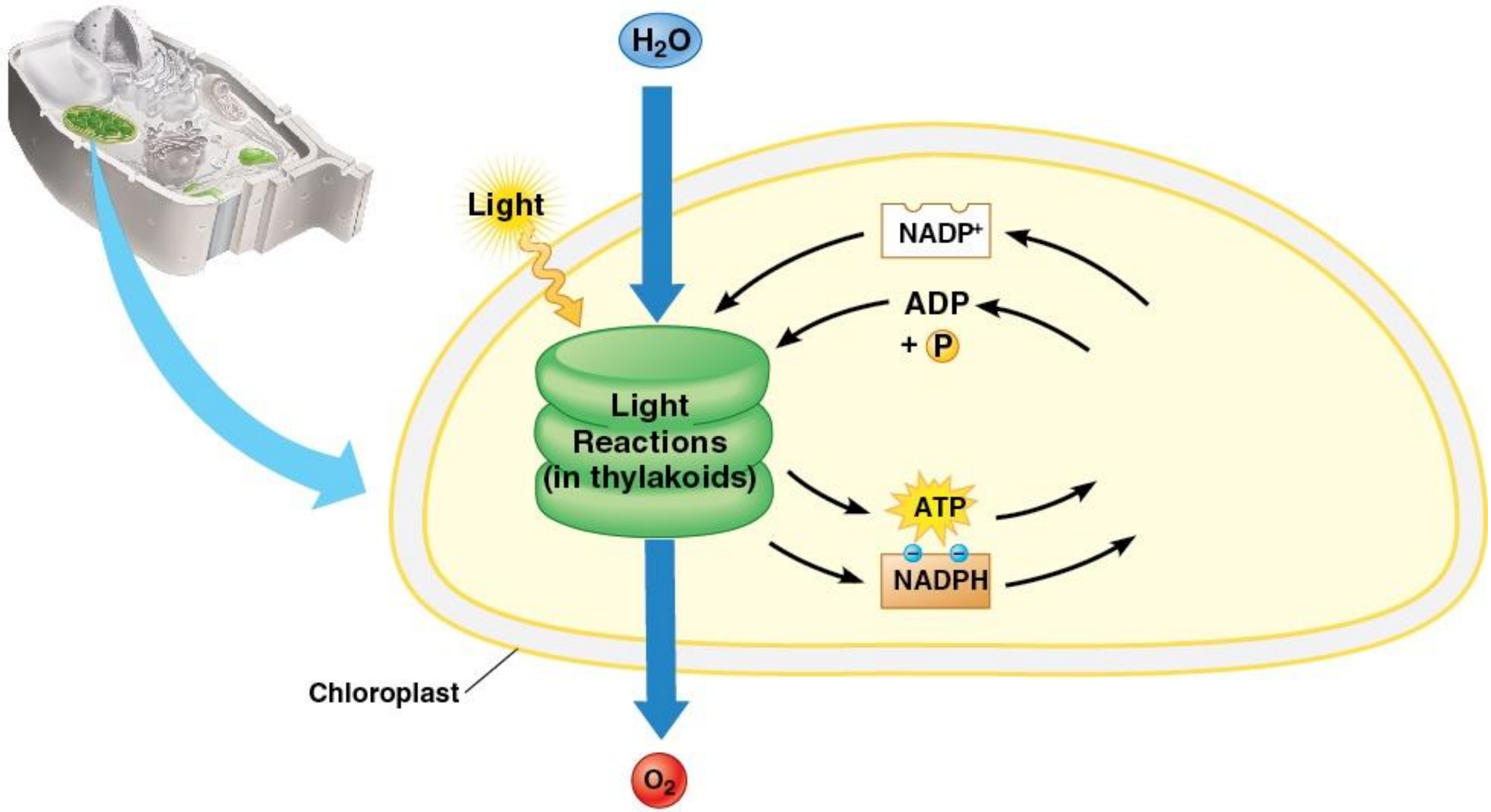
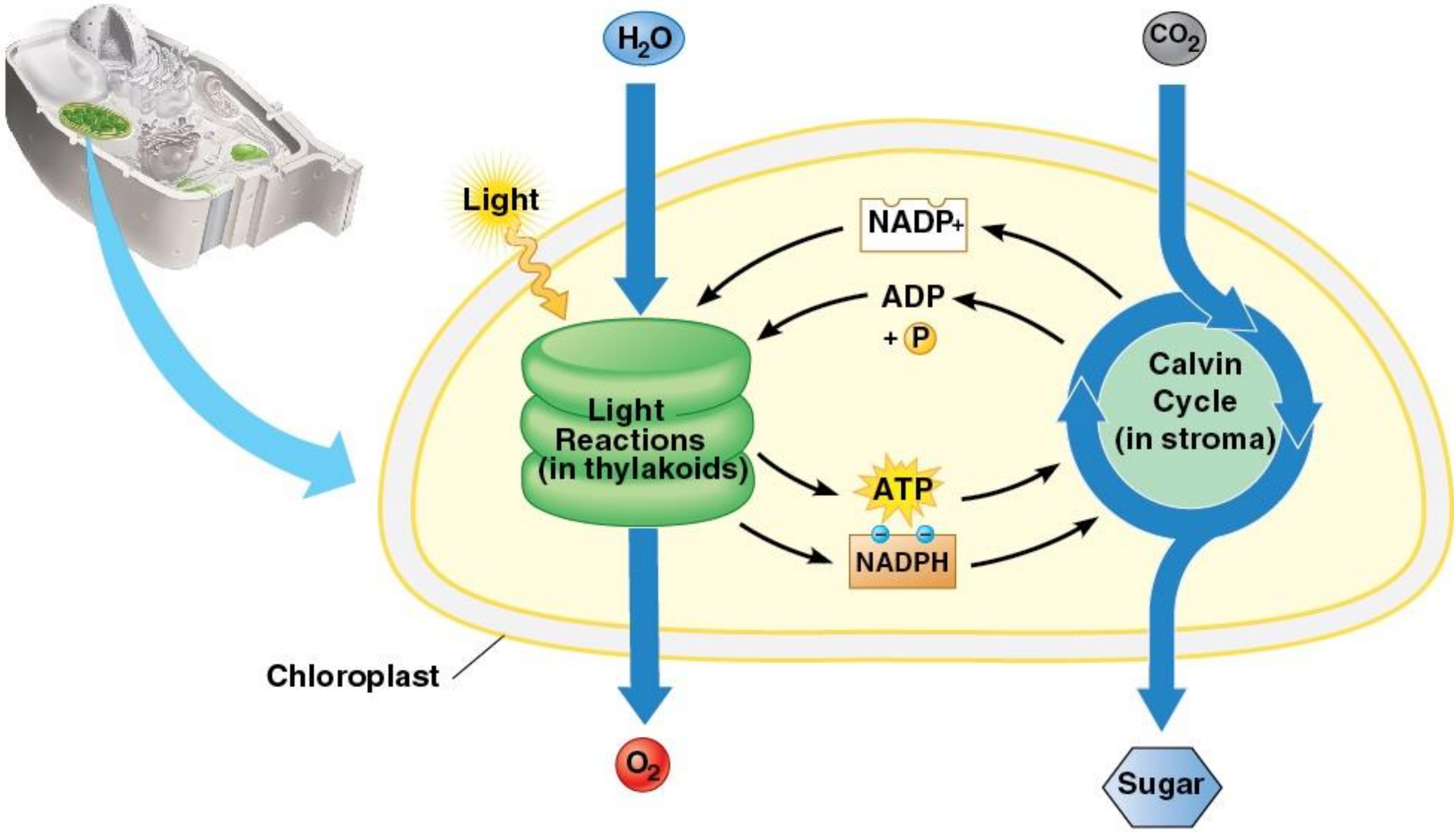


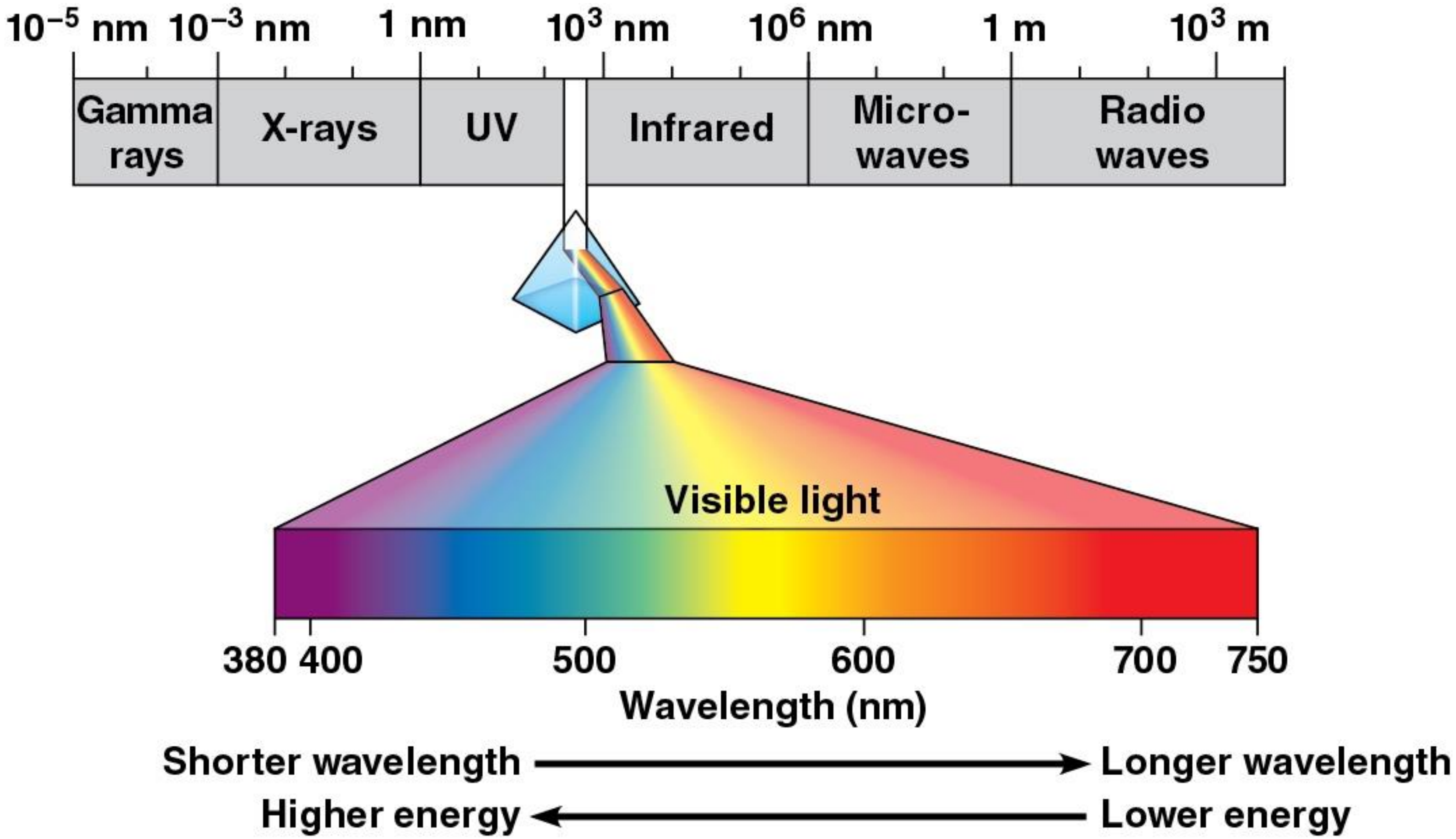
Photosynthesis Occurs in Two Stages, linked by ATP and NADPH



- The **light reactions** occur on and inside the thylakoids, producing ATP and **NADPH** for the **Calvin cycle**, which takes place in the stroma.
- During the Calvin cycle, CO_2 is incorporated into organic compounds in a process called **carbon fixation**.

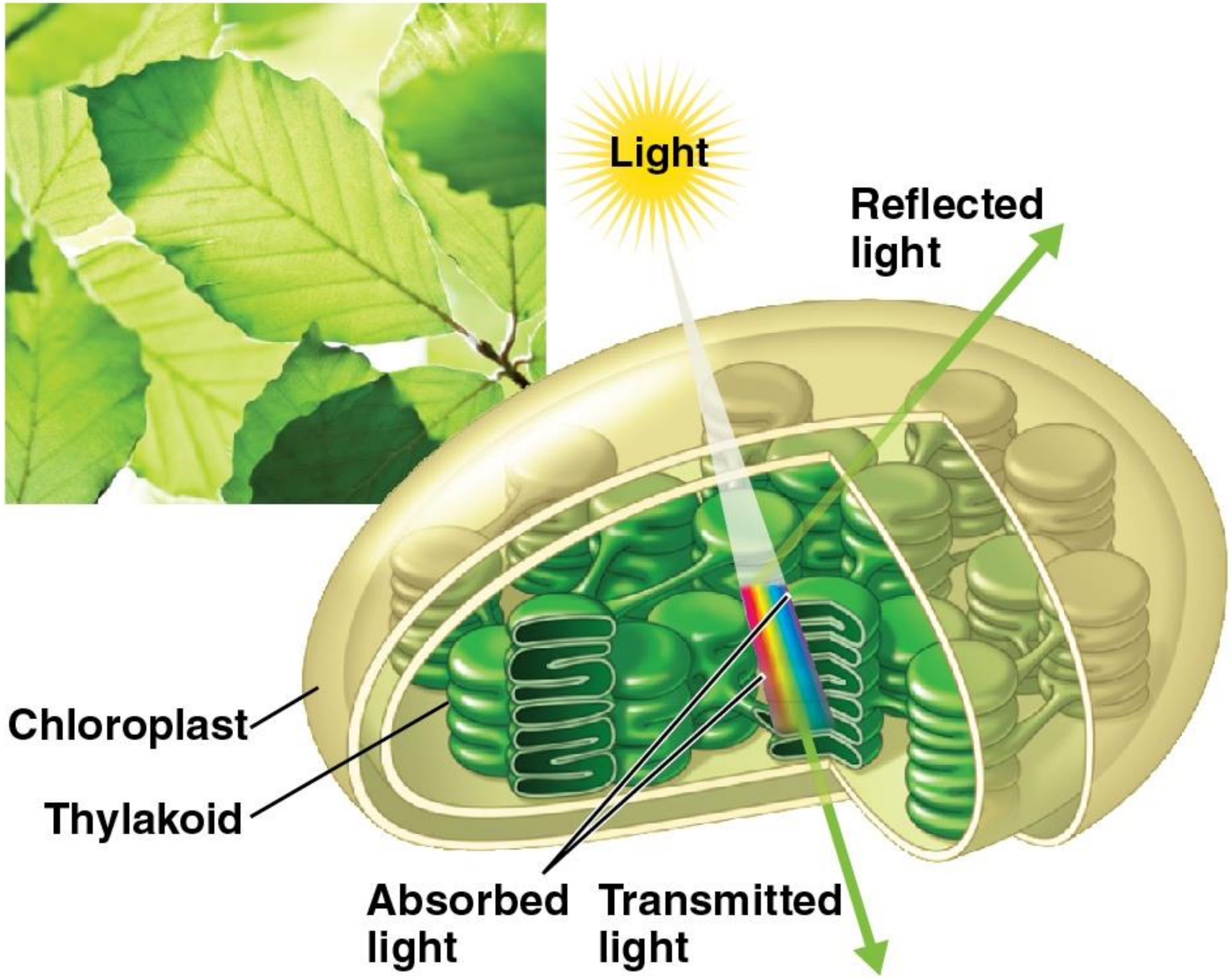
The Light Reactions: Converting Solar Energy to Chemical Energy

Sunlight is a type of energy called electromagnetic energy or radiation



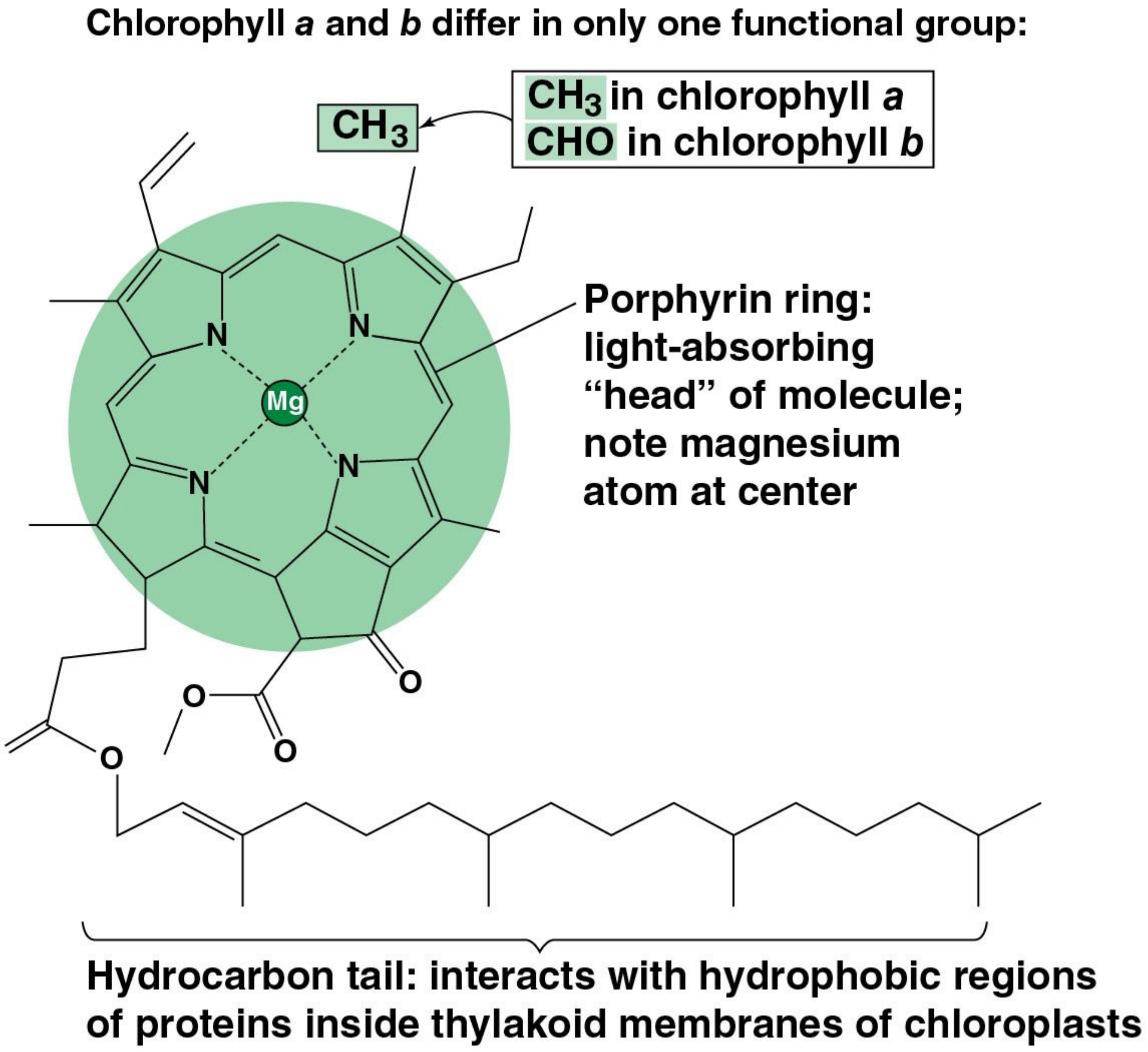
- Certain **wavelengths** of visible light are absorbed by chlorophyll and other pigments.
- Carotenoids also function in photoprotection from excessive light.

What color of light is least effective at driving photosynthesis?

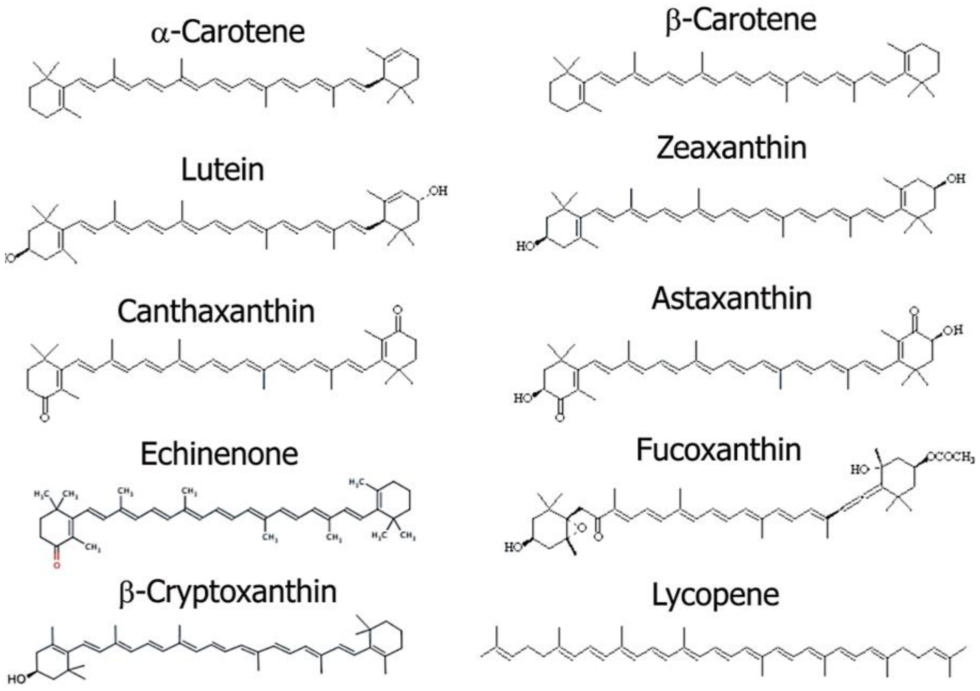


Pigments in chloroplasts

- Three types of pigments in chloroplasts include:
  - **Chlorophyll *a***, the key light-capturing pigment that participates directly in light reactions
  - **Chlorophyll *b***, an accessory pigment
  - **Carotenoids**, a separate group of accessory pigments

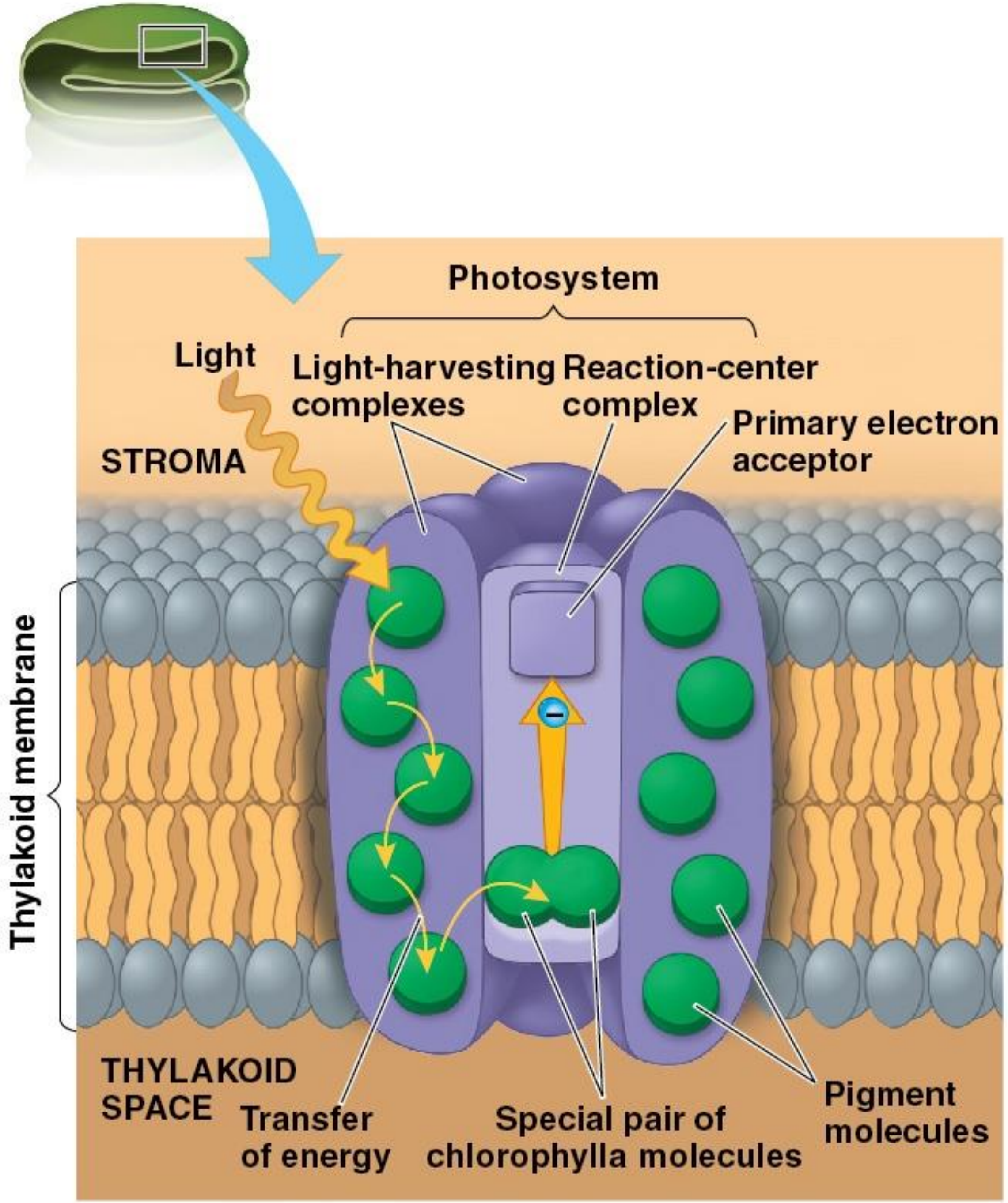


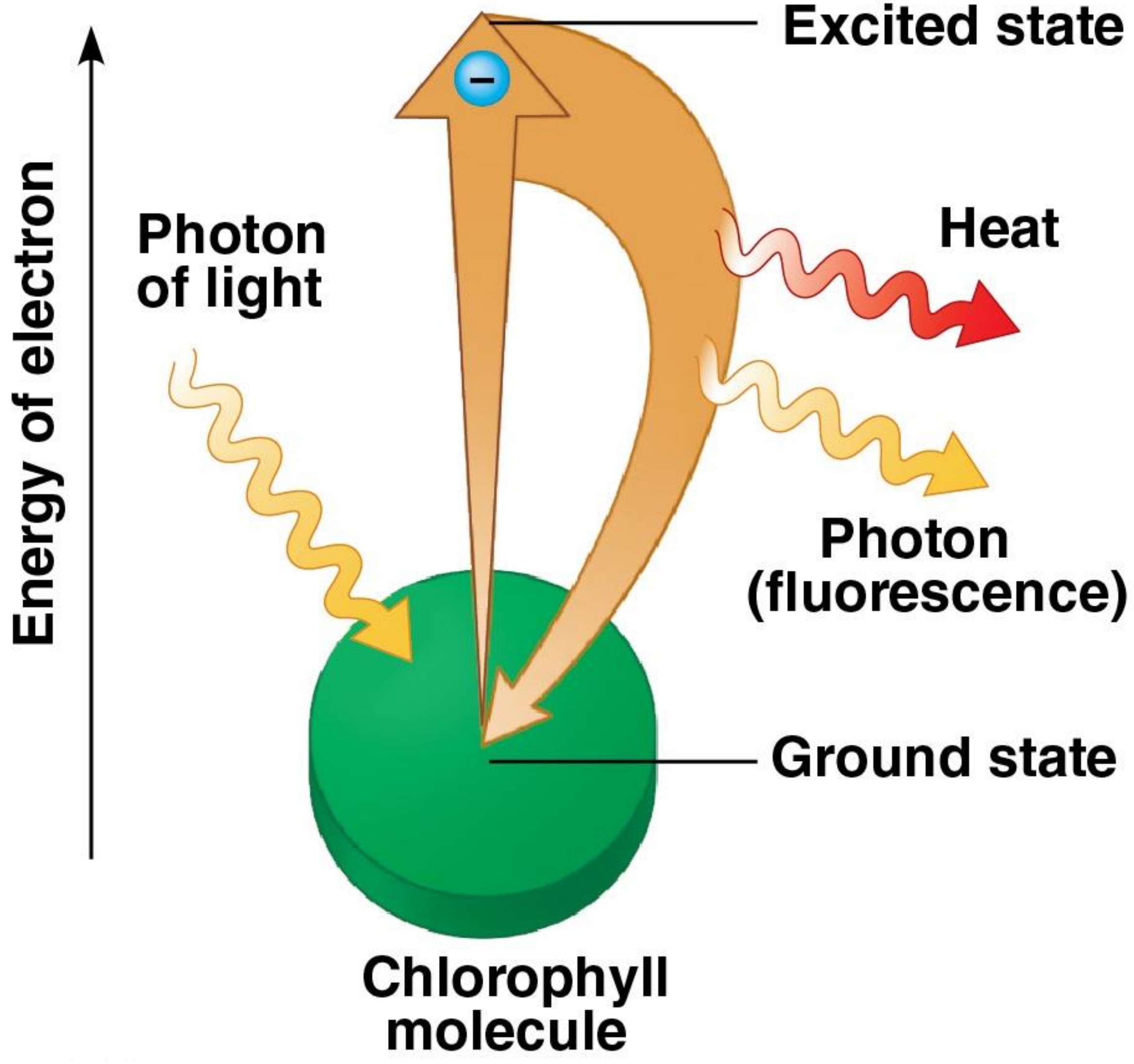
- Other accessory pigments called **carotenoids**, are yellow or orange because they absorb violet and blue-green light
- Carotenoids broaden the spectrum for photosynthesis
- Some are also photoprotective, that is, they absorb excessive light that would otherwise damage chlorophyll or react with oxygen



Photosystems Capture Solar Energy

- Thylakoid membranes contain **photosystems**, each consisting of light-harvesting complexes and a reaction-center complex.
- A primary electron acceptor receives photoexcited electrons from reaction-center chlorophyll *a*.

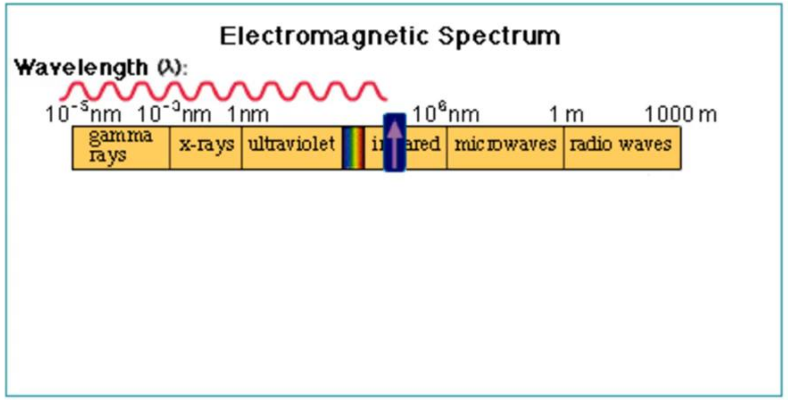




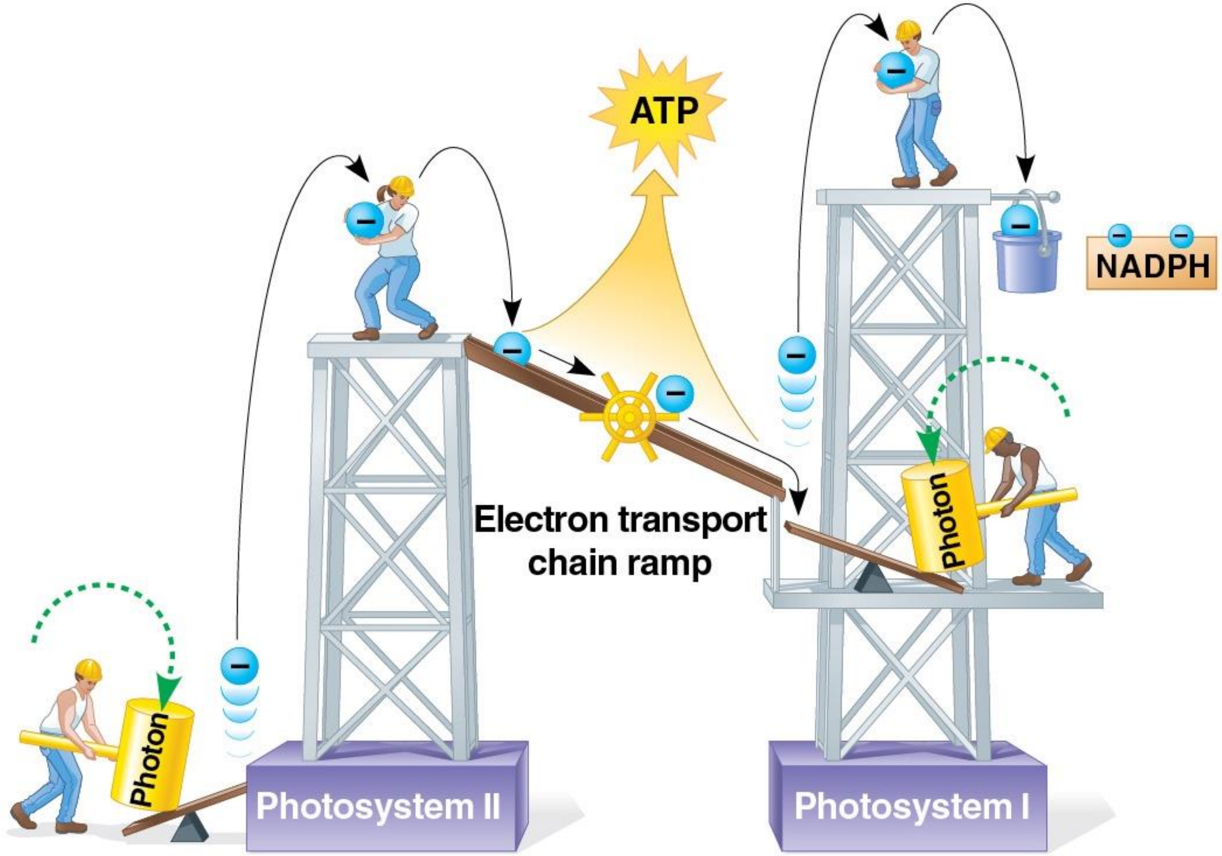
An isolated chlorophyll molecule whose light-excited electron releases heat and light when it falls back to ground state.

Animation: Light and Pigments

Light Energy and Pigments



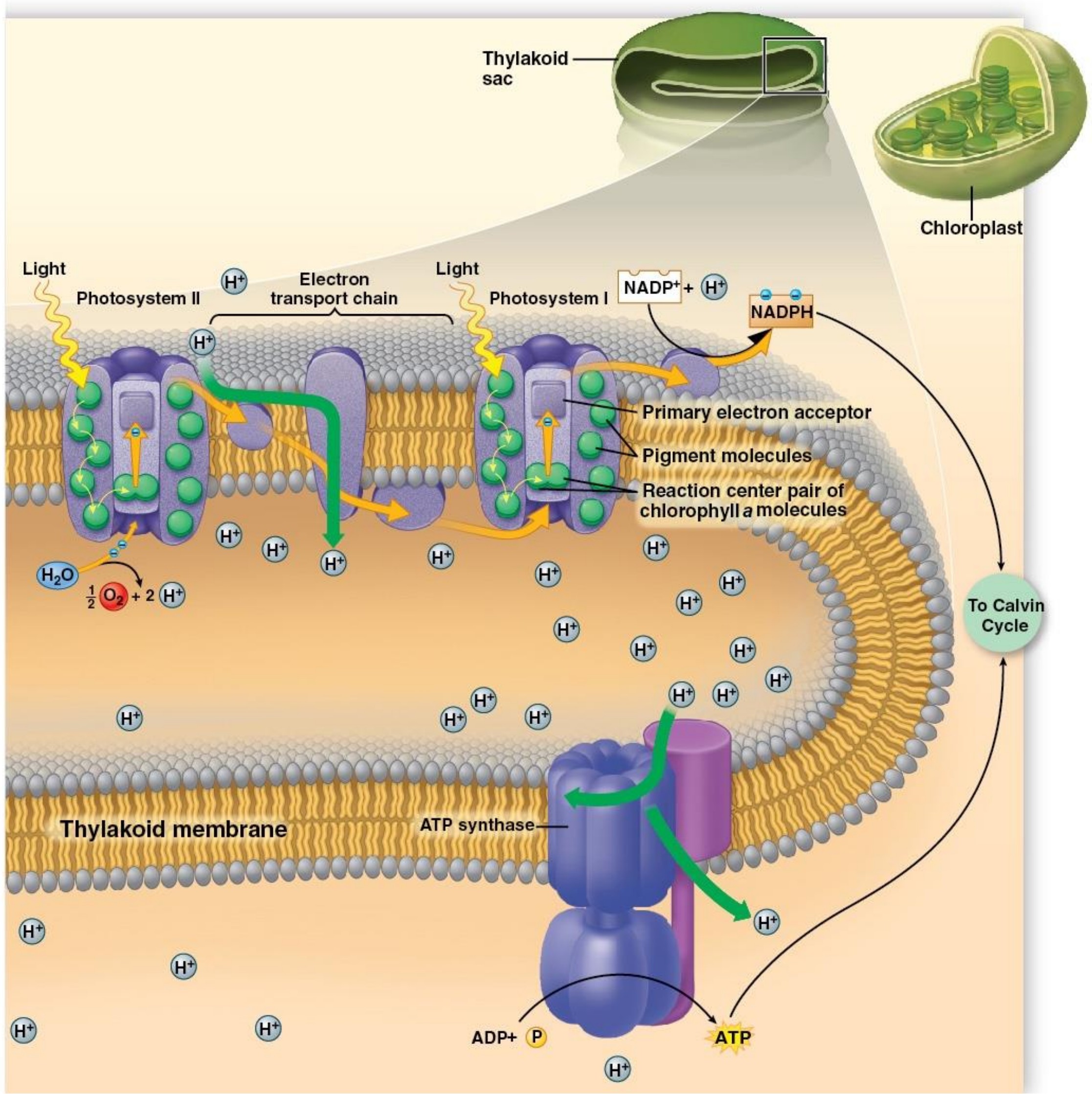
Two Photosystems Connected by an Electron Transport Chain Convert Light Energy to the Chemical Energy of ATP and NADPH

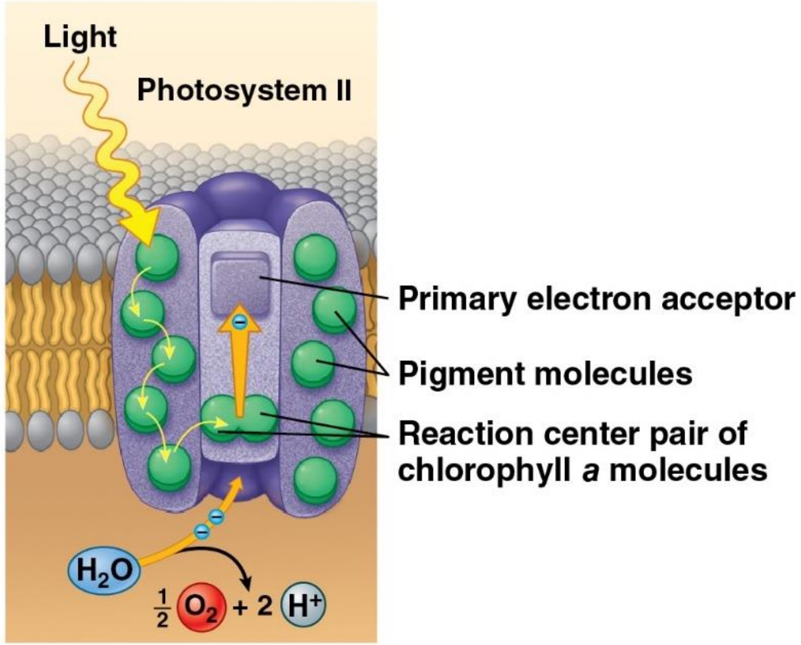


- Electrons shuttle from photosystem II to photosystem I, providing energy to make ATP, and then reduce $NADP^+$ to NADPH.
- Photosystem II regains electrons as water is split and O_2 released.

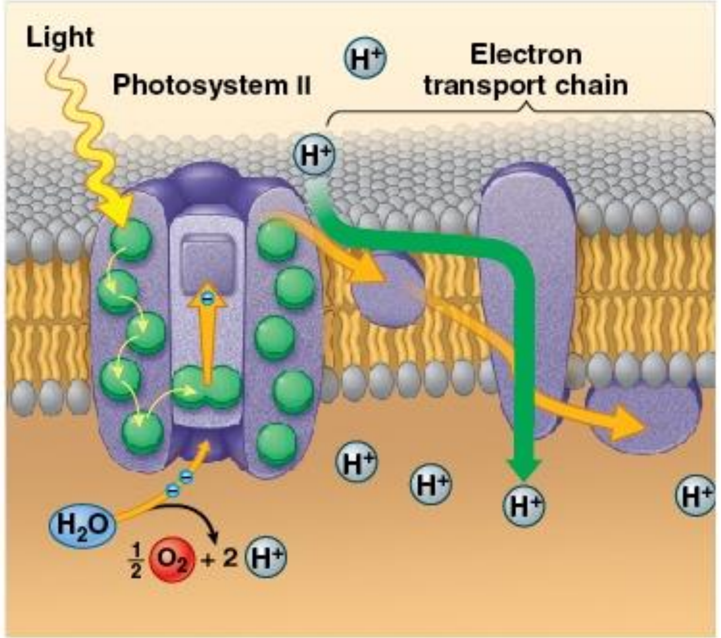
Light Reactions Take Place Within the Thylakoid Membranes

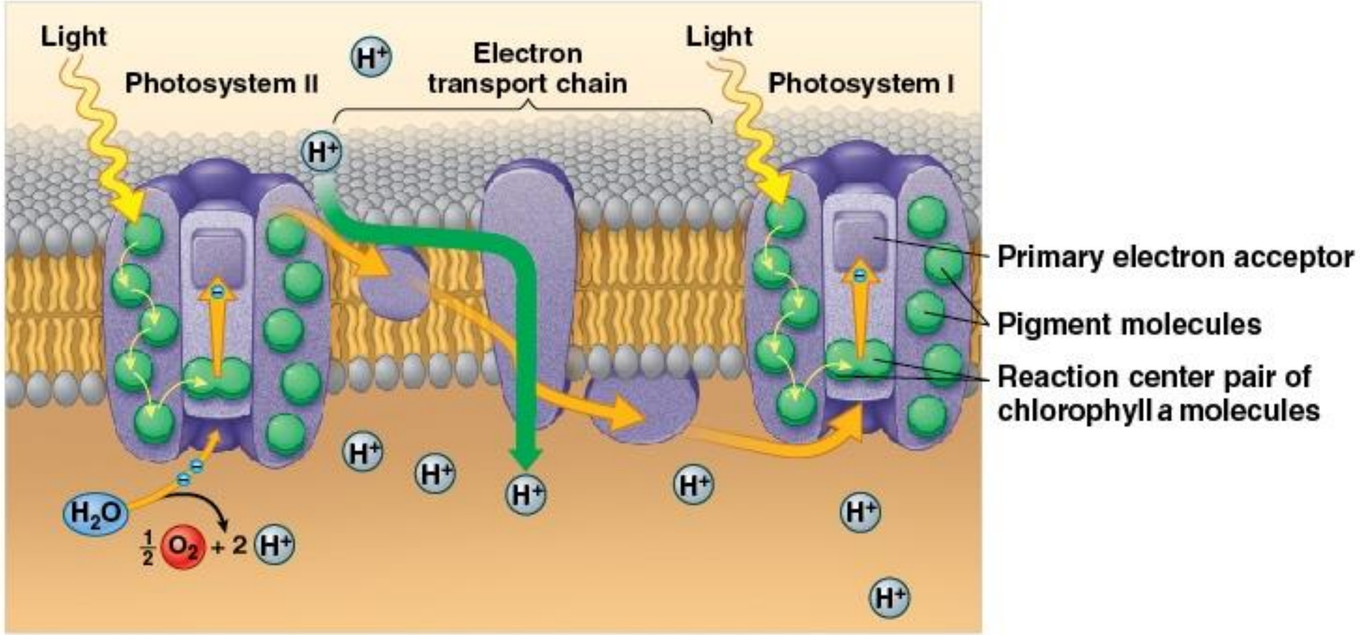
- In **photophosphorylation**, the electron transport chain pumps H^+ into the thylakoid space.
- The concentration gradient drives H^+ back through ATP synthase, powering the synthesis of ATP.

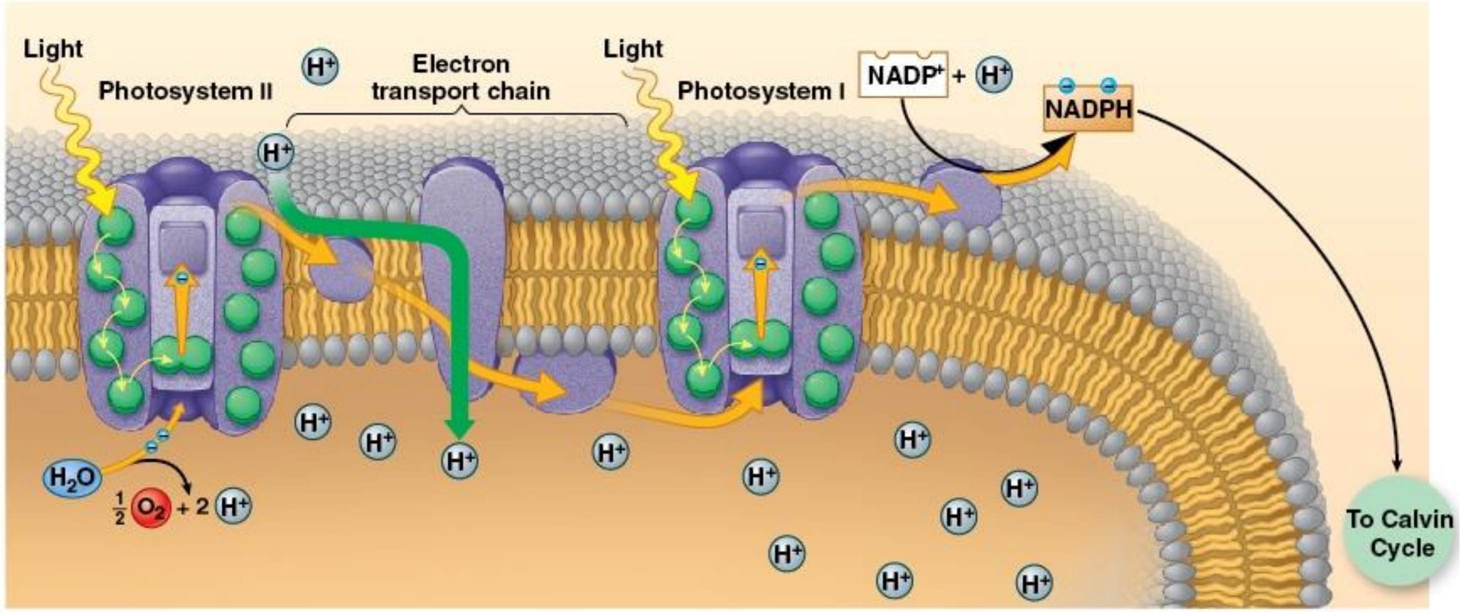




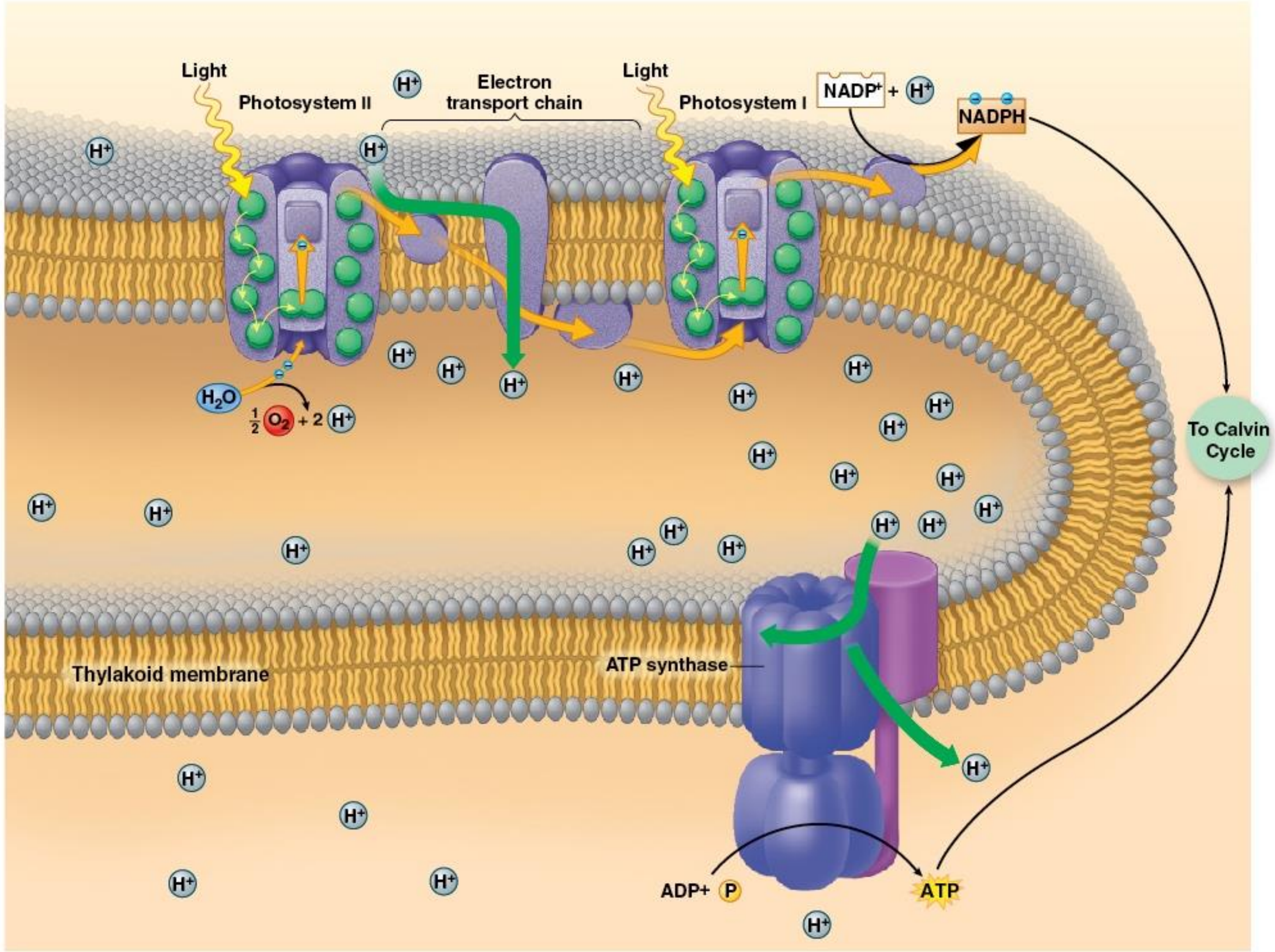
Light
Photosystem II
Primary electron acceptor
Pigment molecules
Reaction center pair of chlorophyll *a* molecules
H_2O
$\frac{1}{2}$ O_2 + 2 H^+


Light
Photosystem II
H+
Electron transport chain
H+
H+
H+
H+
H+
H2O
1/2 O2 + 2 H+


Light
Photosystem II
H+
Electron transport chain
Light
Photosystem I
Primary electron acceptor
Pigment molecules
Reaction center pair of chlorophyll a molecules
H2O
½ O2 + 2 H+



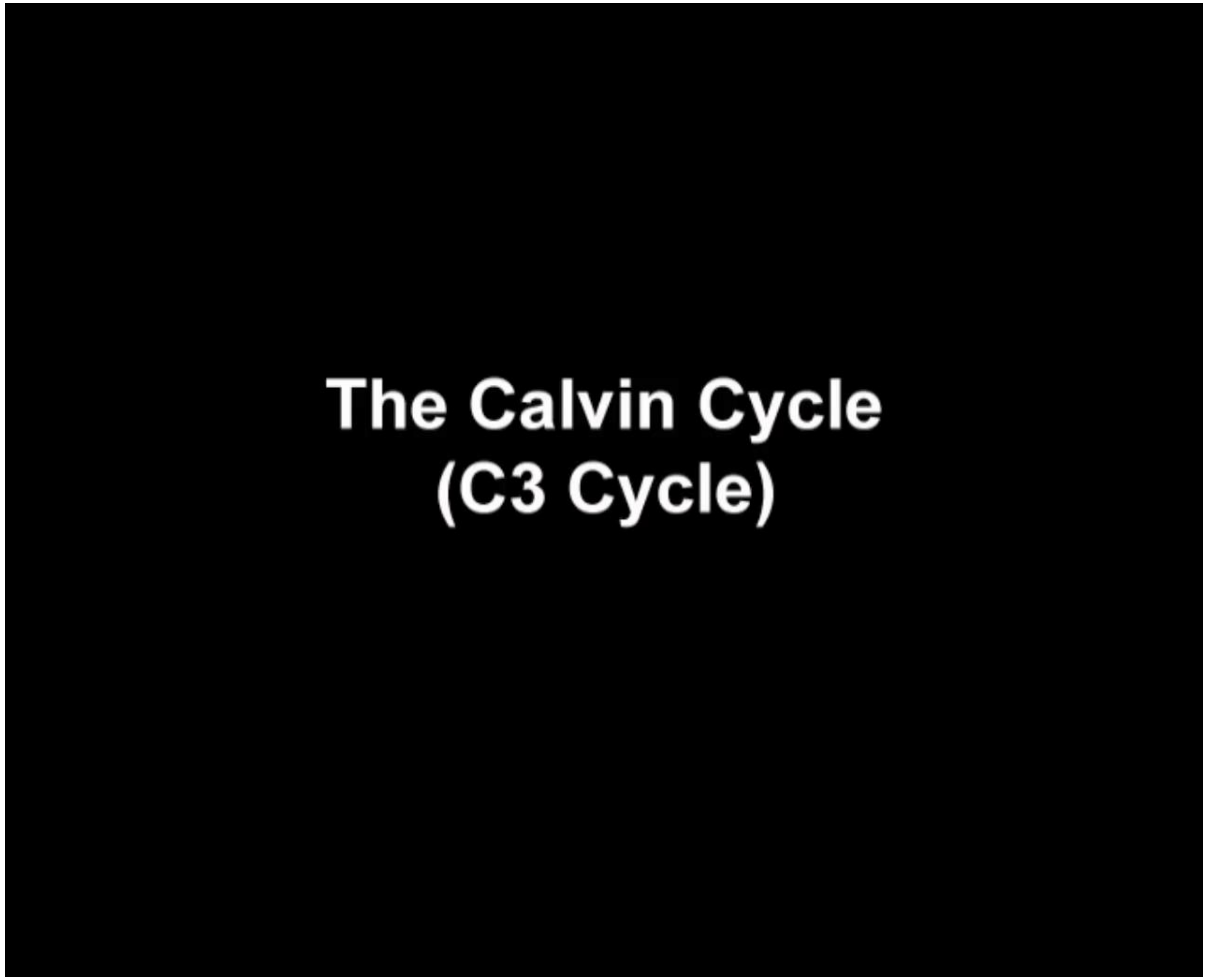
Light
Photosystem II
H+
Electron
transport chain
Light
Photosystem I
NADP+ + H+
NADPH
H+
H2O
1/2 O2 + 2 H+
To Calvin
Cycle


Light
Photosystem II
Electron transport chain
Light
Photosystem I
NADP+ + H+
NADPH
H+
H2O
1/2 O2 + 2 H+
To Calvin Cycle
Thylakoid membrane
ATP synthase
ADP+ P
ATP

The Calvin Cycle: Reducing CO_2 to Sugar

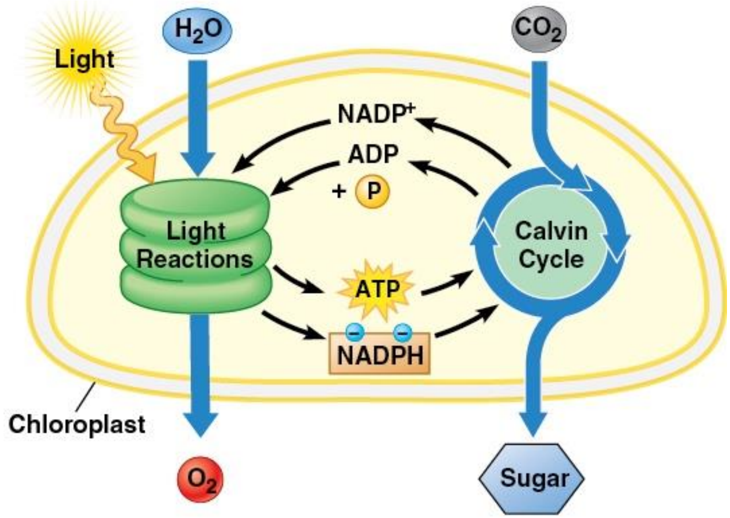
Animation: The Calvin Cycle

Animation: The Calvin Cycle

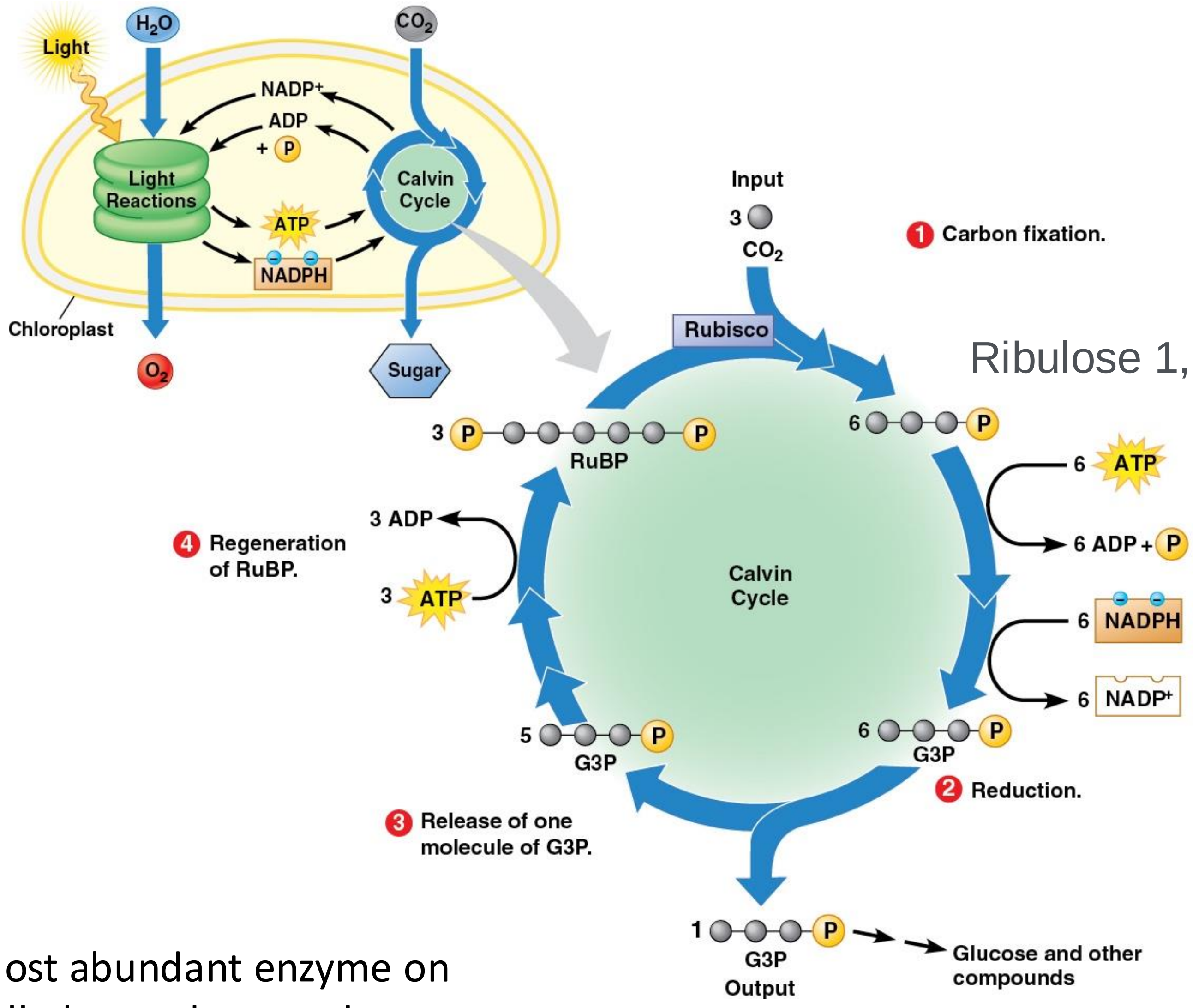


ATP and NADPH Power Sugar Synthesis in the Calvin Cycle

- The steps of the Calvin cycle include
  - carbon fixation,
  - reduction,
  - release of G3P, and
  - regeneration of RuBP.
- Using carbon from CO_2, electrons from NADPH, and energy from ATP, the cycle constructs G3P, which is used to build glucose and other organic molecules.

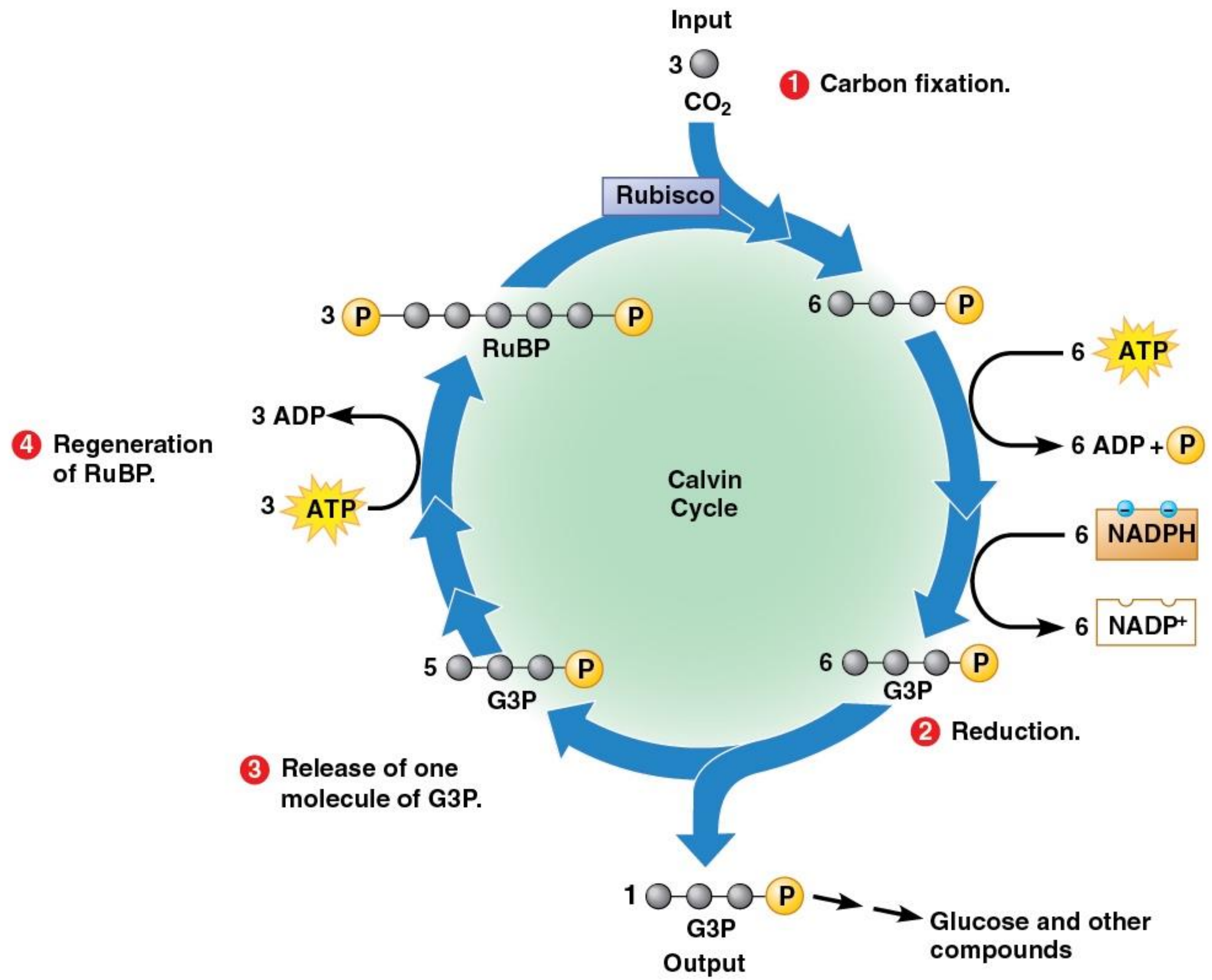


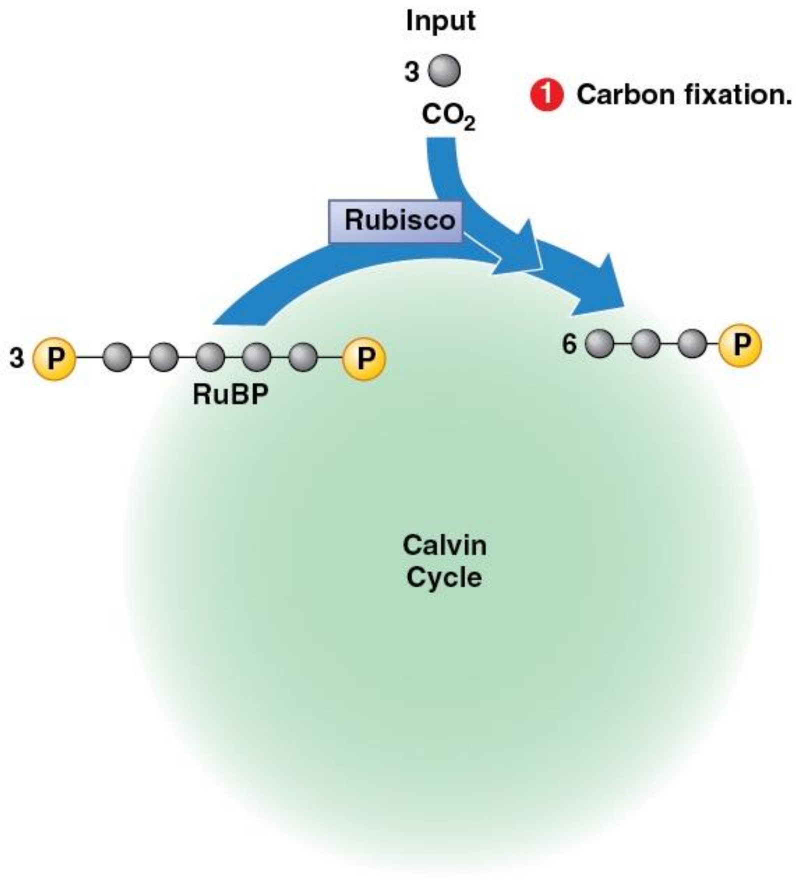
RUBISCO: Ribulose-1,5-bisphosphate carboxylase/oxygenase



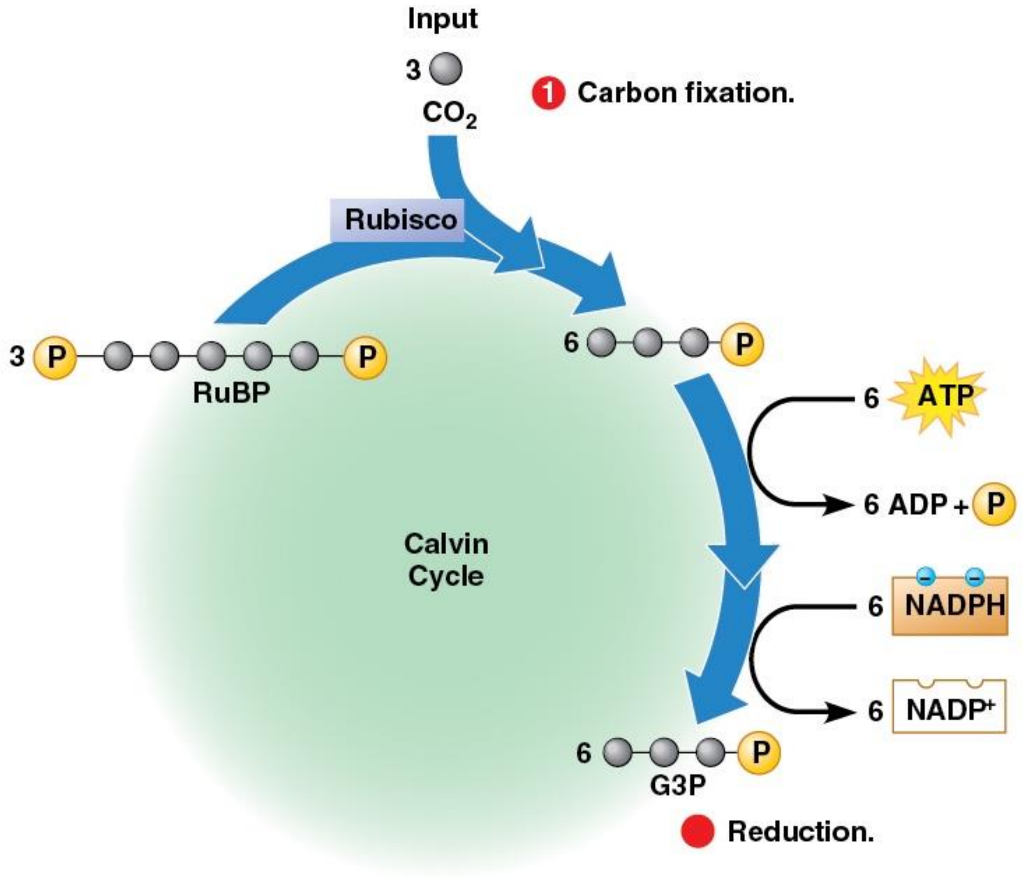
Ribulose 1,5-bisphosphate (RuBP)

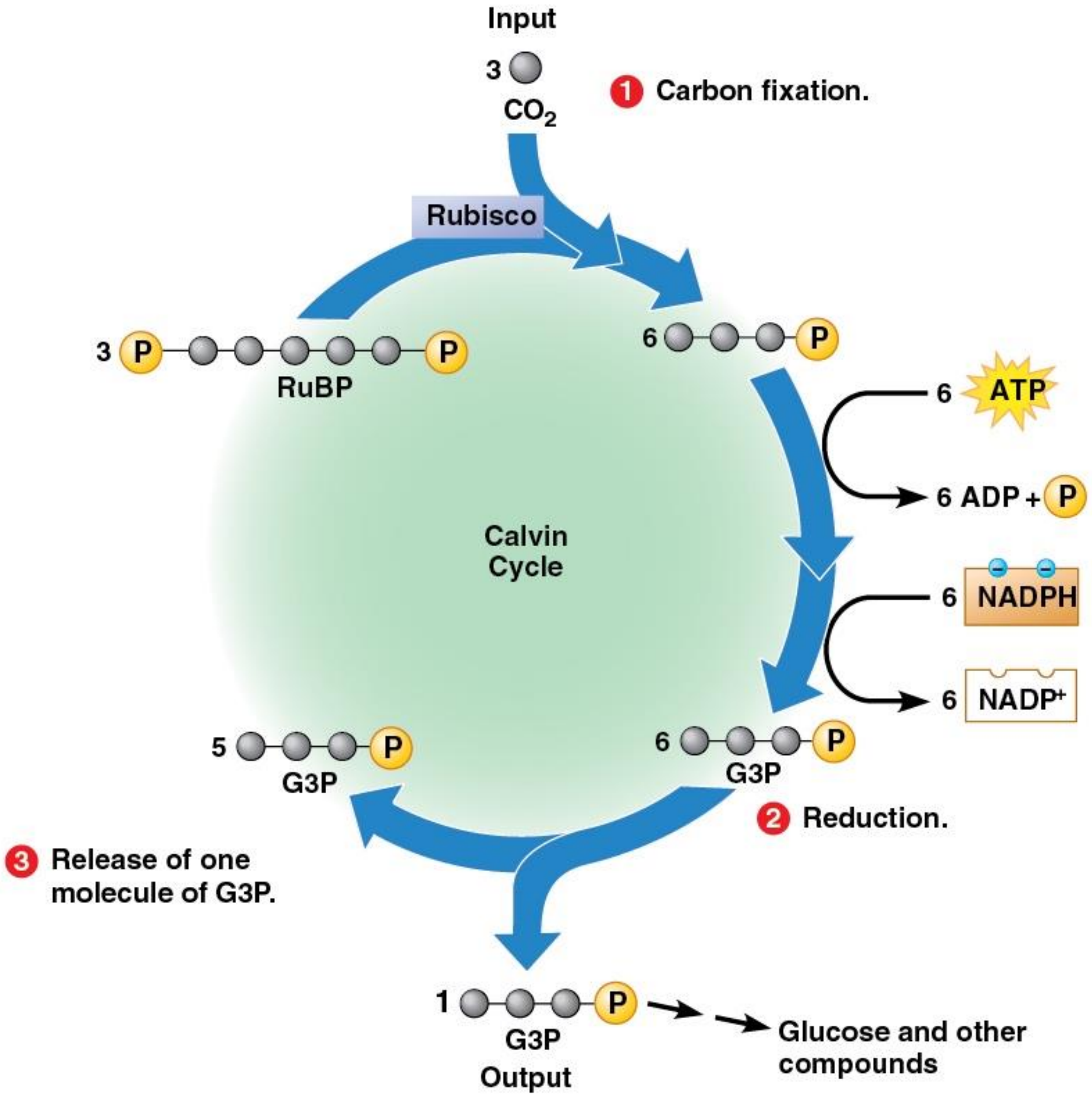
RuBisCO is considered the most abundant enzyme on Earth because it is found in all plants, algae, and many bacteria that perform photosynthesis.


Input
3
CO_2
1 Carbon fixation.
Rubisco
3 P P
RuBP
6 P
6 ATP
6 ADP + P
3 ADP
4 Regeneration of RuBP.
3 ATP
Calvin Cycle
6 NADPH
6 $NADP^+$
5 P
G3P
6 P
G3P
2 Reduction.
3 Release of one molecule of G3P.
1 P
G3P
Output
Glucose and other compounds



Input
3
CO_2
1 Carbon fixation.
Rubisco
3
RuBP
6
P
Calvin Cycle


Input
3
CO_2
1 Carbon fixation.
Rubisco
3 P P
RuBP
6 P
6 ATP
6 ADP + P
Calvin
Cycle
6 NADPH
6 $NADP^+$
6 P
G3P
Reduction.


Input
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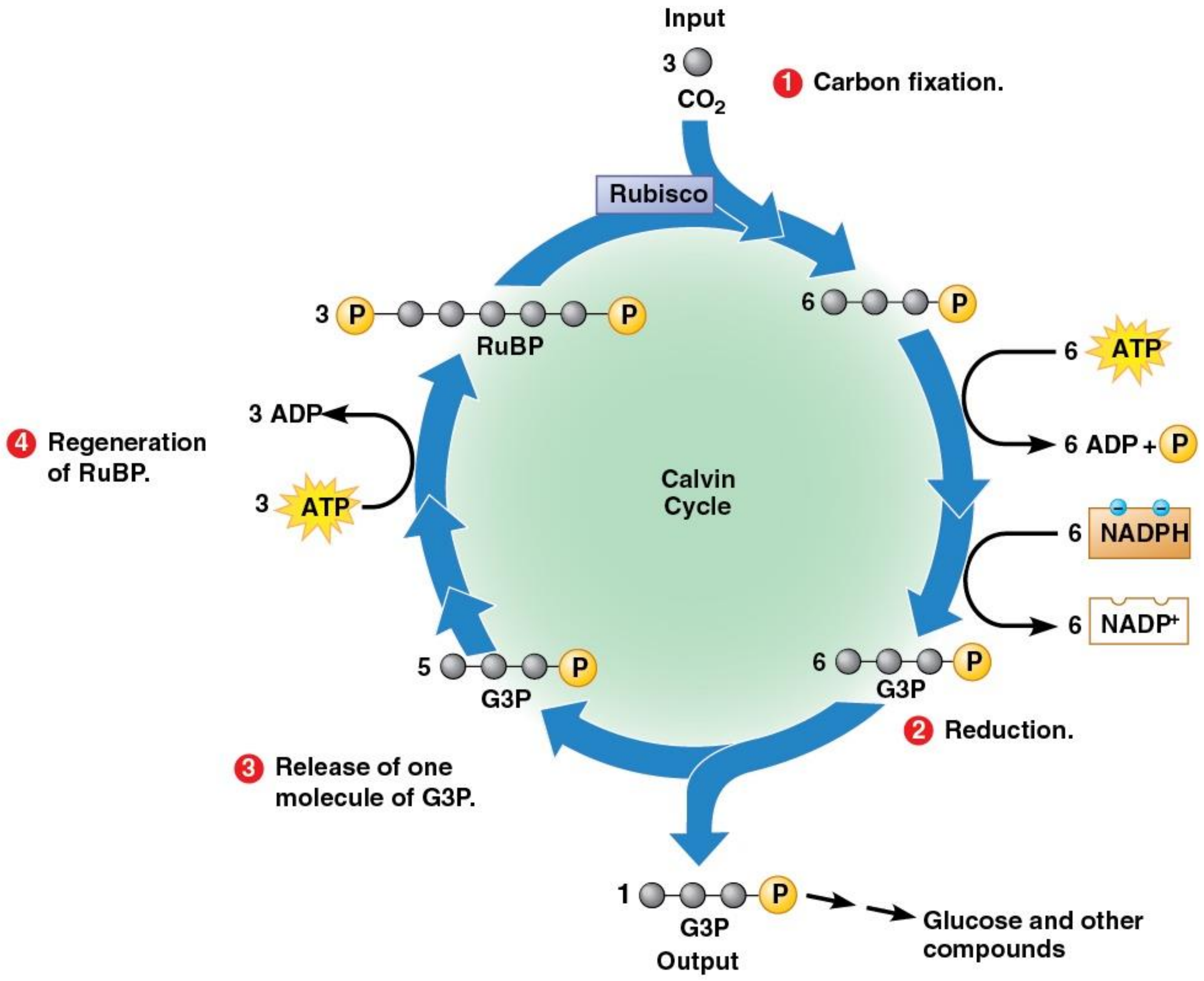
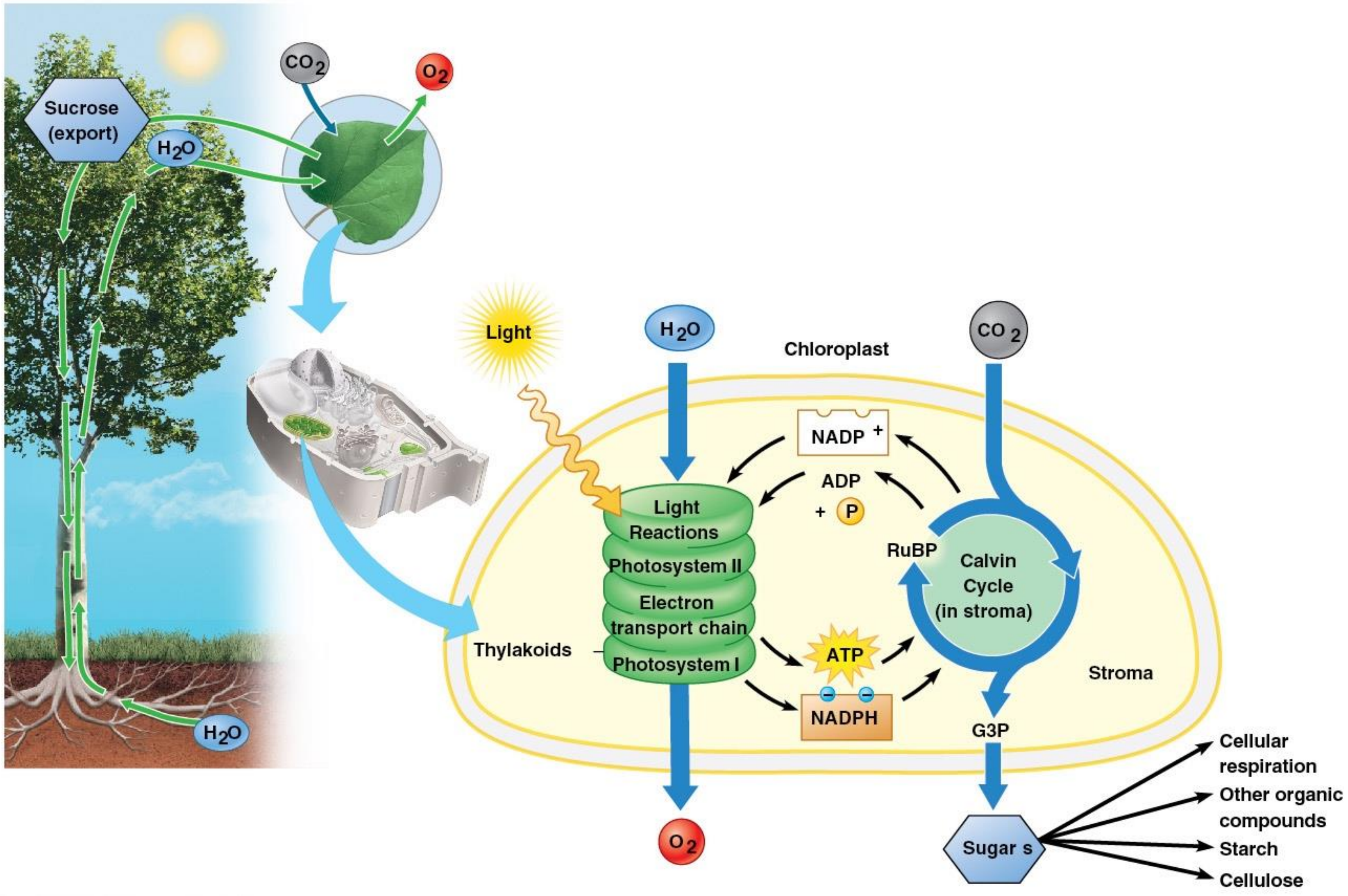
CO_2
1 Carbon fixation.
Rubisco
3 P P
RuBP
6 P
6 ATP
6 ADP + P
Calvin Cycle
6 NADPH
6 $NADP^+$
5 P
G3P
6 P
G3P
2 Reduction.
3 Release of one molecule of G3P.
1 P
G3P
Output
Glucose and other compounds

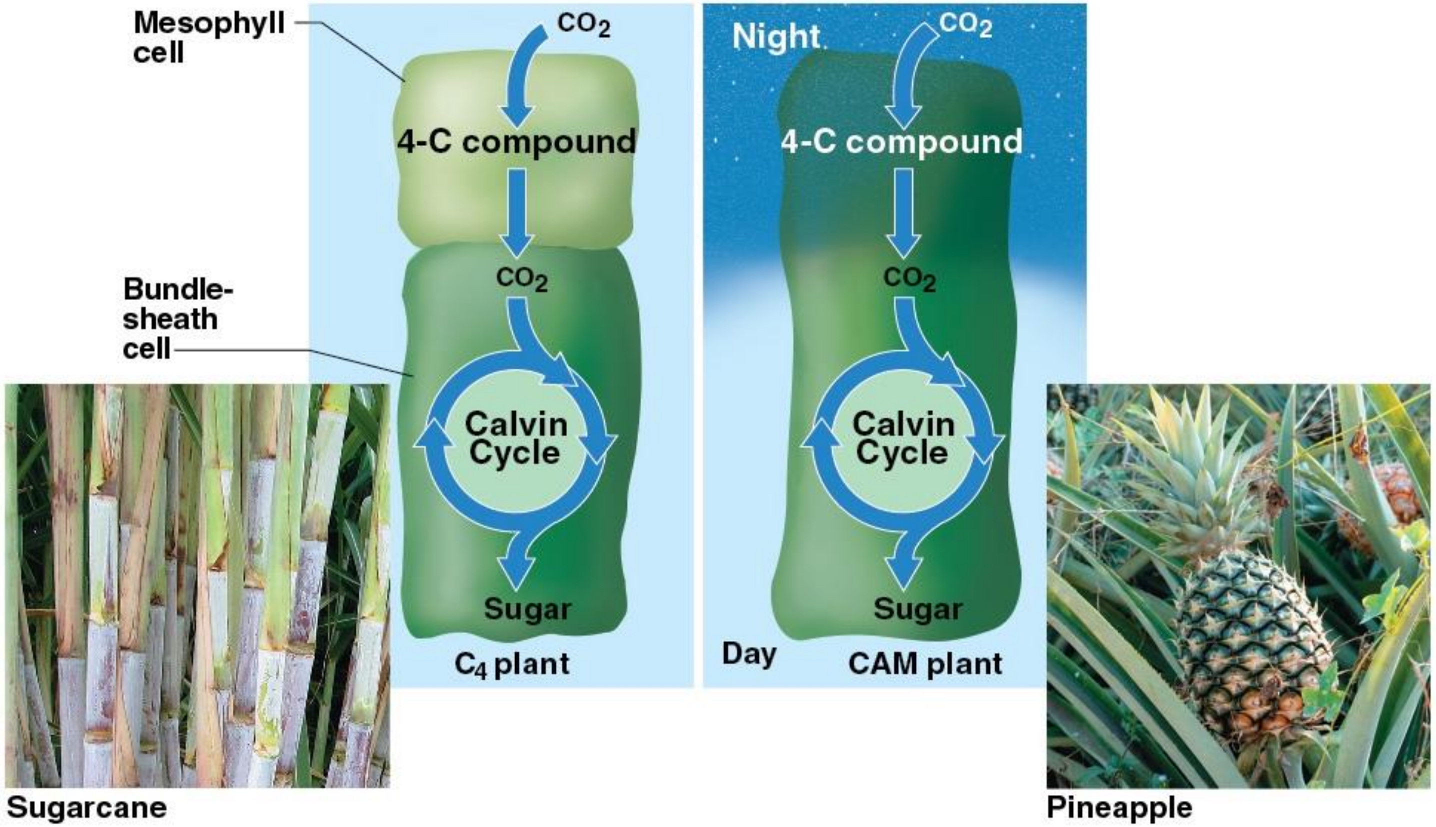

Input
3
CO_2
1 Carbon fixation.
Rubisco
6 P
6 ATP
6 ADP + P
6 NADPH
6 NADP+
6 P
G3P
2 Reduction.
3 P P
RuBP
3 ADP
4 Regeneration of RuBP.
3 ATP
Calvin Cycle
5 P
G3P
3 Release of one molecule of G3P.
1 P
G3P
Output
Glucose and other compounds



Sucrose (export)
CO_2
O_2
H_2O
H_2O
Light
H_2O
Chloroplast
CO_2
$NADP^+$
ADP
+ P
Light Reactions
Photosystem II
Electron transport chain
Photosystem I
Thylakoids
RuBP
Calvin Cycle (in stroma)
ATP
NADPH
Stroma
G3P
O_2
Sugar s
Cellular respiration
Other organic compounds
Starch
Cellulose

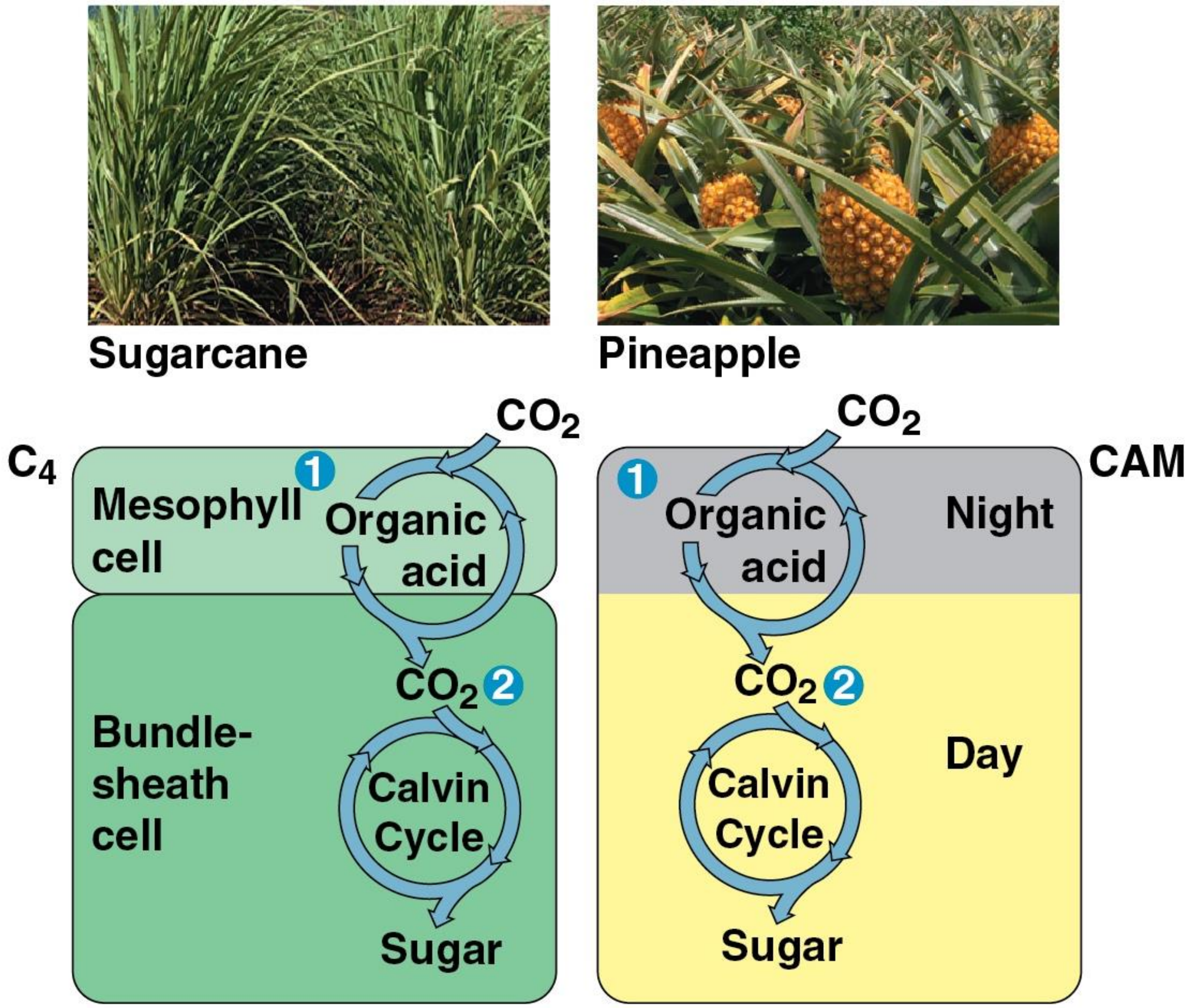
Evolution Connection: Other Methods of Carbon Fixation Have Evolved in Hot, Dry Climates

- In **C_3 plants**, a drop in CO_2 and rise in O_2 when stomata close divert the Calvin cycle to **photorespiration**.
- **C_4 plants** and **CAM plants** first fix CO_2 into four-carbon compounds that provide CO_2 to the Calvin cycle even when stomata close on hot, dry days.



Animation: Photosynthesis in Dry Climates

C_4 and CAM photosynthesis compared



(a) Spatial separation of steps

(b) Temporal separation of steps

Proliferation of toxic cyanobacteria blooms due to global warming

What are Cyanobacteria?

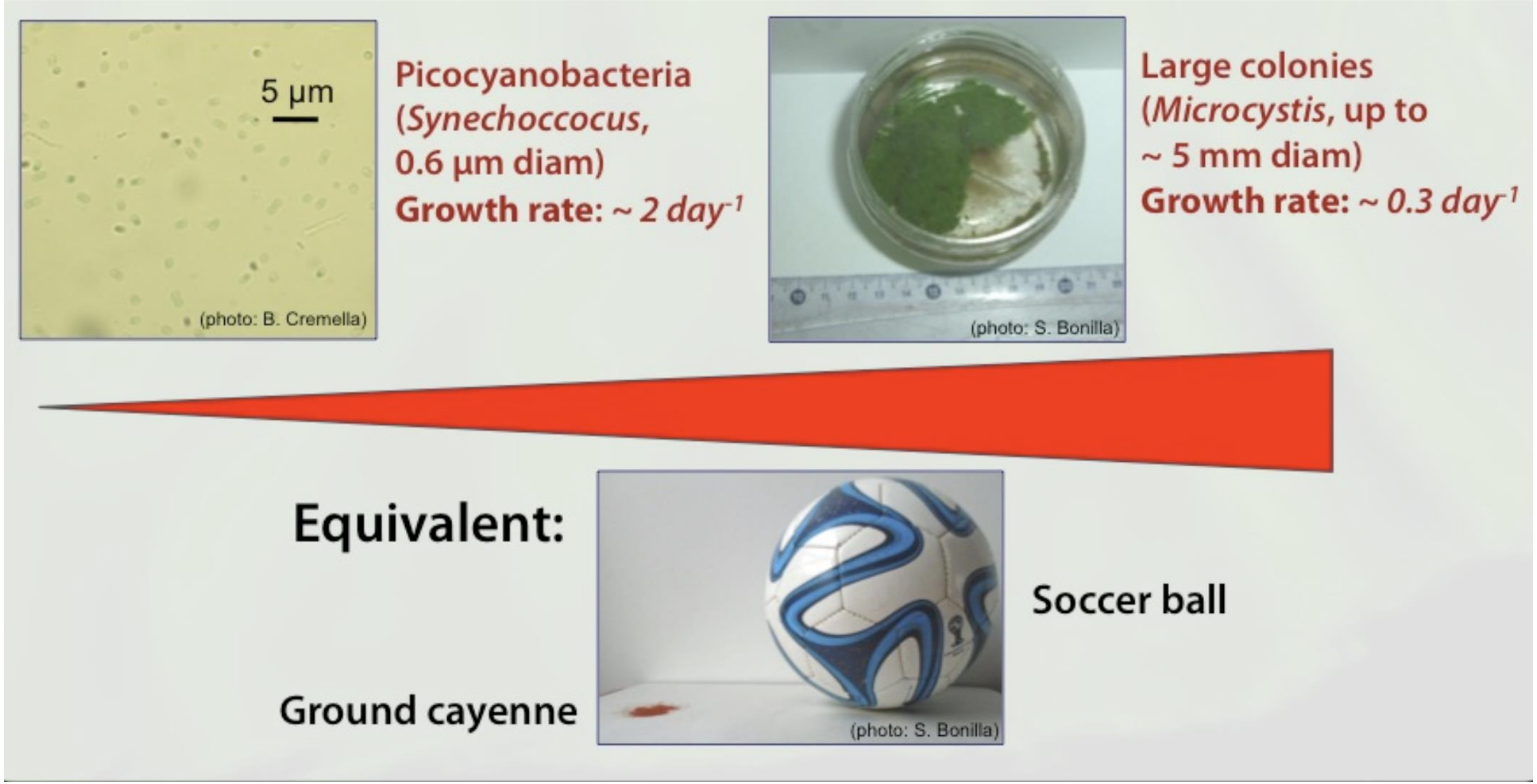
- Prokaryotes (bacteria) that emerged during the Precambrian and produce oxygenic photosynthesis.
- Critical during early evolution of the Earth: created the present oxygenic atmosphere.

Ancient cyanobacteria mats (stromatolites, Greenland)

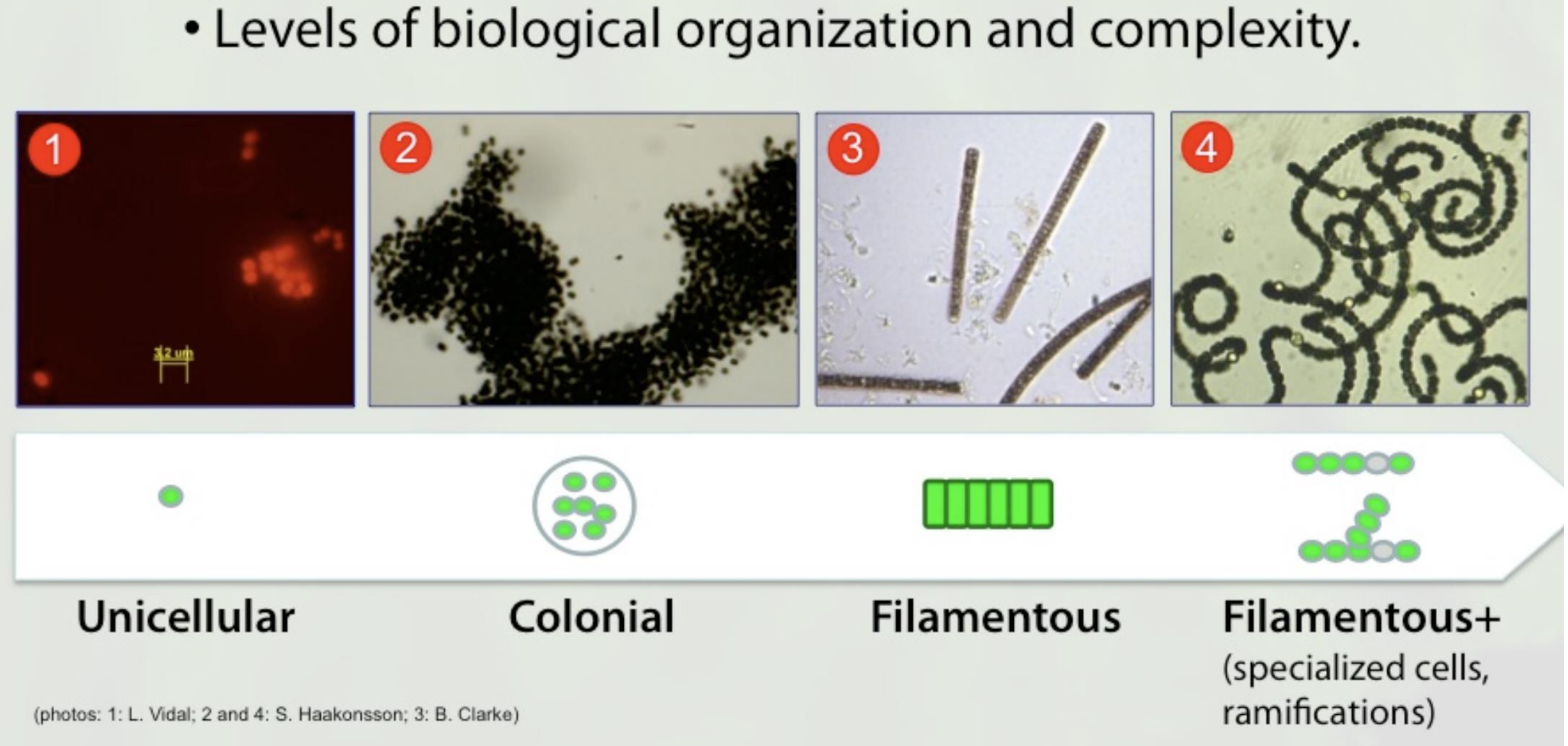
What is the current contribution to global biomass?

> 1000 million metric tones (10^{15} grams) of wet biomass (humans: 350 million metric tones of wet biomass).

How do cyanobacteria look like?



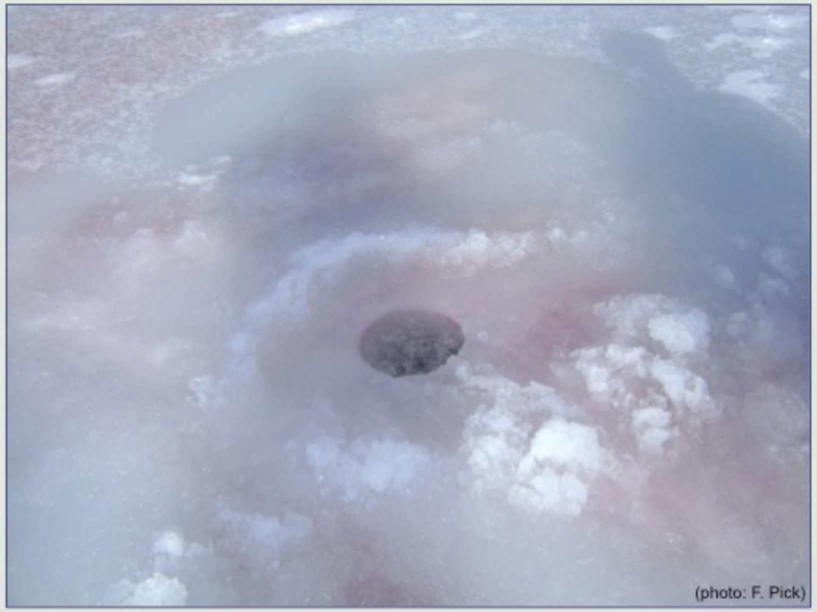
How do cyanobacteria look like?



Where are the cyanobacteria?

- Any habitat with light such as ice, deserts, soils, but especially aquatic ecosystems.
- In freshwater ecosystems; high species diversity, formation of blooms.
- Also in symbiosis with other organisms.

Mats in hotsprings, Greenland



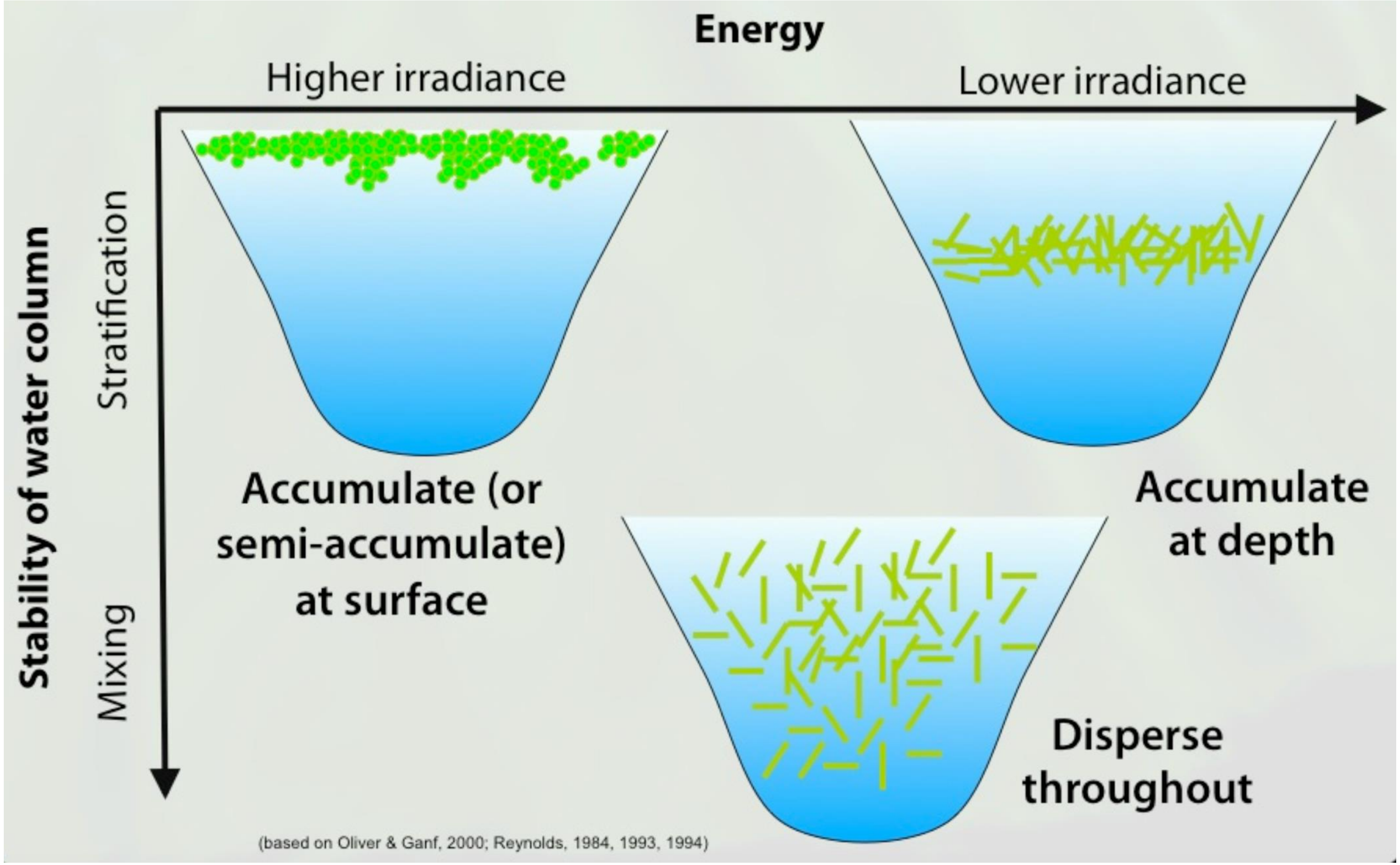
Pink fishing hole in Outaouais lake, Canada, due to cyanobacteria rich in phycoerythrin pigment.

What is a bloom?

- Visible increase in phytoplankton biomass
- Can last from days to months or even become permanent
- Biomass accumulation can be highly variable (about 50 µg/ liter Chl a to mg in scums)
- Cyanobacteria can produce toxins that may be highly concentrated in blooms and represent a public health and ecological concern

Planktothrix rubescens

Types of cyanobacteria blooms



Traits of cyanobacteria leading to dominance and bloom formation

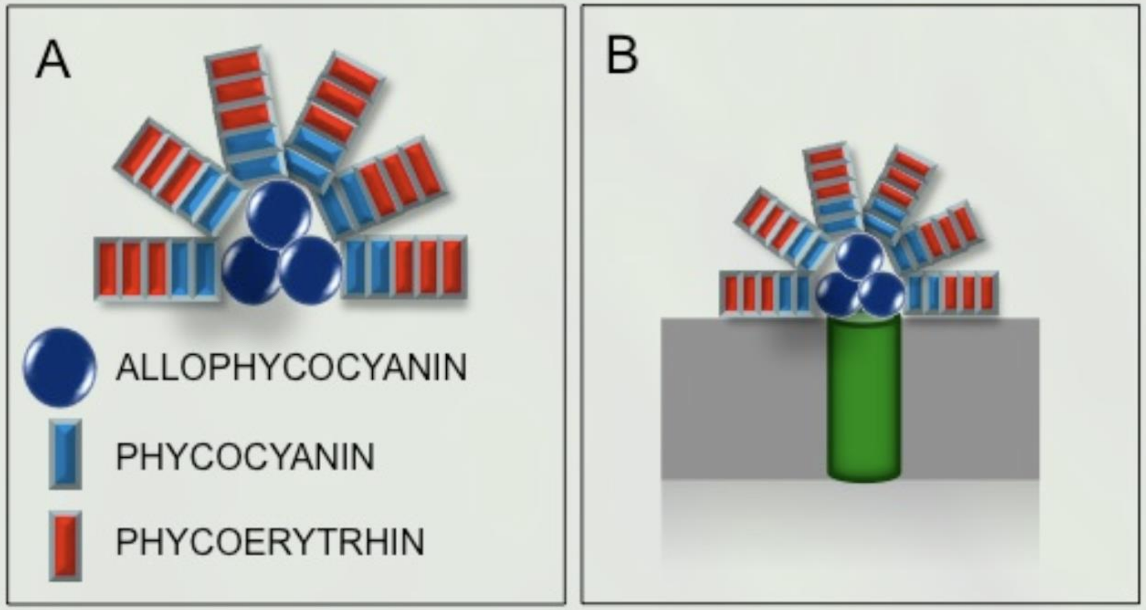
1. **Large size** of colonies or filaments
2. **Tolerance of extremes** in solar radiation
3. Particular **pigments**
4. Nutrient **storage**
5. N_2 fixation
6. **Buoyancy** regulation through gas vacuoles
7. Benthic **resting** stages
8. Toxins

and more…

Light acquisition pigments

- Major light harvesting pigments: **Phycobilins** (allophycocyanin, phycocyanin and phycoerythrin).

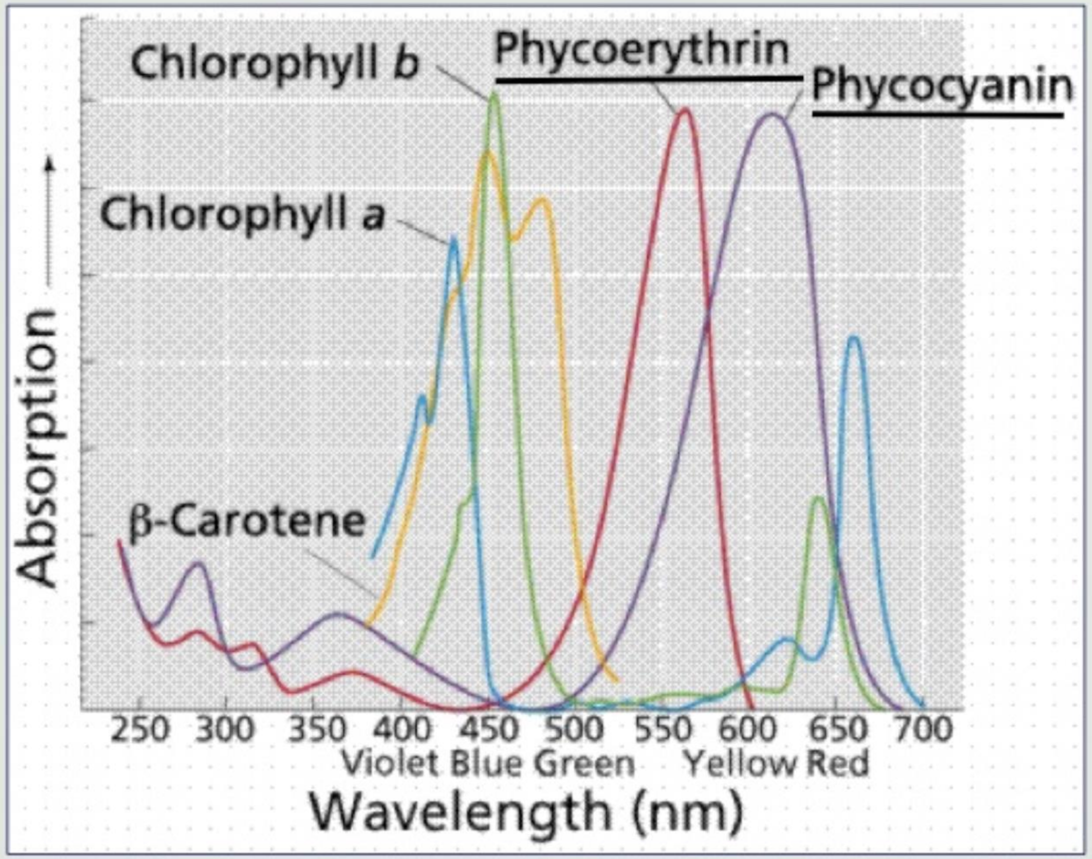
Picocyanobacteria cultures rich in phycoerythrin (left) and phycocyanin (right).



A) General structure of phycobilisomes (PHYS).
B) PHYS are located on the surface of thylakoids. Cylinder in green: PS I & II with chlorophyll *a*; in grey: thylakoid.

Light acquisition pigments

- **Phycobilins:** Capture light at intermediate wavelengths (~562 to ~650 nm).



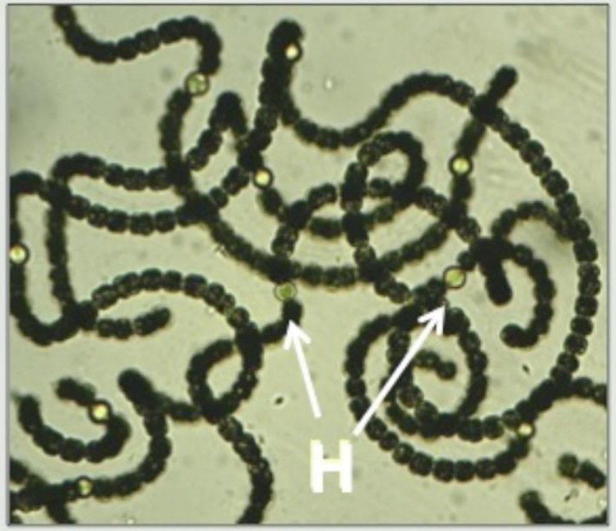
(From: http://www.cas.miamioh.edu/~meicenrd/ANATOMy/Ch8_Absorptive/carotdnoisimg009.html)

Absorption spectra of major pigments in algae and cyanobacteria.

Phycoerythrin and phycocyanin are major pigments in cyanobacteria. (Chlorophyll *b* only present in some cyanobacteria).

Exclusive capacity for nitrogen fixation

Cyanobacteria: only phytoplankton able to fix atmospheric nitrogen (N_2).



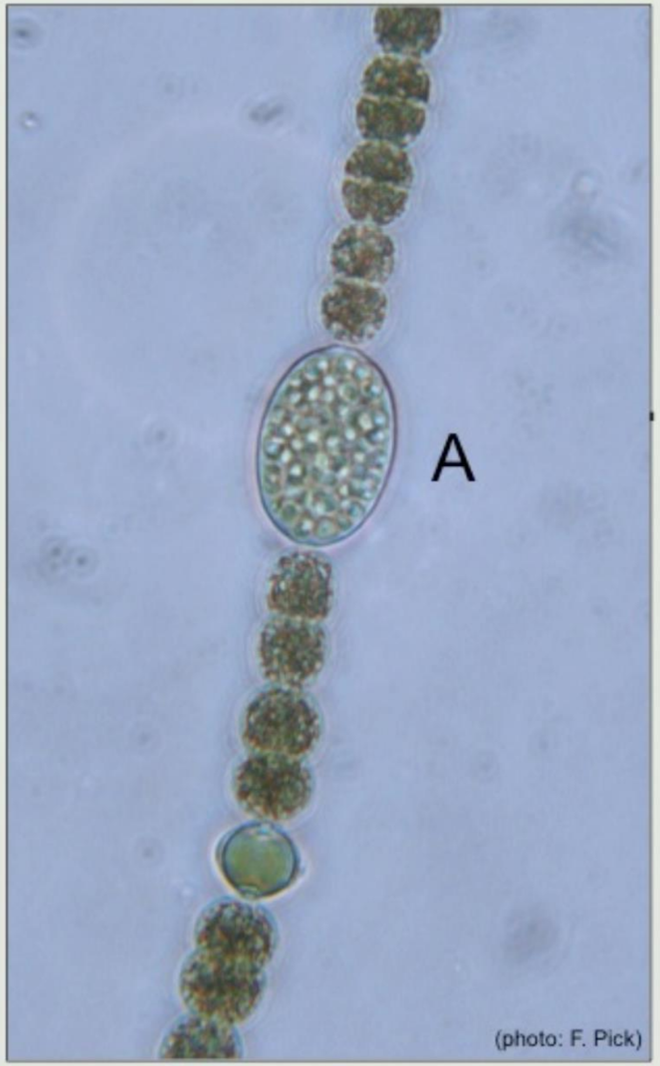
(photos: S. Haakonsson and M. C. Pérez)

Heterocyte (H): site of N_2 fixation in Nostocales

- thick cell walls
- pale and uniform content due to absence of PSII and less photosynthetic pigments (leading to low internal $[O_2]$)
- nitrogenase enzyme

Dolichospermum (Anabaena): a common bloom-forming, diazotrophic, filamentous cyanobacterium; top (x200) and bottom (x1000).

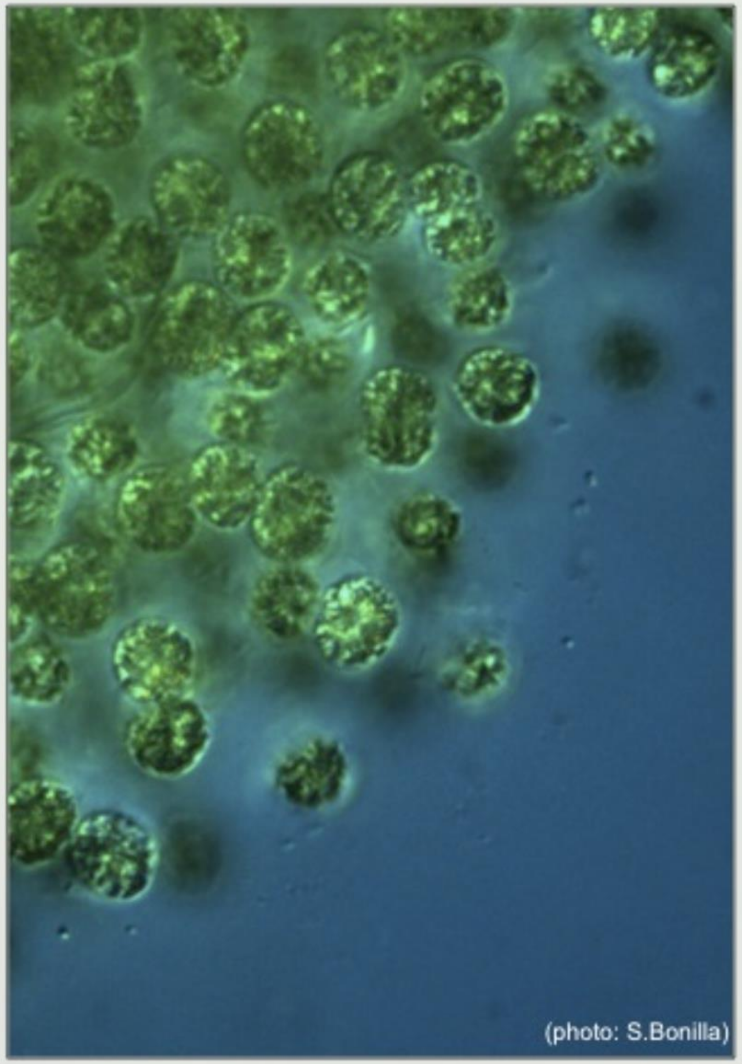
Resting stage cells



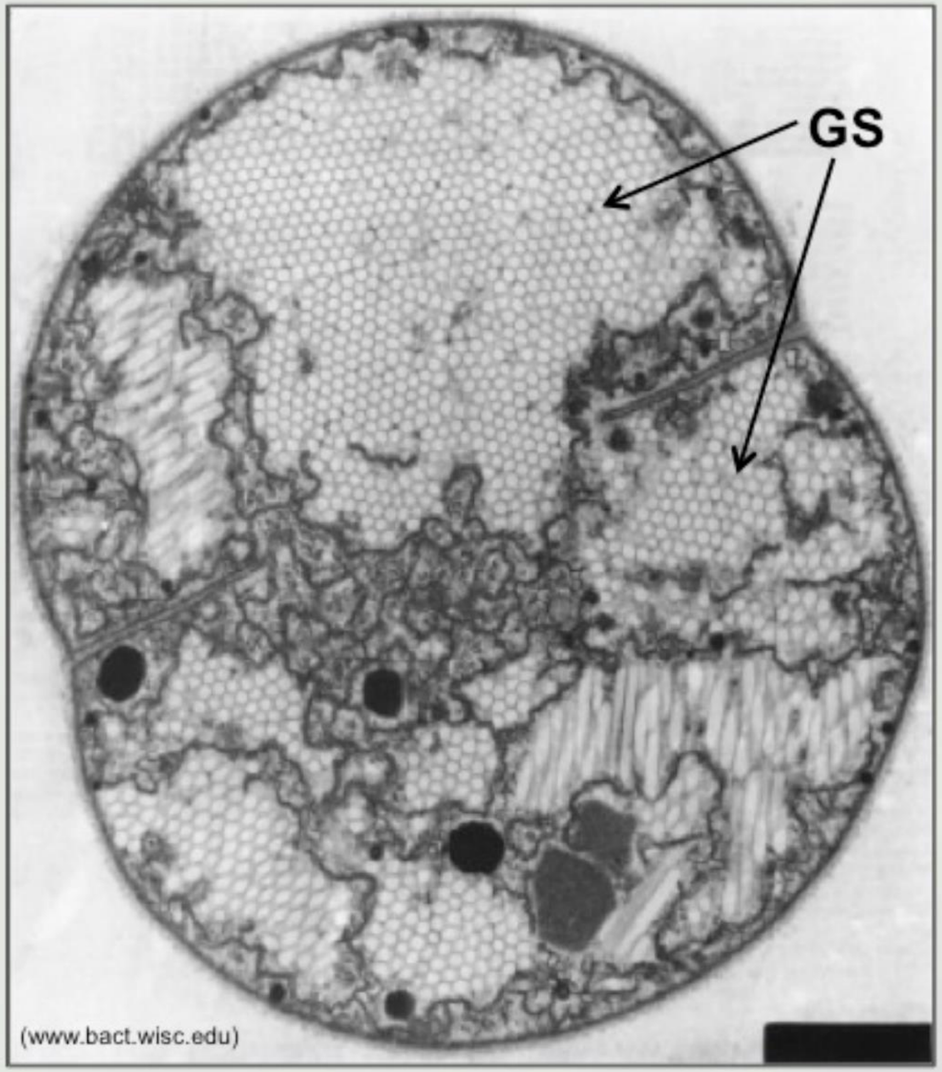
- **Akinete** (A): specialized dormancy cell (resting stage) in Nostocales.
- Thick cell wall, rich in nutrients
- Shape, location on filament is characteristic of species.
- Can detach and persist in sediments/soil to germinate when conditions improve.

Dolichospermum with large akinete (A)

Gas vesicles = buoyancy regulation



Microcystis cells filled with vacuola (grouped gas vesicles) (x1000).

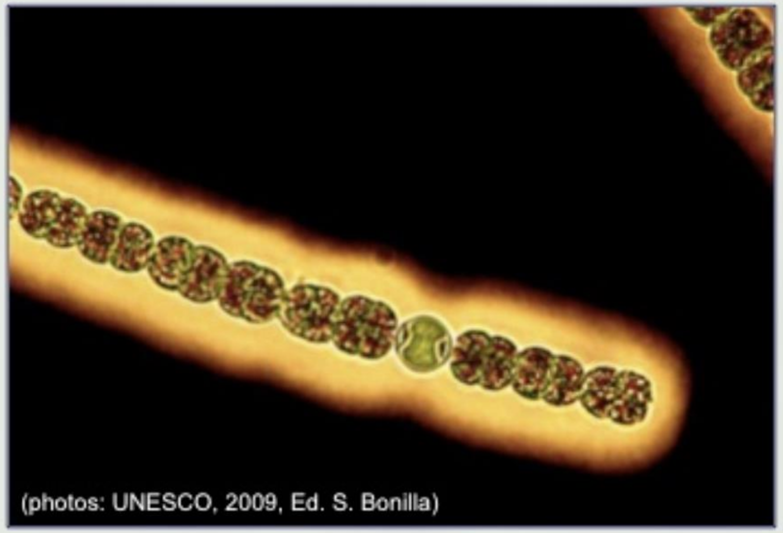


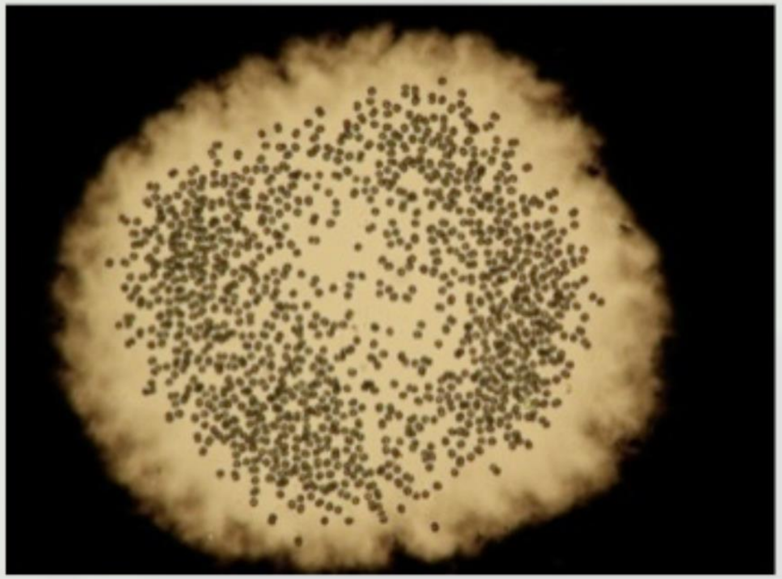
TEM image of a cyanobacterial cell full of gas vesicles (GS) (hexagonal structures). (From Walsby, 1974).

Cell wall mucilage

Functions:

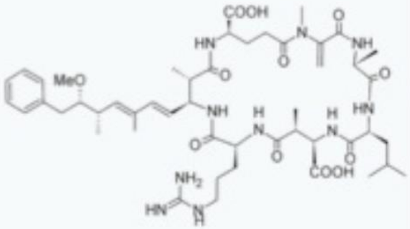
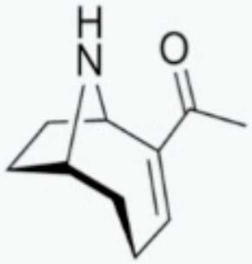
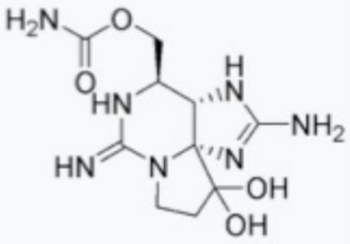
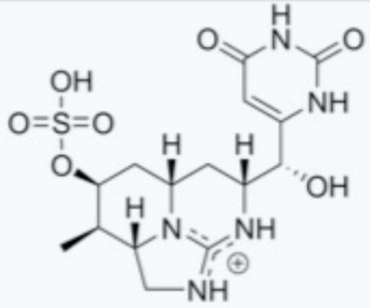
1. Formation of colonies.
2. Protection against desiccation.
3. Protection against UV radiation.
4. Nutrient uptake (e.g. Fe).
5. Filter against contaminants (e.g. heavy metals).
6. Decrease organism density.
7. Decrease predation pressure (predator avoidance, low digestibility).



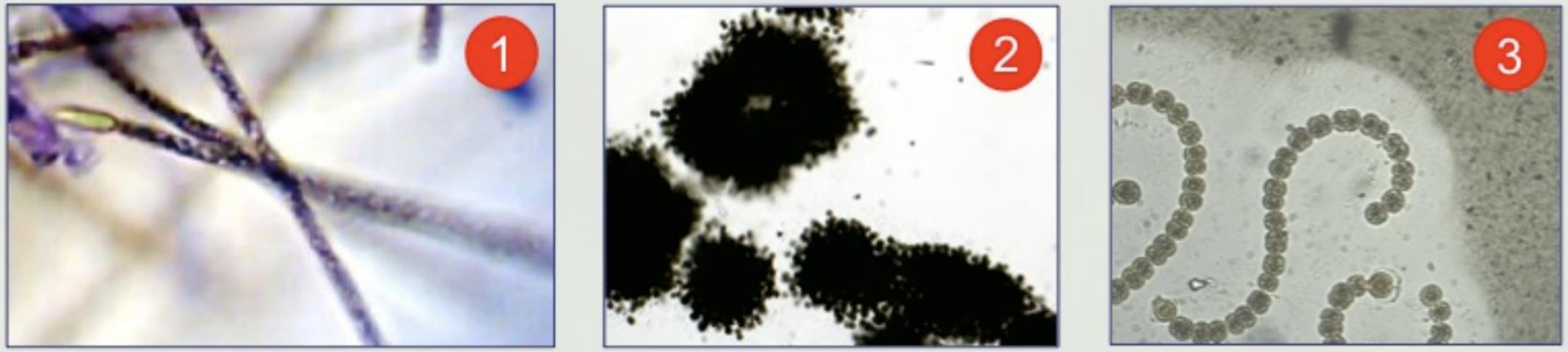


Cyanobacteria at 1000x with black ink to highlight the transparent mucilage. (top: *Dolichospermum*, and bottom: *Microcystis*)

Cyanotoxins

	Microcystins	Anatoxins	Saxitoxins	Cylindro-spermopsins
Molecular Weight	909 - 1115	165 - 252	299	415
Chemical structure				
Number of variants	> 200	3	> 19	3
Toxin type	Hepatotoxic	Neurotoxic	Neurotoxic	Cytotoxic
LD_{50} (µg kg^{-1} b.w.)	50 - >1200	20 - 250	10	2100

Many genera can produce multiple cyanotoxins



Same toxin can be produced by multiple genera

Photos: 1: *Cylindrospermopsis raciborksii*, B. Cremella; 2: *Radiocystis* sp., M.C. Pérez; 3: *Dolichospermum* sp., S. Haakonsson; 4: *Woronichinia* sp., F. Pick; 5: *Planktothrix* sp., B. Clarke; 6: *Dolichospermum lemmermanii,* F. Pick).

In Switzerland…