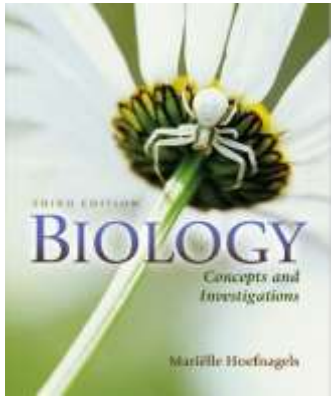
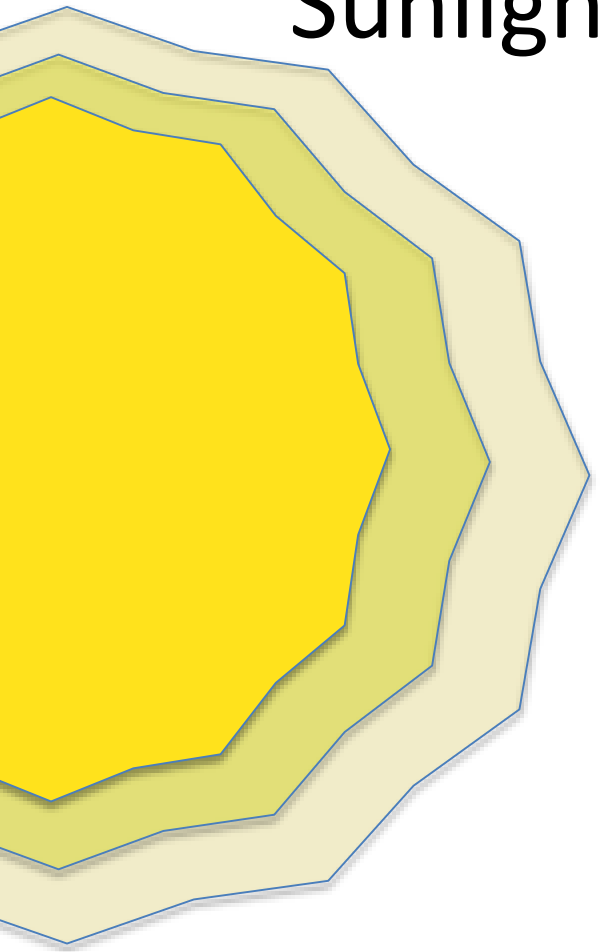
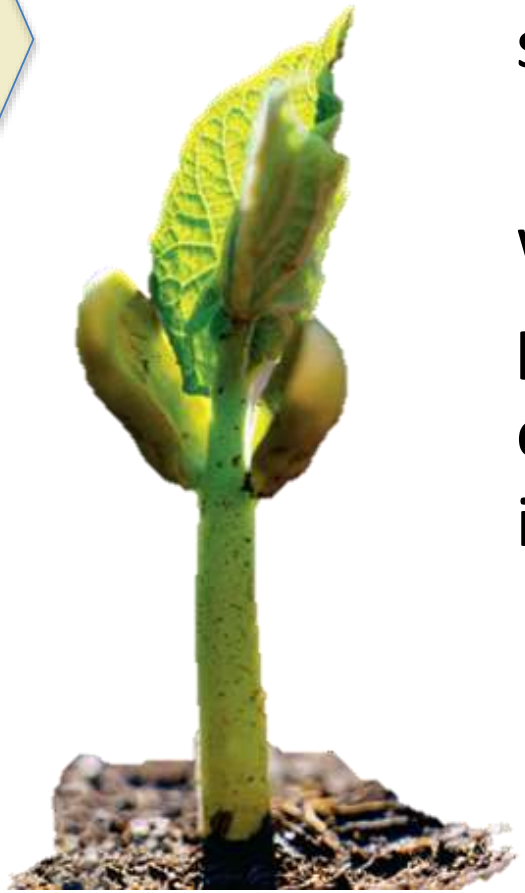


Chapter 5
Photosynthesis

Photosynthetic coral © Andrew J. Martinez/Science Source

Sunlight Powers Photosynthesis

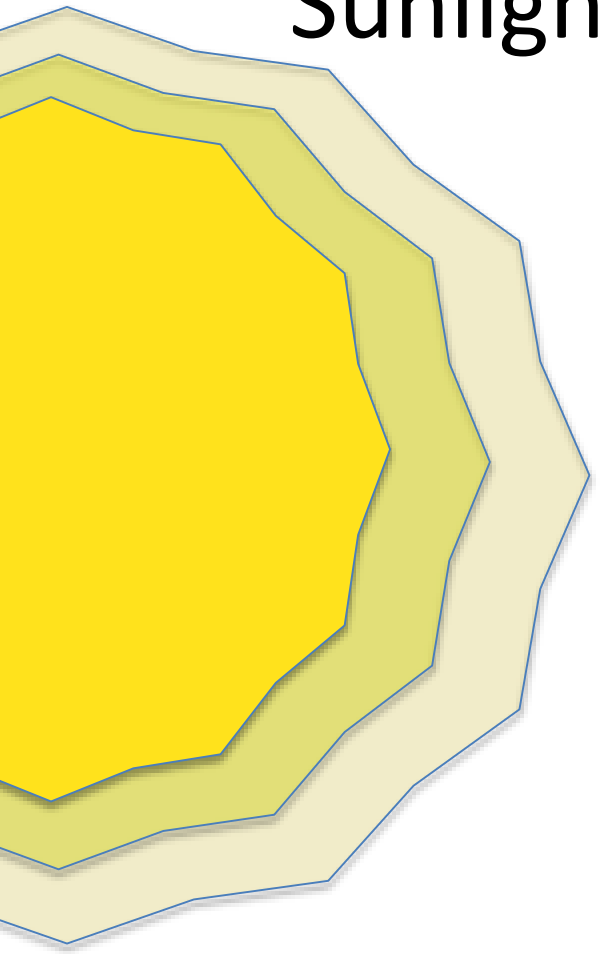




This seedling is soaking up the sun.

Within its leaves, **photosynthesis** is converting sunlight into food.

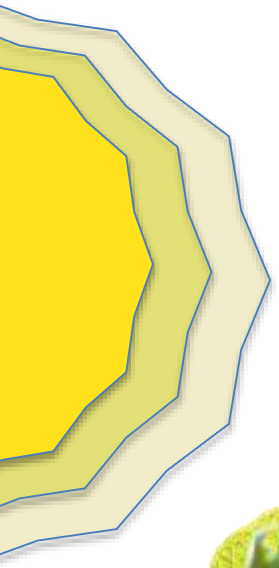
Sunlight Powers Photosynthesis

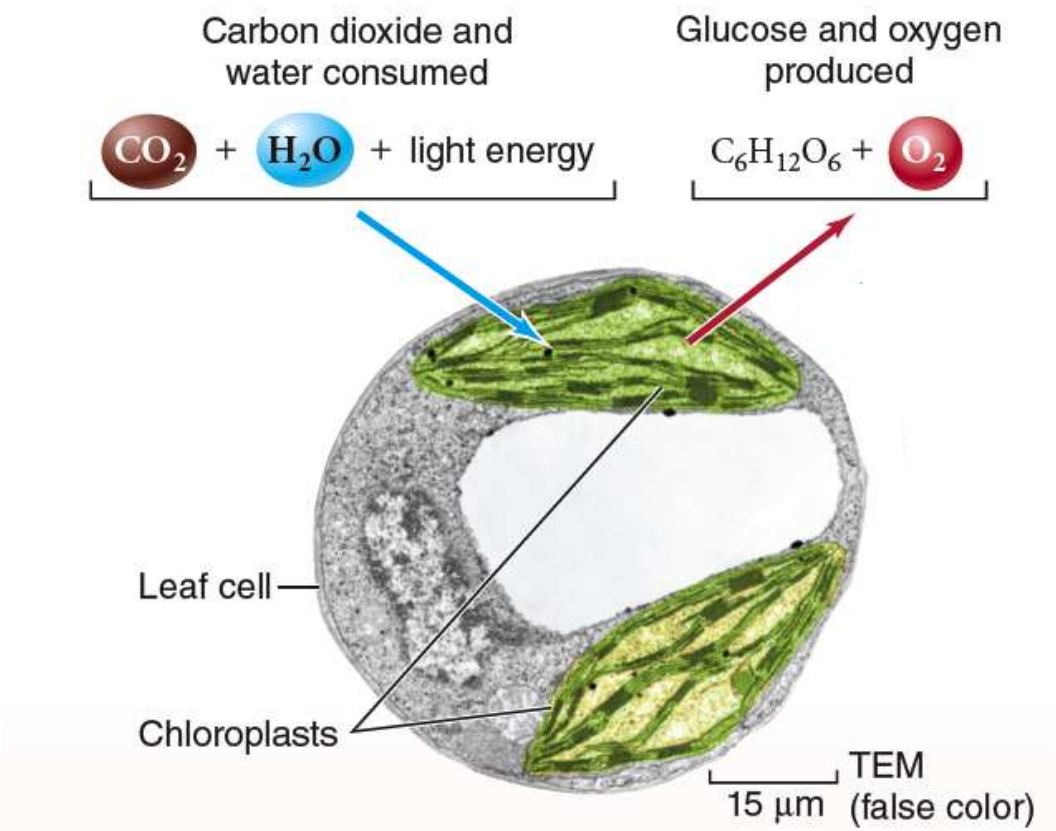


Plants need few simple ingredients to make their own food:

- Sunlight
- Carbon dioxide (CO_2)
- Water

Sunlight Powers Photosynthesis





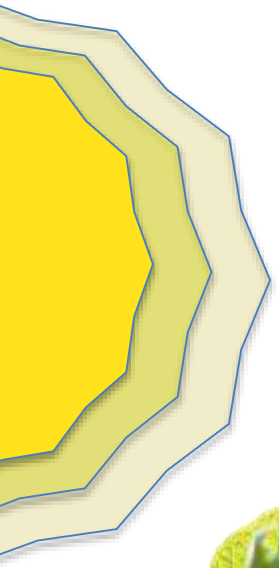
Section 5.1

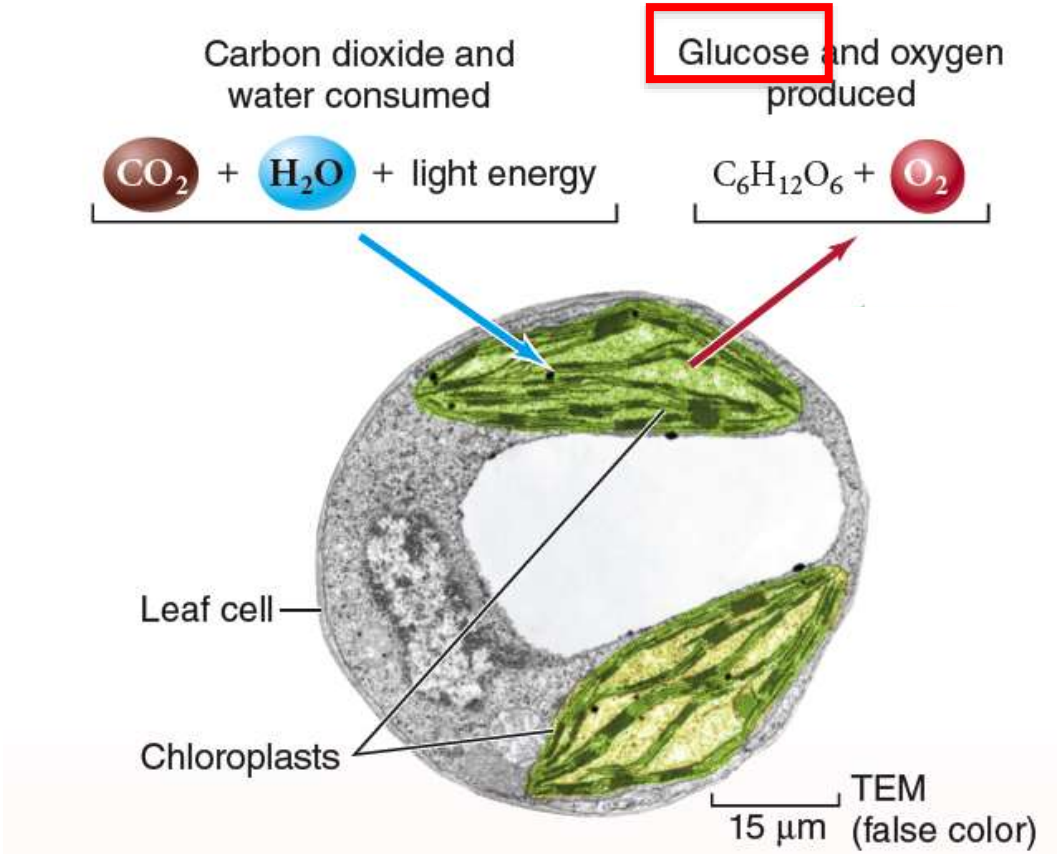
Sprout: © Corbis (RF); Electron micrograph by Wm. P. Wergin, courtesy of Eldon H. Newcomb, University of Wisconsin-Madison.

Figure 5.1

Sunlight Powers Photosynthesis

Plants use these simple ingredients to make sugars, like glucose.



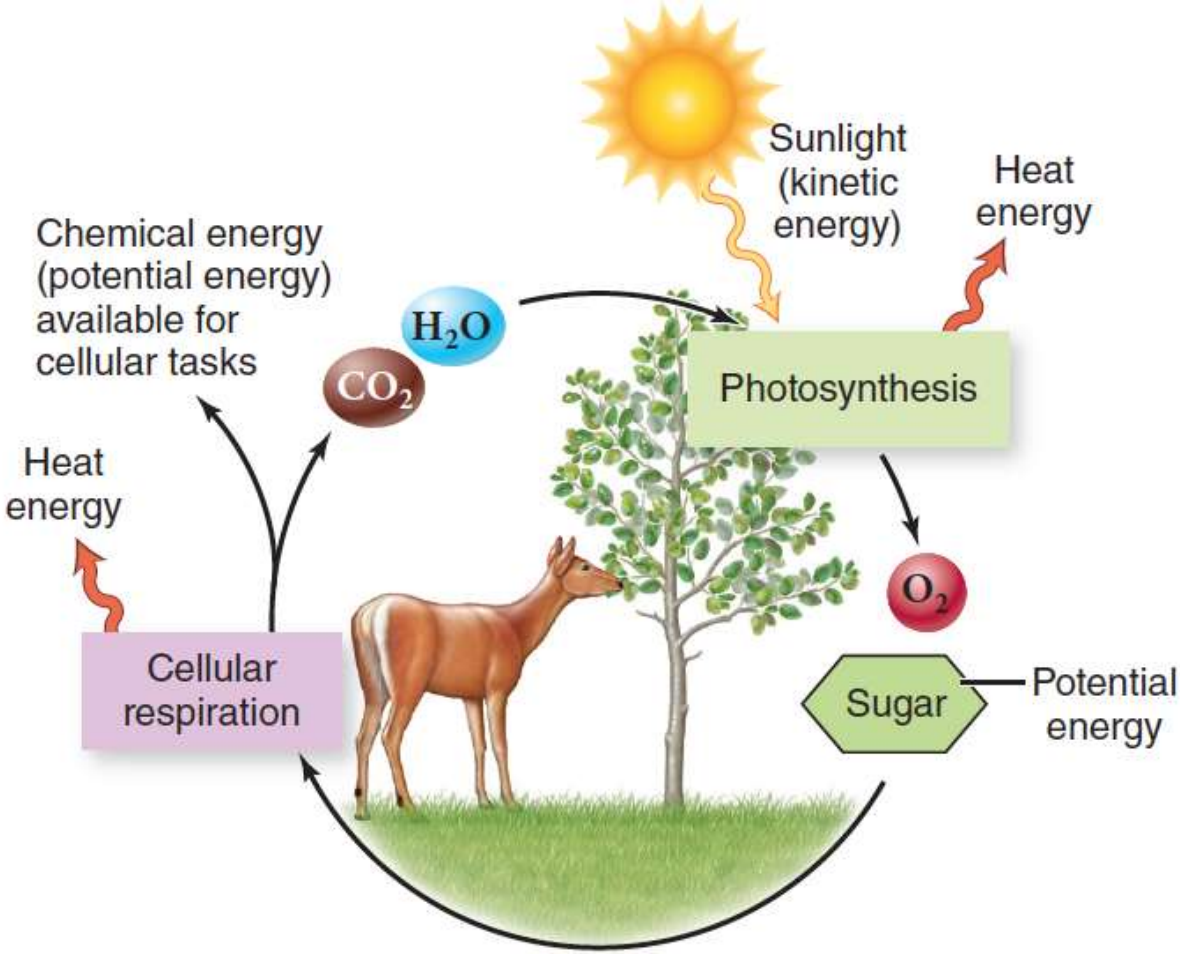


Section 5.1

Sprout: © Corbis (RF); Electron micrograph by Wm. P. Wergin, courtesy of Eldon H. Newcomb, University of Wisconsin-Madison.

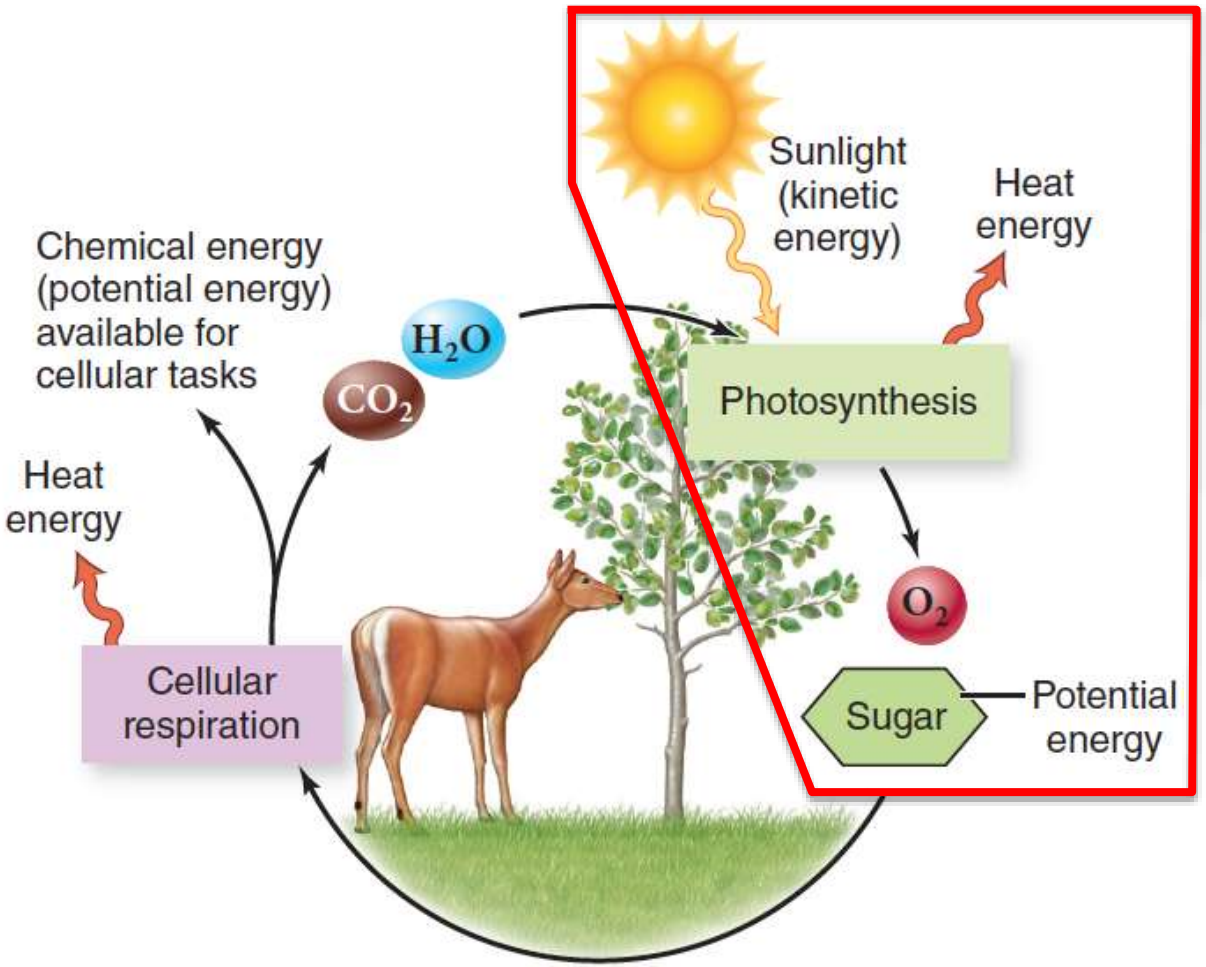
Figure 5.1

Life Depends On Photosynthesis



Without photosynthesis, neither the plants nor the animal in this image would survive.

Life Depends On Photosynthesis



Photosynthesis is essential to sustaining life on Earth.

Section 5.1

How are they connected?

Respiration

glucose + oxygen → carbon dioxide + water + energy

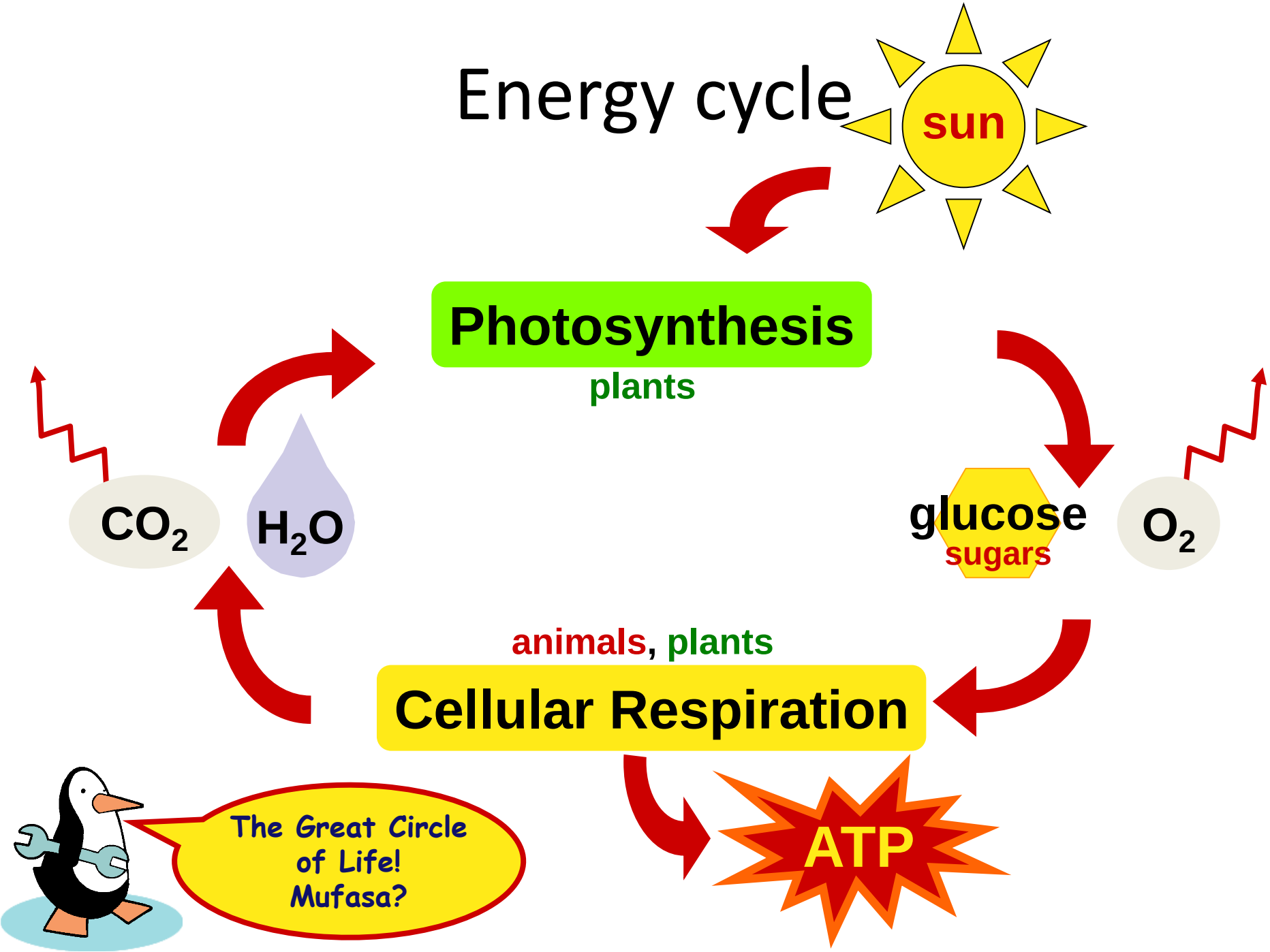
$$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O + ATP$$

Photosynthesis

carbon dioxide + water + sun energy → glucose + oxygen

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

Energy cycle



The poetic perspective

- All of the solid material of every plant was built out of thin air
- All of the solid material of every animal was built from plant material

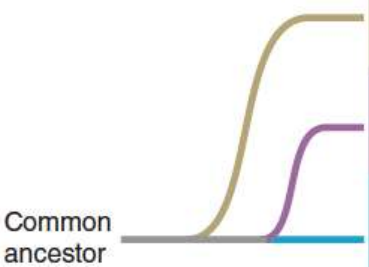
air

sun

Then all the cats, dogs, mice, people & elephants… are really strands of air woven together by sunlight!

Life Depends On Photosynthesis

Some bacteria and eukaryotes carry out photosynthesis, but archaea do not.



	Does Photosynthesis Occur?	Location of Photosynthetic Reactions	Examples	Habitats where Photosynthesis Occurs
Domain Bacteria	Yes	Cytoplasm	Cyanobacteria	Aquatic (mostly) and terrestrial
Domain Archaea	No	N/A	N/A	N/A
Domain Eukarya	Yes	Chloroplasts	Plants, algae	Aquatic and terrestrial

Figure 5.2

Clicker Question #1

Evolution favored the development of photosynthesis because photosynthetic organisms

A. produce oxygen.
B. make their own food.
C. make food for heterotrophs.
D. use carbon dioxide.
E. All of the choices are correct.

Clicker Question #1

Evolution favored the development of photosynthesis because photosynthetic organisms

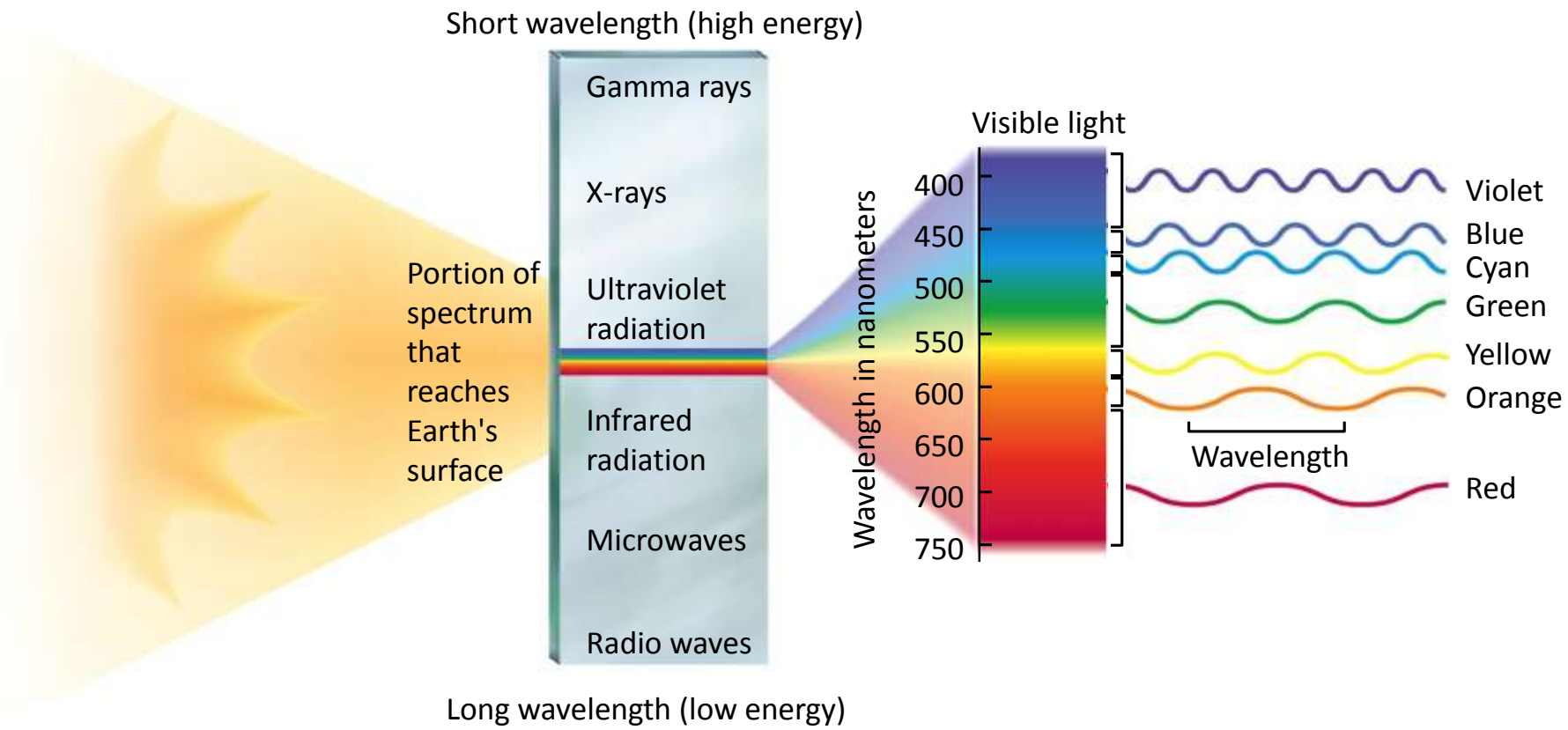
A. produce oxygen.
B. make their own food.
C. make food for heterotrophs.
D. use carbon dioxide.
E. All of the choices are correct.

5.1 Mastering Concepts

Why is photosynthesis essential to life?

Photosynthetic coral © Andrew J. Martinez/Science Source

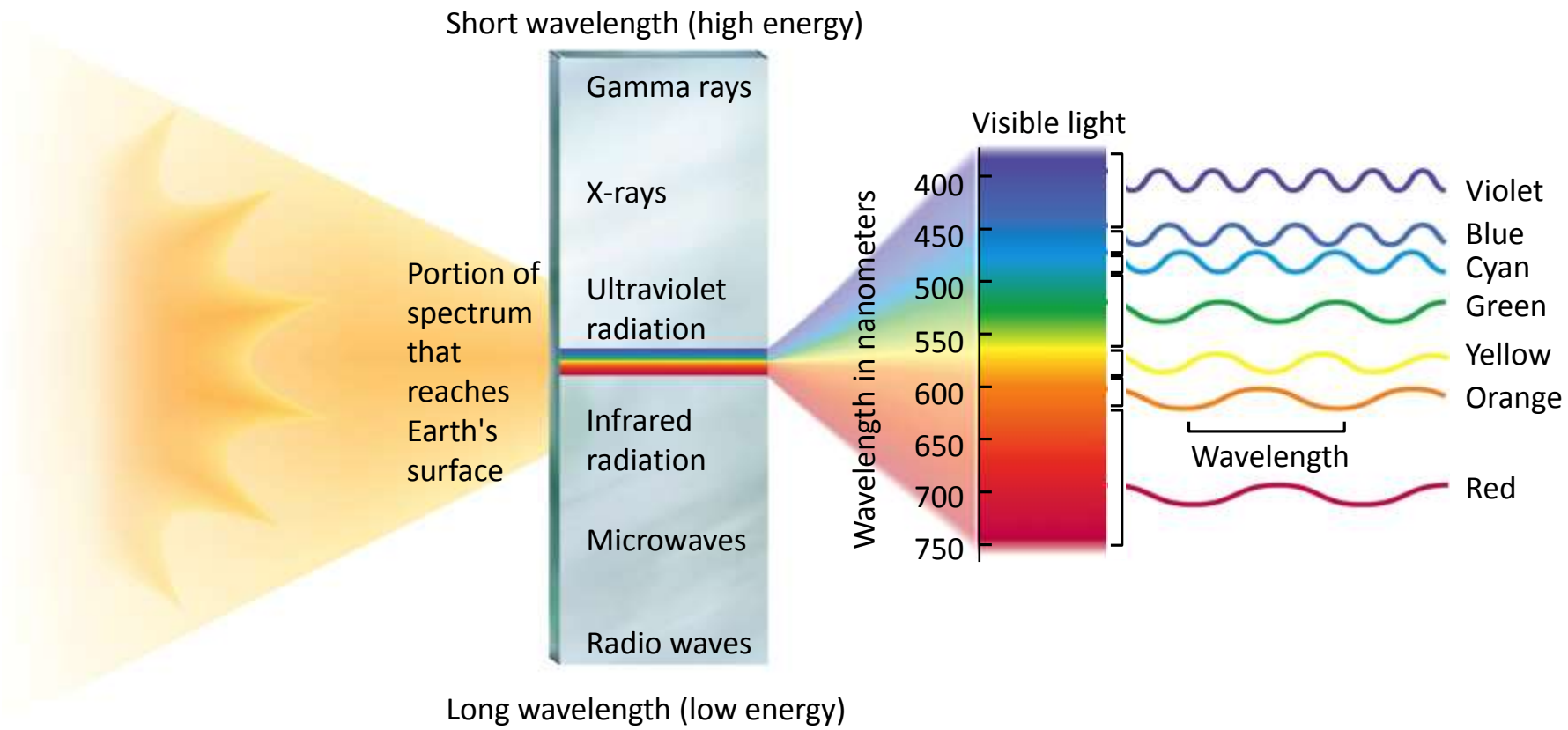
The Sun Emits a Spectrum of Wavelengths



The sun releases energy in waves.

Figure 5.3

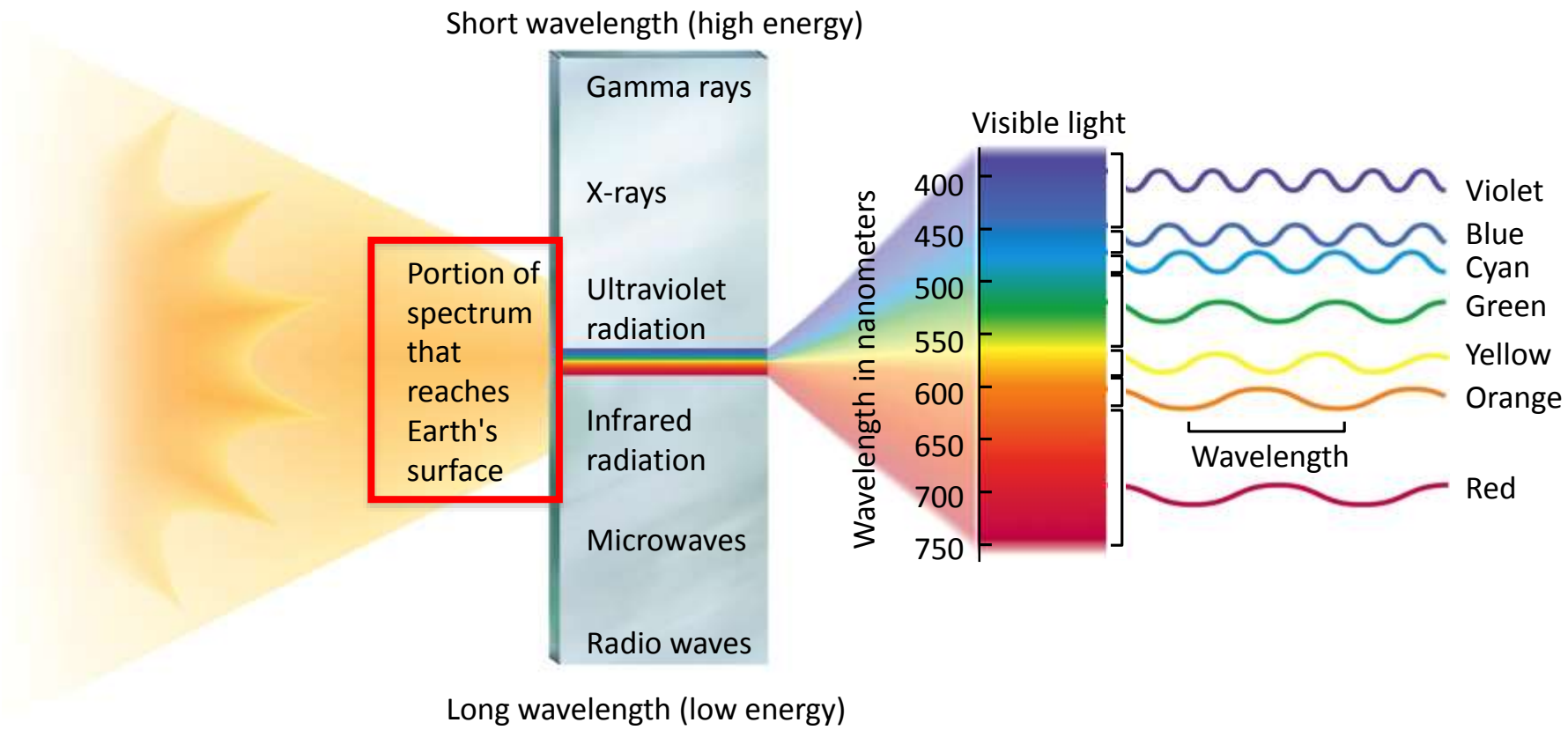
The Sun Emits a Spectrum of Wavelengths



Shorter wavelengths have higher energy than longer wavelengths.

Figure 5.3

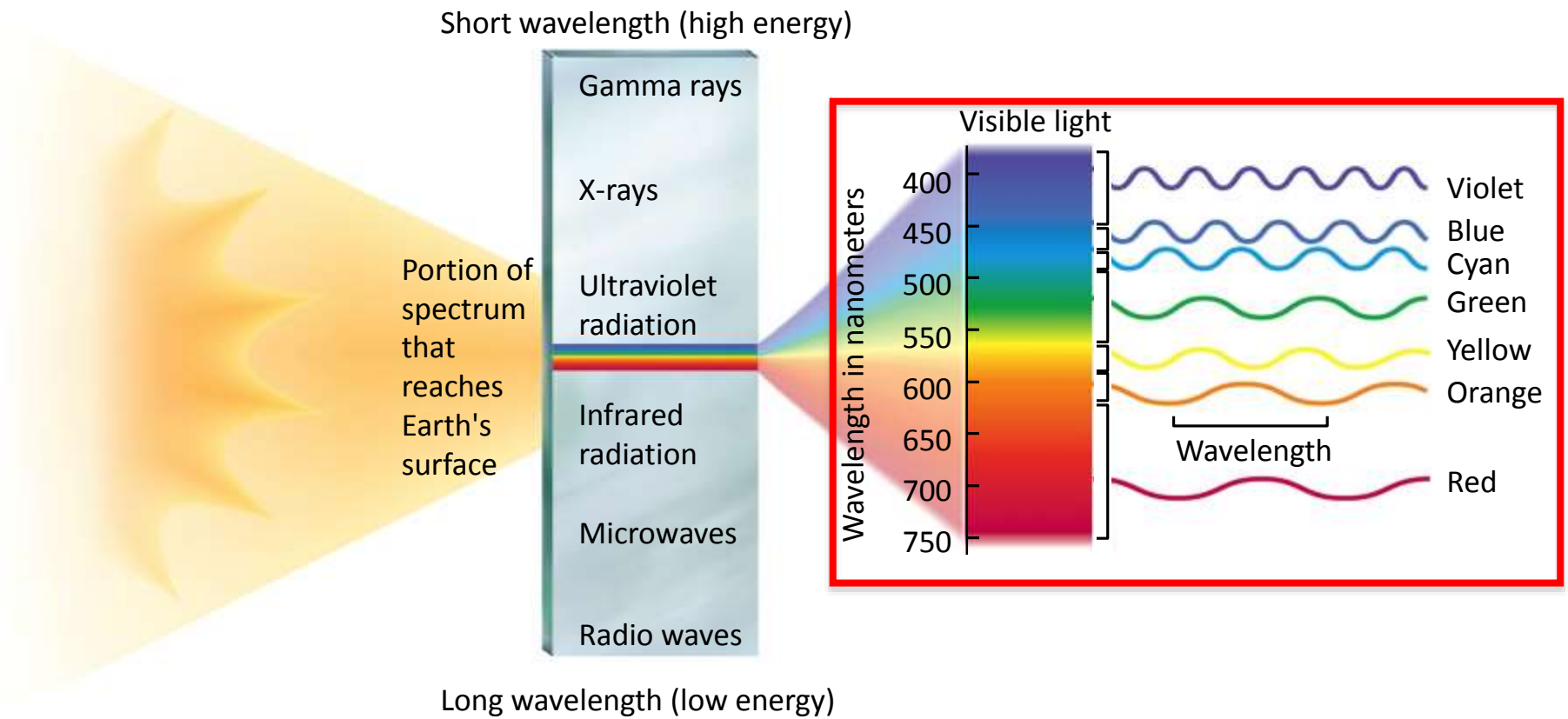
The Sun Emits a Spectrum of Wavelengths



But only some wavelengths reach Earth.

Figure 5.3

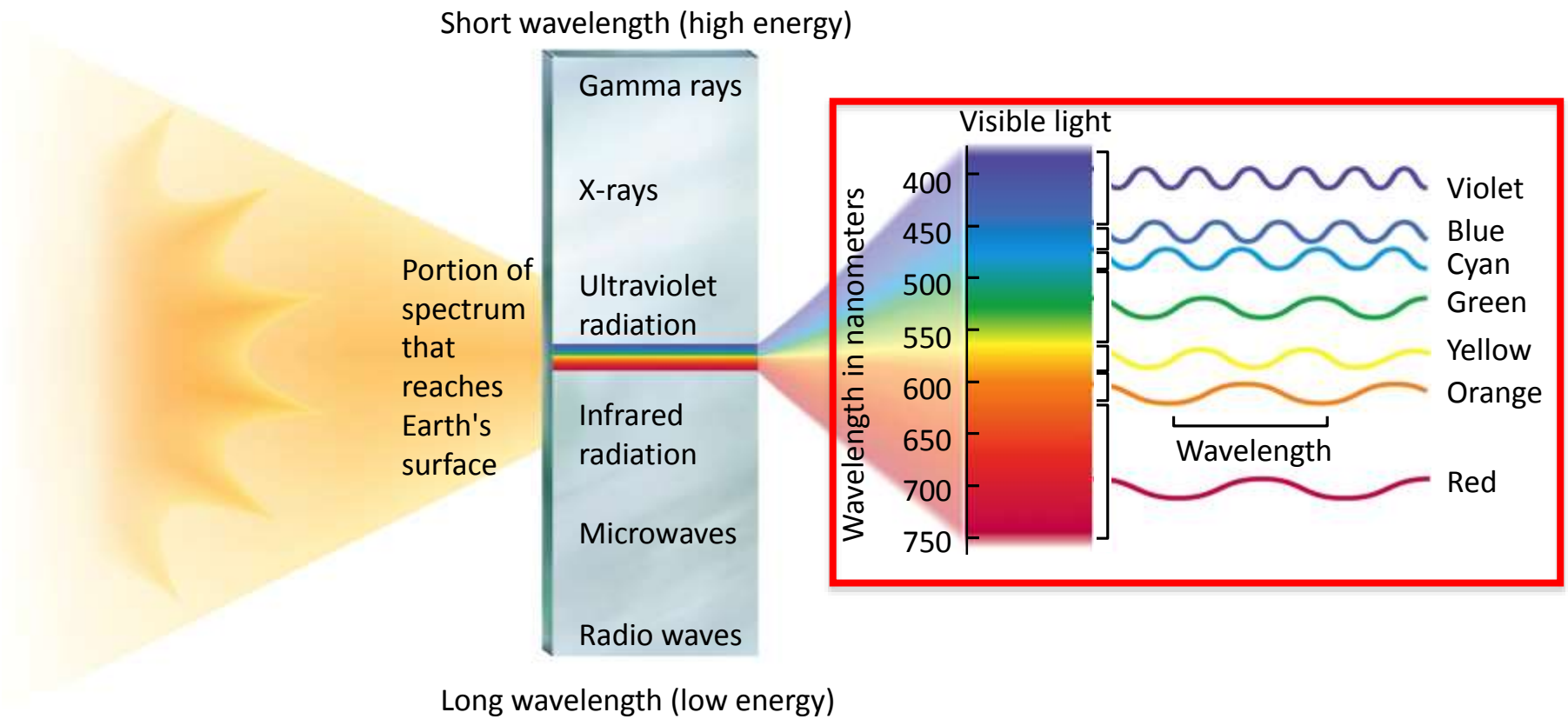
The Sun Emits a Spectrum of Wavelengths



And only some wavelengths are visible to us.
We perceive these wavelengths as colors.

Figure 5.3

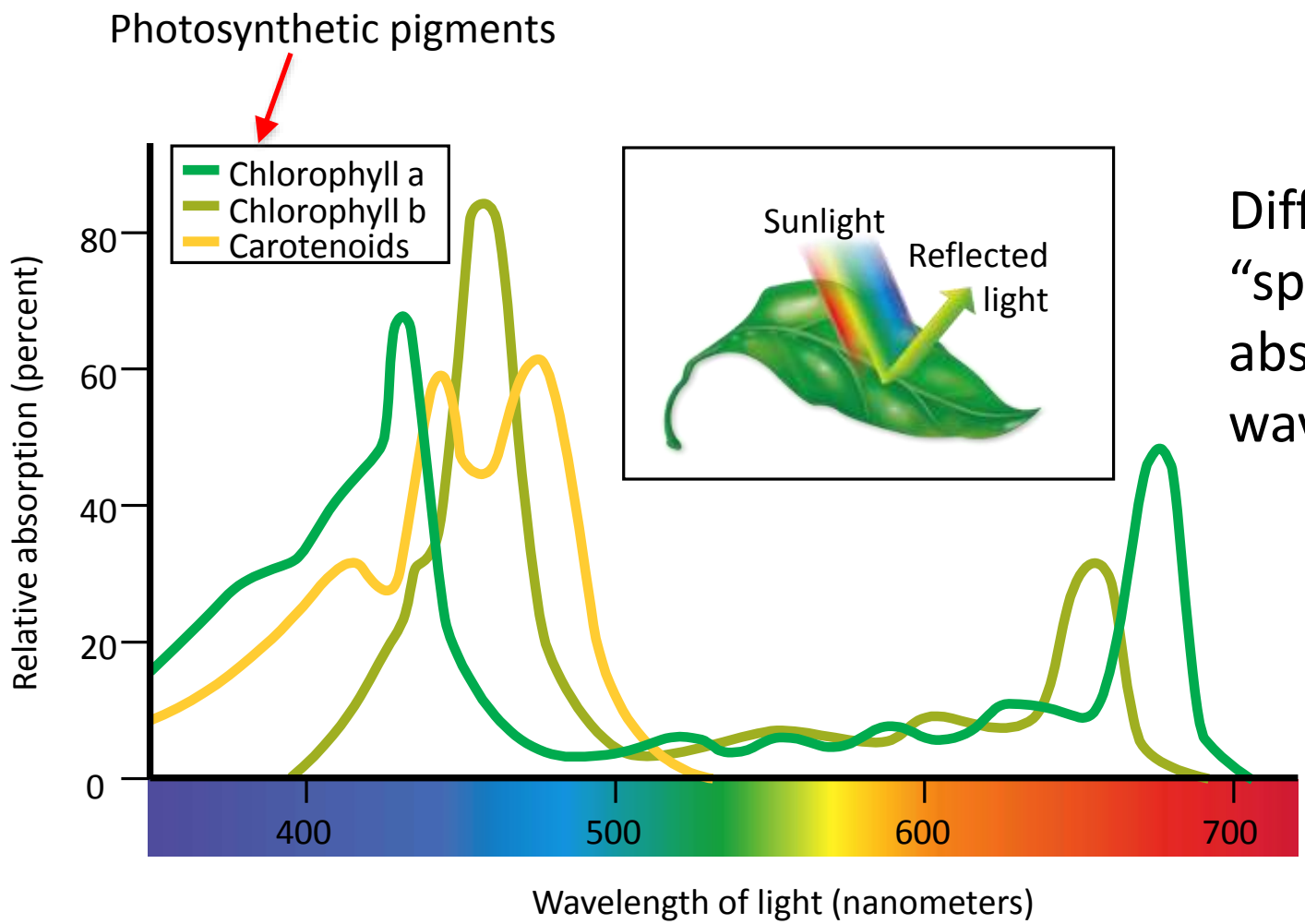
The Sun Emits a Spectrum of Wavelengths



Photons are packets of light energy. Plants capture photons of visible light.

Figure 5.3

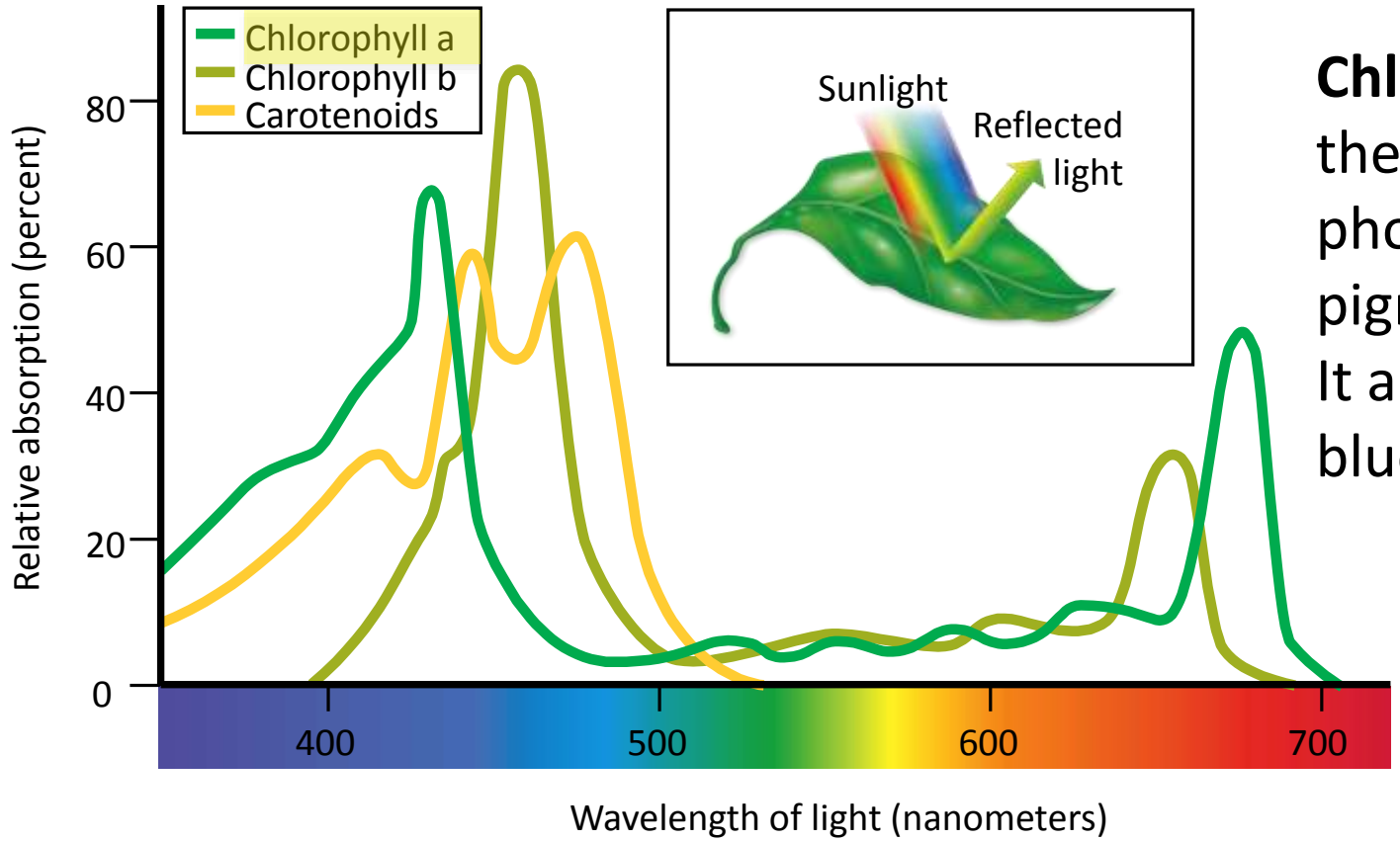
Photosynthetic Pigments Capture Sunlight



Different pigments "specialize" in absorbing different wavelengths.

Figure 5.4

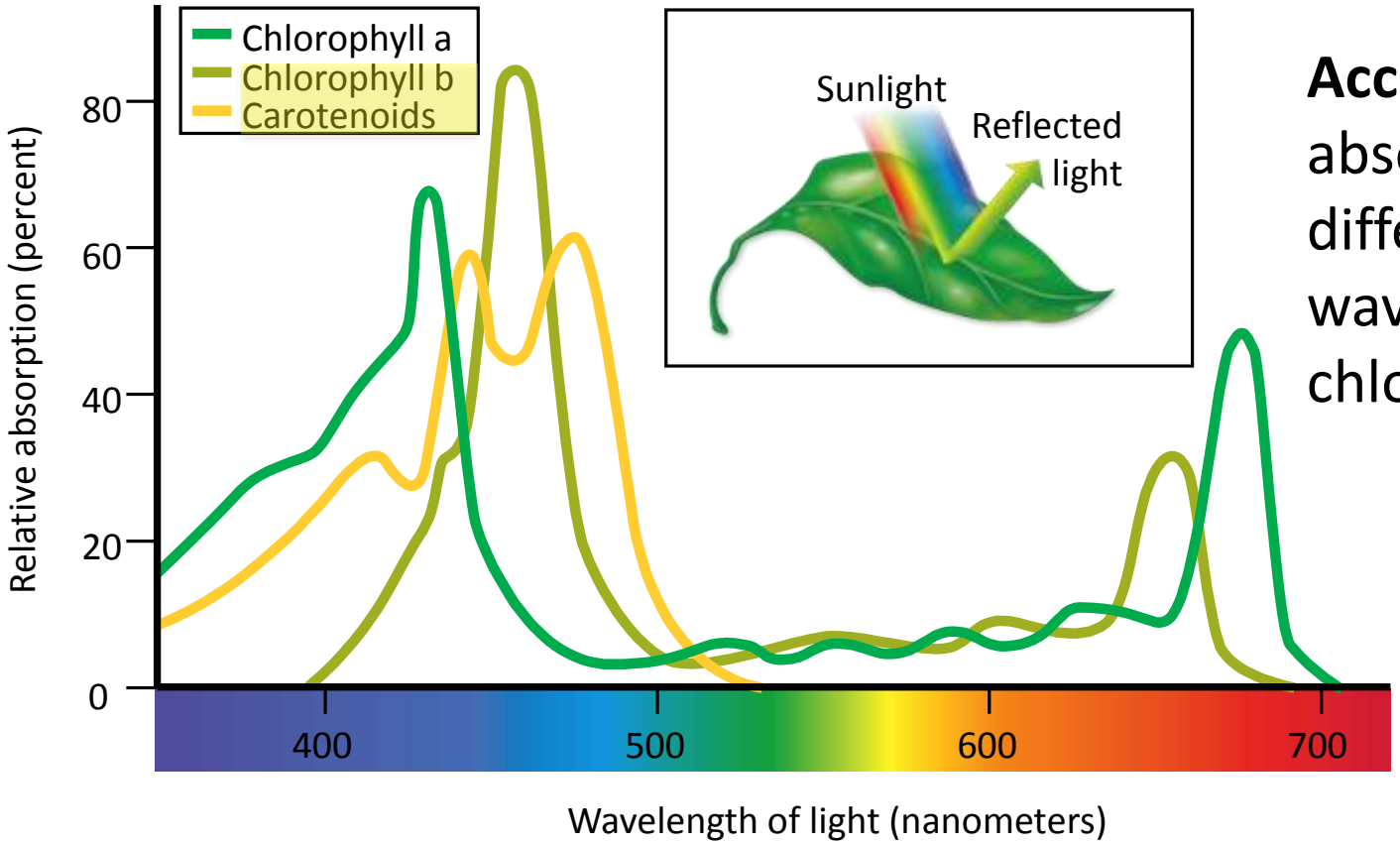
Photosynthetic Pigments Capture Sunlight



Chlorophyll *a* is the primary photosynthetic pigment in plants. It absorbs mostly blue and red light.

Figure 5.4

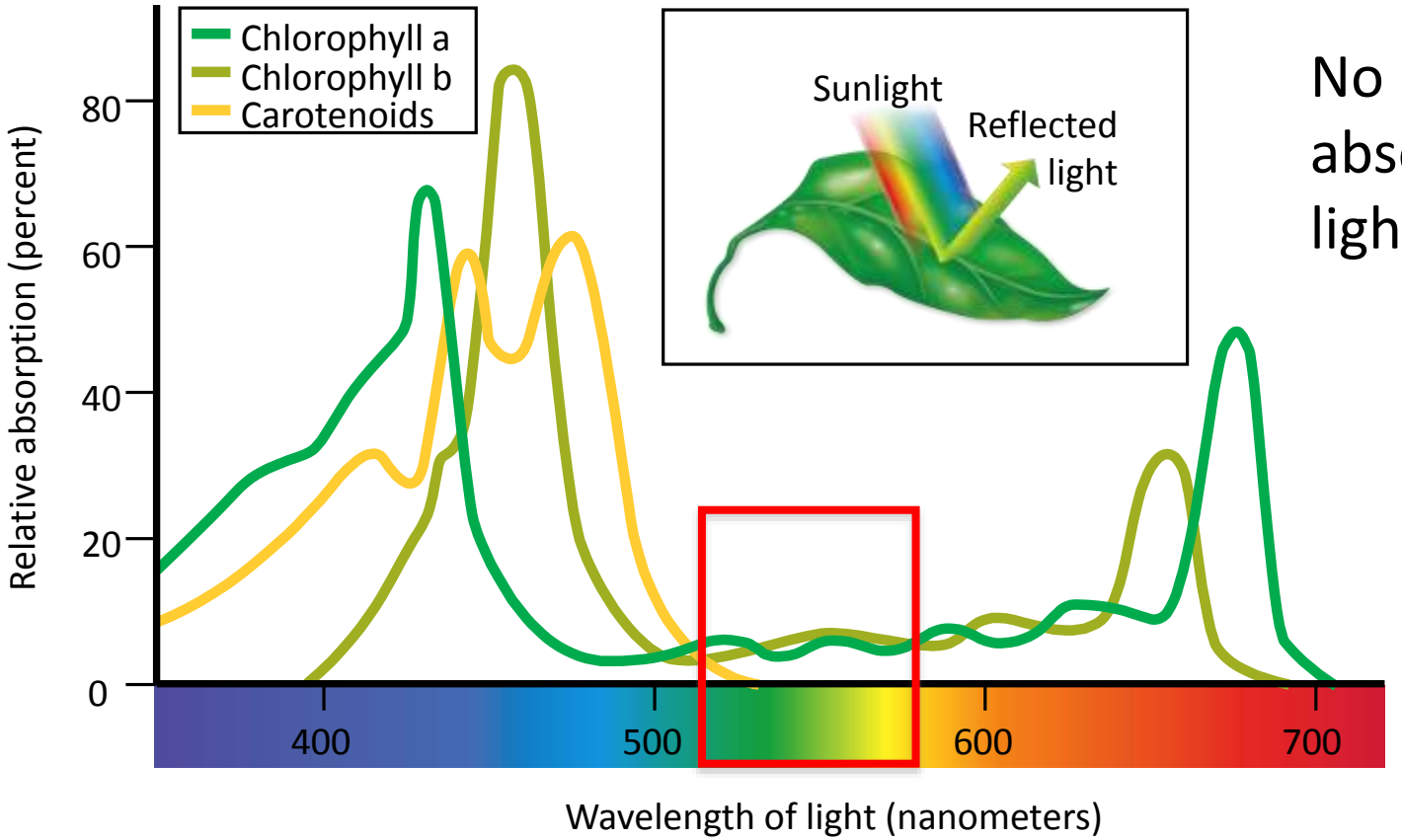
Photosynthetic Pigments Capture Sunlight



Accessory pigments absorb slightly different wavelengths than chlorophyll *a*.

Figure 5.4

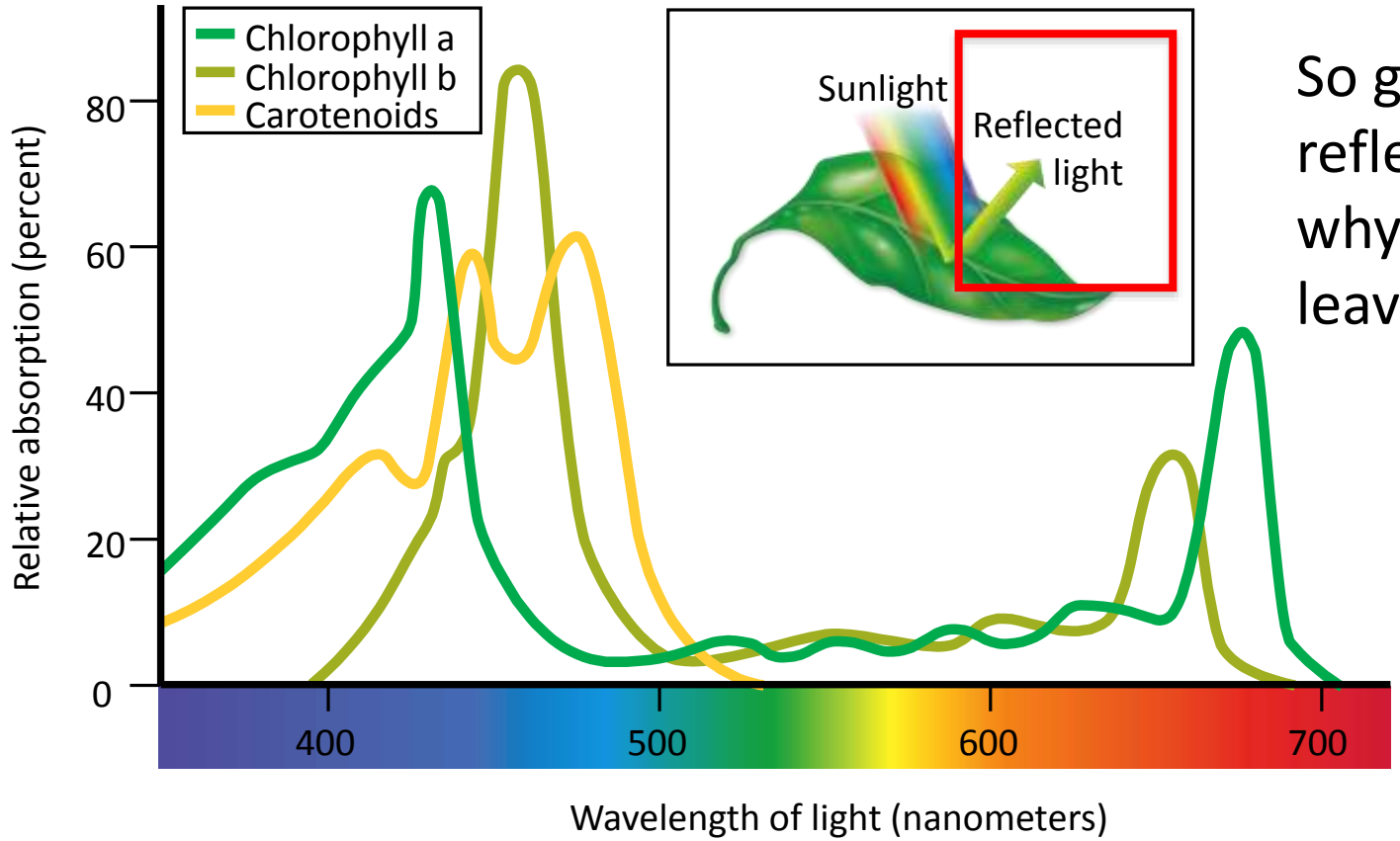
Photosynthetic Pigments Capture Sunlight



No pigment absorbs green light.

Figure 5.4

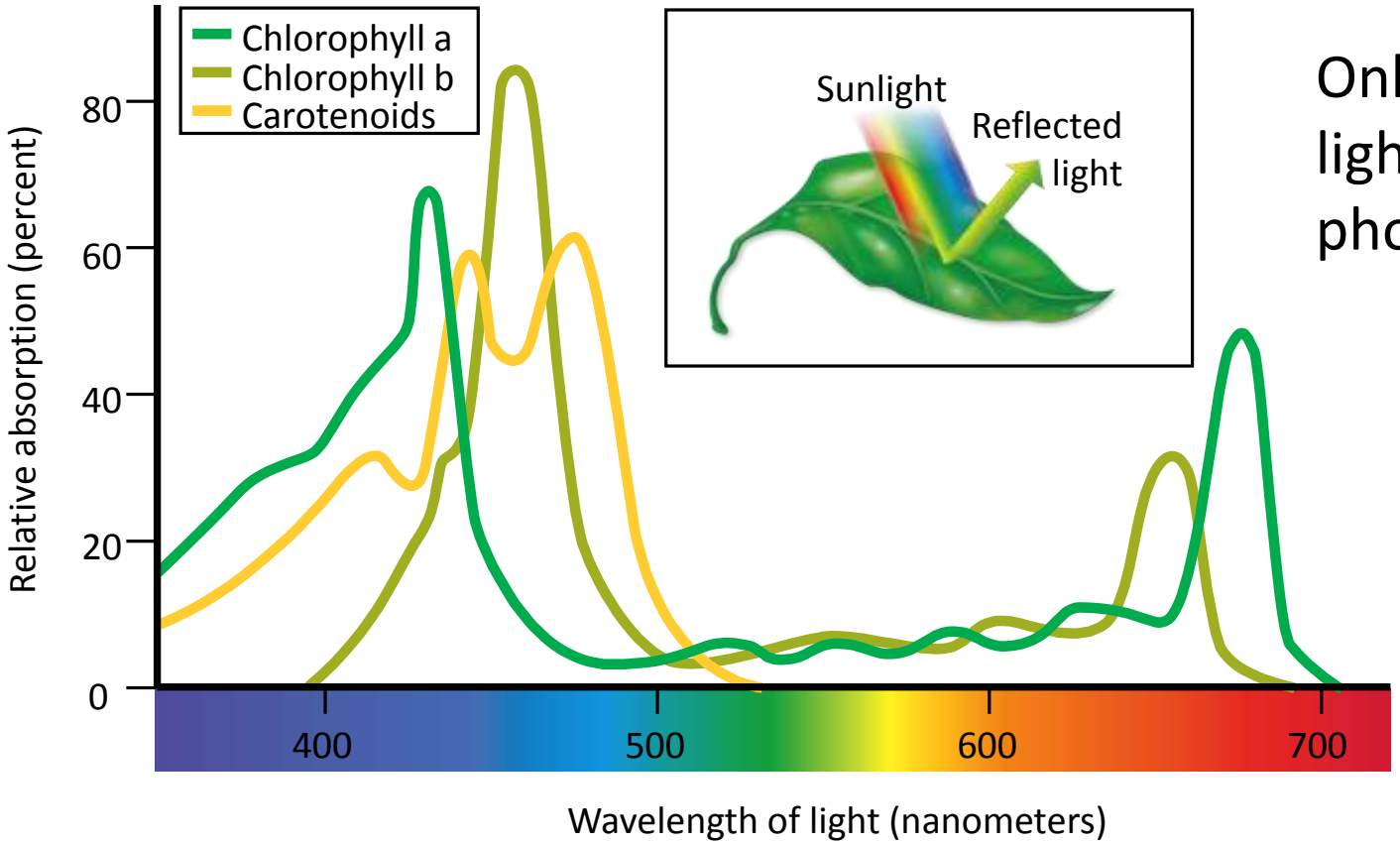
Photosynthetic Pigments Capture Sunlight



So green light is reflected, which is why we perceive leaves to be green.

Figure 5.4

Photosynthetic Pigments Capture Sunlight



Only absorbed light is useful for photosynthesis.

Figure 5.4

Clicker Question #2

Why are leaves green?

A. Heterotrophs see green better than any other color.
B. Plant pigments absorb green light.
C. Plant pigments absorb almost every wavelength except for green.
D. Plant pigments change yellow light that they absorb to green light that we see.

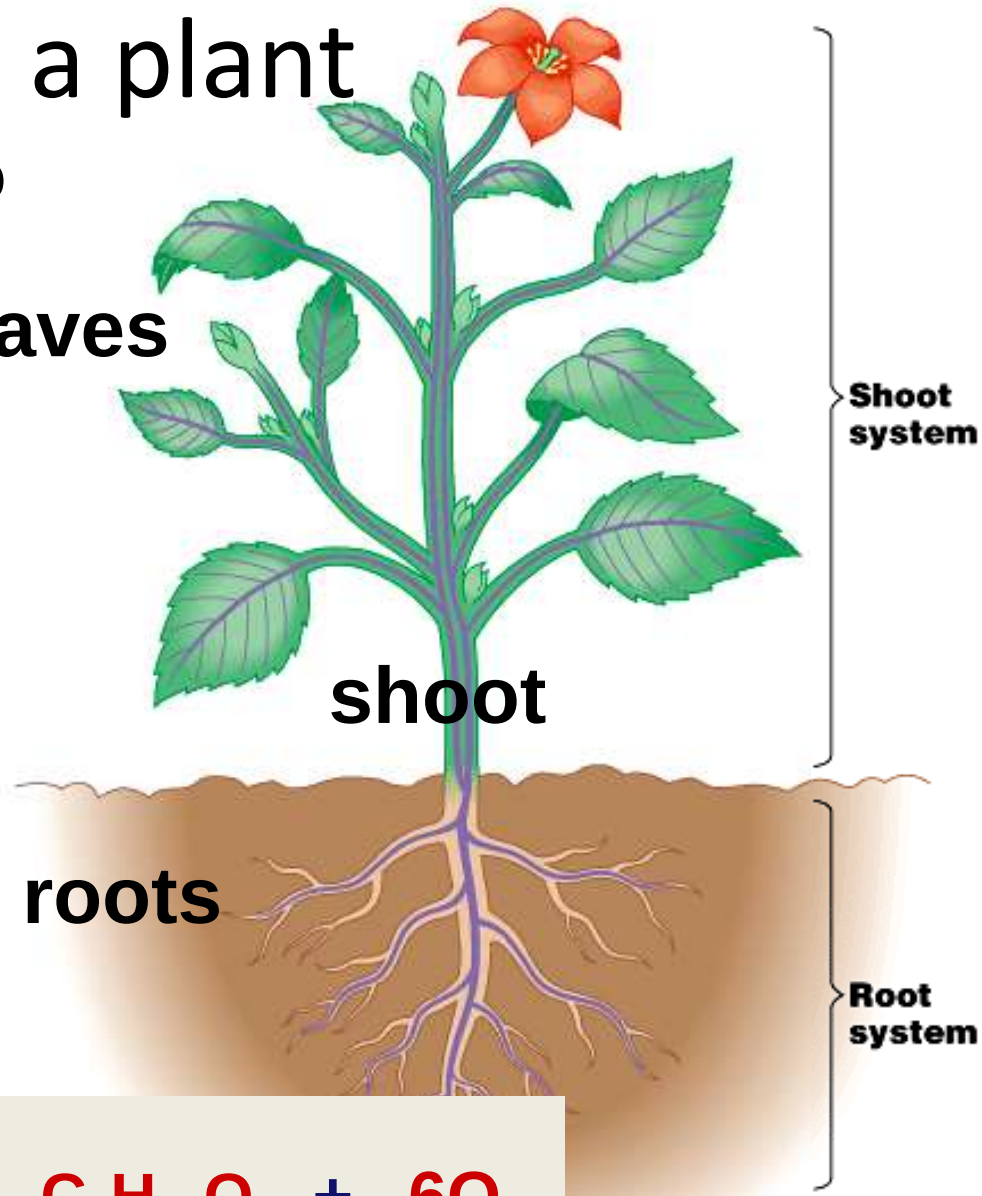
Clicker Question #2

Why are leaves green?

A. Heterotrophs see green better than any other color.
B. Plant pigments absorb green light.
C. Plant pigments absorb almost every wavelength except for green.
D. Plant pigments change yellow light that they absorb to green light that we see.

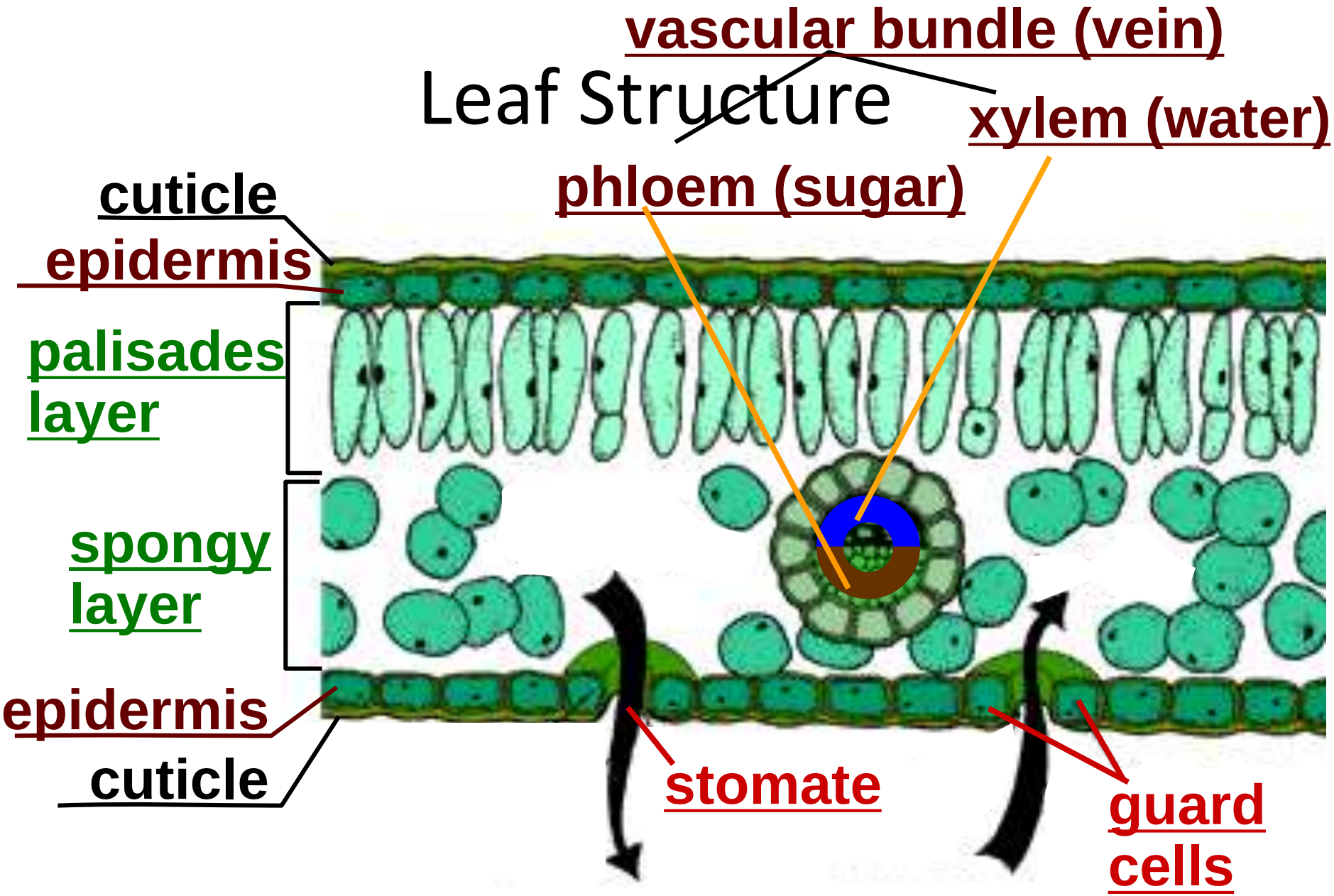
So what does a plant need?

- Bring In
  - light
  - CO_2
  - H_2O
- Let Out
  - O_2
- Move Around
  - sugars



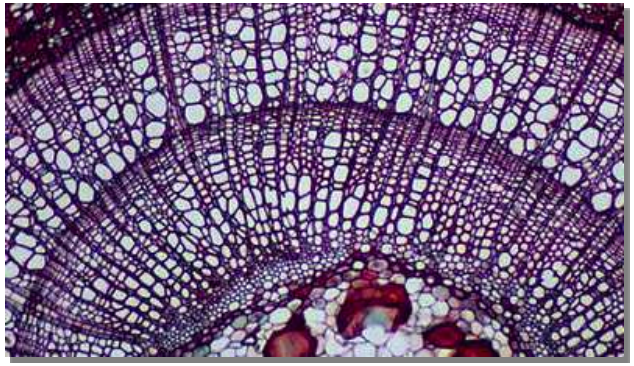
$$6CO_2 + 6H_2O + \text{light energy} \rightarrow C_6H_{12}O_6 + 6O_2$$

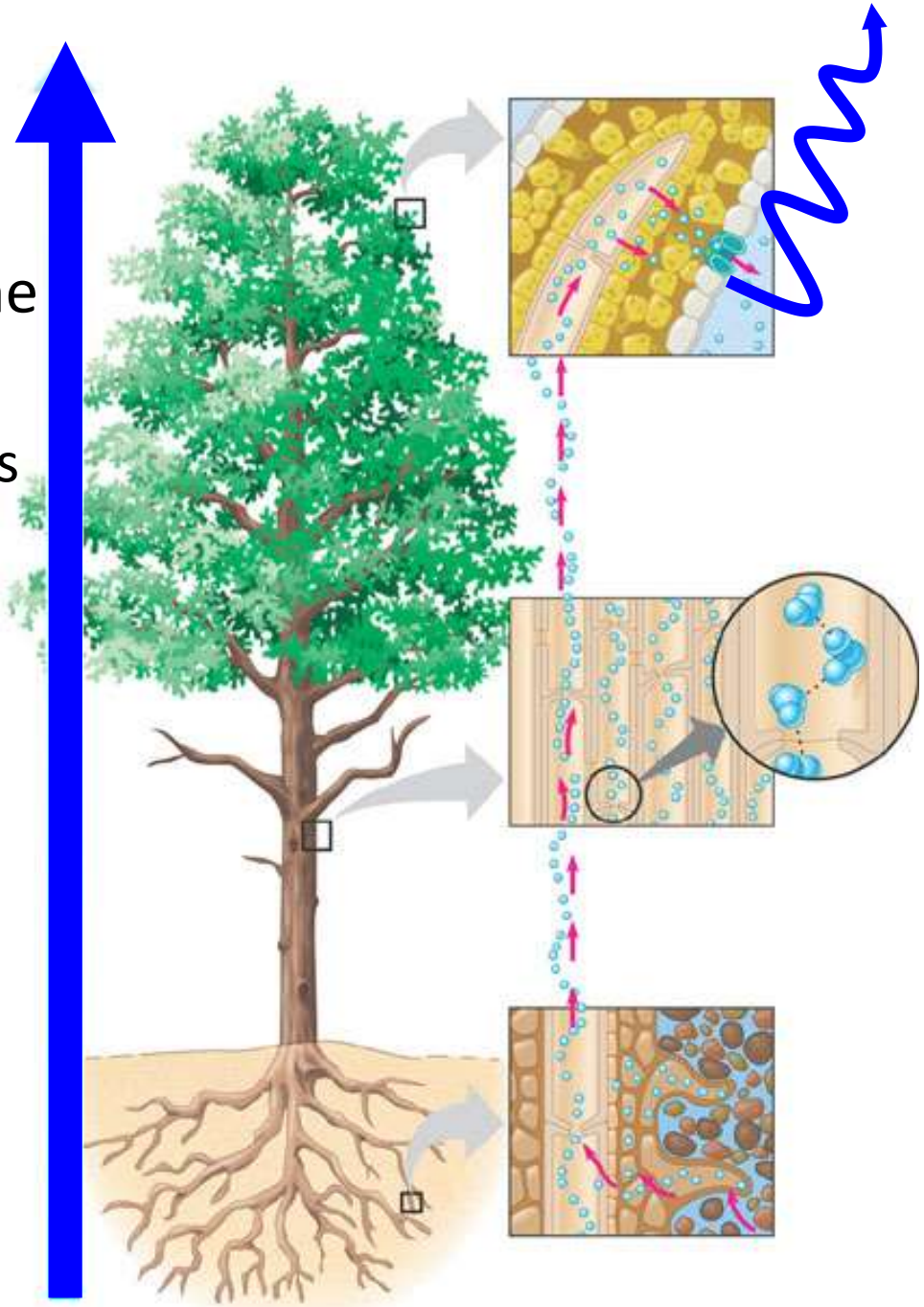
Leaf Structure



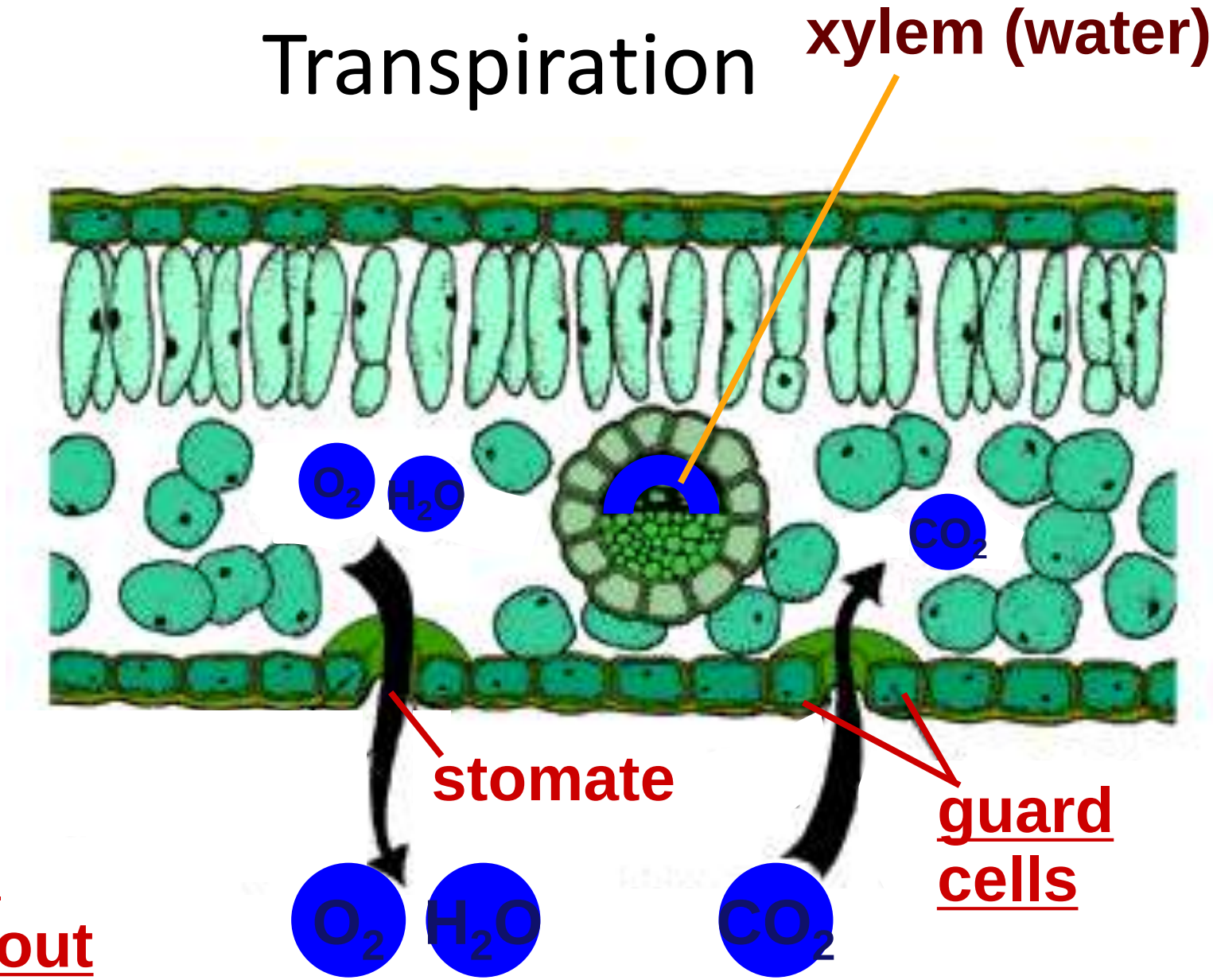
Transpiration

- Water evaporates from the stomates in the leaves
  - pulls water up from roots
    - water molecules stick to each other
  - more water is pulled up tree from ground



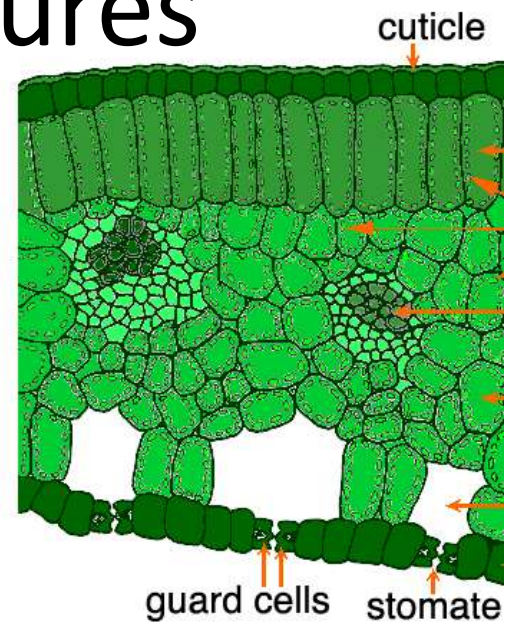


Transpiration

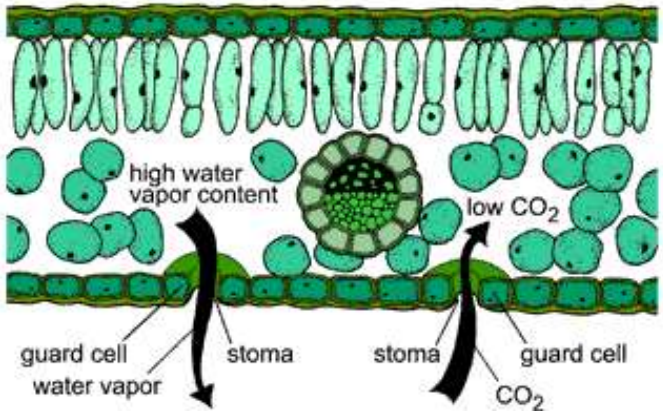


- CO
- O_2 out
- water out
  - so it gets to leaves from roots

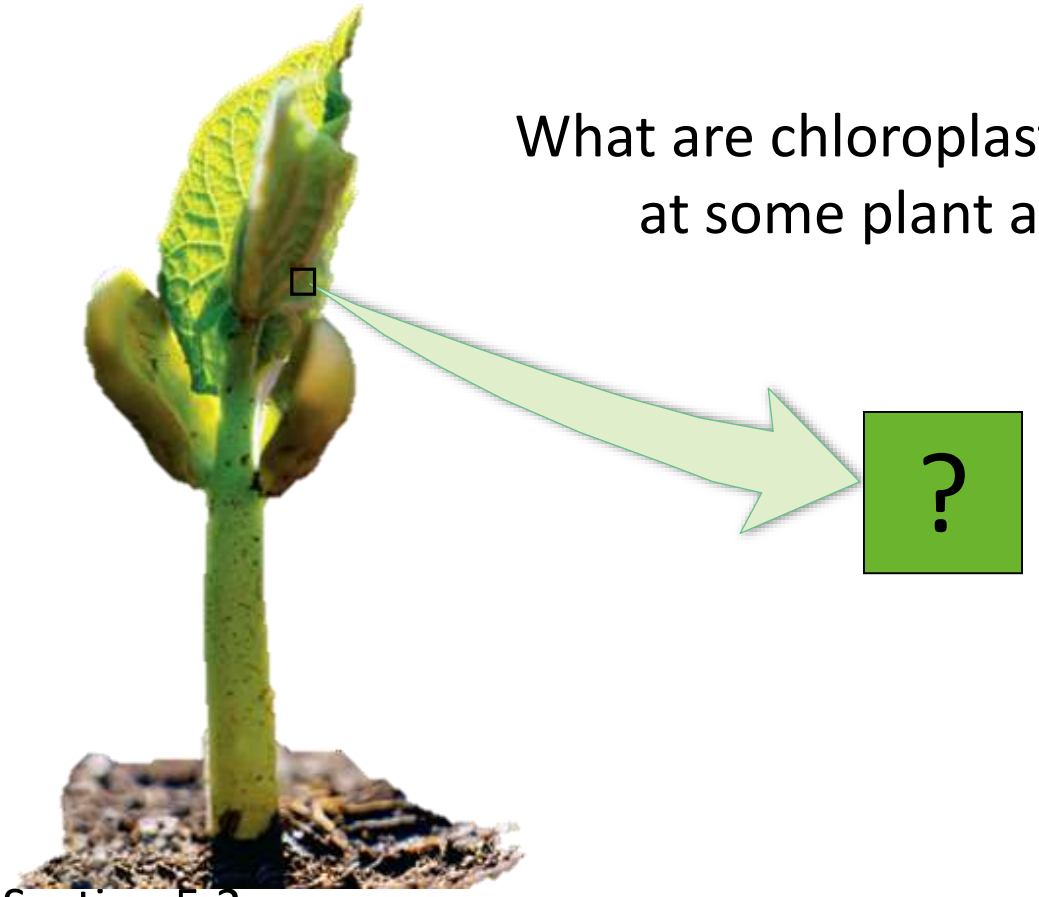
Function of Leaf Structures



- Cuticle
  - waxy coating reduces water loss
- Epidermis
  - skin protecting leaf tissues
- Palisades layer
  - high concentration of chloroplasts
    - collecting sun's energy
  - photosynthesis
    - making ATP & sugars
- Spongy layer
  - air spaces
    - gas exchange
      - CO_2 in for sugar production, remove waste O_2



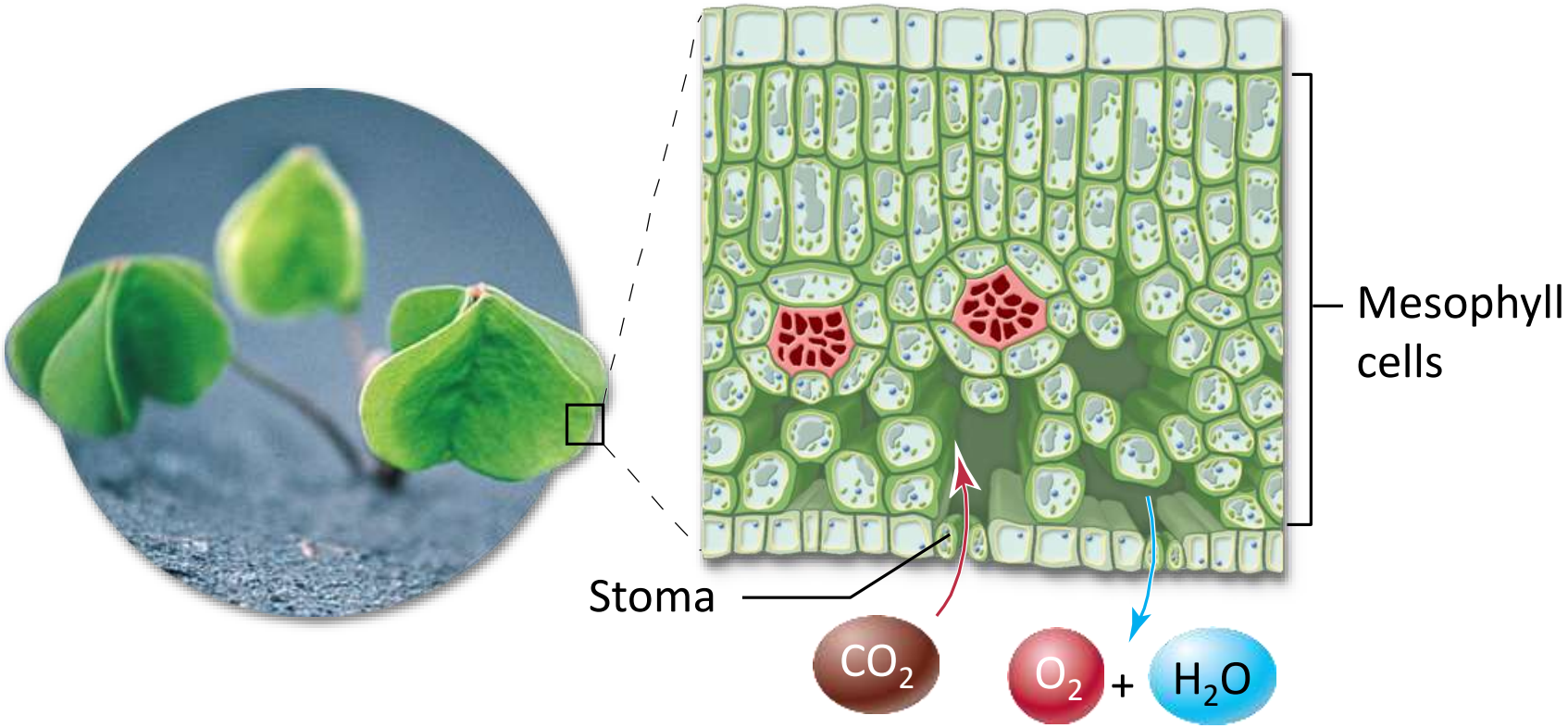
Photosynthesis Occurs in the Chloroplasts



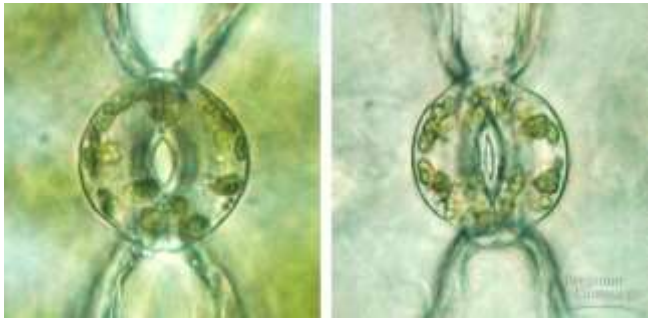
What are chloroplasts? Let's look at some plant anatomy.

Photosynthesis Occurs in the Chloroplasts

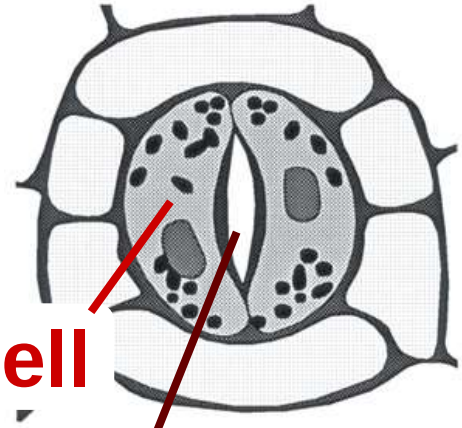
Gas exchange occurs at leaf pores called **stomata**.

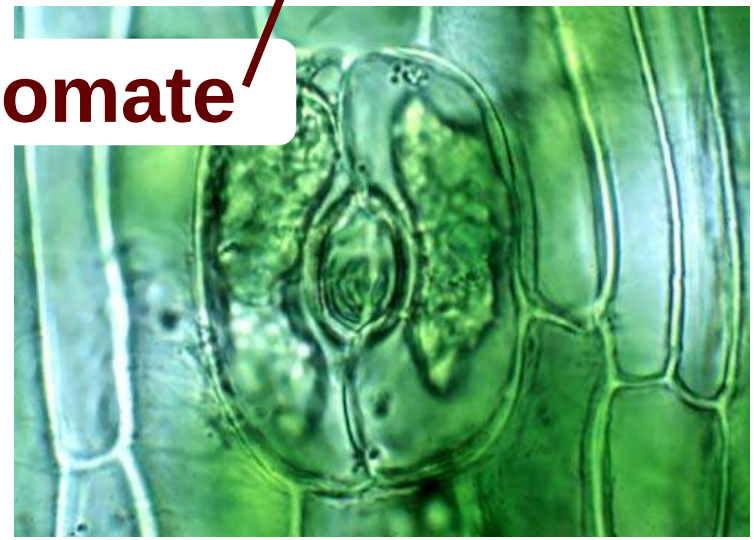


Stomates & Guard Cells



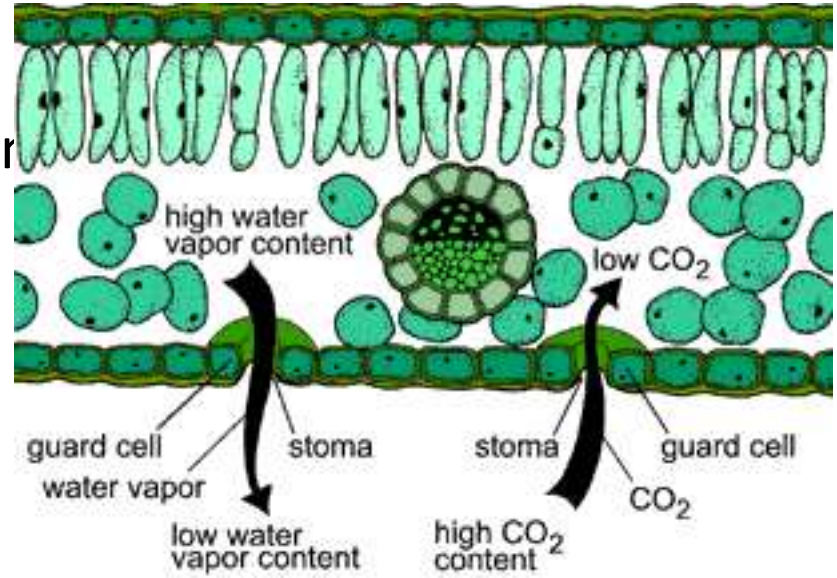
- Function of stomates
  - CO_2 in
  - O_2 out
  - H_2O out
    - gets to leaves for photosynthesis
- Function of guard cells
  - open & close stomates

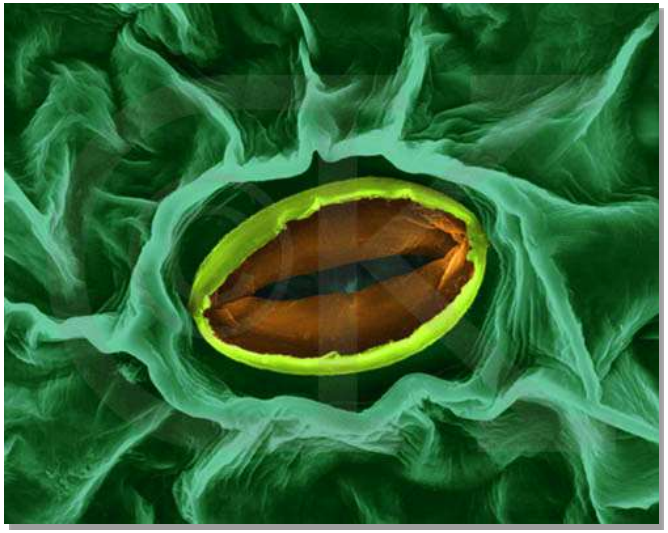




Guard cells & Homeostasis

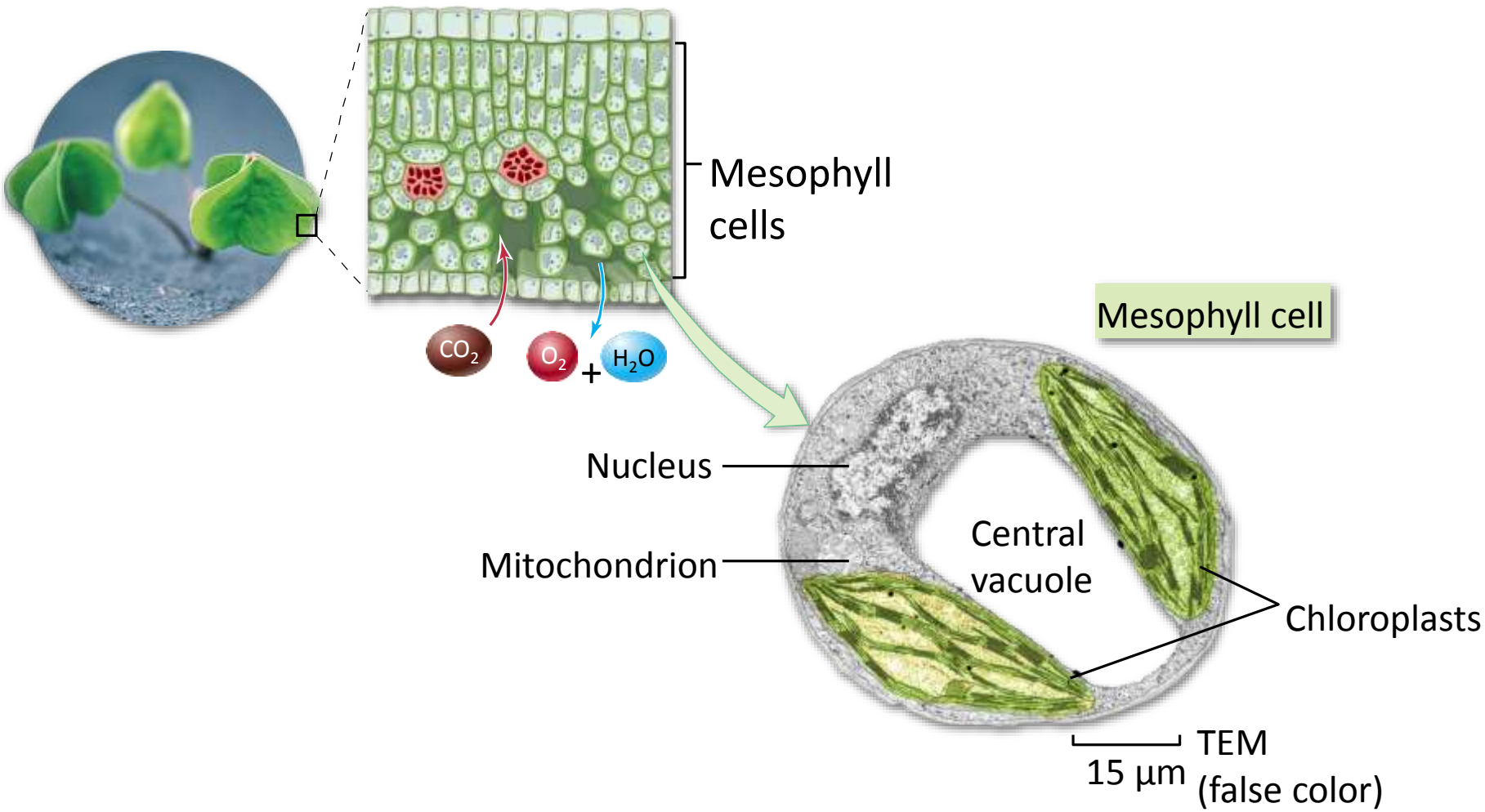
- Homeostasis
  - keeping the internal environm of the plant balanced
- Stomates open
  - let CO_2 in
    - needed to make sugar
  - let H_2O out
    - so it gets to leaves
  - let O_2 out
    - get rid of waste product
- Stomates close
  - if too much H_2O evaporating





Photosynthesis Occurs in the Chloroplasts

Each leaf contains many **mesophyll** cells.



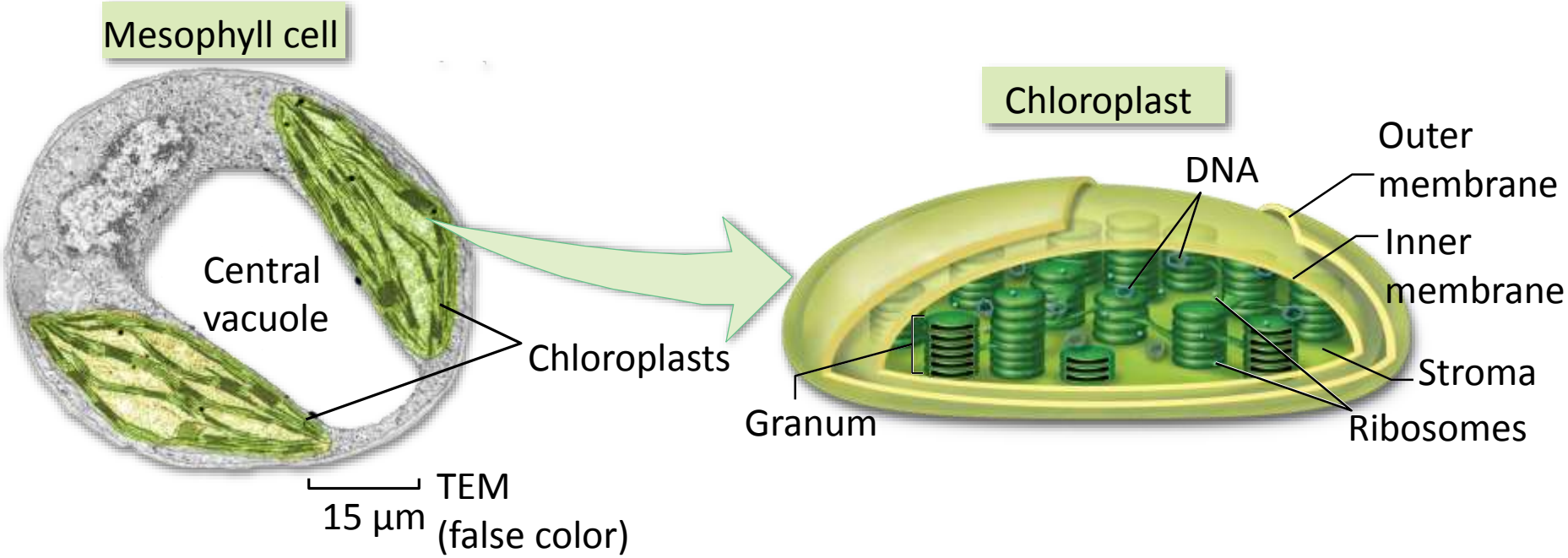
Section 5.2

Leaves: ©Steve Raymer/NGS Image Collection; Sprout: © Corbis (RF); Electron micrograph by Wm. P. Wergin, courtesy of Eldon H. Newcomb, University of Wisconsin-Madison.

Figure 5.5

Photosynthesis Occurs in the Chloroplasts

Each mesophyll cell contains several **chloroplasts**.



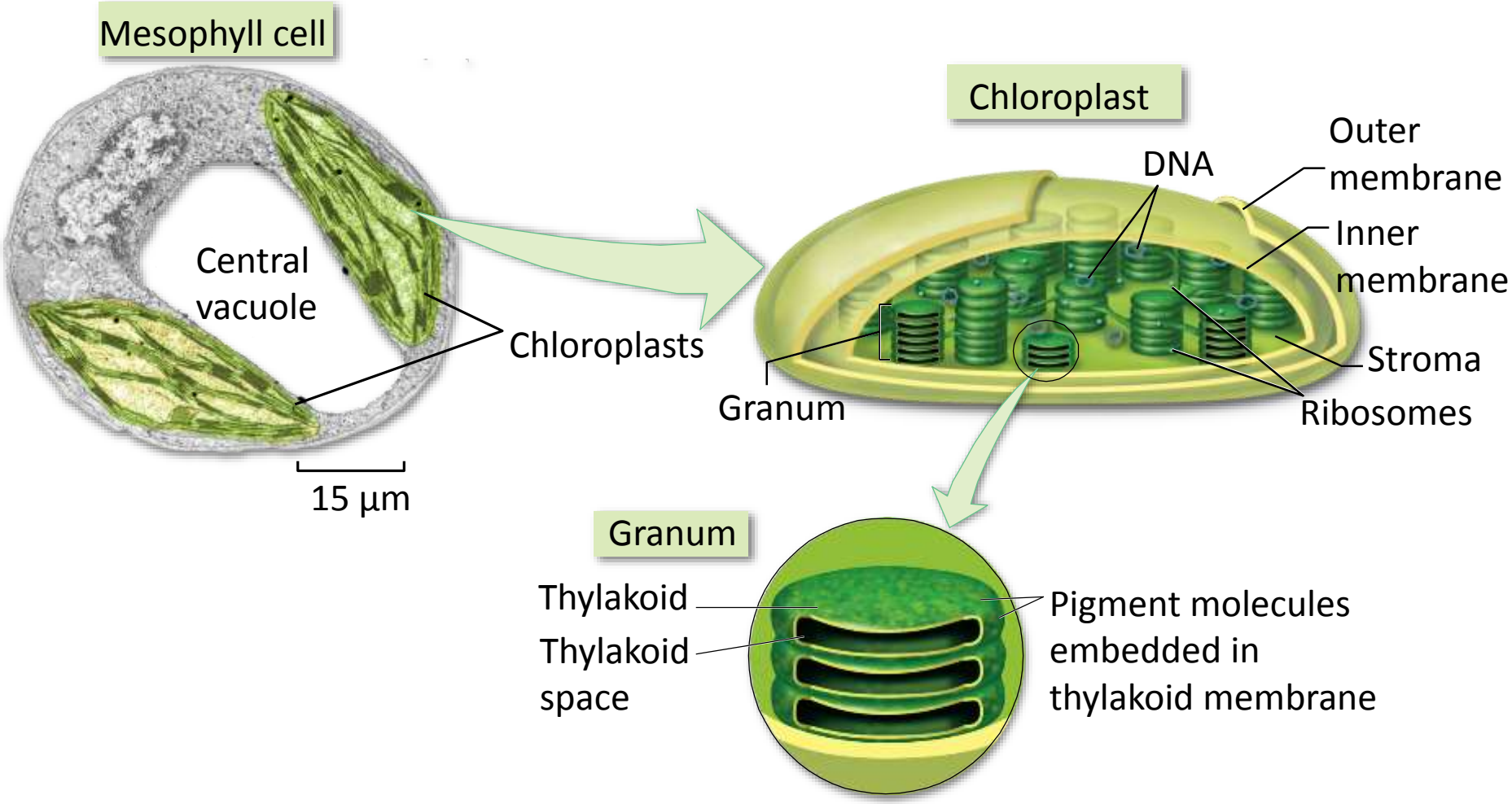
Section 5.2

Electron micrograph by Wm. P. Wergin, courtesy of Eldon H. Newcomb, University of Wisconsin-Madison.

Figure 5.5

Photosynthesis Occurs in the Chloroplasts

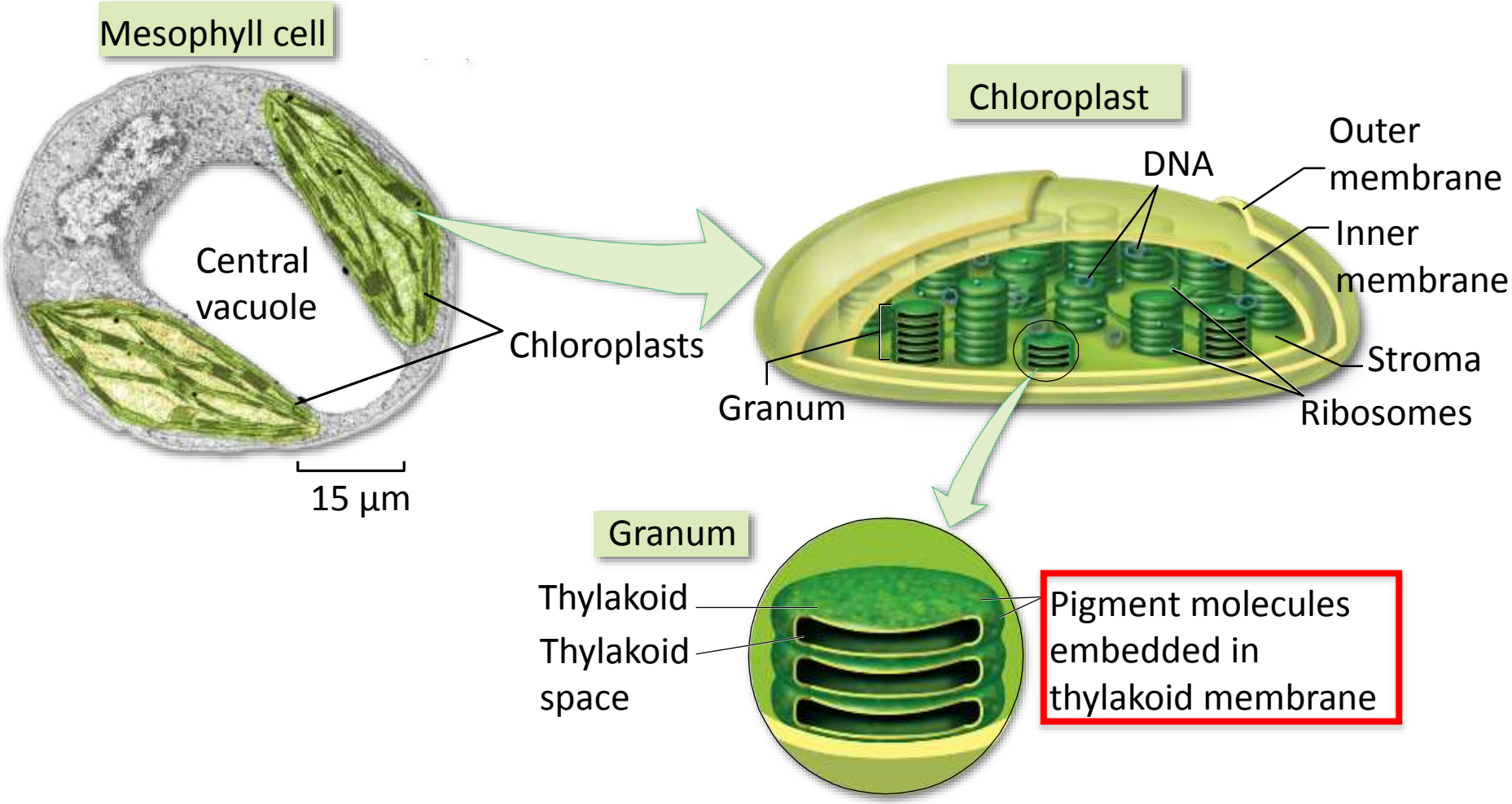
Each chloroplast contains several **grana**, or stacks of **thylakoids**.



Electron micrograph by Wm. P. Wergin, courtesy of Eldon H. Newcomb, University of Wisconsin-Madison.

Photosynthesis Occurs in the Chloroplasts

Pigment molecules in the thylakoid membrane capture sunlight.



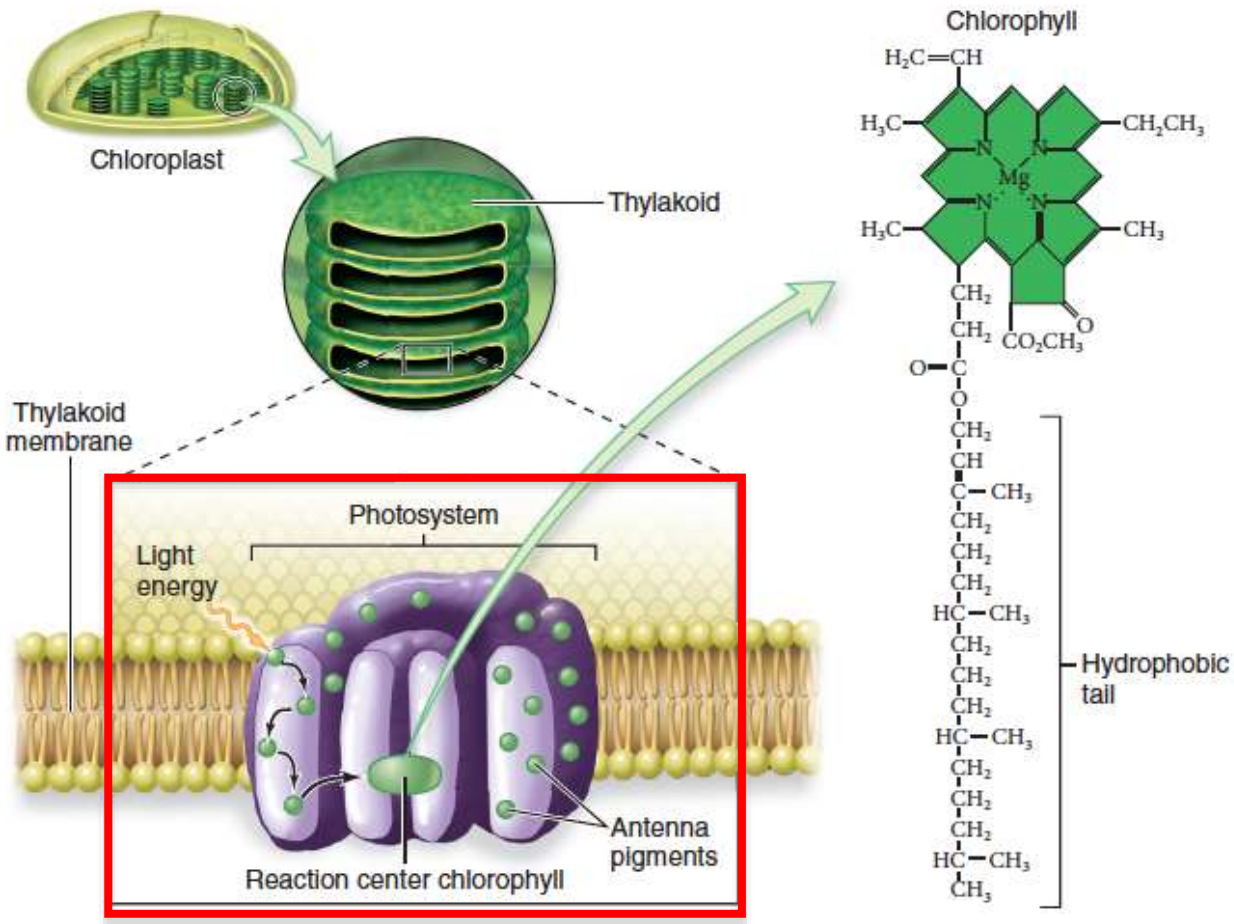
Section 5.2

Electron micrograph by Wm. P. Wergin, courtesy of Eldon H. Newcomb, University of Wisconsin-Madison.

Figure 5.5

Photosynthesis Occurs in the Chloroplasts

A **photosystem** is a large protein structure in the thylakoid membrane.

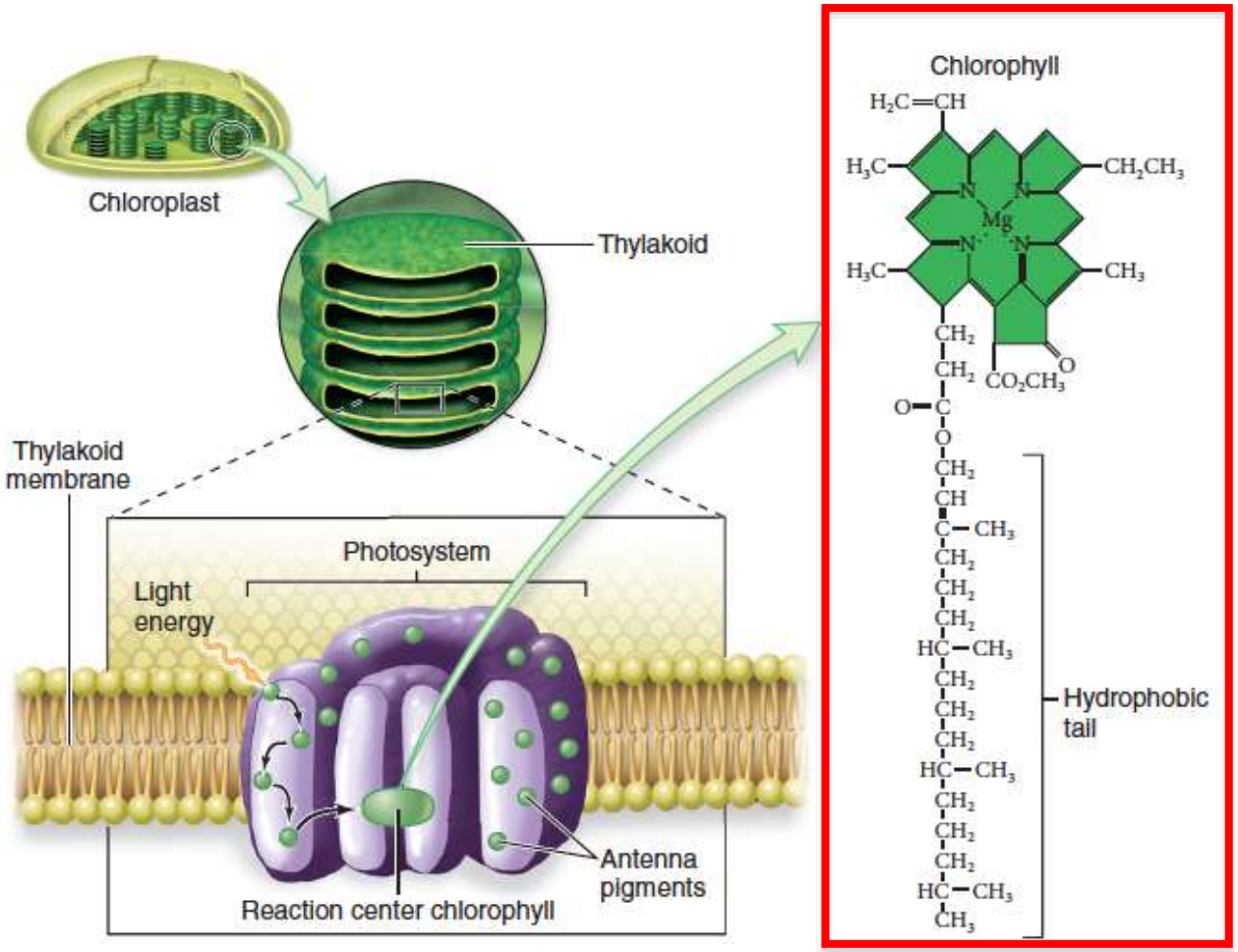


Section 5.2

Figure 5.6

Photosynthesis Occurs in the Chloroplasts

A photosystem consists of **antenna pigments** and a **reaction center** that contains chlorophyll.



Section 5.2

Figure 5.6

Clicker Question #3

Of the following list of plant structures, which is the second smallest?

A. chloroplast
B. granum
C. mesophyll cell
D. chlorophyll
E. thylakoid

Clicker Question #3

Of the following list of plant structures, which is the second smallest?

A. chloroplast
B. granum
C. mesophyll cell
D. chlorophyll
E. thylakoid

5.2 Mastering Concepts

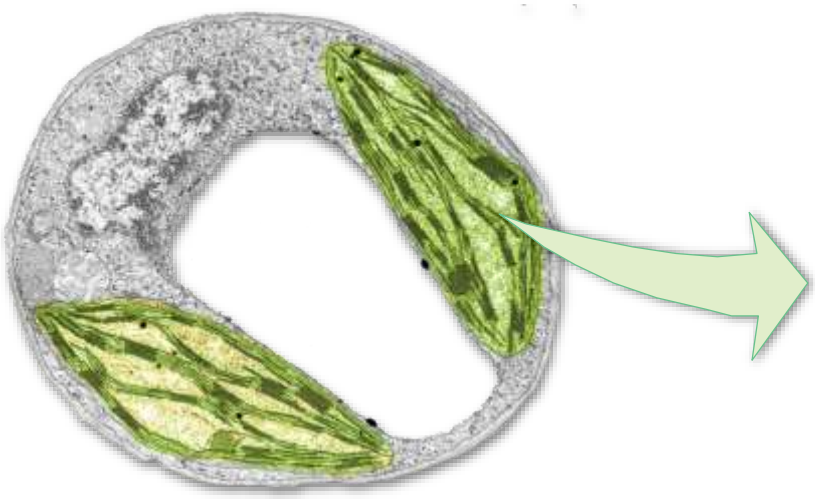
Describe the relationship among the chloroplast, stroma, grana, and thylakoids.

NO QUIZ TODAY!!!

Lab Report Due Next Thursday (10/6)
No late reports accepted
Extra Credit due by October 11th

Photosynthesis Occurs in Two Stages

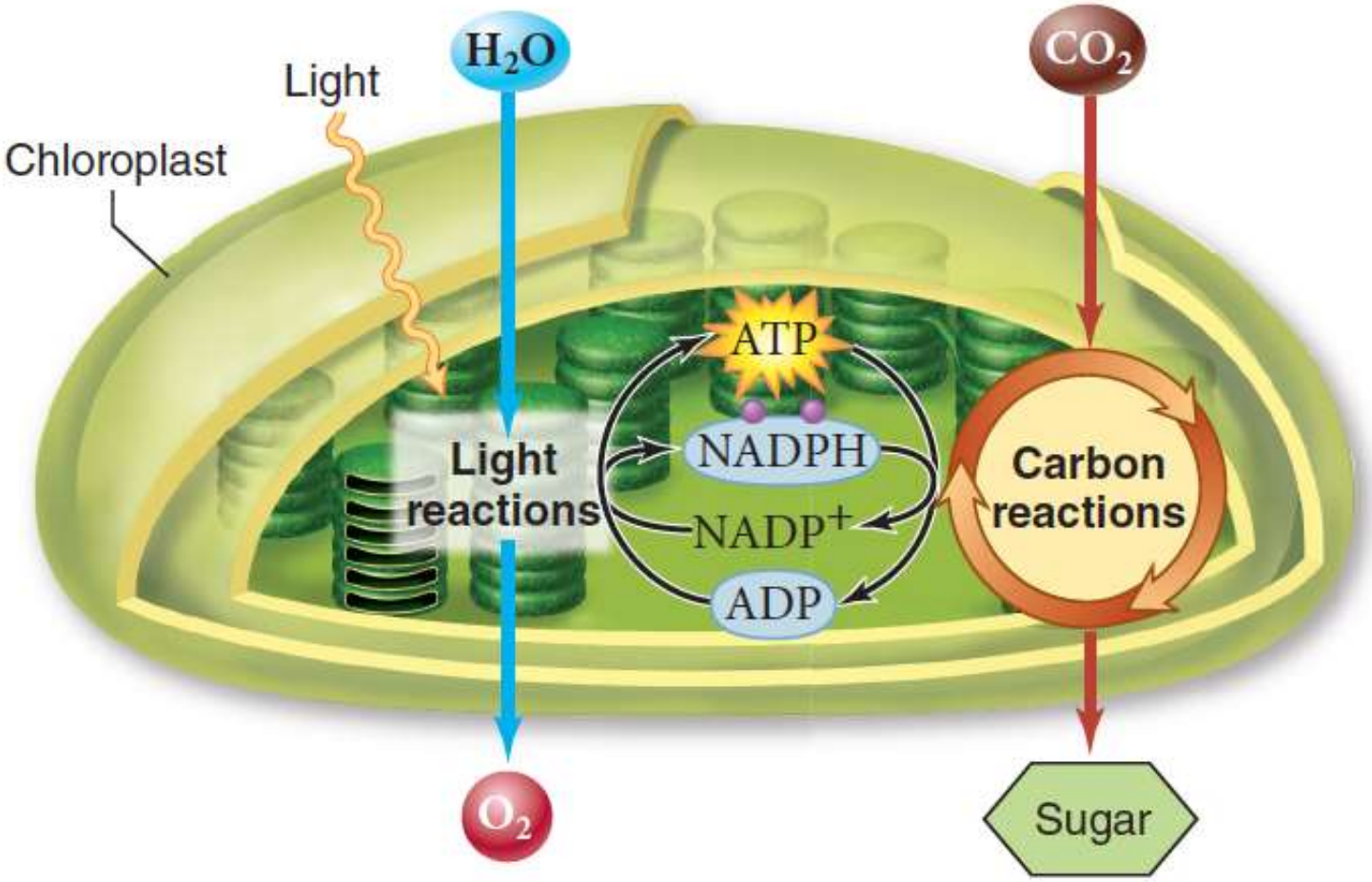
Now that we know *where* photosynthesis occurs, let's look at some of the details about how it happens.



What happens in the chloroplasts?

Electron micrograph by Wm. P. Wergin, courtesy of Eldon H. Newcomb, University of Wisconsin-Madison.

Photosynthesis Occurs in Two Stages



Section 5.3

Figure 5.7

PHOTOSYNTHESIS

- 2 Phases
  - Light-dependent reaction
  - Light-independent reaction aka Calvin Cycle

- Light-dependent: converts light energy into chemical energy; produces ATP and NADPH molecules to be used to fuel light-independent reaction

- Light-independent: uses ATP produced to make simple sugars.

5.3 Mastering Concepts

What happens in each of the two main stages of photosynthesis?

Photosynthetic coral © Andrew J. Martinez/Science Source

Photosynthesis Occurs in Two Stages

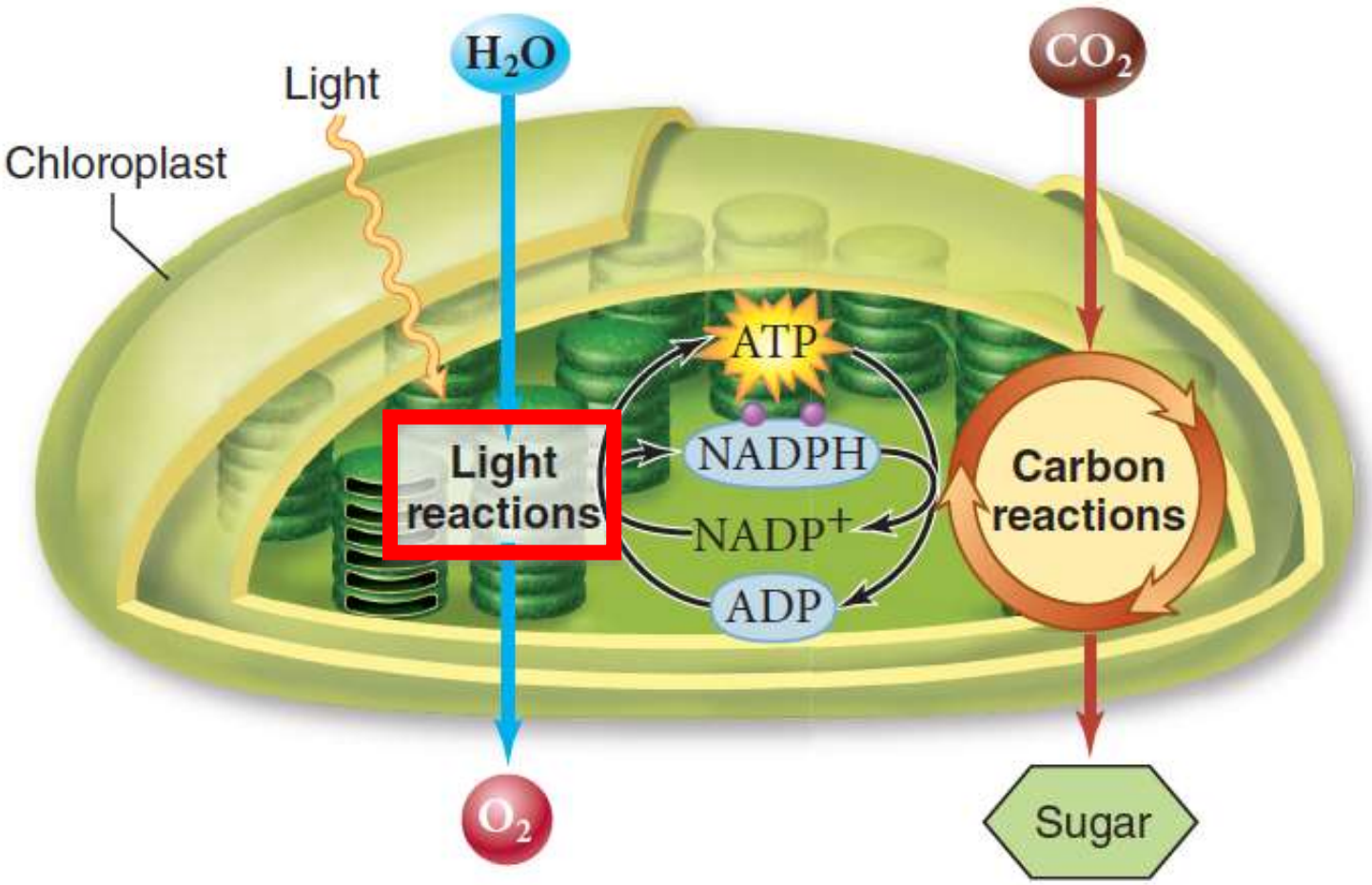
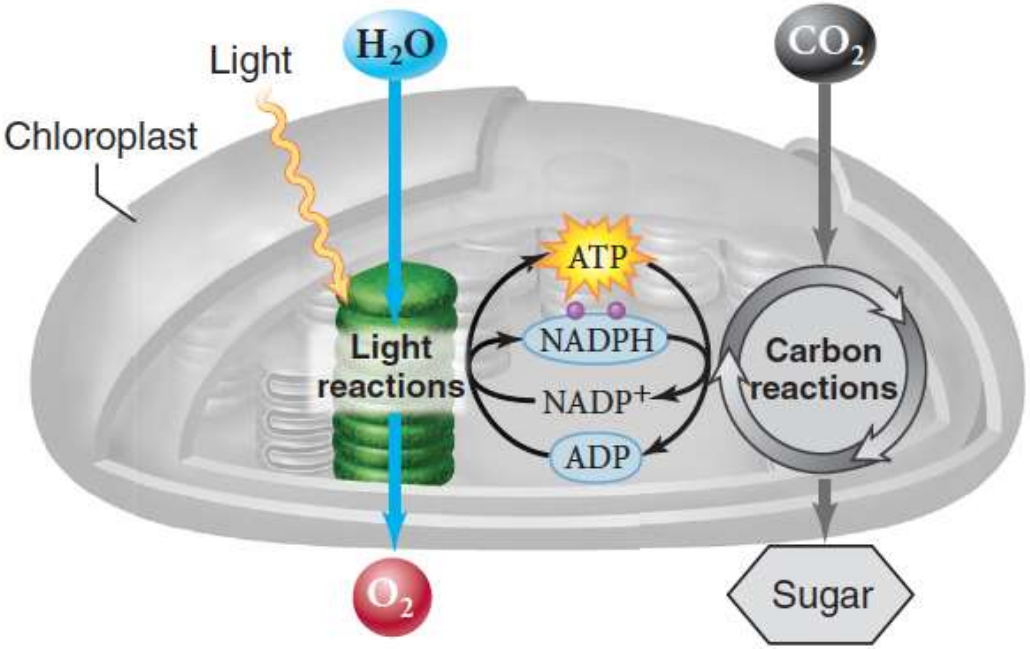


Figure 5.7

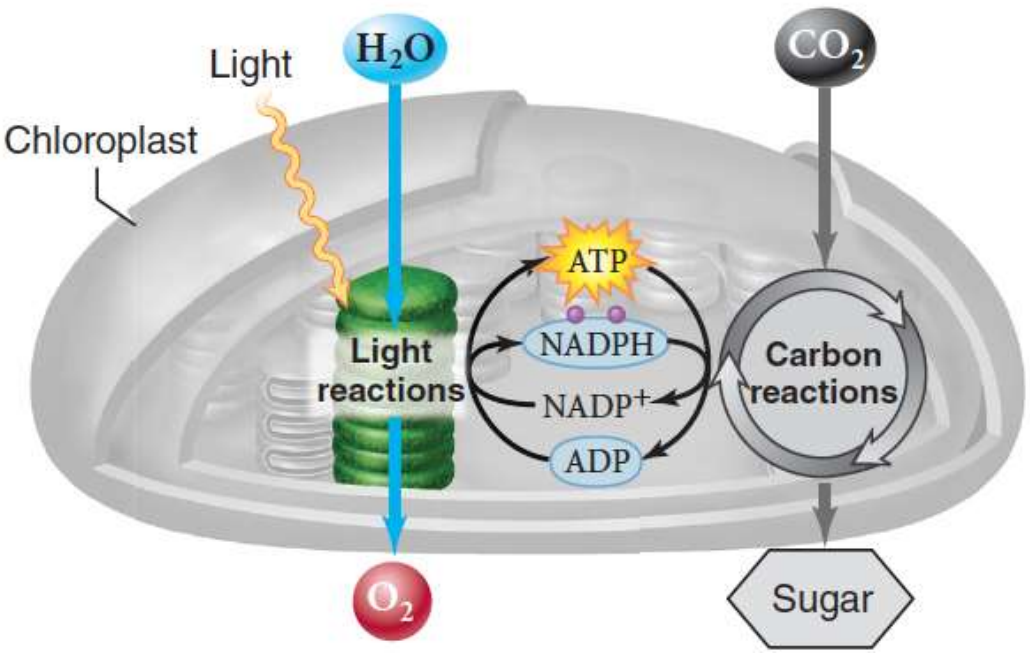
The Light Reactions Begin Photosynthesis



The light reactions occur in the thylakoids and require water and light.

Figure 5.8

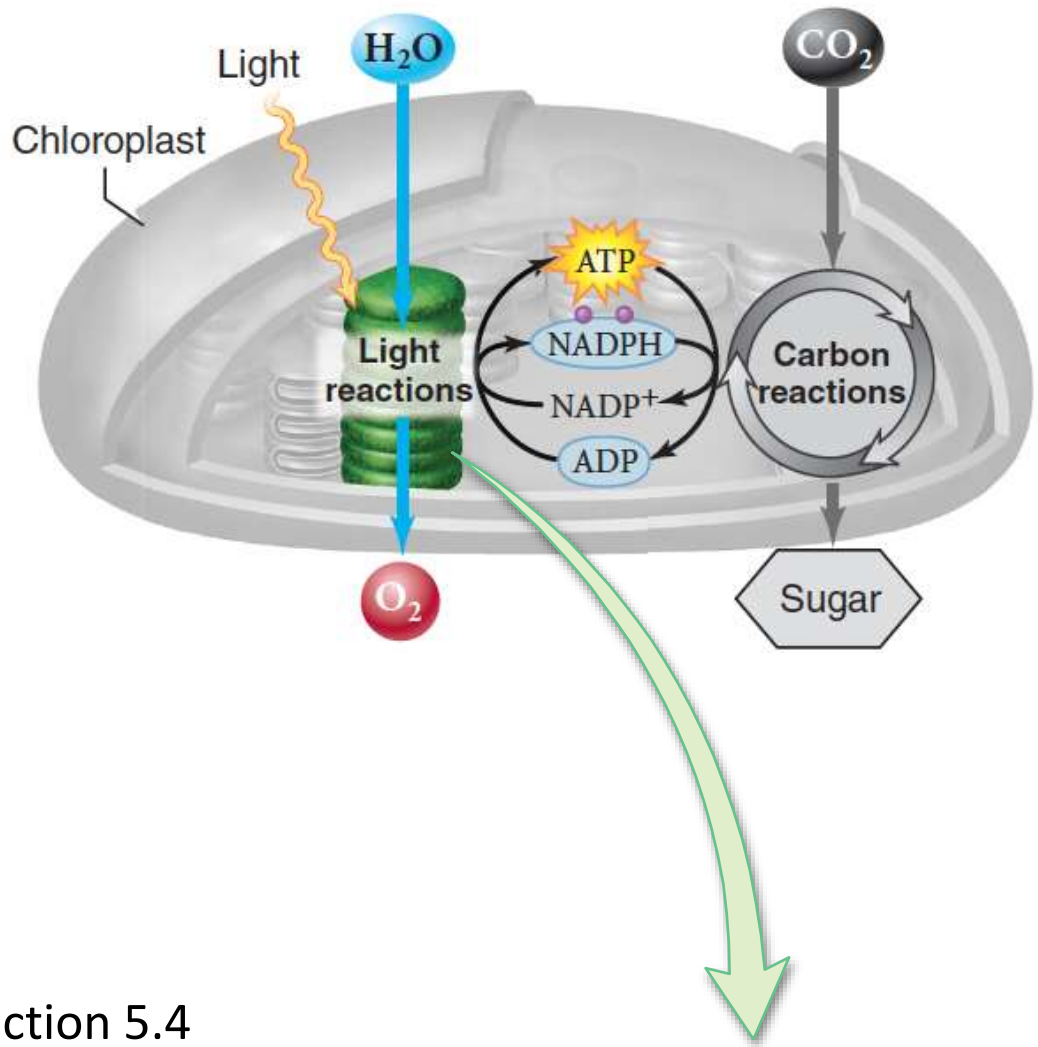
The Light Reactions Begin Photosynthesis



ATP and NADPH are produced. Oxygen gas (O_2) is a byproduct.

Figure 5.8

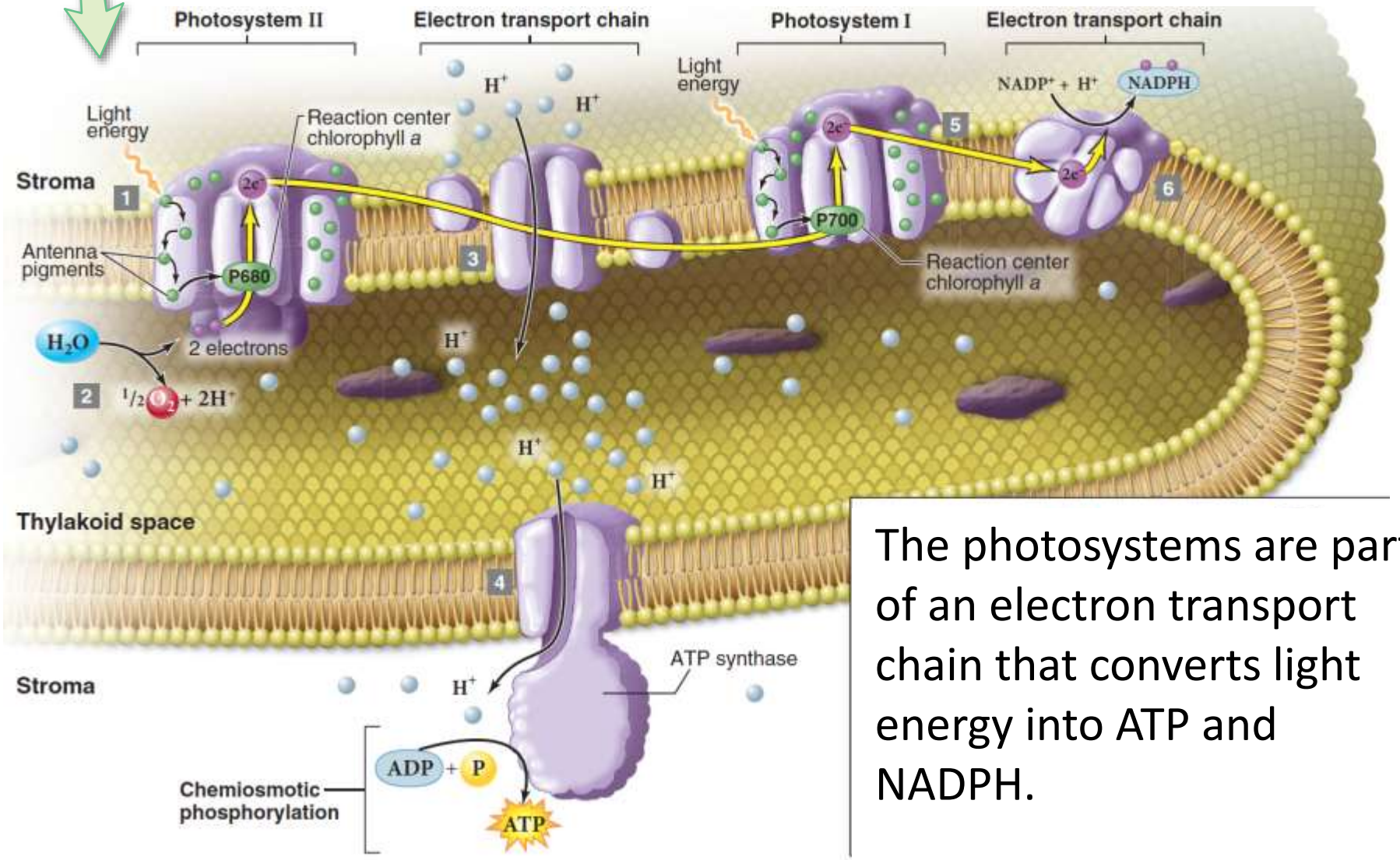
The Light Reactions Begin Photosynthesis



Now let's zoom in to a thylakoid membrane to see the chemical reactions happening there.

Figure 5.8

The Light Reactions Begin Photosynthesis

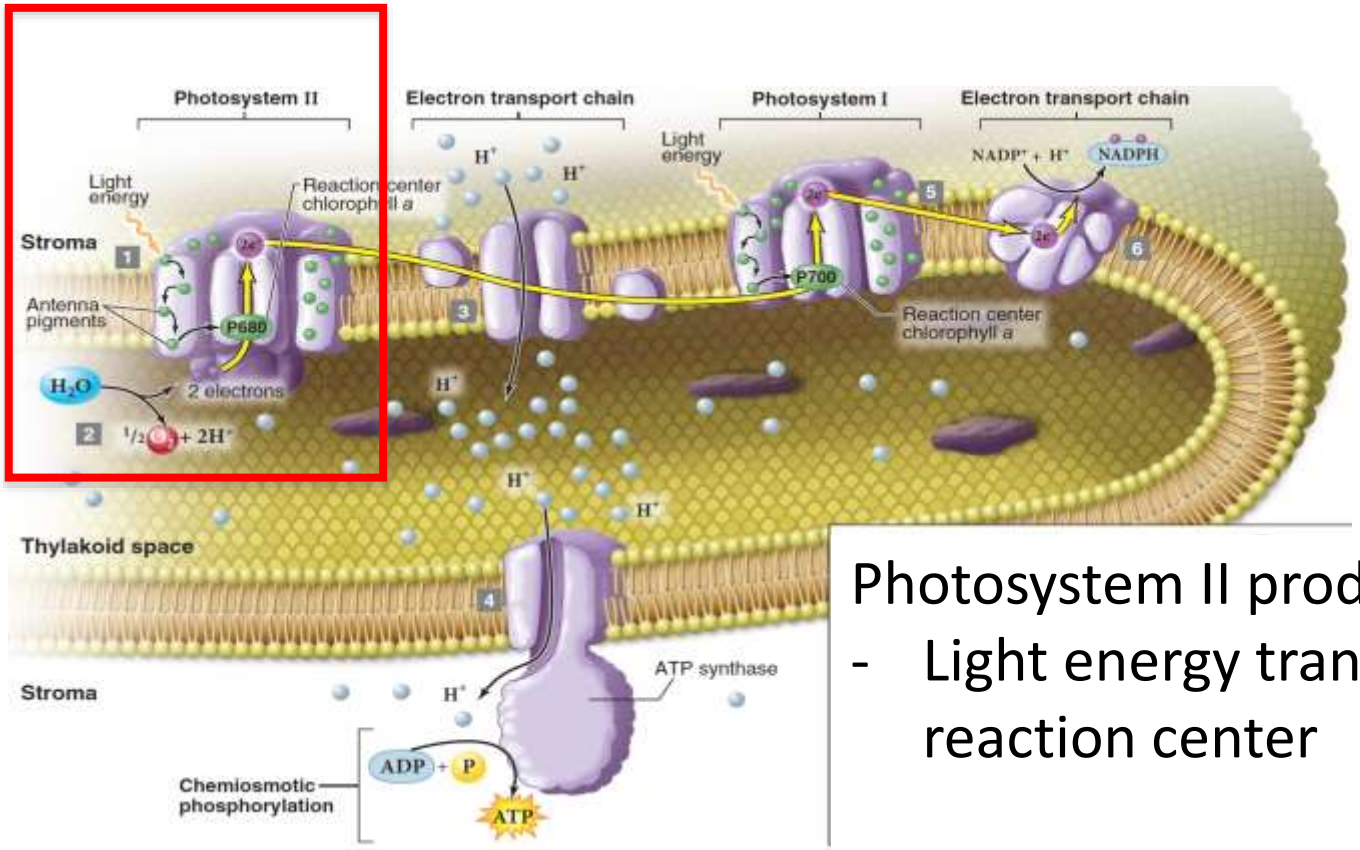


The photosystems are part of an electron transport chain that converts light energy into ATP and NADPH.

Section 5.4

Figure 5.8

The Light Reactions Begin Photosynthesis



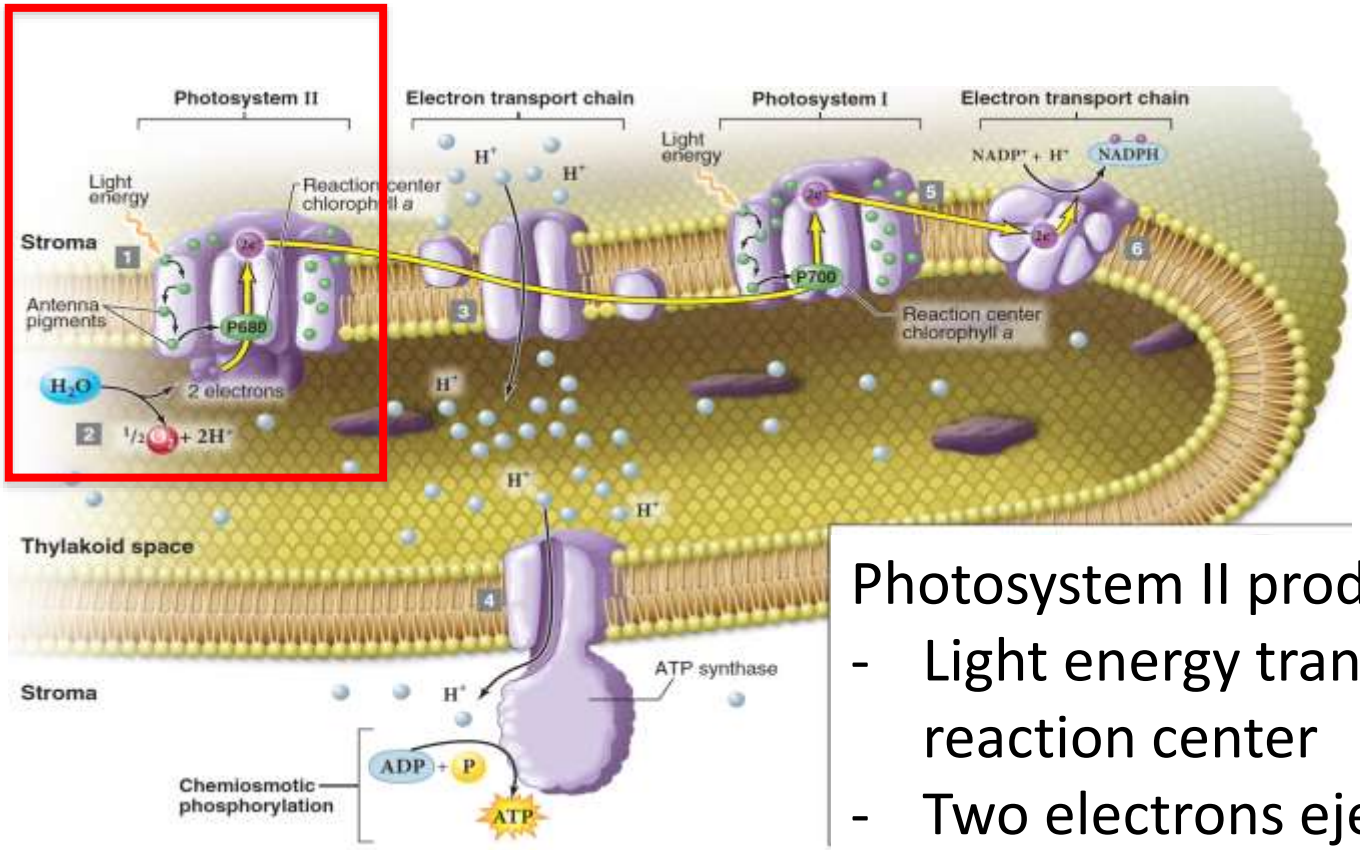
Photosystem II produces ATP

- Light energy transferred to reaction center

Section 5.4

Figure 5.8

The Light Reactions Begin Photosynthesis



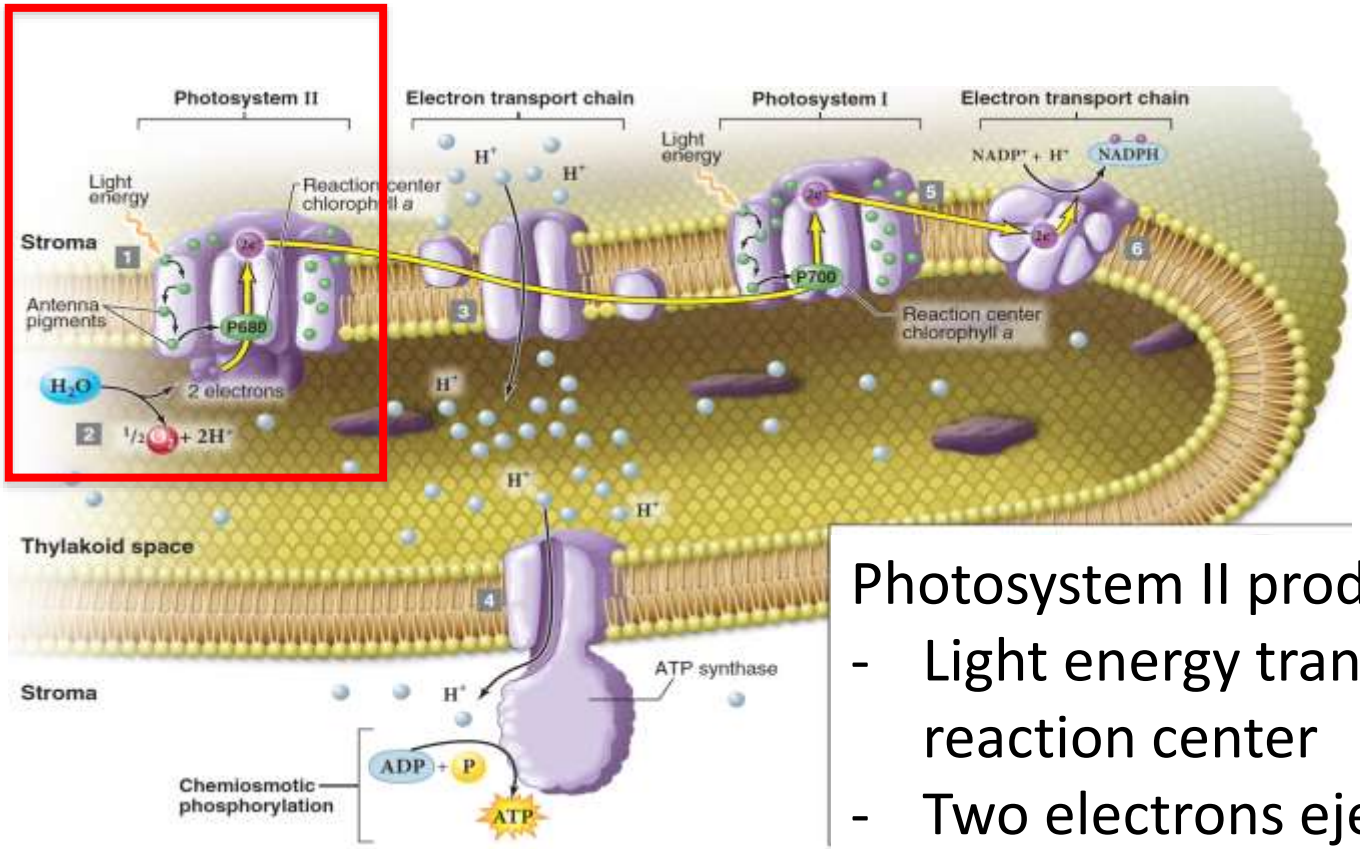
Photosystem II produces ATP

- Light energy transferred to reaction center
- Two electrons ejected

Section 5.4

Figure 5.8

The Light Reactions Begin Photosynthesis



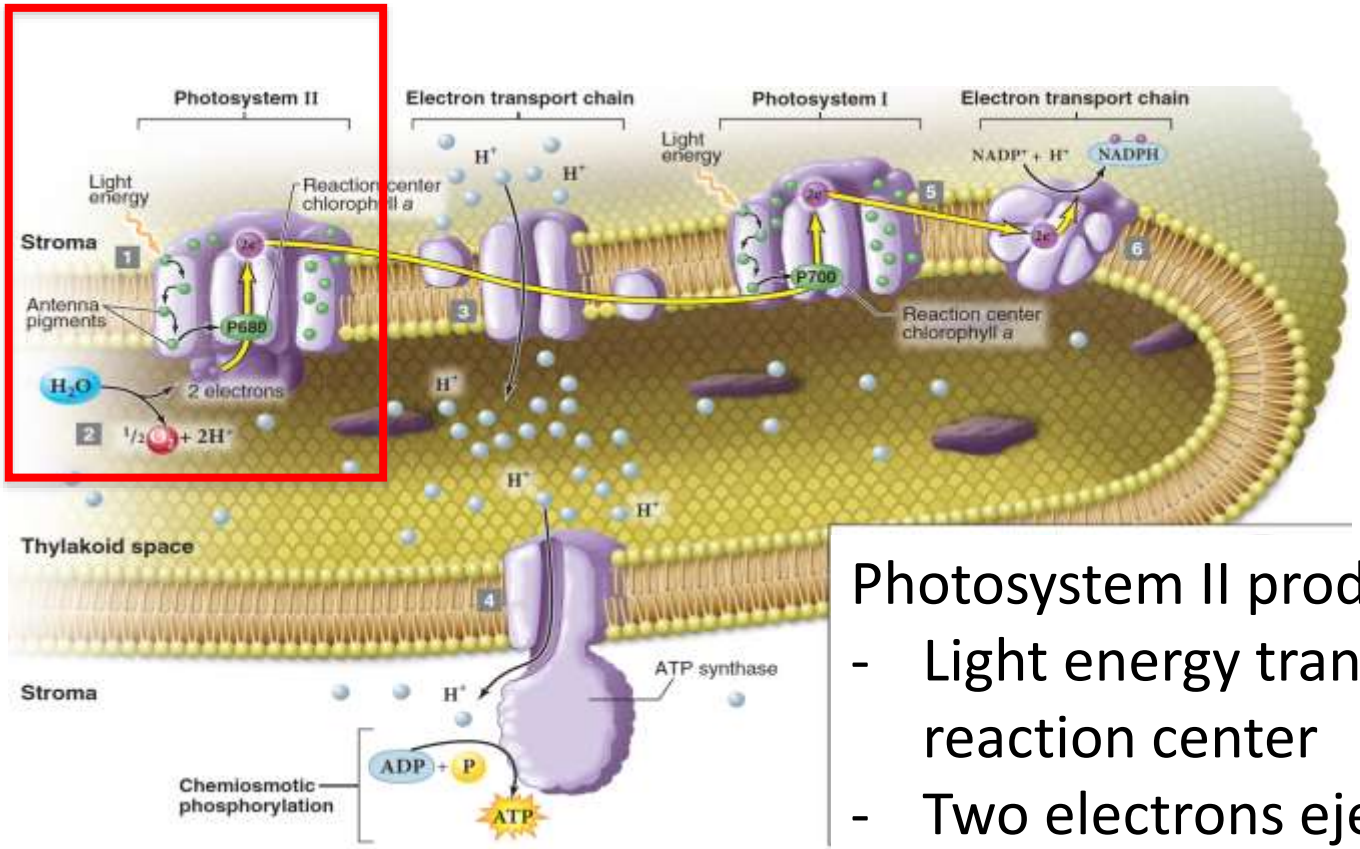
Photosystem II produces ATP

- Light energy transferred to reaction center
- Two electrons ejected
- Water is split to replace electrons

Section 5.4

Figure 5.8

The Light Reactions Begin Photosynthesis



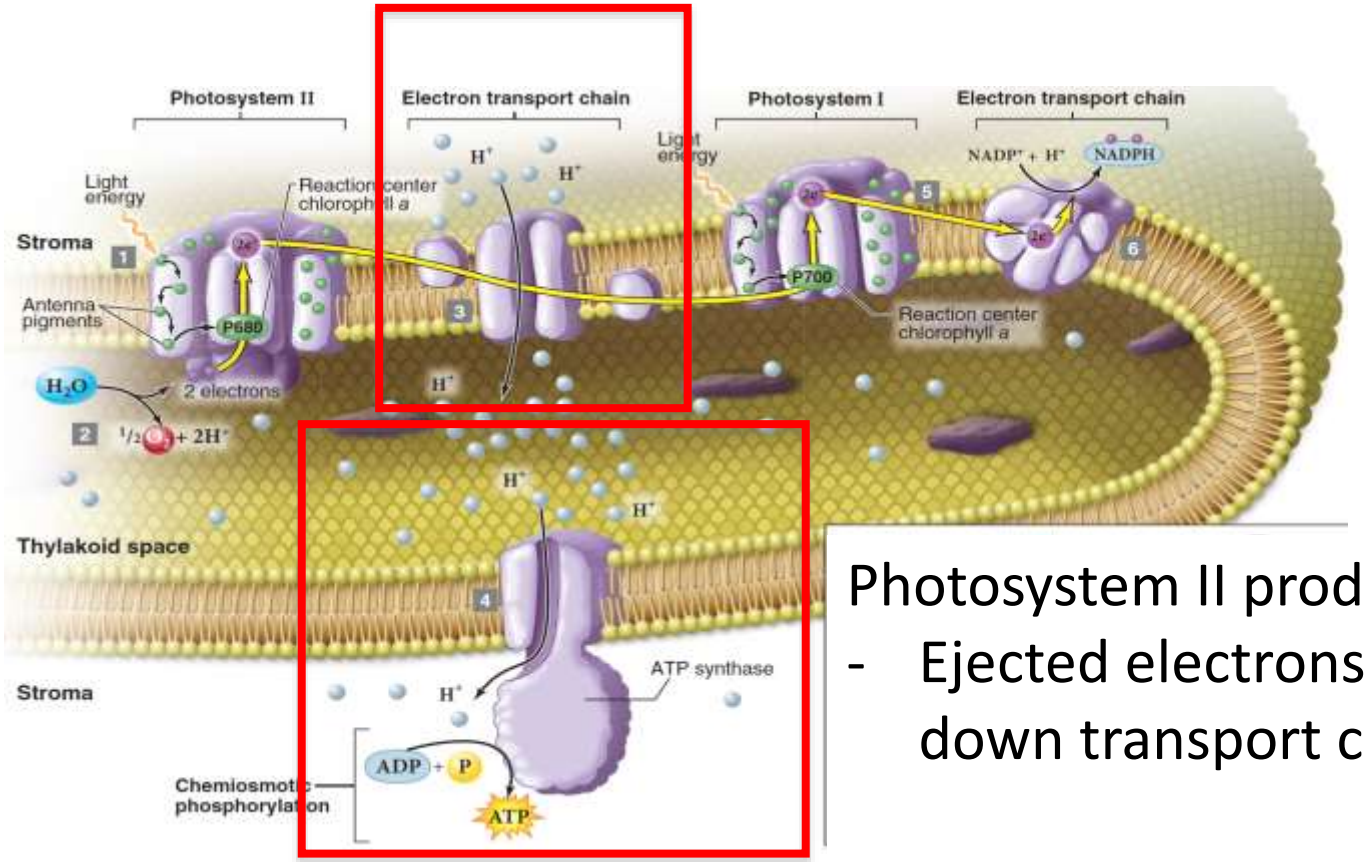
Photosystem II produces ATP

- Light energy transferred to reaction center
- Two electrons ejected
- Water is split to replace electrons
  - O_2 is a byproduct

Section 5.4

Figure 5.8

The Light Reactions Begin Photosynthesis

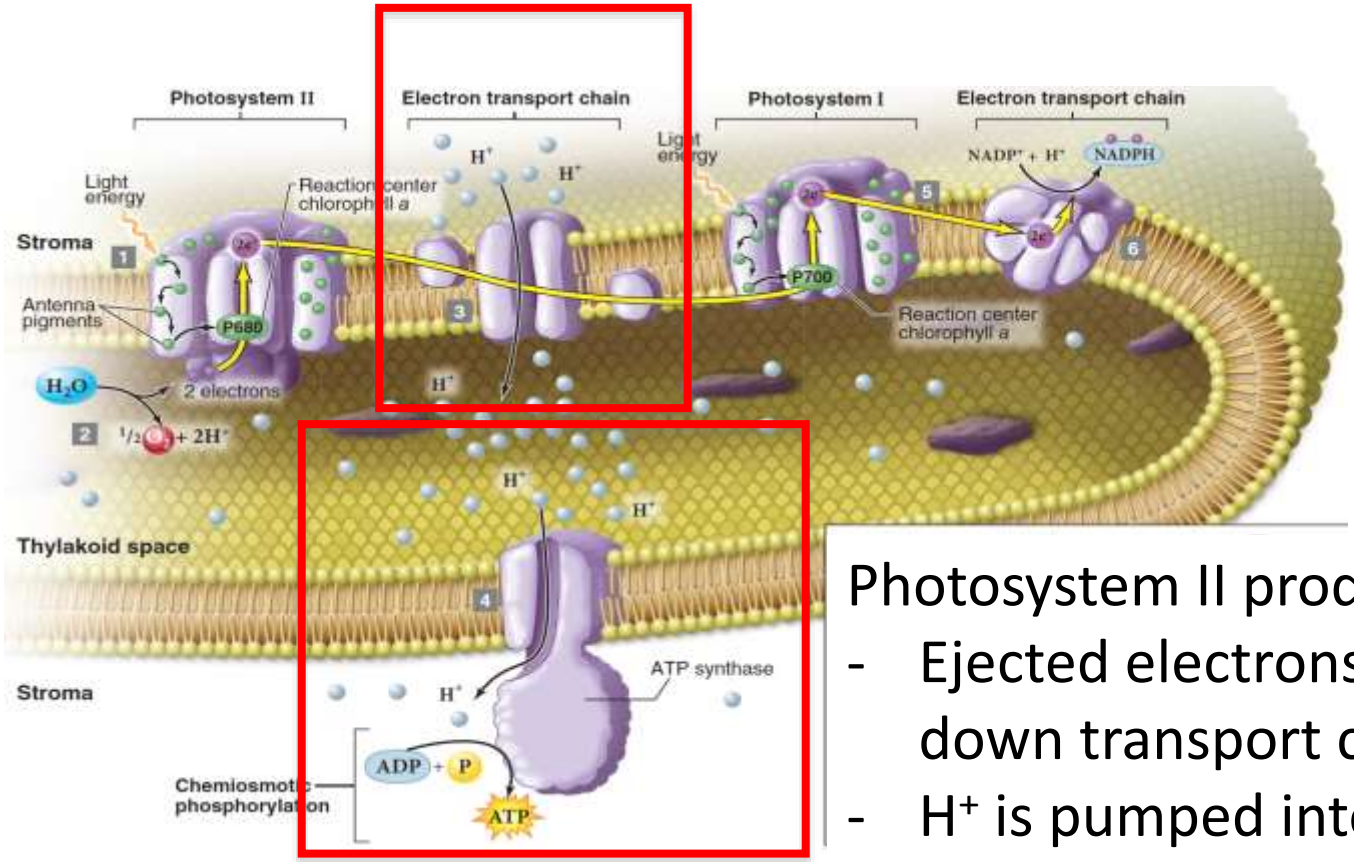


Photosystem II produces ATP

- Ejected electrons move down transport chain

Figure 5.8

The Light Reactions Begin Photosynthesis

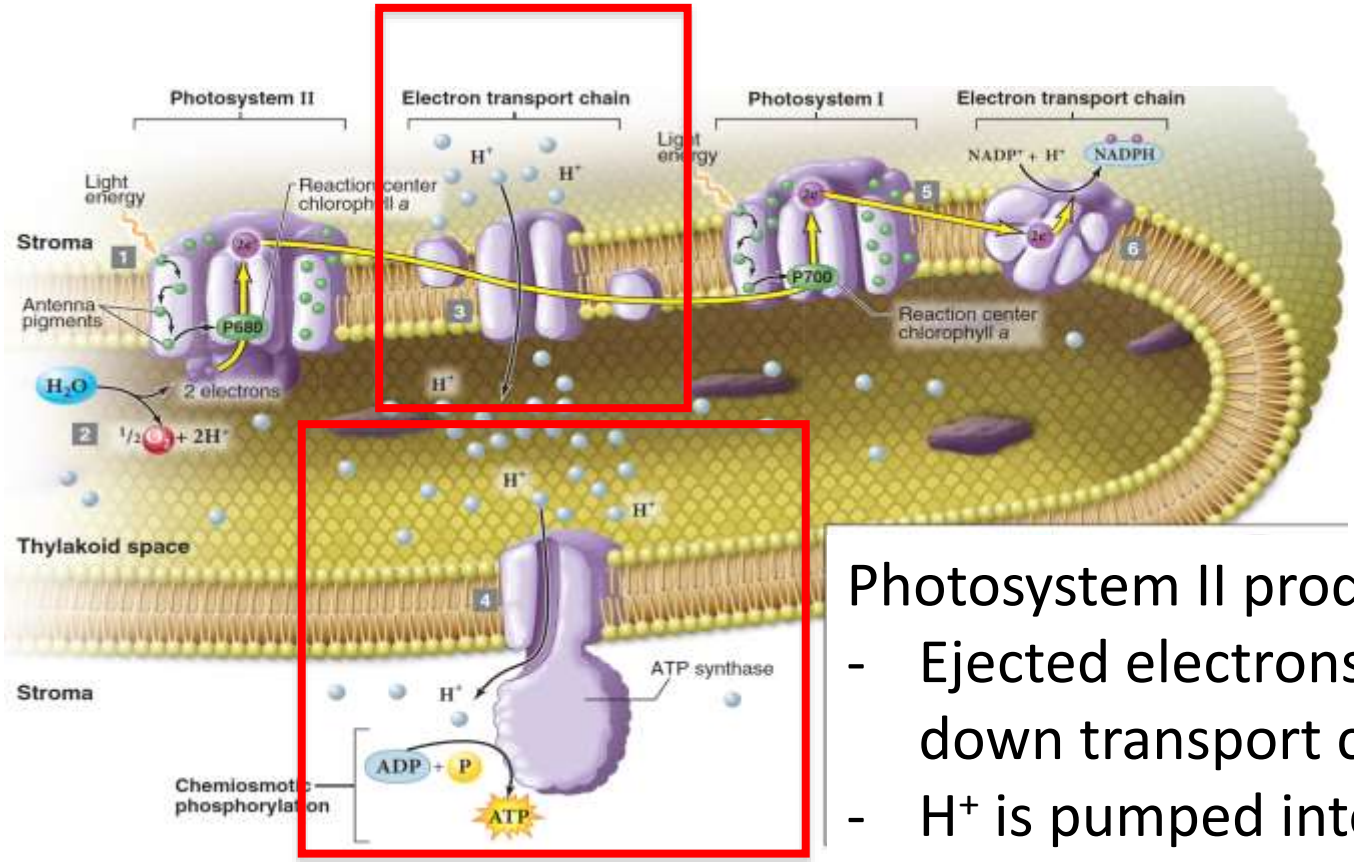


Photosystem II produces ATP

- Ejected electrons move down transport chain
- H^+ is pumped into thylakoid

Figure 5.8

The Light Reactions Begin Photosynthesis

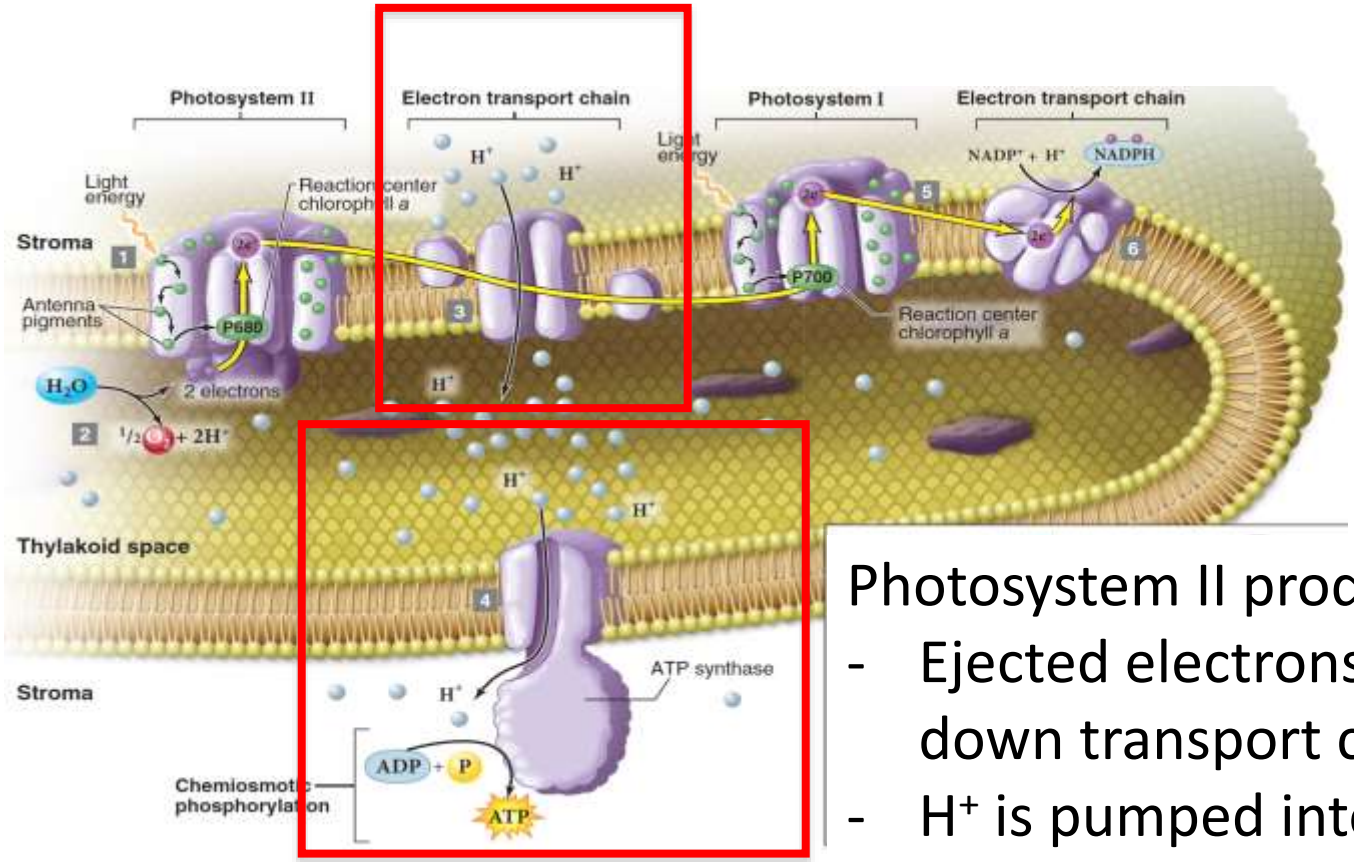


Photosystem II produces ATP

- Ejected electrons move down transport chain
- H^+ is pumped into thylakoid
- H^+ leaves through **ATP synthase**

Figure 5.8

The Light Reactions Begin Photosynthesis

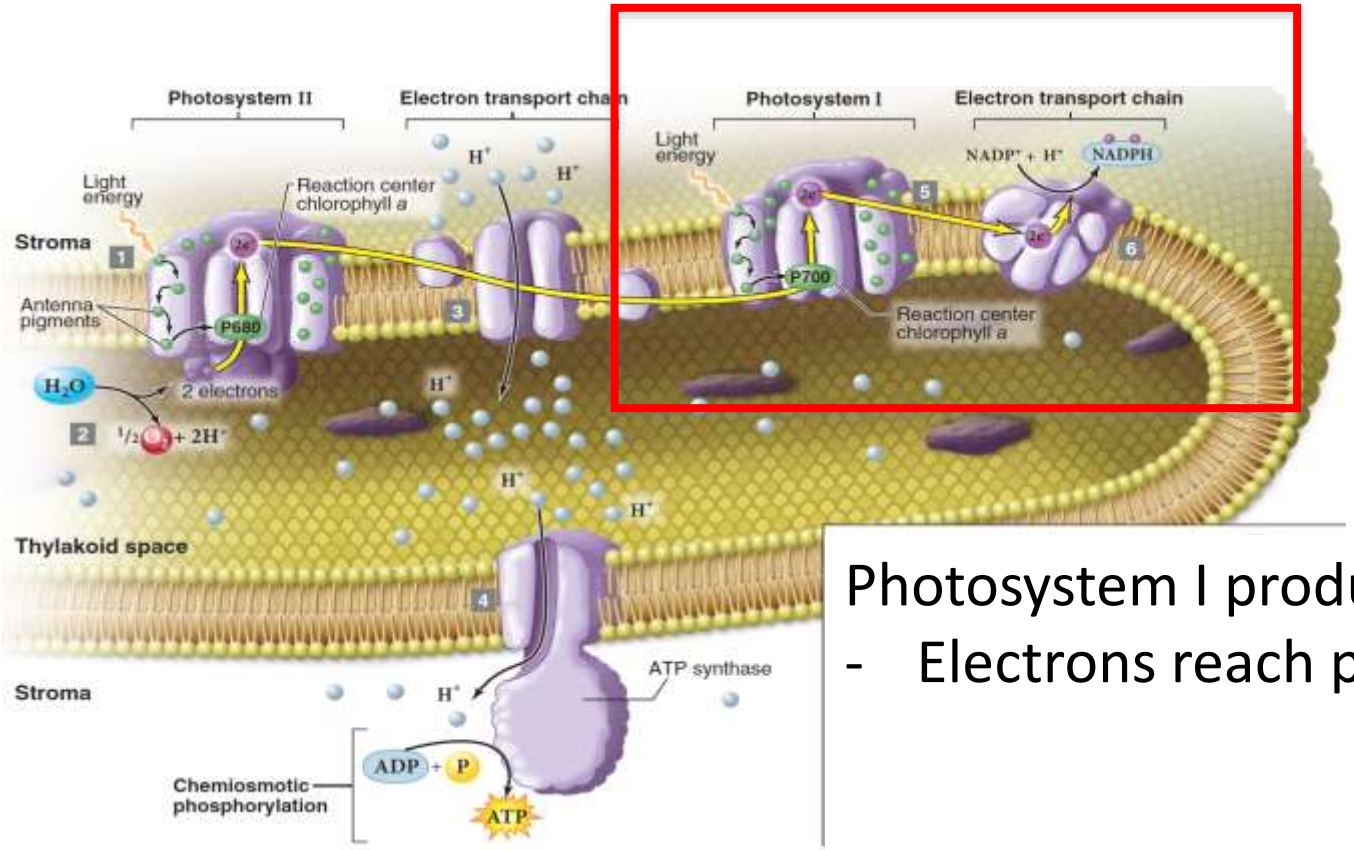


Photosystem II produces ATP

- Ejected electrons move down transport chain
- H^+ is pumped into thylakoid
- H^+ leaves through ATP synthase
- ATP is produced by **chemiosmotic phosphorylation**

Figure 5.8

The Light Reactions Begin Photosynthesis



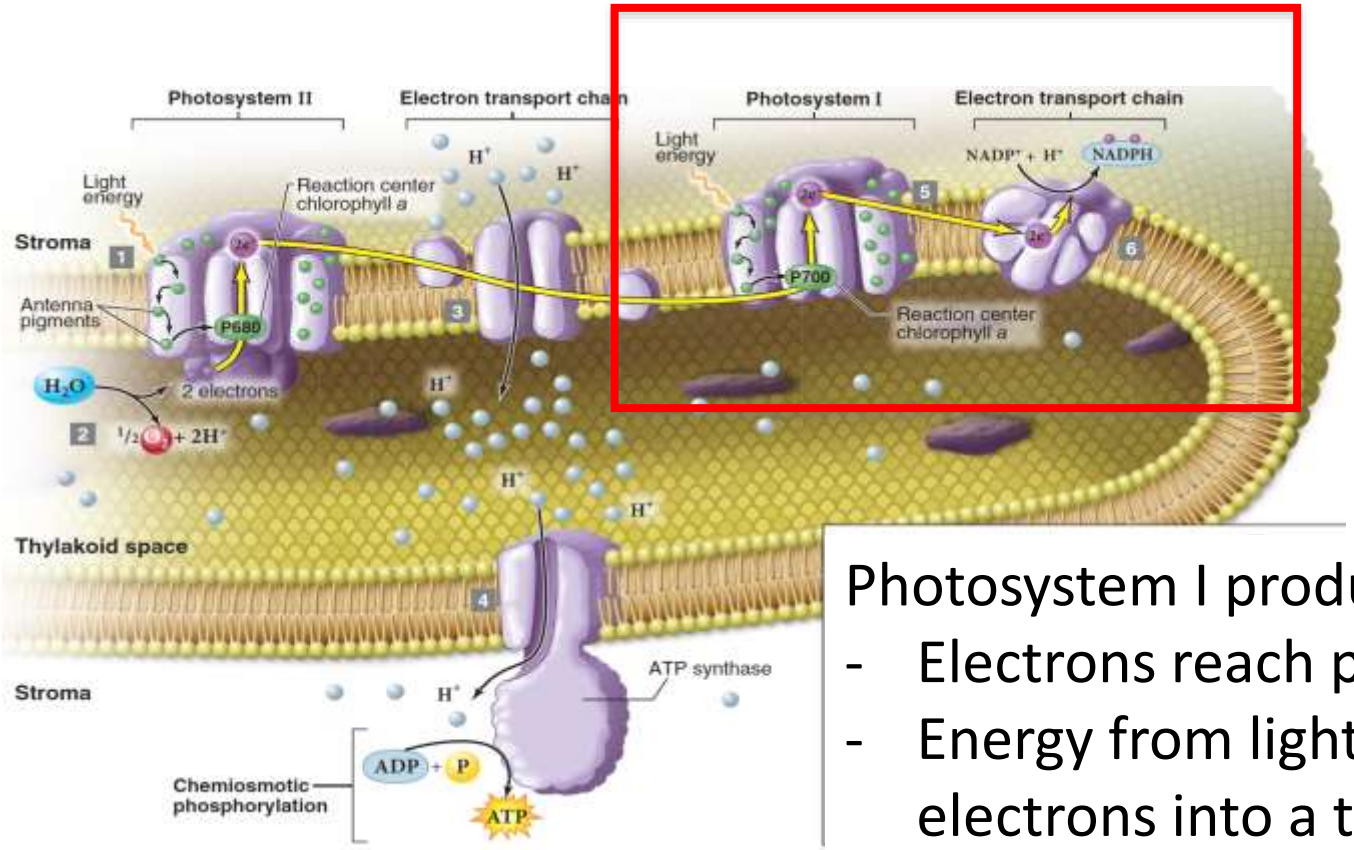
Photosystem I produces NADPH

- Electrons reach photosystem I

Section 5.4

Figure 5.8

The Light Reactions Begin Photosynthesis



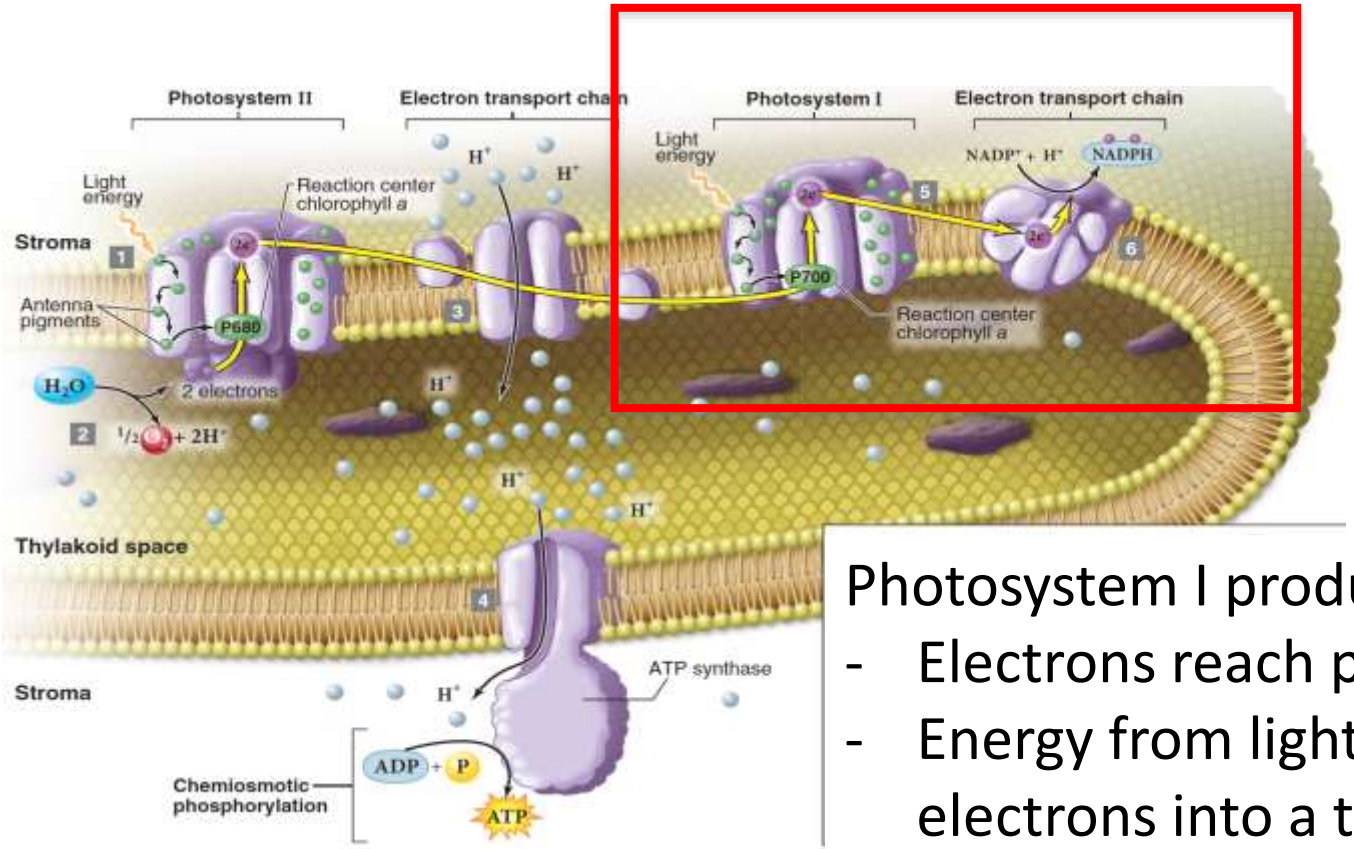
Photosystem I produces NADPH

- Electrons reach photosystem I
- Energy from light again ejects electrons into a transport chain

Section 5.4

Figure 5.8

The Light Reactions Begin Photosynthesis



Photosystem I produces NADPH

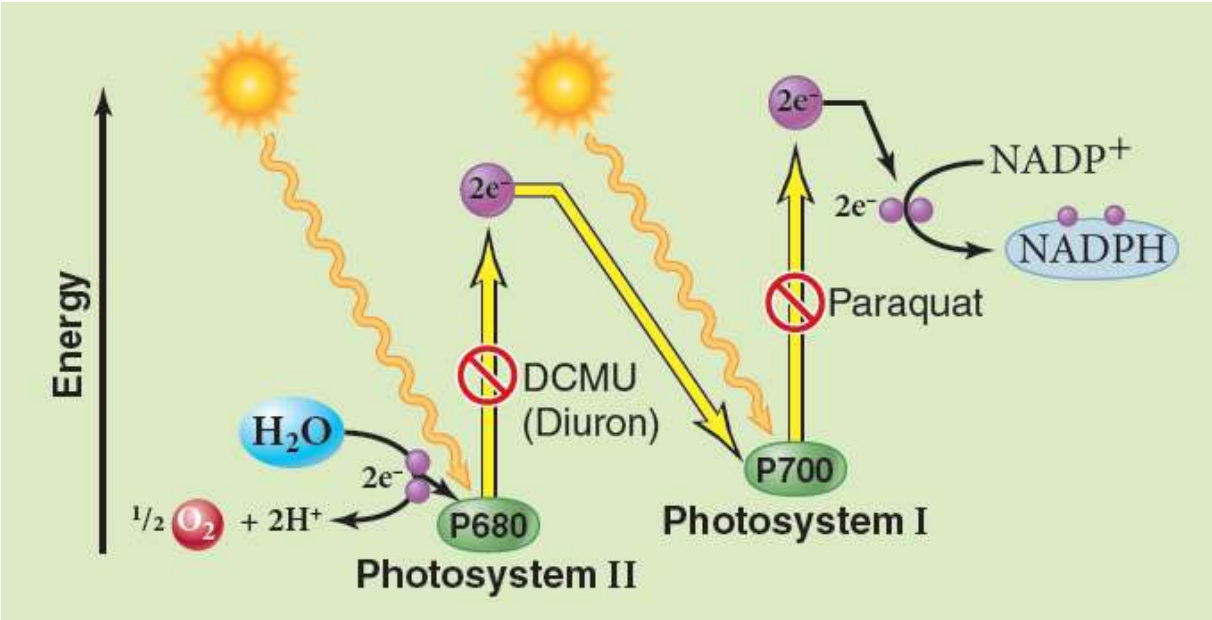
- Electrons reach photosystem I
- Energy from light again ejects electrons into a transport chain
- Electrons reduce $NADP^+$ to NADPH

Section 5.4

Figure 5.8

The Light Reactions Begin Photosynthesis

Some chemicals, such as the weed killers DCMU and Paraquat, block the light reactions.



Section 5.4

Figure 5.A

LIGHT DEPENDENT REACTION OVERVIEW

Requires ____LIGHT____

Molecules are part of THYLAKOID membranes

Made up of PHOTOSYSTEMS II & I

connected by ELECTRON TRANSPORT CHAIN

& ATP SYNTHASE

Uses light energy to change

ADP + P → ATP

$NADP^+ + 2e^- + H^+ \rightarrow$ NADPH

Breaks apart H_20 molecules and

releases oxygen

Clicker Question #4

How do the light reactions produce ATP? (Select the one best answer.)

A. Potential energy stored in a hydrogen ion gradient is used to synthesize ATP.
B. Photosystem I *directly adds* a phosphate to ADP.
C. Photosystem II *directly adds* a phosphate to ADP.
D. Energy released by electrons is directly used to synthesize ATP.

Clicker Question #4

How do the light reactions produce ATP? (Select the one best answer.)

A. Potential energy stored in a hydrogen ion gradient is used to synthesize ATP.

B. Photosystem I *directly adds* a phosphate to ADP.

C. Photosystem II *directly adds* a phosphate to ADP.

D. Energy released by electrons is directly used to synthesize ATP.

5.4 Mastering Concepts

Describe the events that occur after light strikes photosystem II, ending with the production of ATP.

Photosynthetic coral © Andrew J. Martinez/Science Source

- Be sure to tell me what is produced at the end of light cycle and where these products end up

Photosynthesis Occurs in Two Stages

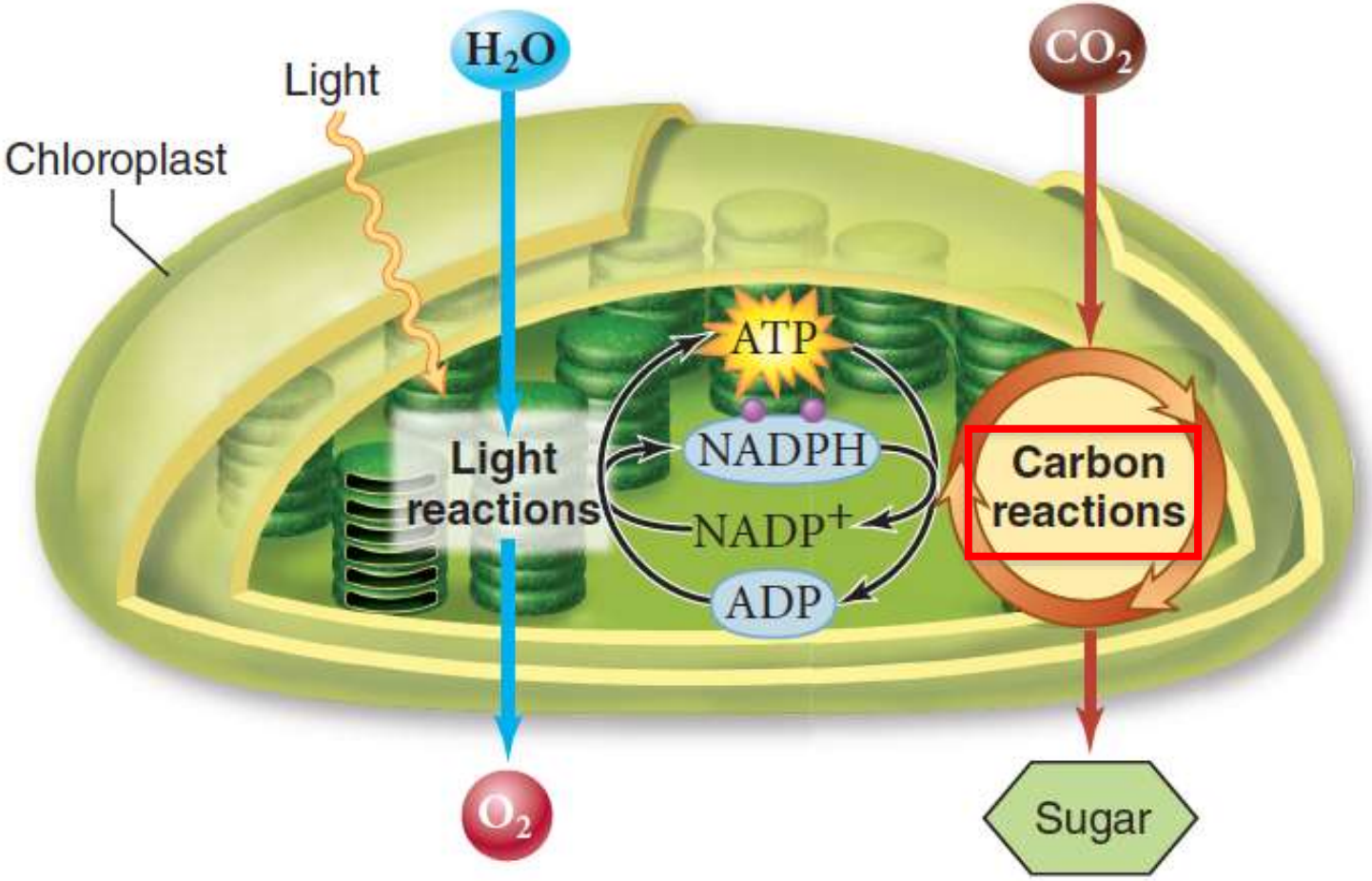
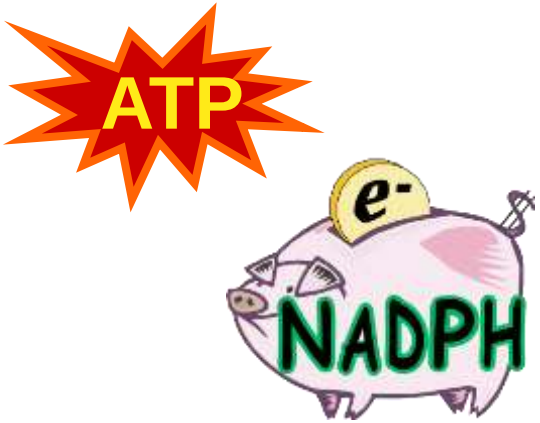
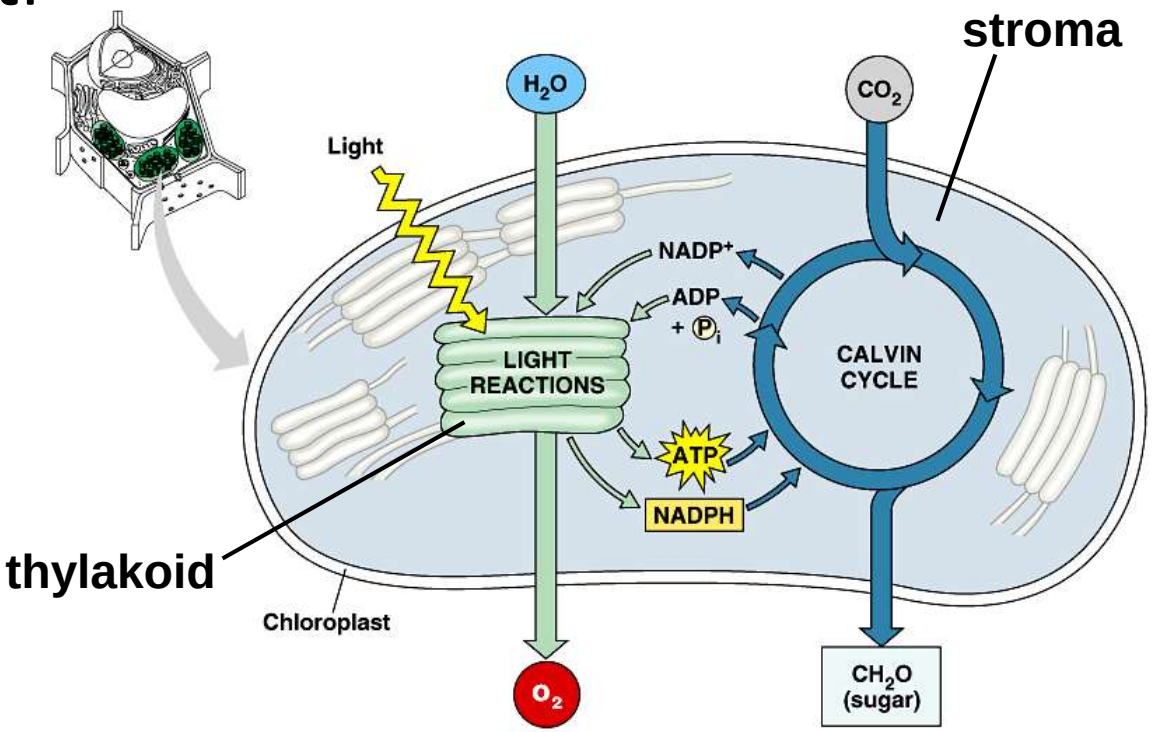


Figure 5.7

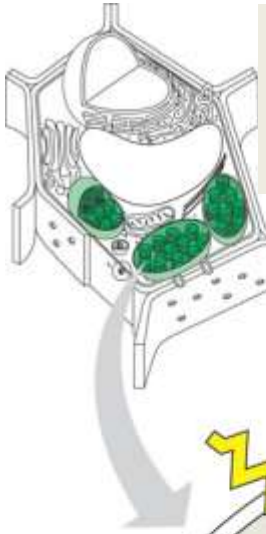
From Light reactions to Calvin cycle

- Calvin cycle
  - chloroplast stroma
- Need products of light reactions to drive synthesis reactions
  - ATP
  - NADPH

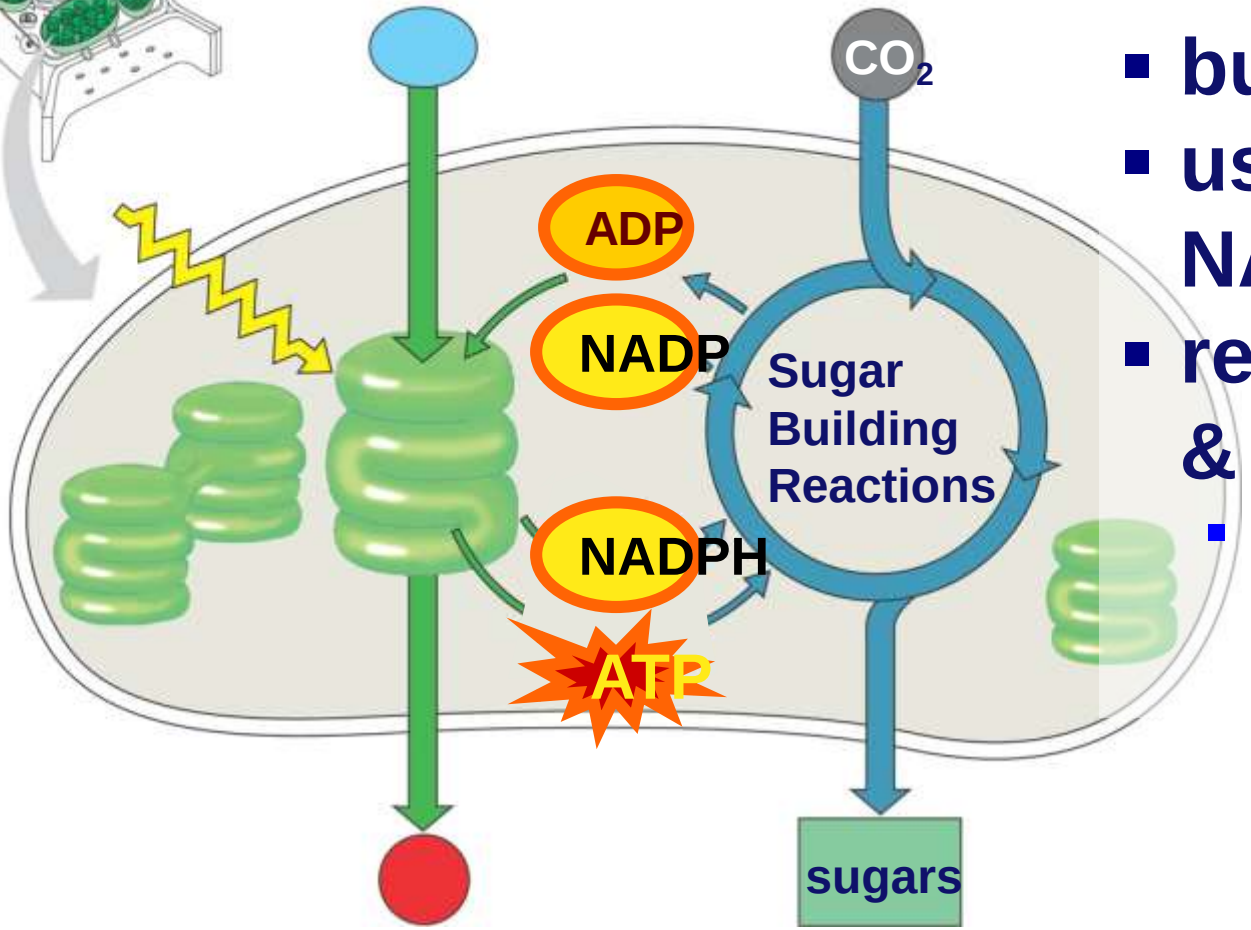




Calvin Cycle



$$CO_2 + ATP + NADPH \rightarrow C_6H_{12}O_6 + ADP + NADP$$



- **builds sugars**
- **uses ATP & NADPH**
- **recycles ADP & NADP**
  - **back to make more ATP & NADPH**

To G3P and Beyond

- Glyceraldehyde-3-P
  - end product of Calvin cycle
  - energy rich 3 carbon sugar
  - "C3 photosynthesis"
- G3P is an important intermediate

G3P → → glucose → → carbohydrates

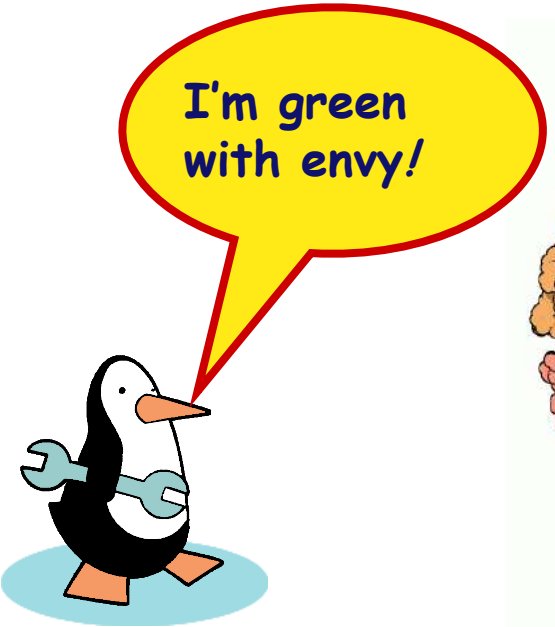
→ → lipids → → phospholipids, fats, waxes

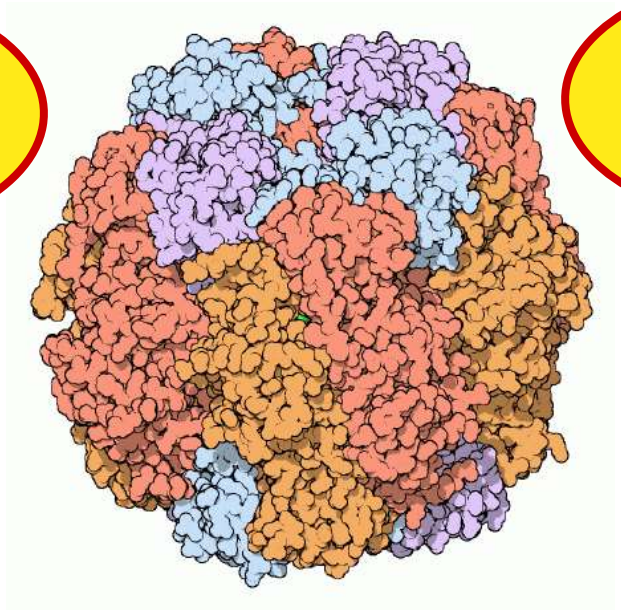
→ → amino acids → → proteins

→ → nucleic acids → → DNA, RNA

RuBisCo

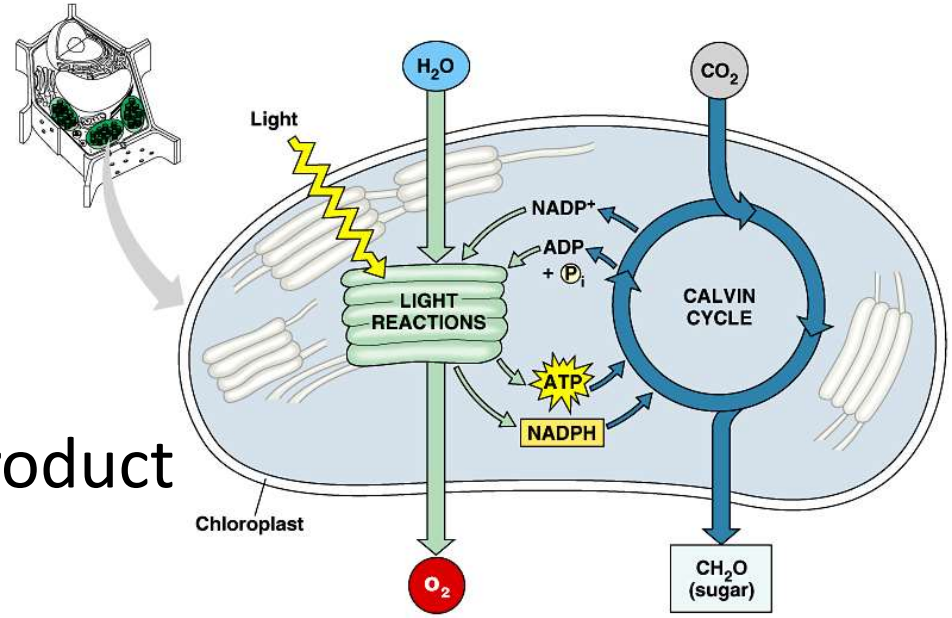
- Enzyme which fixes carbon from air
  - ribulose bisphosphate carboxylase
  - the most important enzyme in the world!
    - it makes life out of air!
  - definitely the most abundant enzyme

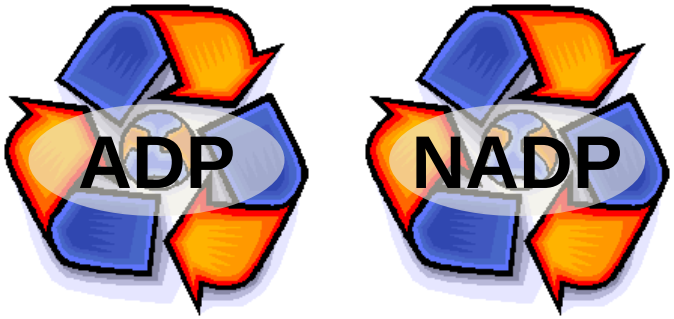




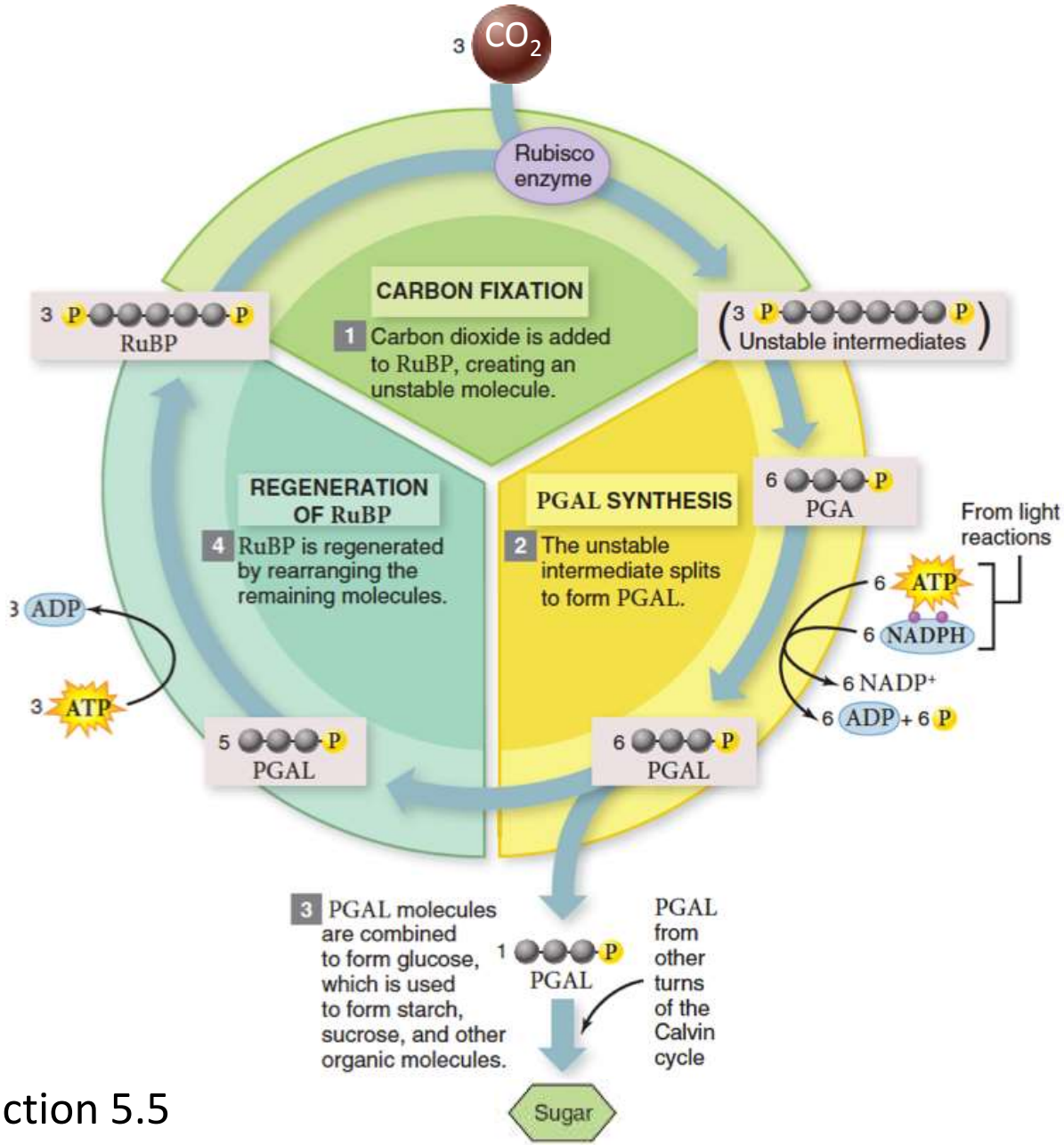
Photosynthesis summary

- Light reactions
  - produced ATP
  - produced NADPH
  - consumed H_2O
  - produced O_2 as byproduct
- Calvin cycle
  - consumed CO_2
  - produced G3P (sugar)
  - regenerated ADP
  - regenerated NADP





Carbon Reactions Produce Carbohydrates

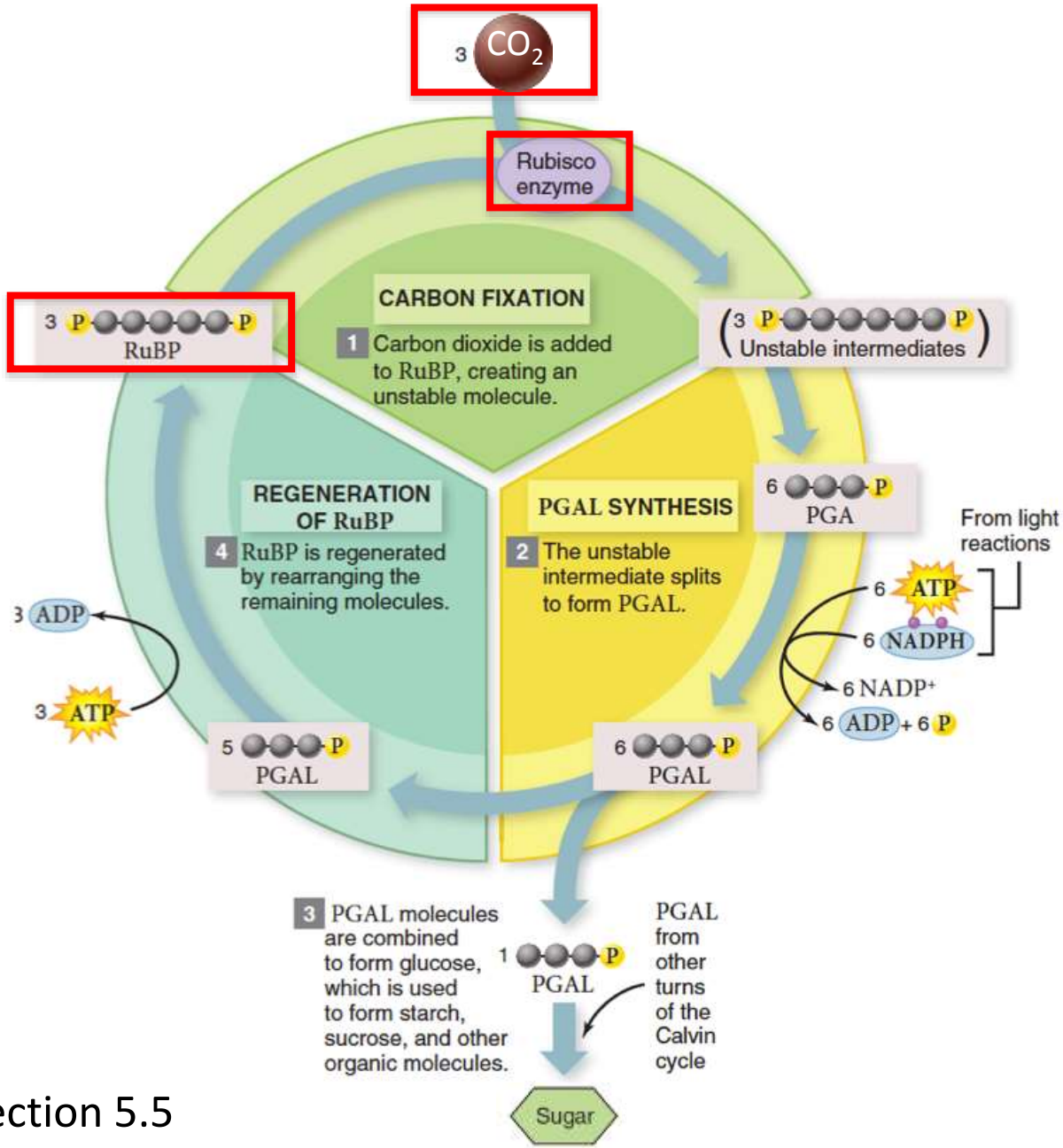


These are the carbon reactions, also known as the Calvin cycle.

Section 5.5

Figure 5.9

Carbon Reactions Produce Carbohydrates

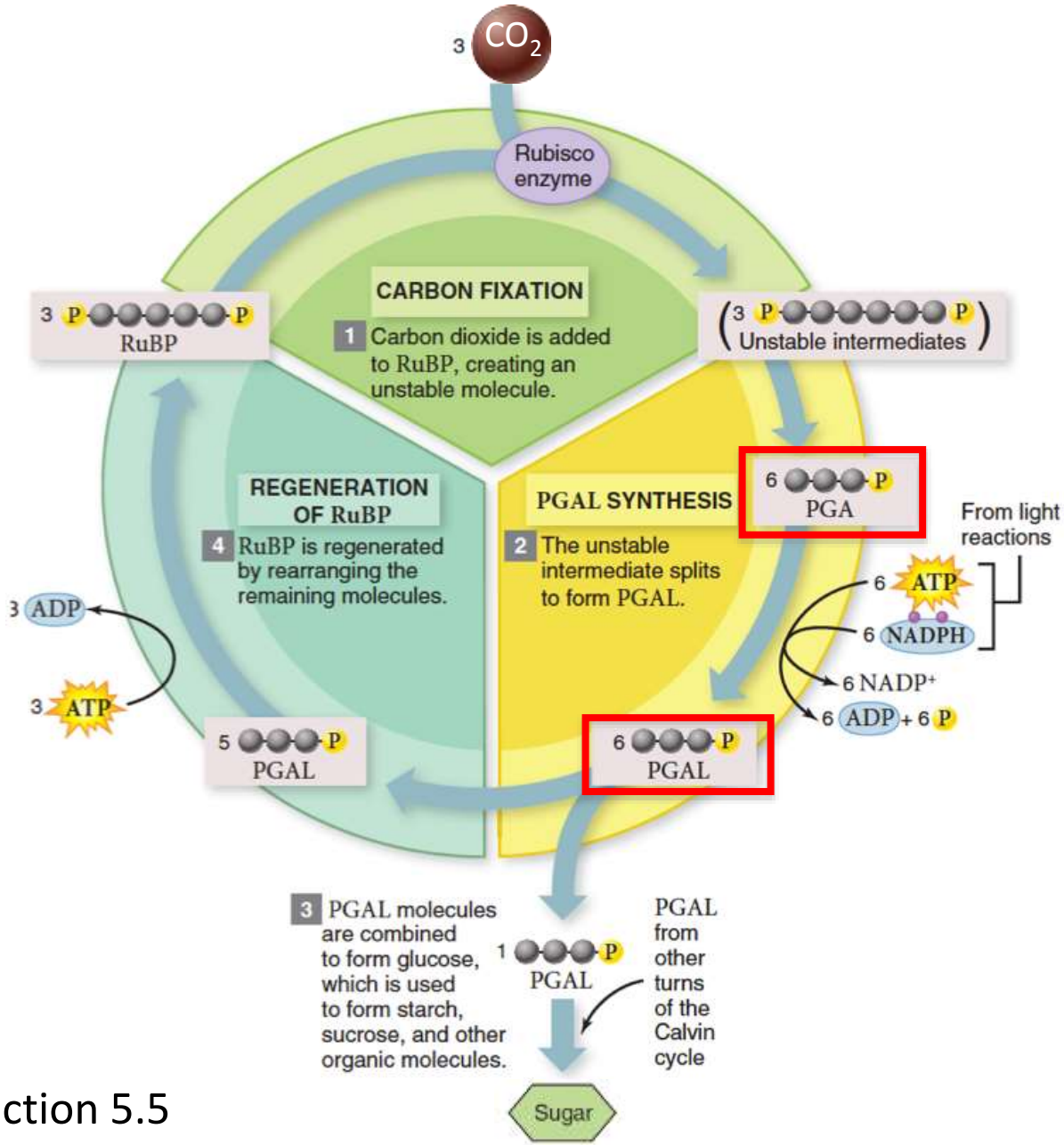


Carbon fixation

- Rubisco adds CO_2 to RuBP
- An unstable 6-carbon molecule is produced

Figure 5.9

Carbon Reactions Produce Carbohydrates



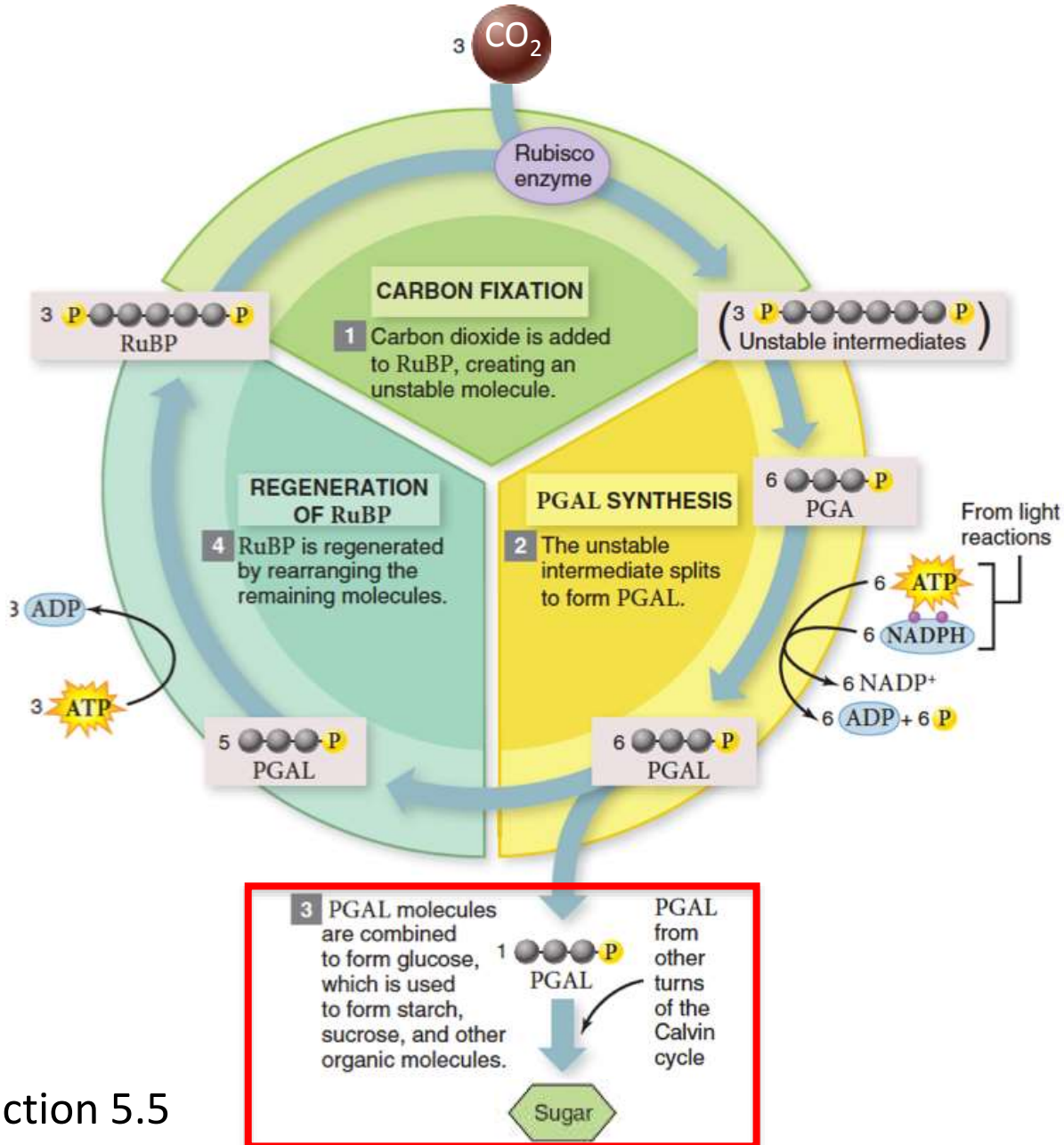
PGAL synthesis

- ATP and NADPH from light reactions are cashed in
- PGA is converted to PGAL

Section 5.5

Figure 5.9

Carbon Reactions Produce Carbohydrates



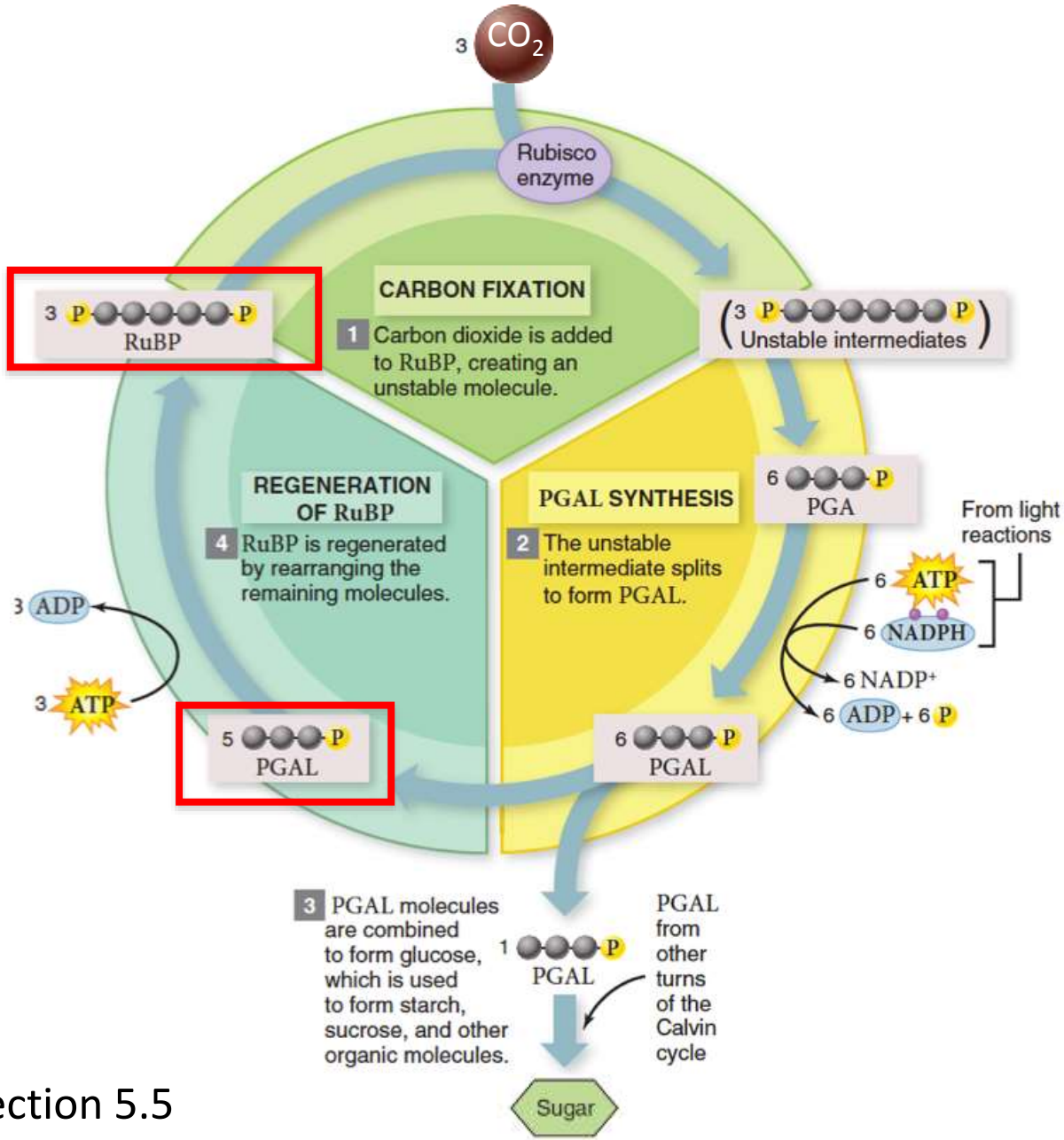
PGAL exit

- One PGAL leaves
- Multiple PGALs combine to form sugars

Section 5.5

Figure 5.9

Carbon Reactions Produce Carbohydrates



Regeneration of **RuBP**

- RuBP is reformed, starting the cycle anew

Section 5.5

Figure 5.9

CALVIN CYCLE

(also called LIGHT INDEPENDENT)

DOES NOT require LIGHT

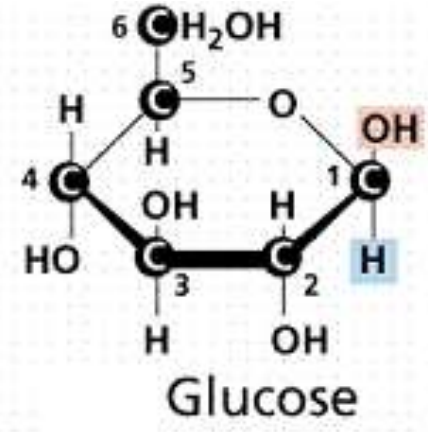
Happens in STROMA between thylakoids

NADPH donates Hydrogen + electrons

ATP donates ENERGY

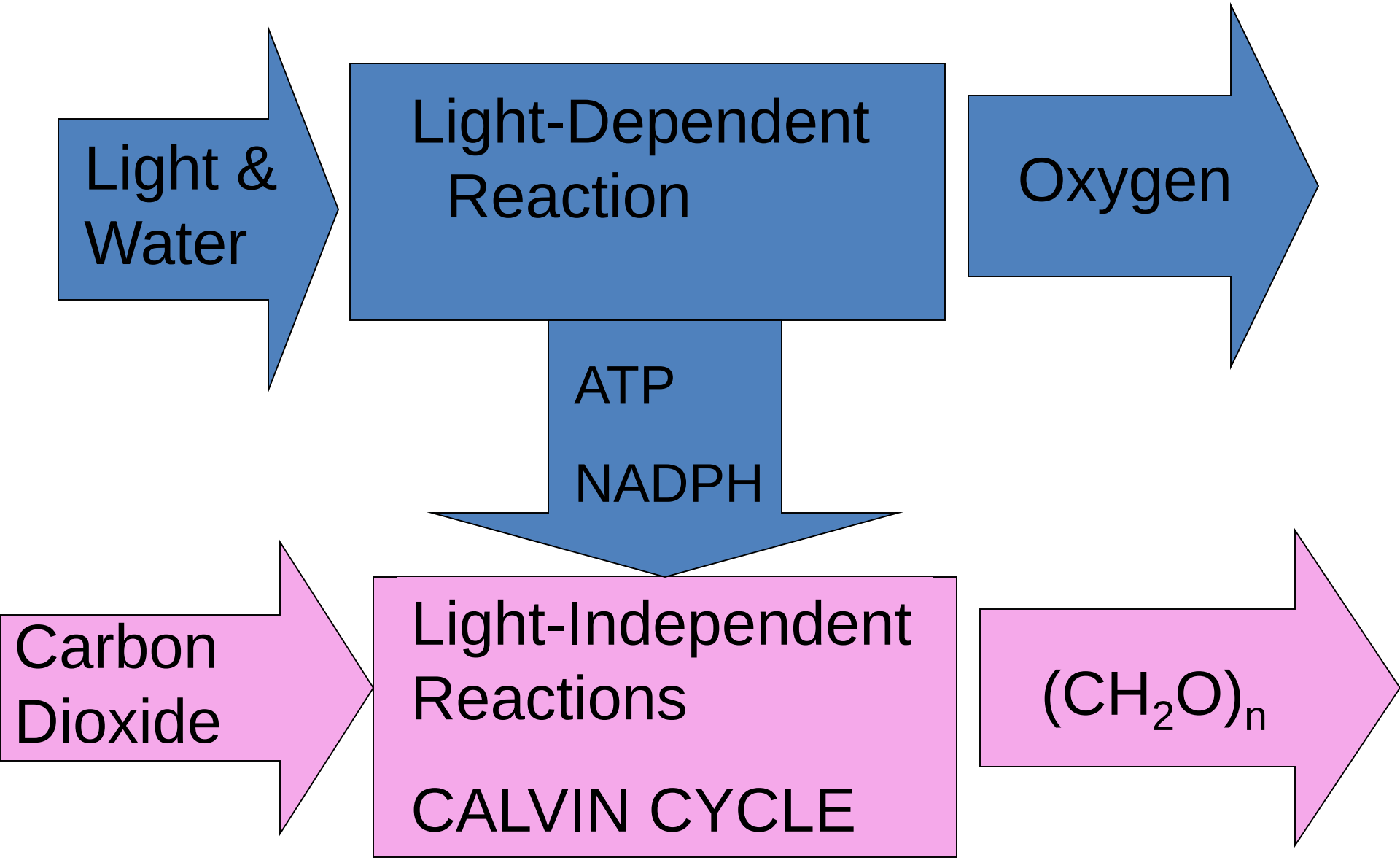
CO_2 donates Carbon & oxygen

to make GLUCOSE



http://www.estrellamountain.edu/faculty/farabee/biobk/BioBookCHEM2.html

PHOTOSYNTHESIS



Clicker Question #5

How does a plant cell use the ATP that it produces in the light reactions?

A. to fuel processes and reactions *throughout the cell*
B. to fuel the carbon reactions
C. to break down glucose
D. to convert $NADP^+$ to NADPH

Clicker Question #5

How does a plant cell use the ATP that it produces in the light reactions?

A. to fuel processes and reactions *throughout the cell*

B. to fuel the carbon reactions

C. to break down glucose

D. to convert $NADP^+$ to NADPH

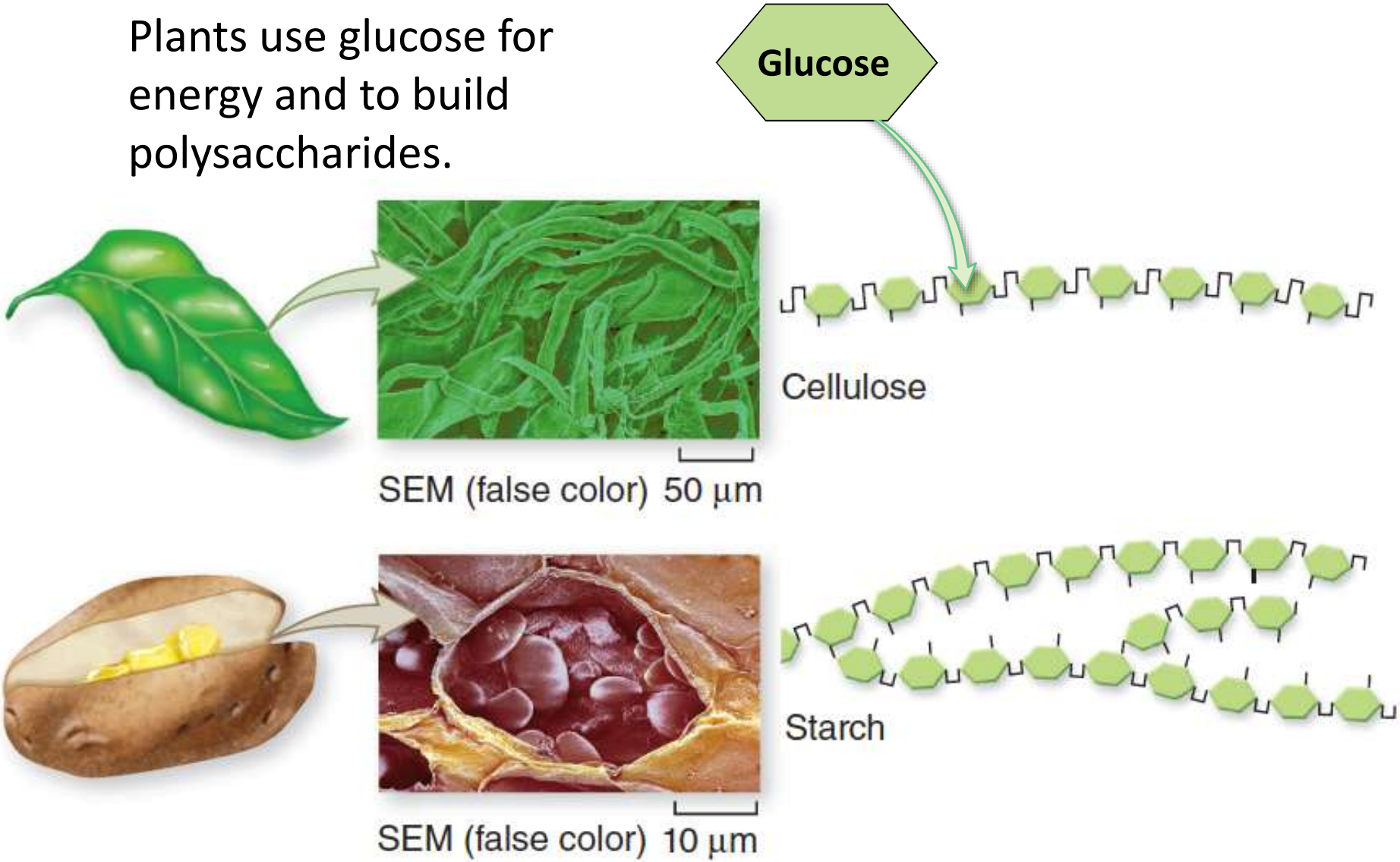
5.5 Mastering Concepts

What are the roles of CO_2, ATP, and NADPH in the Calvin cycle?

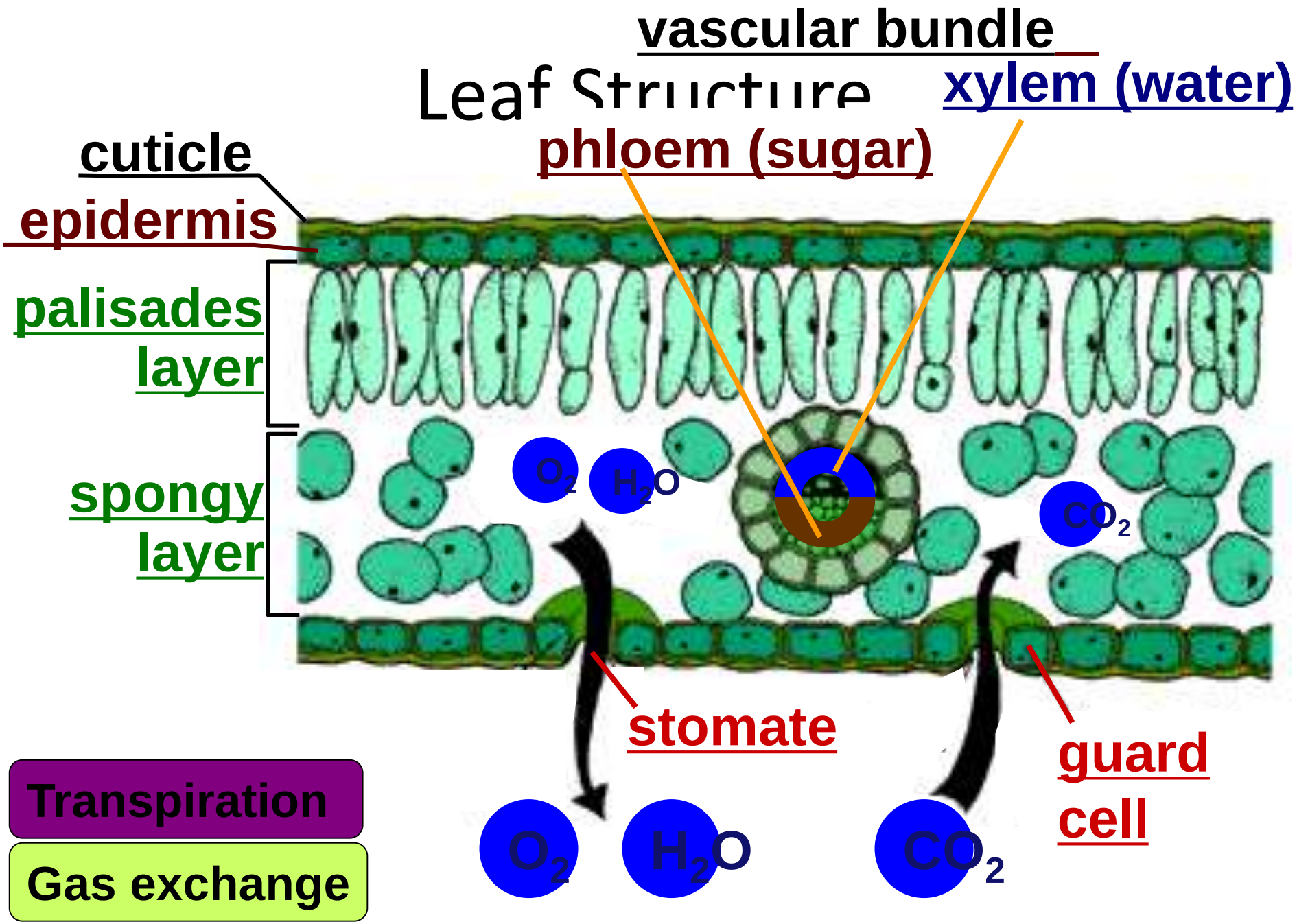
Photosynthetic coral © Andrew J. Martinez/Science Source

Carbon Reactions Produce Carbohydrates

Plants use glucose for energy and to build polysaccharides.

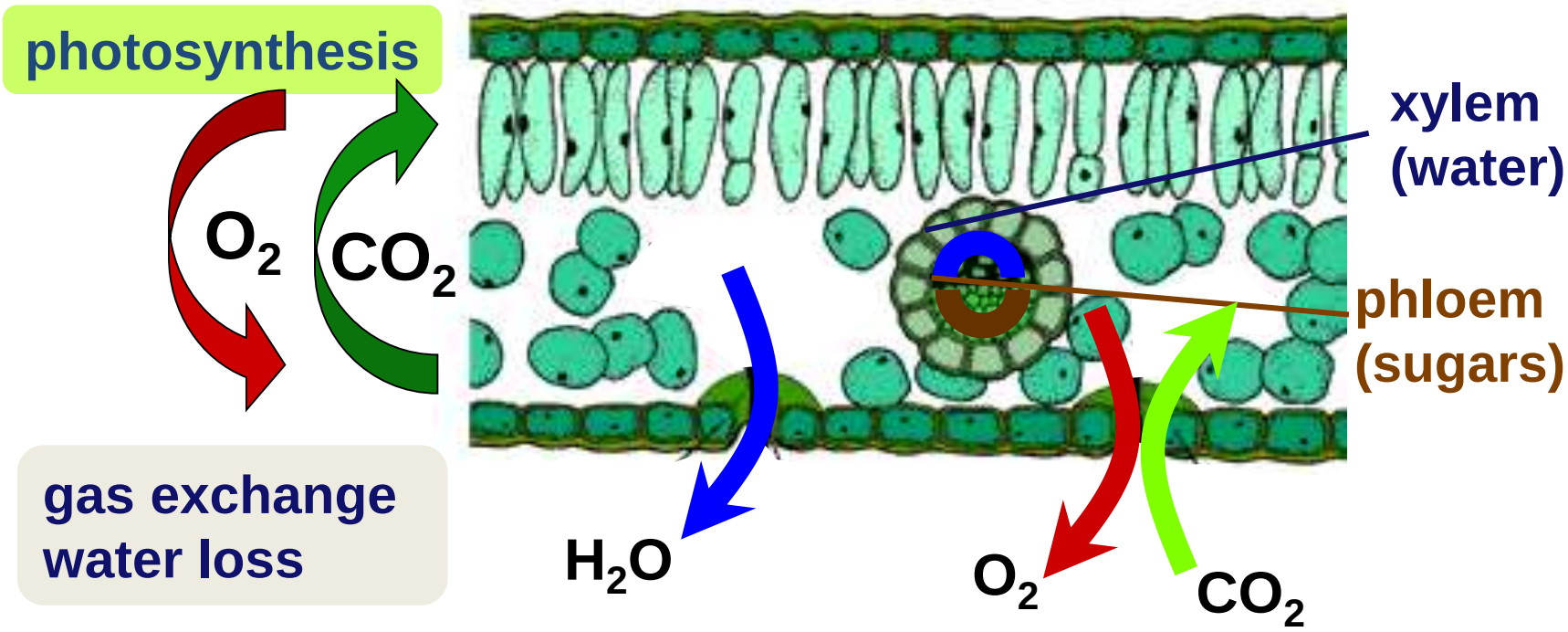


Leaf Structure



A second look inside a leaf

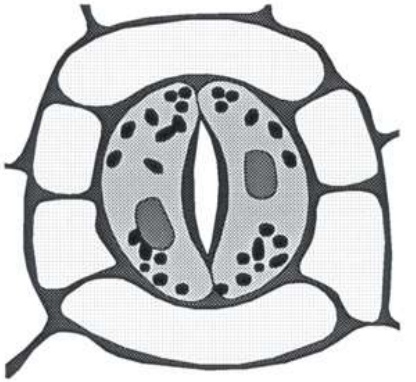
- Gas exchange & water flow
  - CO_2 in → **for Calvin cycle**
  - O_2 out → **waste from light reactions**
  - H_2O out → **for light reactions**

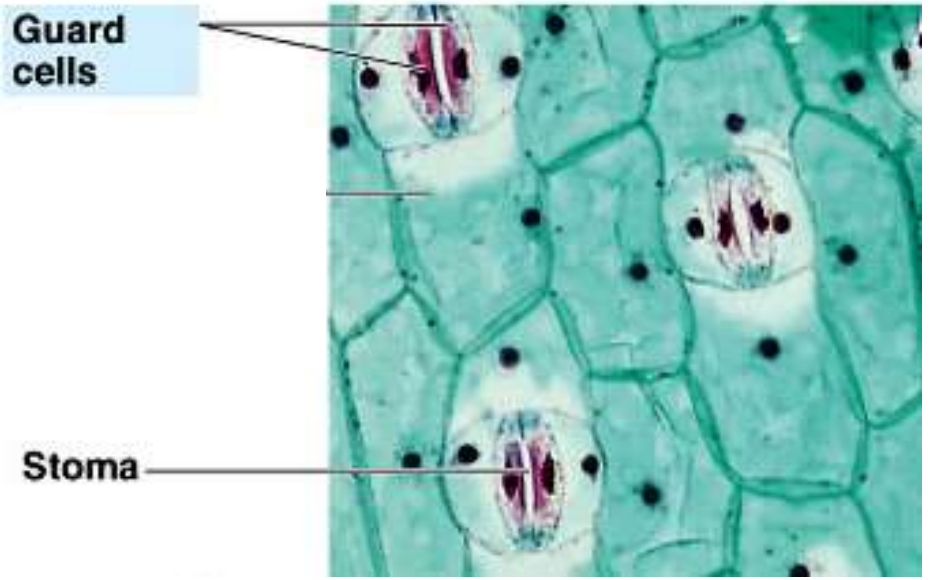


Controlling water loss from leaves

- Hot or dry days
  - stomates close to conserve water
  - guard cells
    - gain H_2O = stomates open
    - lose H_2O = stomates close
  - adaptation to living on land, but…

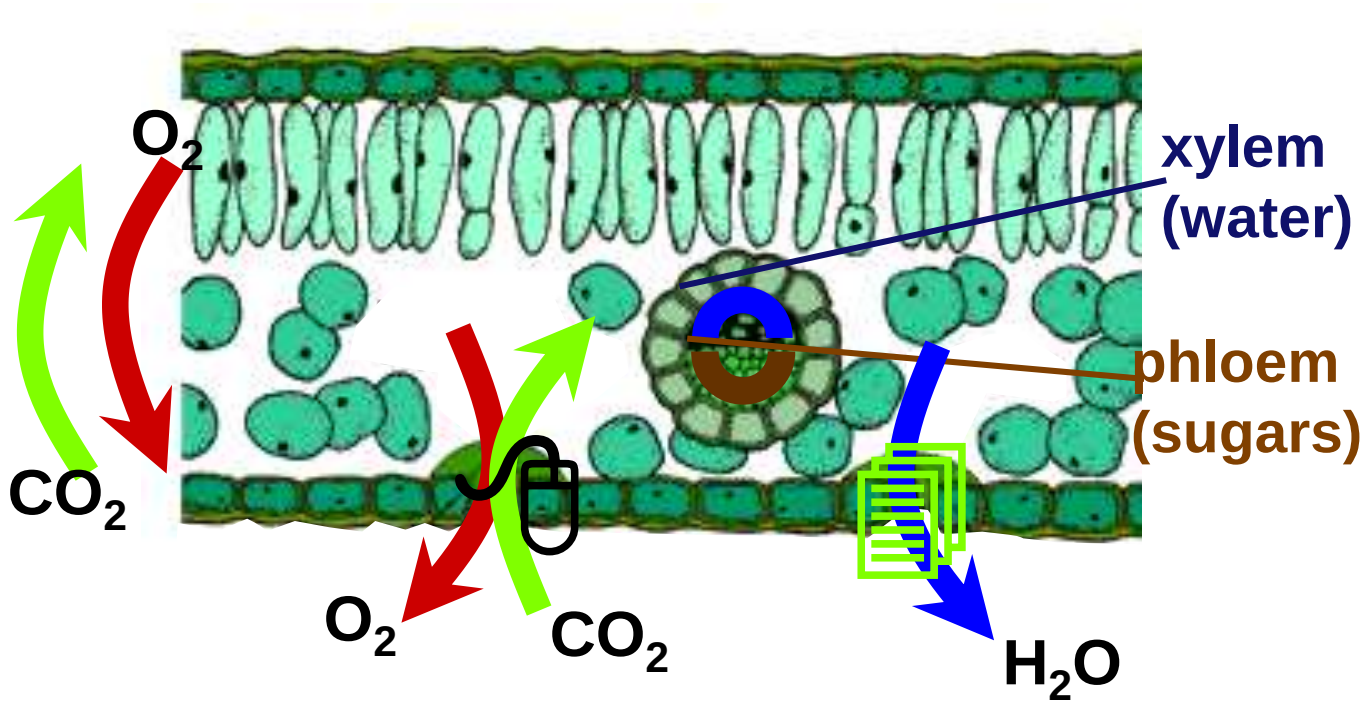
    creates PROBLEMS!

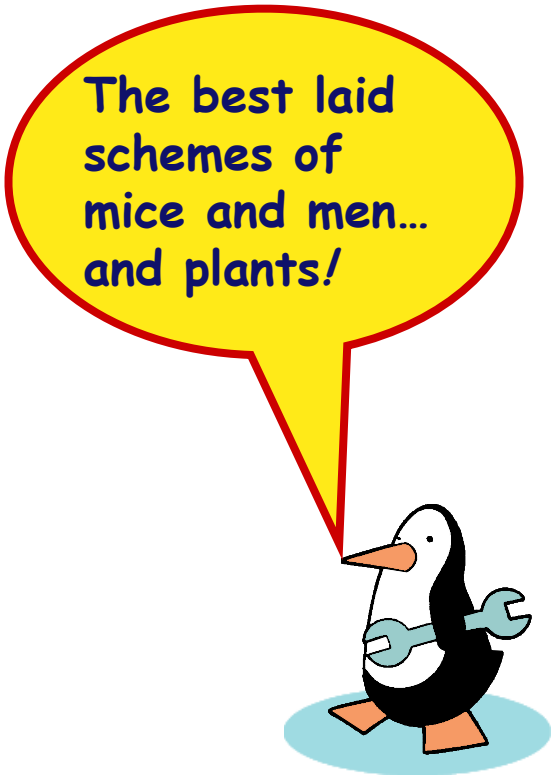




When stomates close…

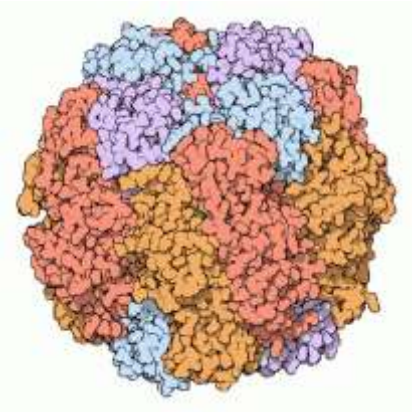
- Closed stomates lead to…
  - O_2 build up → from light reactions
  - CO_2 is depleted → in Calvin cycle
    - causes problems in Calvin Cycle





Inefficiency of RuBisCo: CO_2 vs O_2

- RuBisCo in Calvin cycle
  - carbon fixation enzyme
    - normally bonds C to RuBP
    - CO_2 is the optimal substrate
    - reduction of RuBP
    - building sugars
  - when O_2 concentration is high
    - RuBisCo bonds O to RuBP
    - O_2 is a competitive substrate
    - oxidation of RuBP
    - breakdown sugars



photosynthesis

photorespiration

Reducing photorespiration

- Separate carbon fixation from Calvin cycle
  - C4 plants

    - PHYSICALLY separate carbon fixation from Calvin cycle
      - different cells to fix carbon vs. where Calvin cycle occurs
      - store carbon in 4C compounds
    - different enzyme to capture CO_2 (fix carbon)
      - PEP carboxylase
    - different leaf structure

  - CAM plants
    - separate carbon fixation from Calvin cycle by TIME OF DAY
    - fix carbon during night
      - store carbon in 4C compounds
    - perform Calvin cycle during day

C4 plants

- A better way to capture CO_2
  - 1st step before Calvin cycle, fix carbon with enzyme <u>adaptation to hot, dry climates</u>
    - have to close stomates a lot
    - different leaf anatomy
  - sugar cane, corn, other grasses…

corn

sugar cane

CAM (Crassulacean Acid Metabolism) plants

- **Adaptation to hot, dry climates**
  - **separate carbon fixation from Calvin cycle by TIME**
    - **close stomates during day**
    - **open stomates during night**
  - **at night: open stomates & fix carbon in 4C "storage" compounds**
  - **in day: release CO_2 from 4C acids to Calvin cycle**
    - **increases concentration of CO_2 in cells**
  - **succulents, some cacti, pineapple**

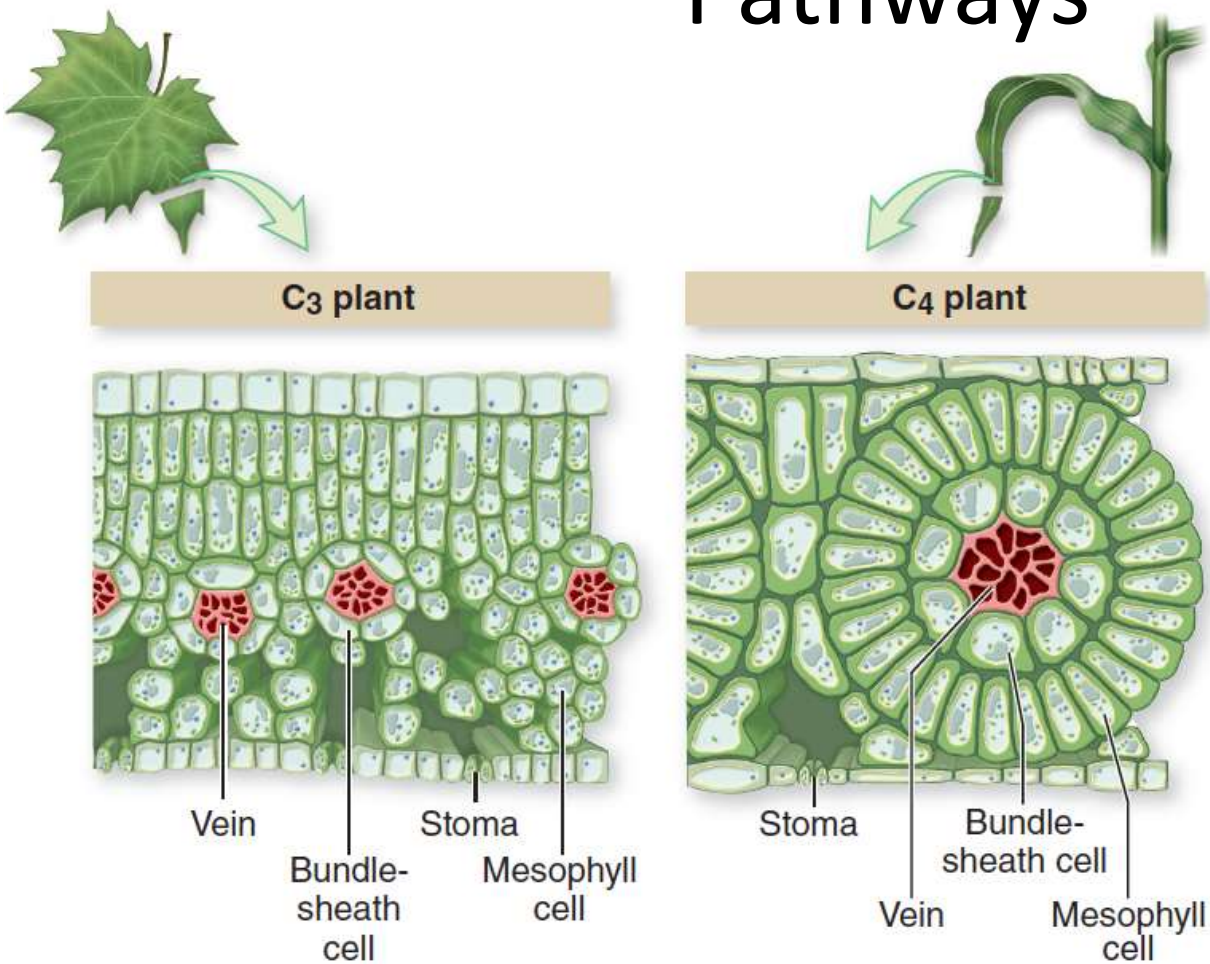
CAM plants

cacti

succulents

pineapple

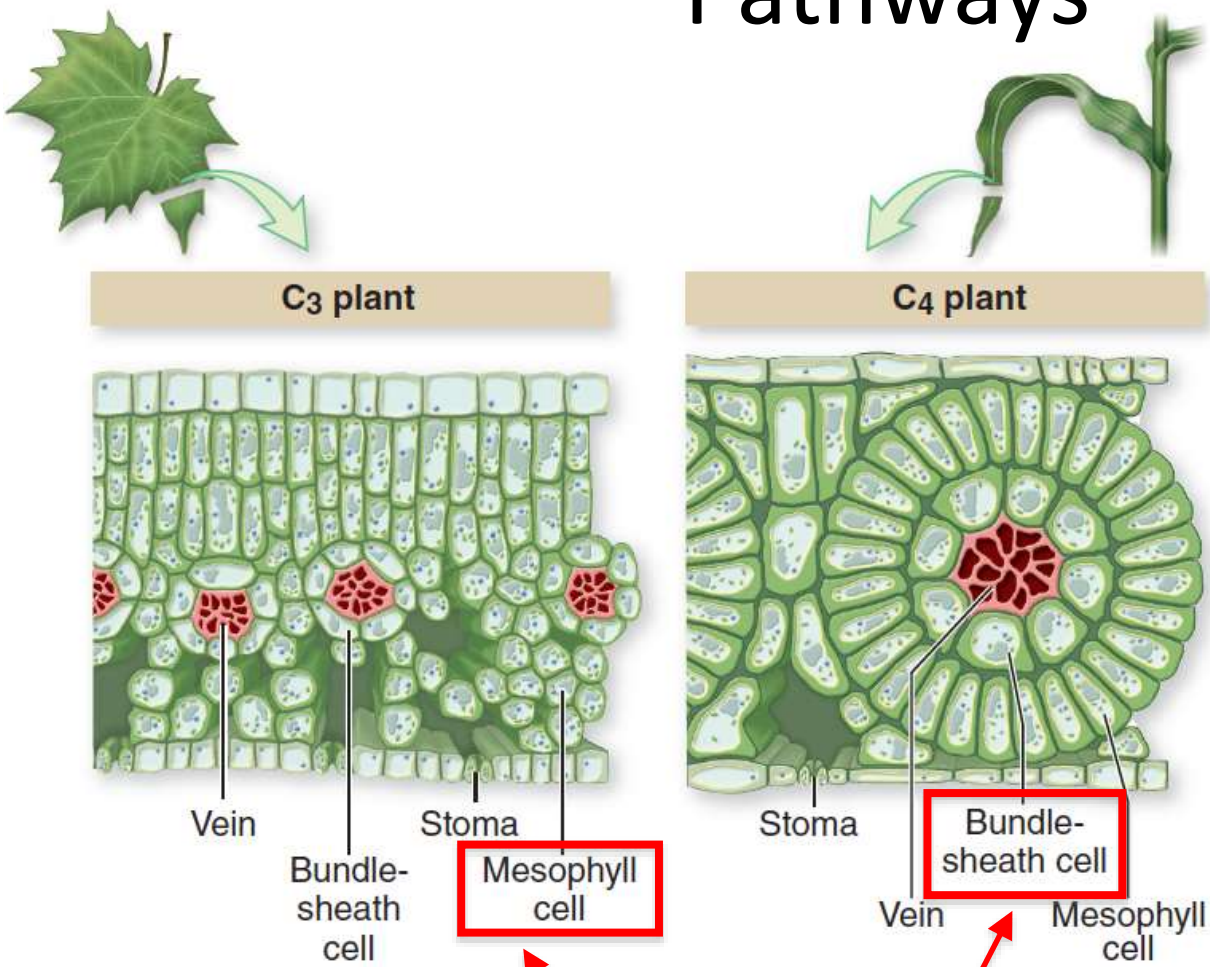
Plants Use Different Carbon Fixation Pathways



C_3 plants, C_4 plants, and CAM plants all use slightly different carbon fixation pathways.

Figure 5.10

Plants Use Different Carbon Fixation Pathways

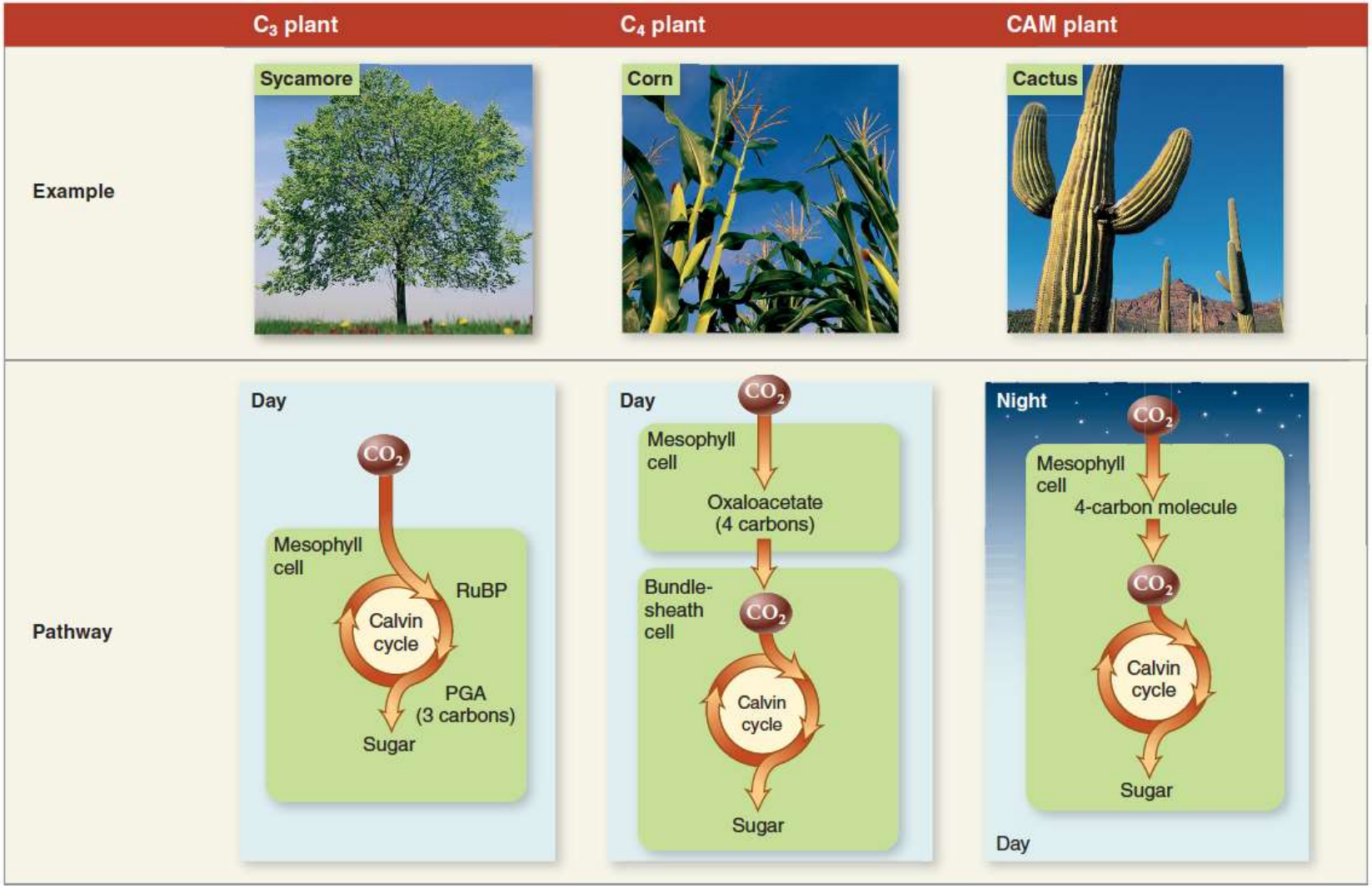


Notice the different leaf anatomy and Calvin cycle position.

The Calvin cycle occurs here.

Figure 5.10

Plants Use Different Carbon Fixation Pathways

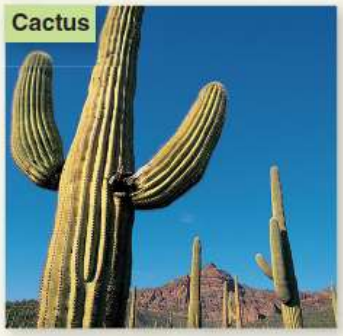


Section 5.6

Tree: © Tony Sweet/Digital Vision/Getty Images RF; corn: © Joeseph Sohm-Visions of America/Getty Images RF; cactus: © Digital Vision/Getty Images RF

Figure 5.11

Plants Use Different Carbon Fixation Pathways

	C_3 plant	C_4 plant	CAM plant
Example			
Limitation	Photorespiration	ATP cost	Reduced carbon availability
How plant avoids photorespiration	N/A	Light reactions and carbon reactions occur in separate cells.	CO_2 is absorbed at night; light reactions and carbon reactions occur during the day.
Habitat	Cool, moist	Hot, dry	Hot, dry
% of plant species	95%	1%	3–4%

Section 5.6

Figure 5.11

5.6 Mastering Concepts

How is the CAM pathway like C4 metabolism, and how is it different?

Check your answers to Mastering Concept questions via the website:

aaitken.weebly.com

Photosynthetic coral © Andrew J. Martinez/Science Source

Factors that Affect Photosynthesis

AMOUNT OF WATER

Water is one of the raw materials needed, so

A shortage of water can slow or stop photosynthesis

Desert plants and conifers that live in dry conditions have a waxy coating on their leaves to prevent water loss.

http://www.hononegah.org/departments/Anderson/cactus.JPG

Factors that Affect Photosynthesis

TEMPERATURE

Photosynthesis enzymes function best between 0° C - 35° C

At temperatures above or below this range, photosynthesis will slow or stop

Conifers in winter may carry out photosynthesis only occasionally

http://www.sustland.umn.edu/maint/images/evergreen10.jpg

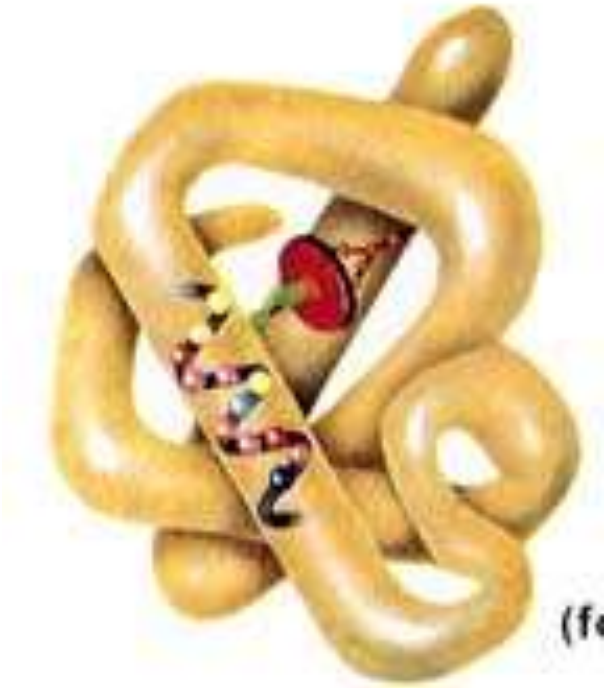
REMEMBER CELL BIO

Enzymes work BEST at a certain _pH_ and _temperature_.

Conditions that are TOO ACIDIC or TOO HOT cause proteins to unwind or _DENATURE_

http://www.desktopfotos.de/Downloads/melt_cd.jpg http://www.nealbrownstudio.com/adm/photo/163_nb_fried_egg.jpg

Denaturing changes the shape of the enzyme making it not work



HOMEOSTASIS (keeping pH and temperature constant) is important for maintaining enzyme function.

Image from:http://www.emc.maricopa.edu/faculty/farabee/BIOBK/BioBookCHEM2.html

Factors that Affect Photosynthesis

LIGHT INTENSITY

More light increases rate of photosynthesis up to a certain level until plant reaches its maximum rate of photosynthesis

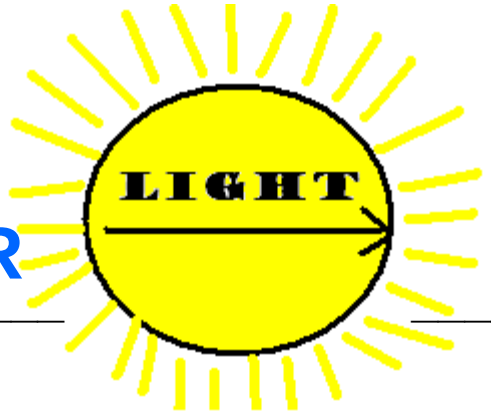
See effect of light experiment

http://www.teachnet.ie/foneill/exper.htm

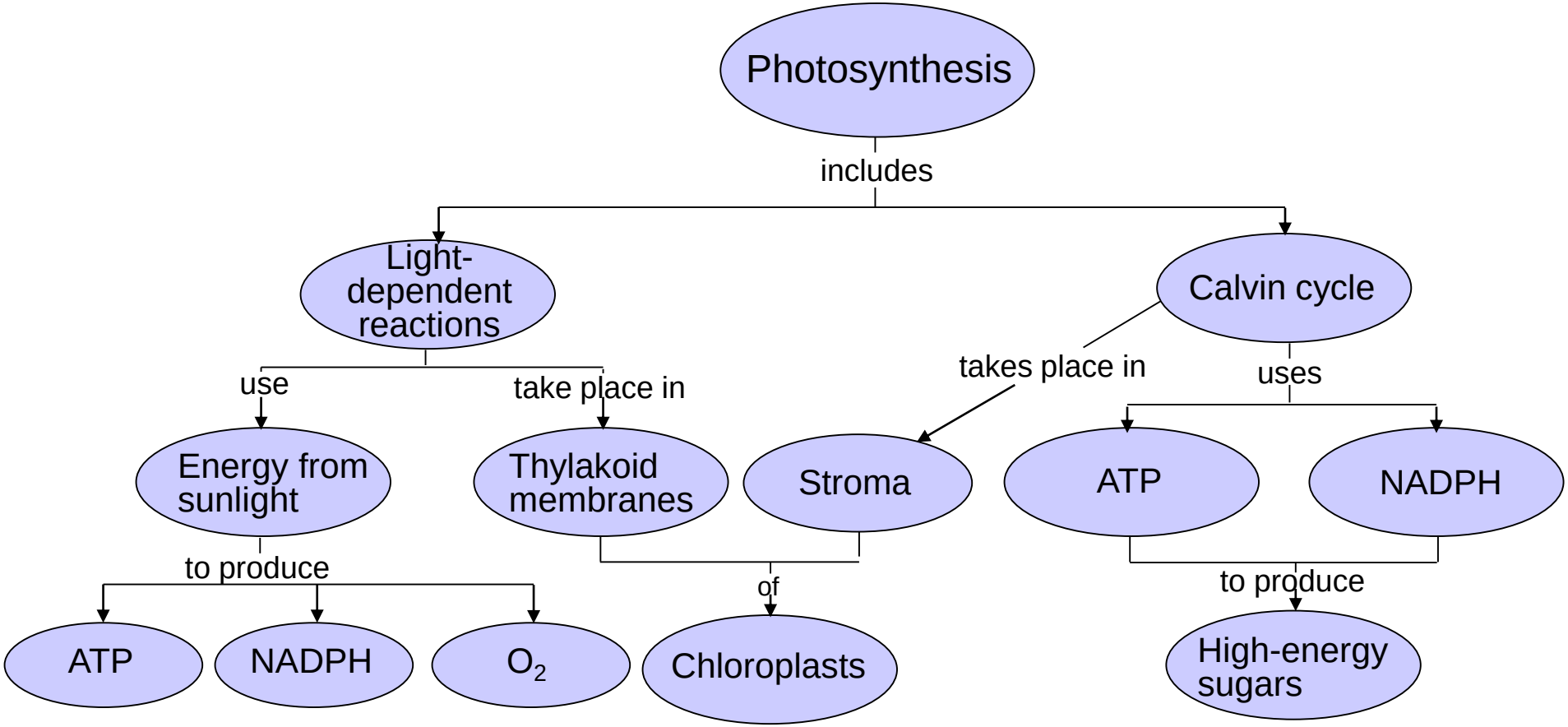
http://206.173.89.42/REALTYWITHALOHA_COM/piphoto/funny%20sun%20with%20sunglasses.gif

THE BIG PICTURE

PHOTOSYNTHESIS provides the _____OXYGEN_____ we breathe and the _____sugars_____ heterotrophs (like us) consume to survive

Carbon dioxide + **WATER** 

Sugars + **Oxygen**


Photosynthesis
includes
Light-dependent reactions
Calvin cycle
use
take place in
takes place in
uses
Energy from sunlight
Thylakoid membranes
Stroma
ATP
NADPH
to produce
of
to produce
ATP
NADPH
O_2
Chloroplasts
High-energy sugars