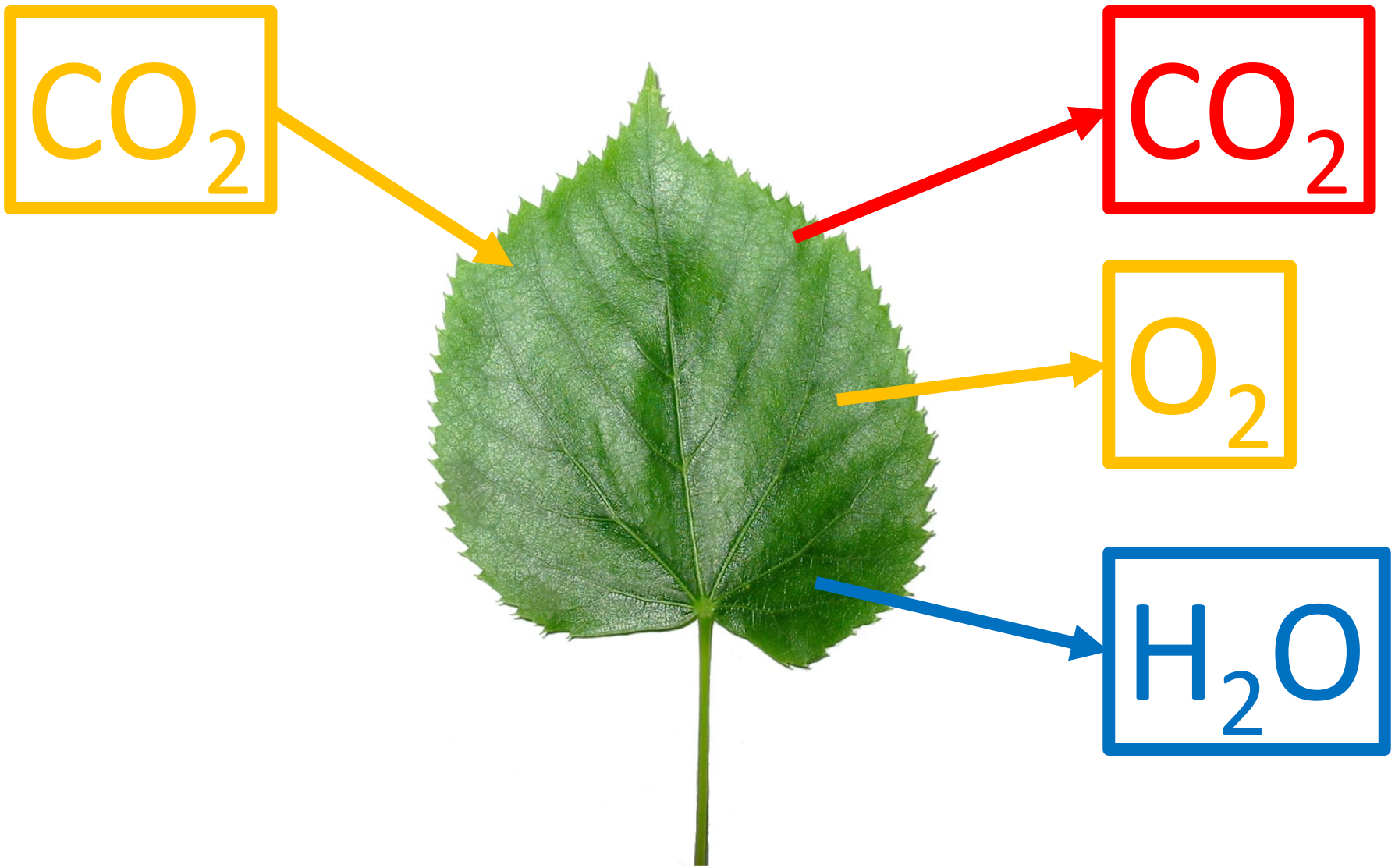
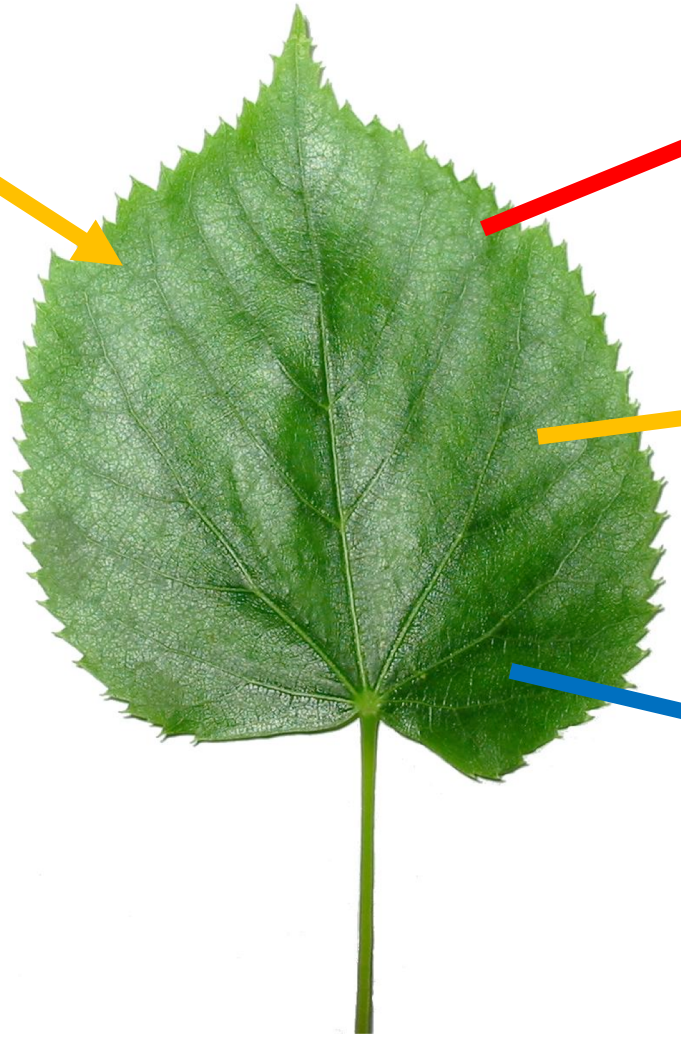
Plant gas exchange


CO_2
CO_2
O_2
H_2O

Photosynthesis

CO_2



Respiration

CO_2

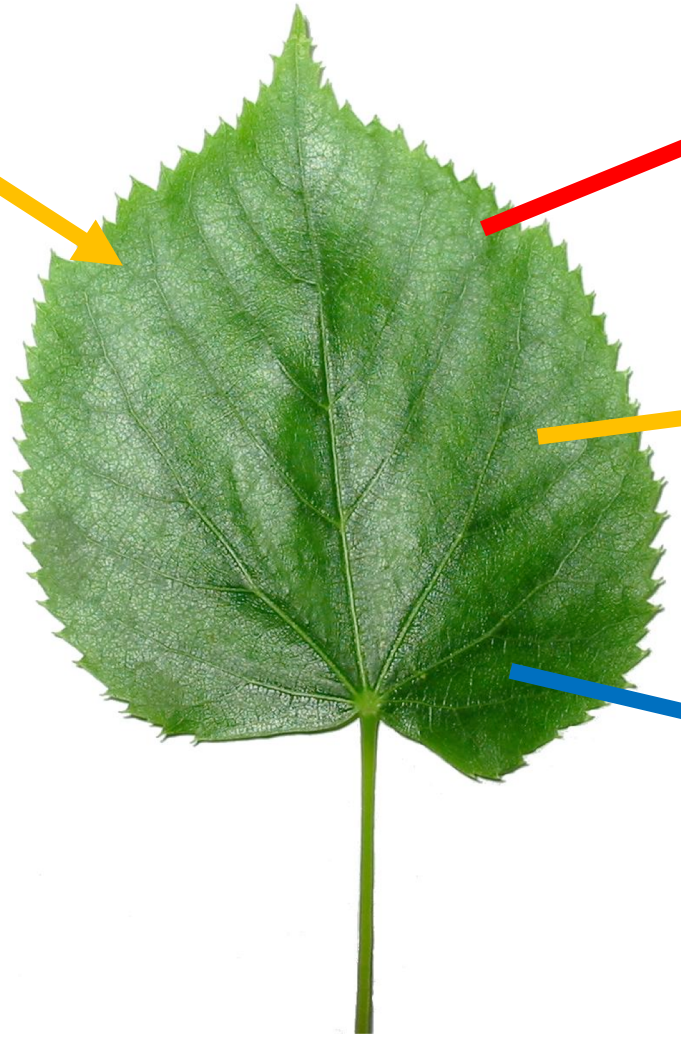
O_2

H_2O

Transpiration

Photosynthesis

CO_2



Respiration

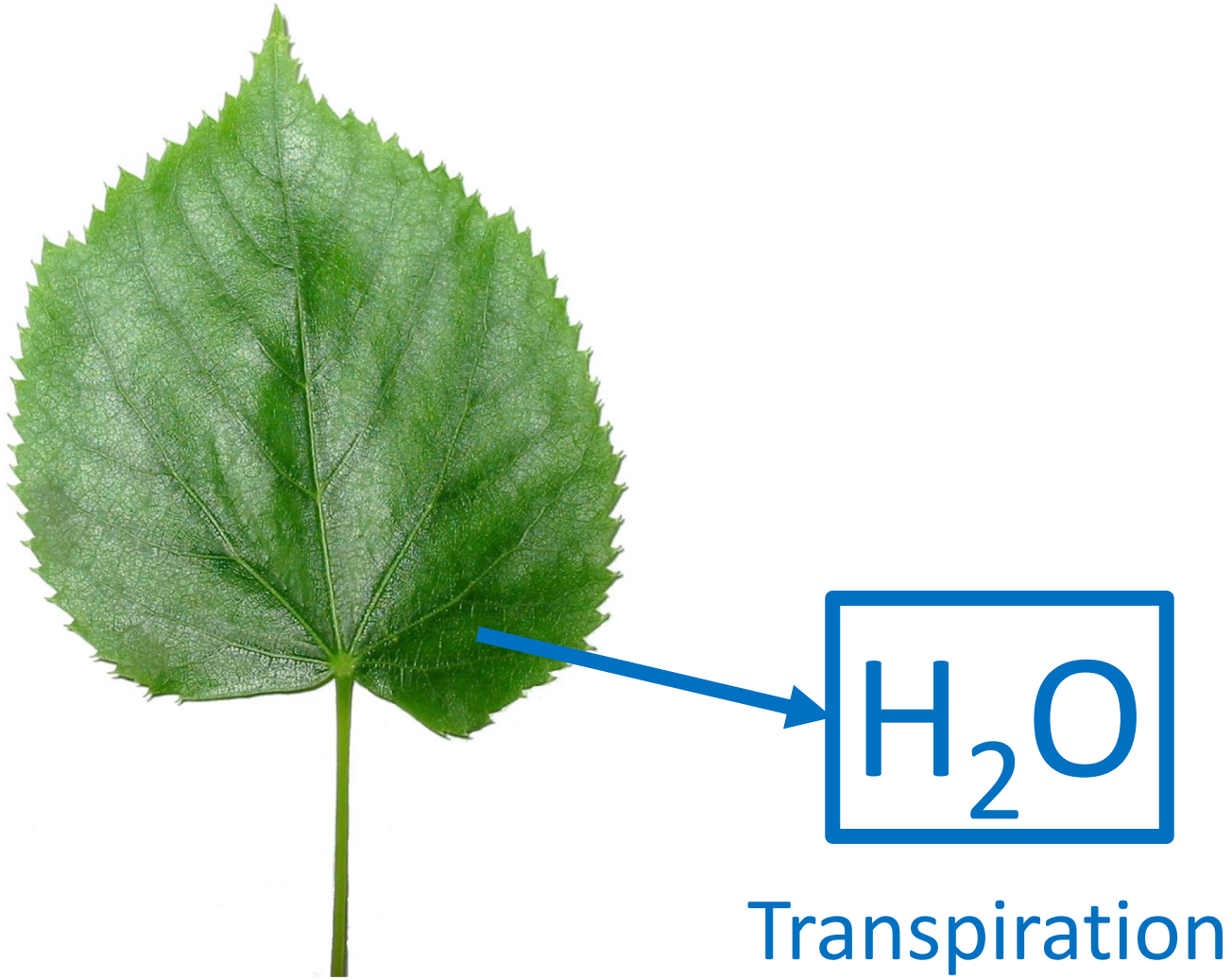
CO_2

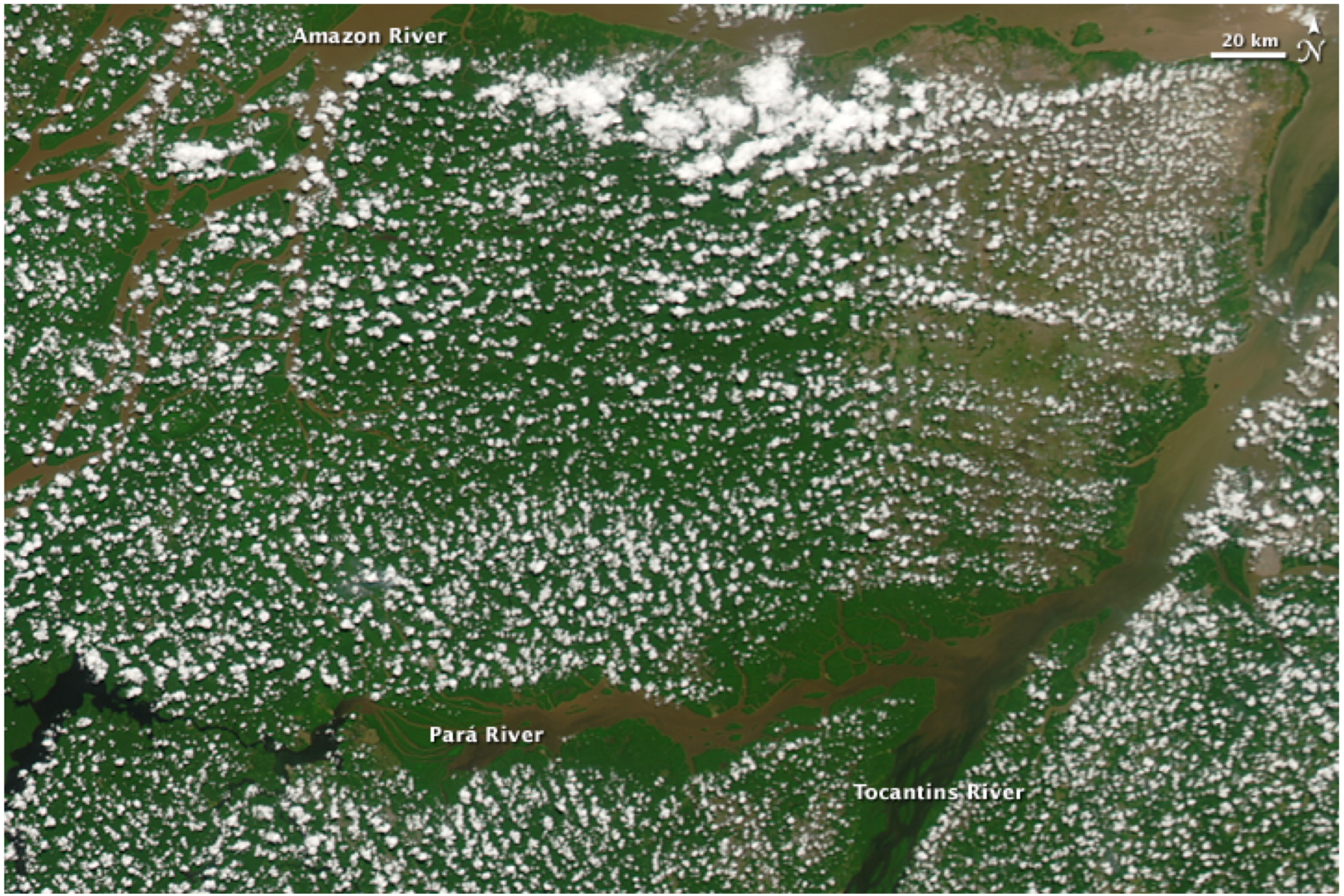
O_2

H_2O

Transpiration

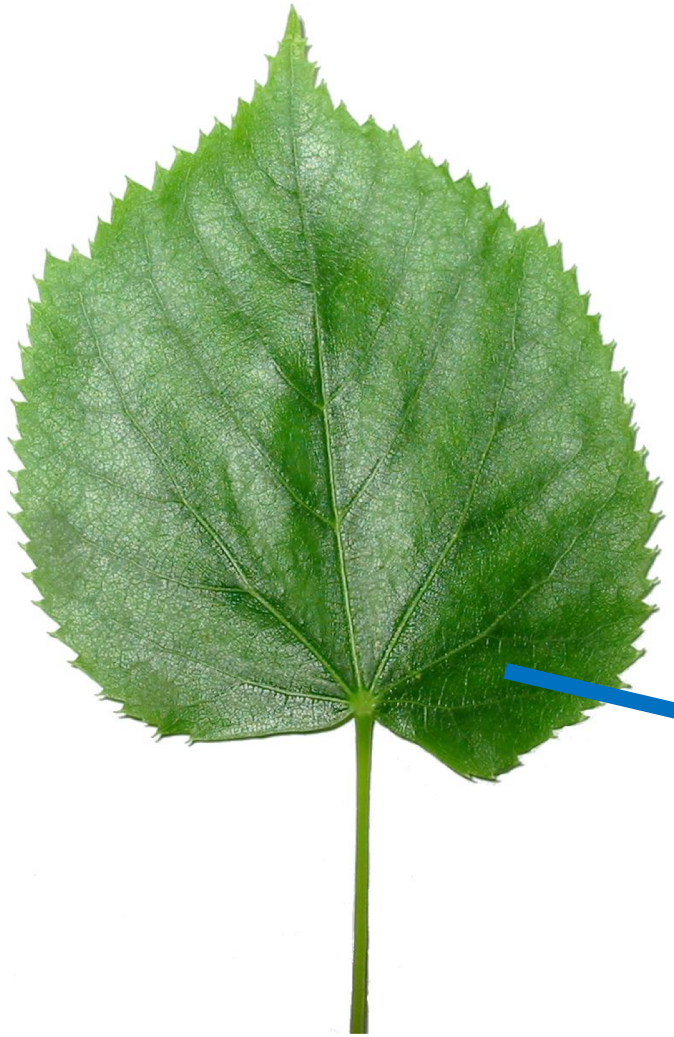
Small groups:
Why do plants do all these physiological processes?
Make a list!


H_2O
Transpiration



NASA

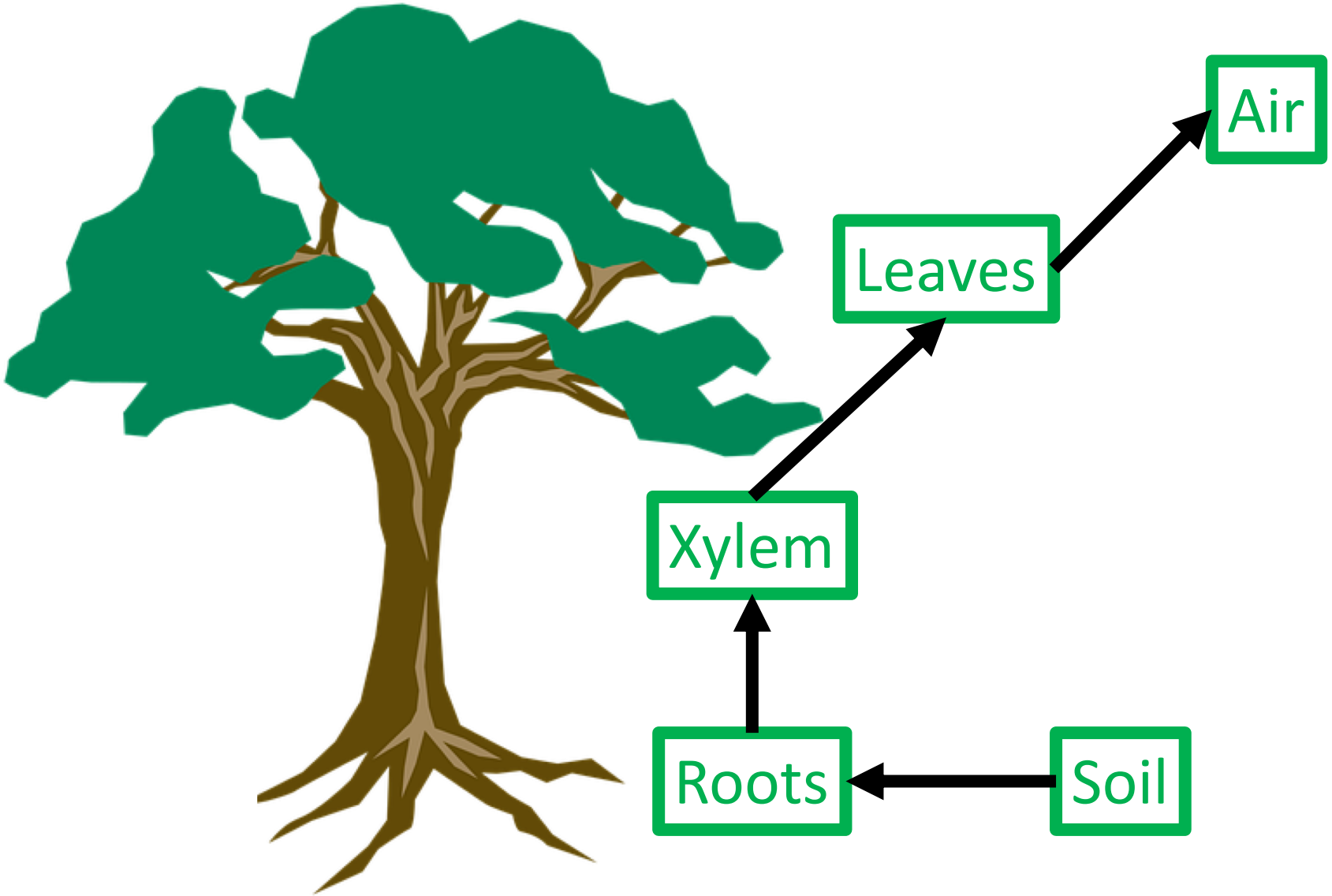
How do plants transpire?



H_2O

Transpiration

Water potential gradients!

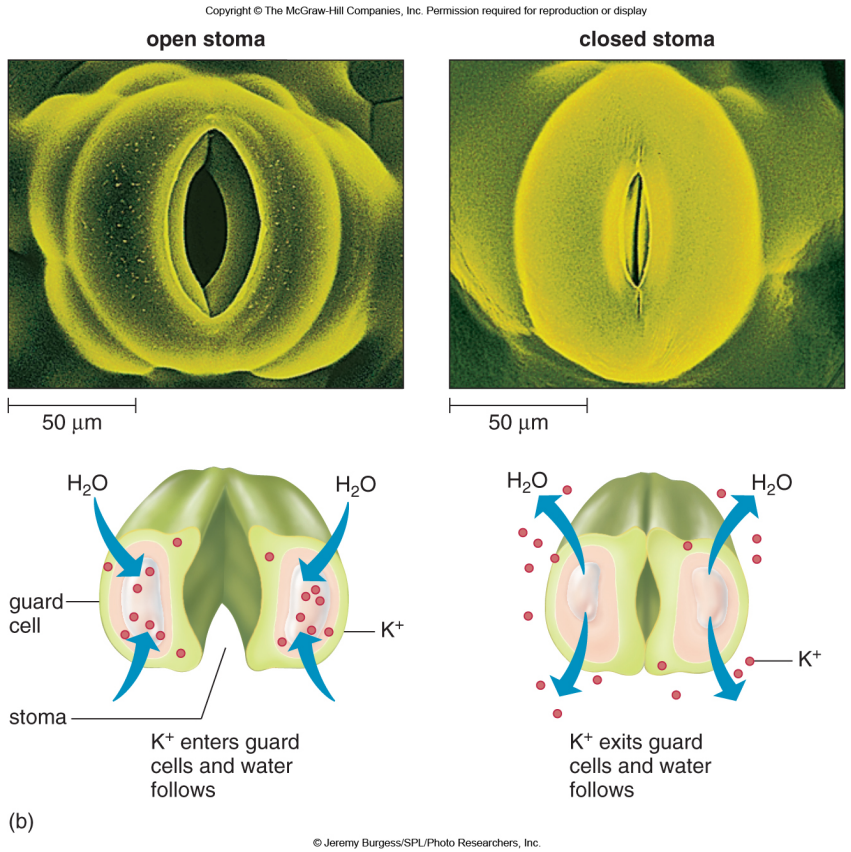


Lowest Ψ (“Dry”)

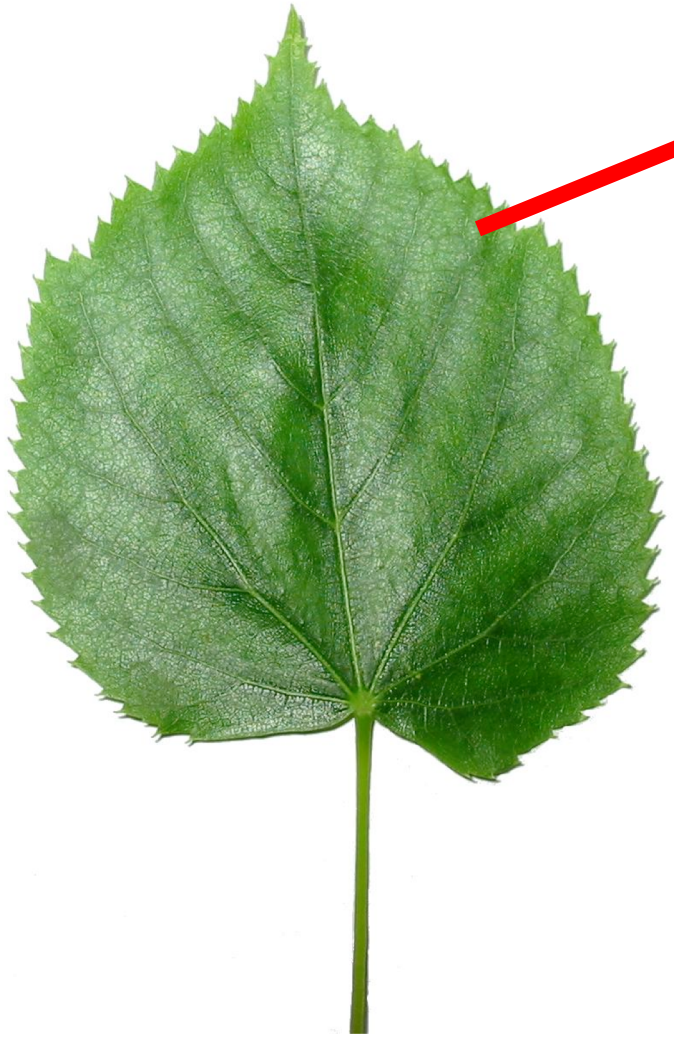
Highest Ψ (“Wet”)

Transpiration regulation: Guard cells

- Create open or closed stomata by changing turgor pressure

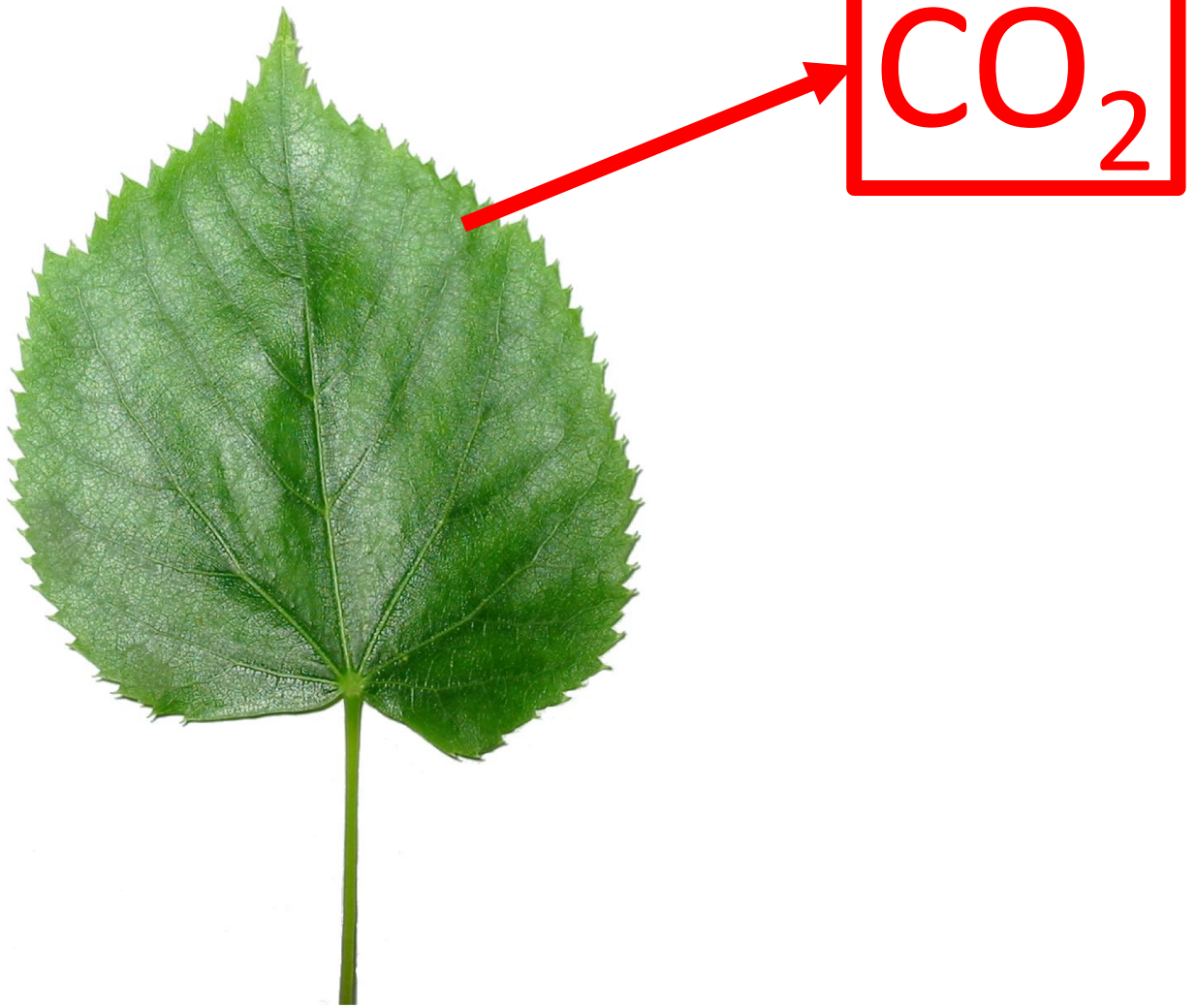


Respiration



CO_2

How do plants respire?



Respiration - the recipe

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

Respiration - the recipe

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

Glucose
(primary substrate)

Respiration - the recipe

Oxygen
(aids efficiency; not always necessary)

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

Glucose
(primary substrate)

Respiration - the recipe

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

Glucose
(primary substrate)

Carbon dioxide + water
(lost)

Respiration - the recipe

Oxygen
(aids efficiency; not always necessary)

Energy!
(primary end product)

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

Glucose
(primary substrate)

Carbon dioxide + water
(lost)

Respiration – Main processes

1. Glycolysis
2. Citric Acid Cycle
3. Electron Transport System

Respiration – Main processes

1. Glycolysis
2. Citric Acid Cycle
3. Electron Transport System

Respiration – Main processes

1. Glycolysis
   - function: make some ATP & substrate for making [x]H
2. Citric Acid Cycle
3. Electron Transport System

Respiration - Glycolysis

- Step 1: “Investment”

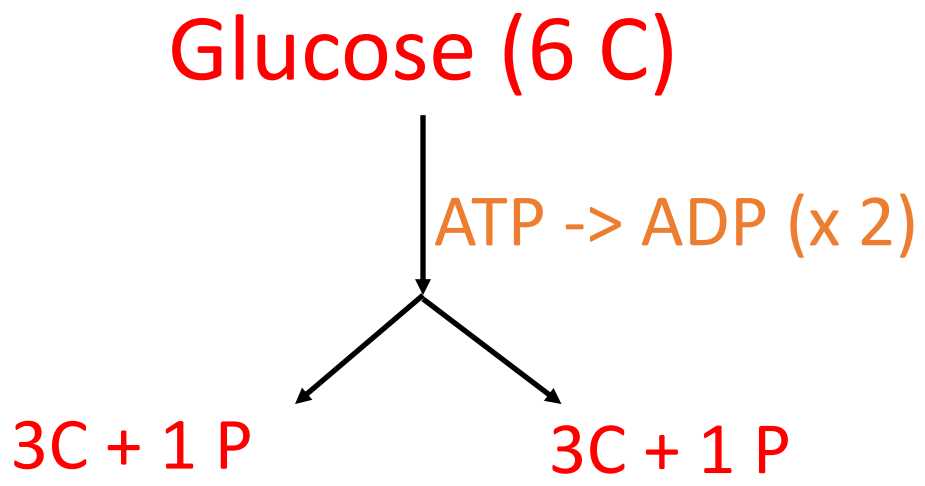
Respiration - Glycolysis

- Step 1: “Investment”
  - Use 2 ATP to create 2 phosphorylated 3-C sugars from glucose

Glucose (6 C)

Respiration - Glycolysis

- Step 1: “Investment”
  - Use 2 ATP to create 2 phosphorylated 3-C sugars from glucose



Respiration - Glycolysis

- Step 2: “Reward”

Respiration - Glycolysis

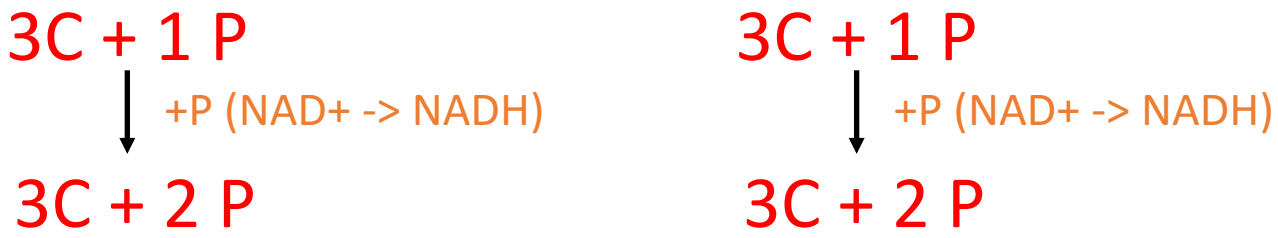
- Step 2: “Reward”
  - Use 2 phosphorylated 3-C sugars to create 4 ATP and Pyruvic acid

3C + 1 P

3C + 1 P

Respiration - Glycolysis

- Step 2: “Reward”
  - Use 2 phosphorylated 3-C sugars to create 4 ATP and Pyruvic acid



Respiration - Glycolysis

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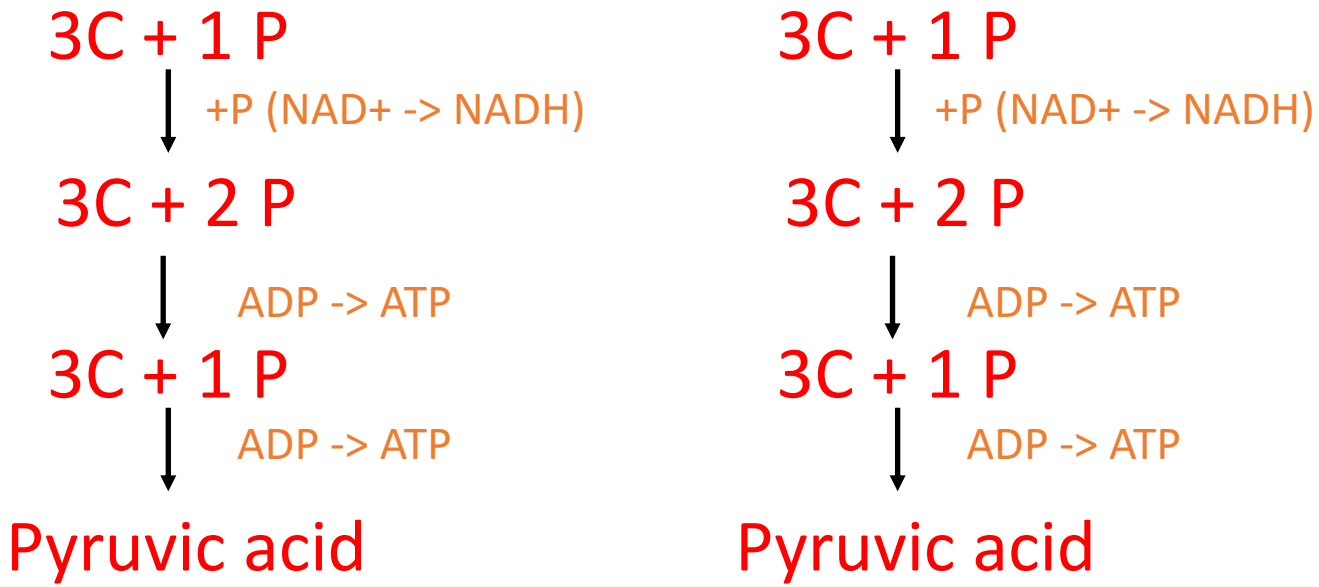


Respiration - Glycolysis

Ingredients

- Glucose
- ATP (2)

Outcomes

- Pyruvic acid
- ATP (4)
- NADH (2)

Respiration – Main processes

1. Glycolysis
2. Citric Acid Cycle
3. Electron Transport System

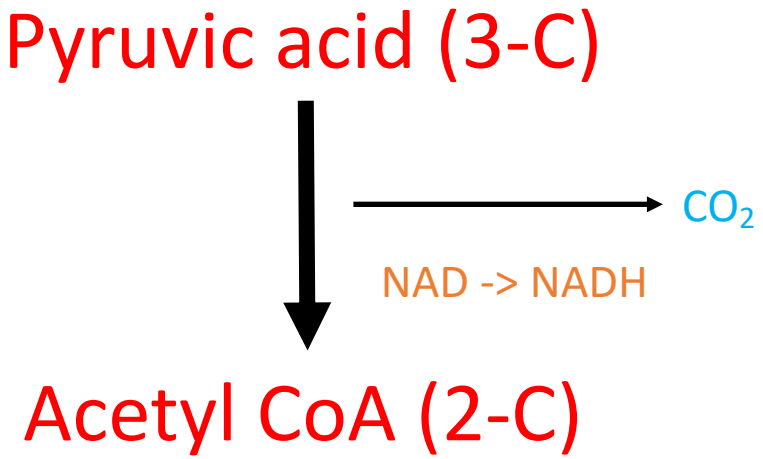
Respiration – Main processes

1. Glycolysis
2. Citric Acid Cycle
   - function: make [x]H
3. Electron Transport System

Respiration – Citric Acid Cycle

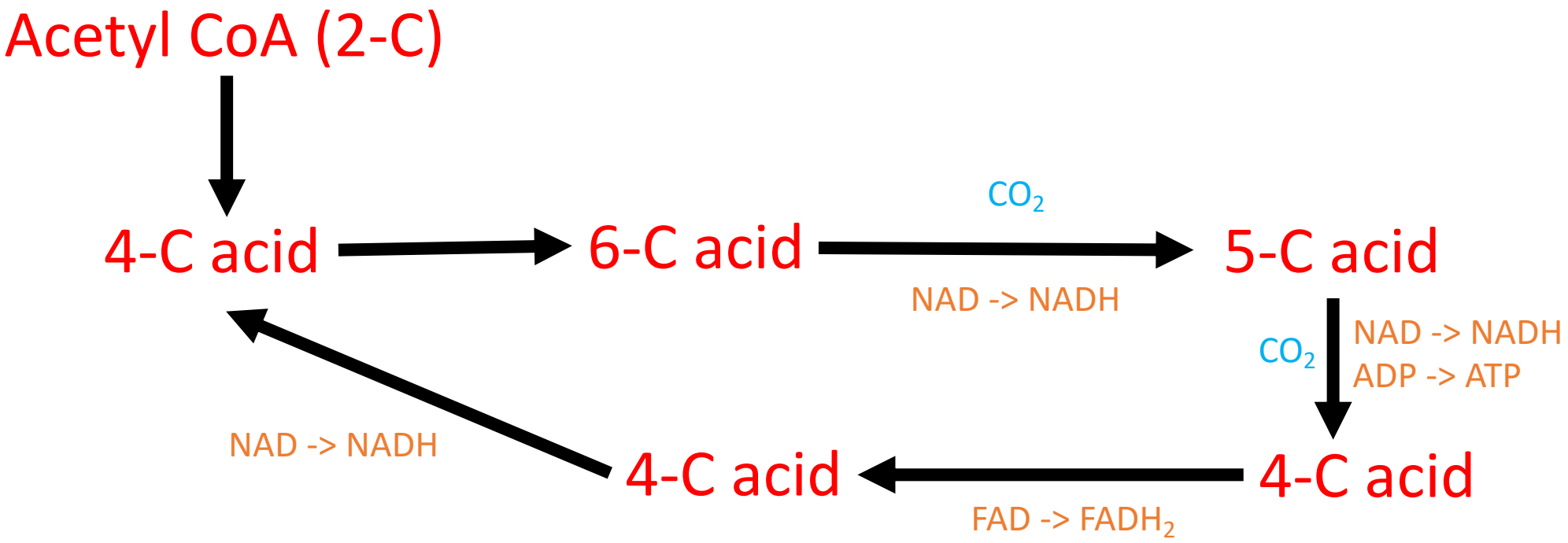
Respiration – Citric Acid Cycle

- Step 1: Production of Acetyl CoA from pyruvic acid (“Transformation”)
  - Produces CO_2 and NADH



Respiration – Citric Acid Cycle

- Step 2: Production of “energy packets” (NADH, $FADH_2$)



Respiration – Citric Acid Cycle

Ingredients

- Pyruvic acid

Outcomes

- NADH
- $FADH_2$
- ATP
- CO_2

Respiration – Main processes

1. Glycolysis
2. Citric Acid Cycle
3. Electron Transport System

Respiration – Main processes

1. Glycolysis
2. Citric Acid Cycle
3. Electron Transport System

- function: make ATP

“Cashing out” - Electron transport system

Respiration – Electron transport system

- Take reduced “energy packets” (NADH, $FADH_2$) and convert ADP to ATP
  - ”Cashing in” electrons for ATP
  - Driven by a series of protein complexes along the mitochondrial membrane

$$NADH + ADP + P + O_2 \rightarrow NAD + H_2O + ATP$$

$$FADH_2 + ADP + P + O_2 \rightarrow FAD + H_2O + ATP$$

Respiration - accounting

Respiration - accounting

1 Glucose => 36 ATP (net)

Respiration - accounting

1 Glucose => 36 ATP (net)

1760 kcal / 1 Glucose

Respiration - accounting

1 Glucose => 36 ATP (net)

1760 kcal / 1 Glucose

19 kcal / 1 ATP

Respiration - accounting

1 Glucose => 36 ATP (net)

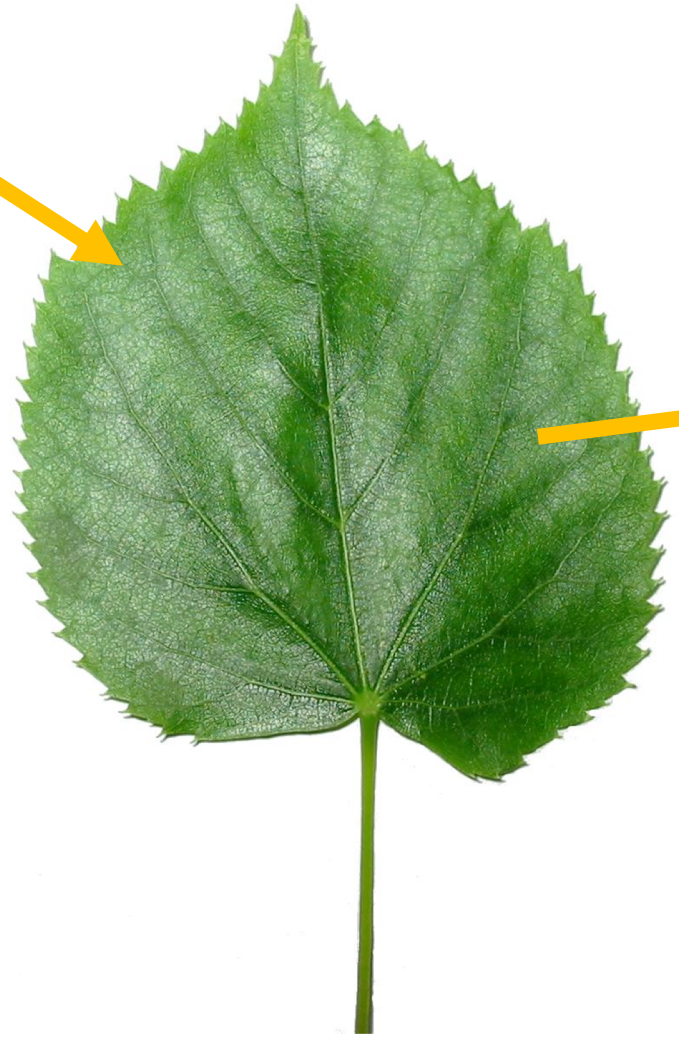
1760 kcal / 1 Glucose

19 kcal / 1 ATP

(19 * 36) / 1760 = 39% total efficiency

Photosynthesis

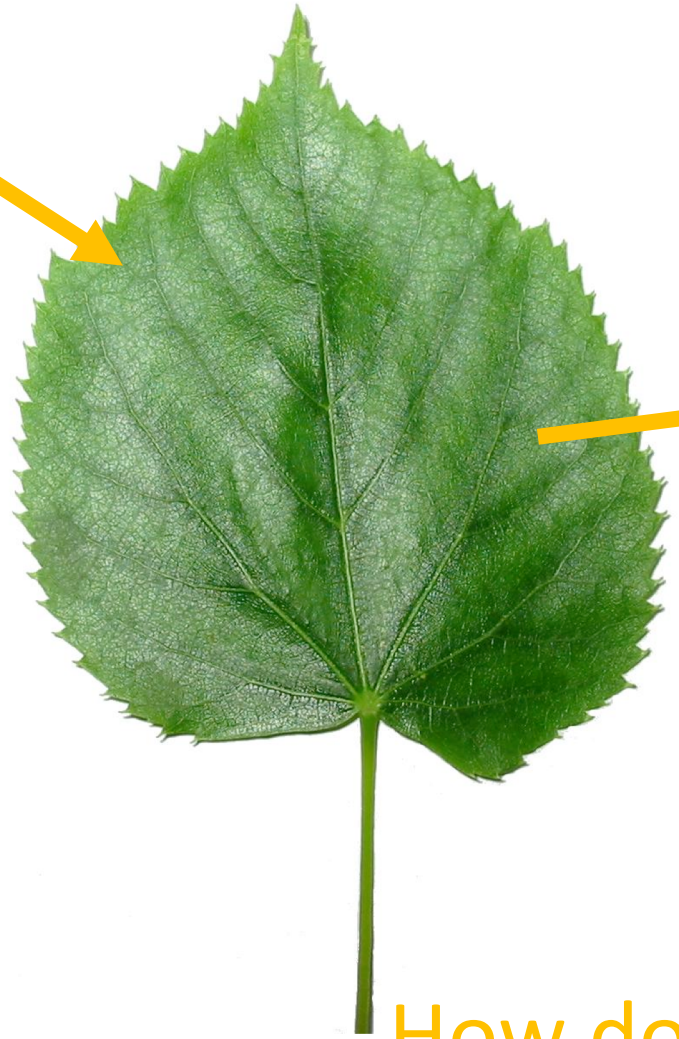
CO_2



O_2

Photosynthesis

CO_2



O_2

How do plants photosynthesize?

Photosynthesis – the recipe

Chlorphyll

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

Enzymes

Photosynthesis – the recipe

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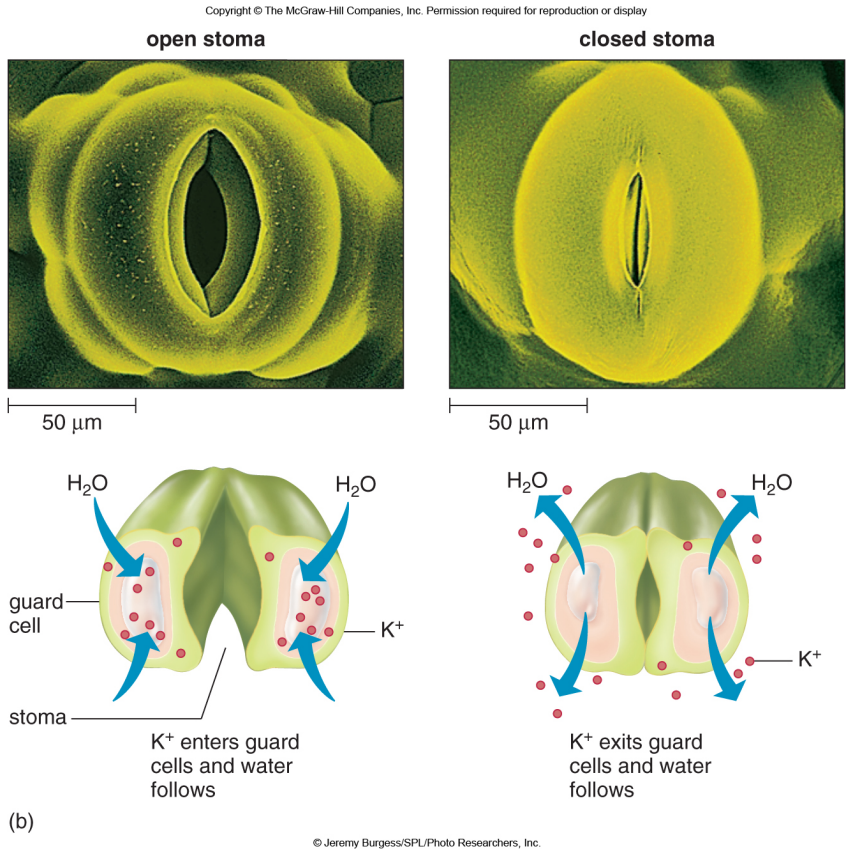
Enzymes

Photosynthesis – CO_2

Photosynthesis – CO_2

- CO_2 diffuses into plant leaves through stomata
- Ultimately reaches the chloroplasts
- Function: provides C



Photosynthesis – CO_2

- 1 acre corn plot takes up > 5000 lbs of CO_2 a year

Photosynthesis – the recipe

Chlorophyll

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

Enzymes

Photosynthesis - Water

- Solution for CO_2 to dissolve
- Source of the electrons involved

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

Photosynthesis – the recipe

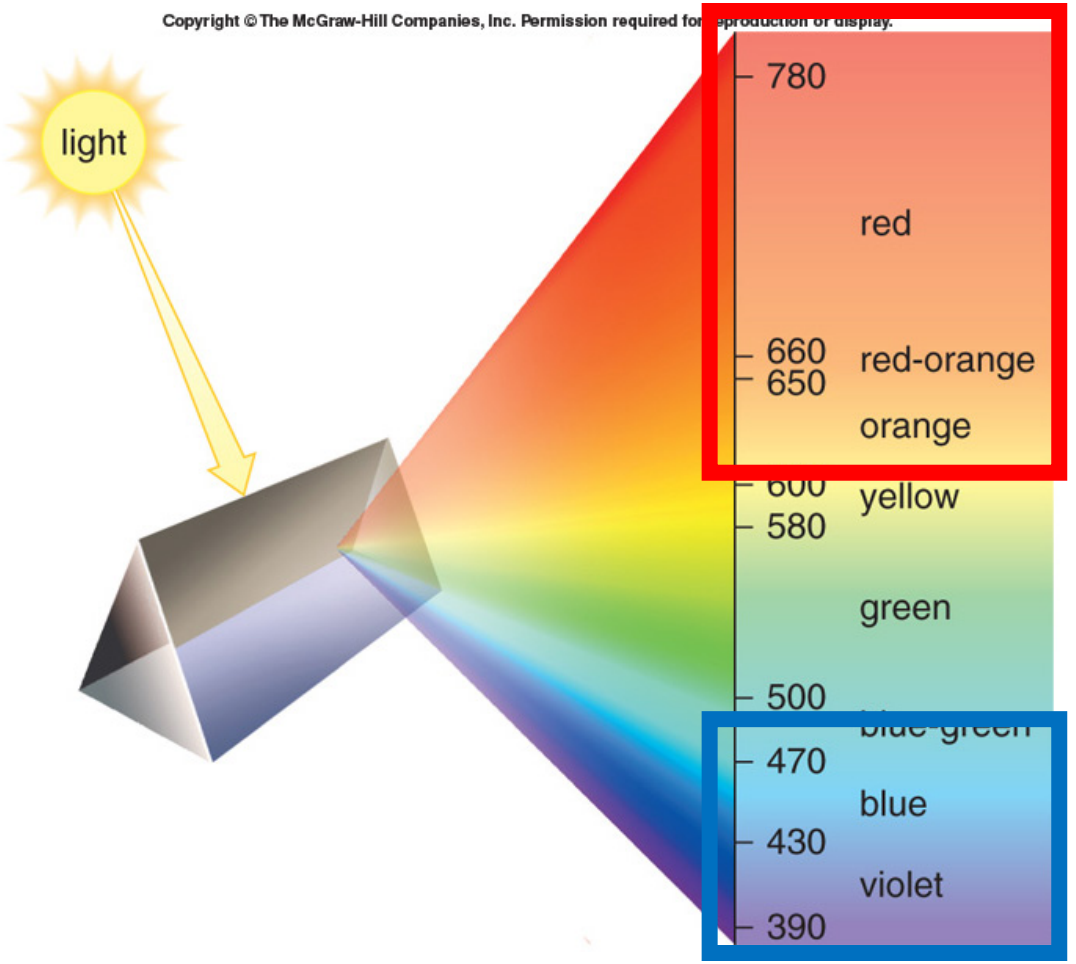
Chlorophyll

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

Enzymes

Photosynthesis - Light

- Provides the energy for photosynthesis
- Absorbed in the red and blue portion of the spectrum



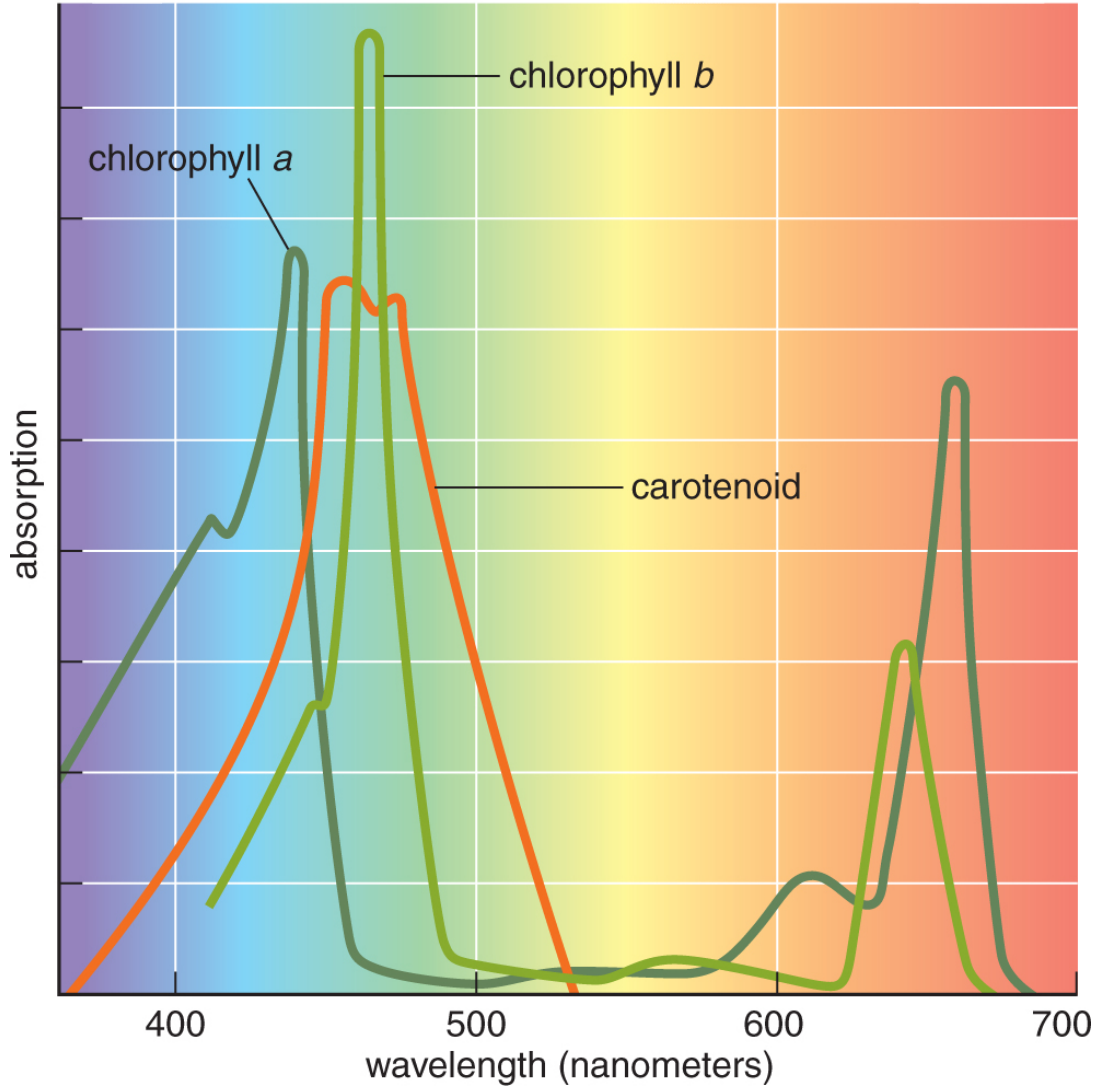
Photosynthesis – the recipe

Chlorophyll

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

Photosynthesis - Chlorophyll

- Molecules that absorb light
- Come in different flavors
  - Absorb in different portions of the spectrum



Photosynthesis – the recipe

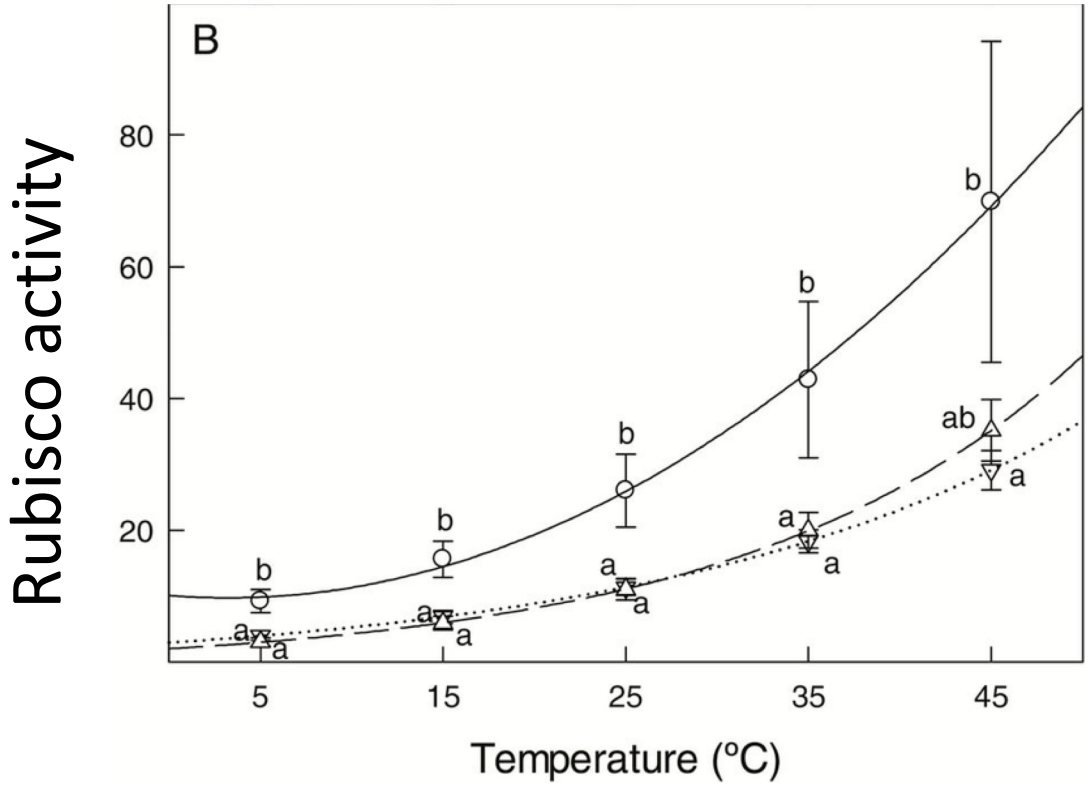
Chlorphyll

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

Enzymes

Photosynthesis - enzymes

- Function: to catalyze the reactions
- Very temperature sensitive
- Example --> Rubisco



Galmes et al. (2016)

Photosynthesis – the recipe

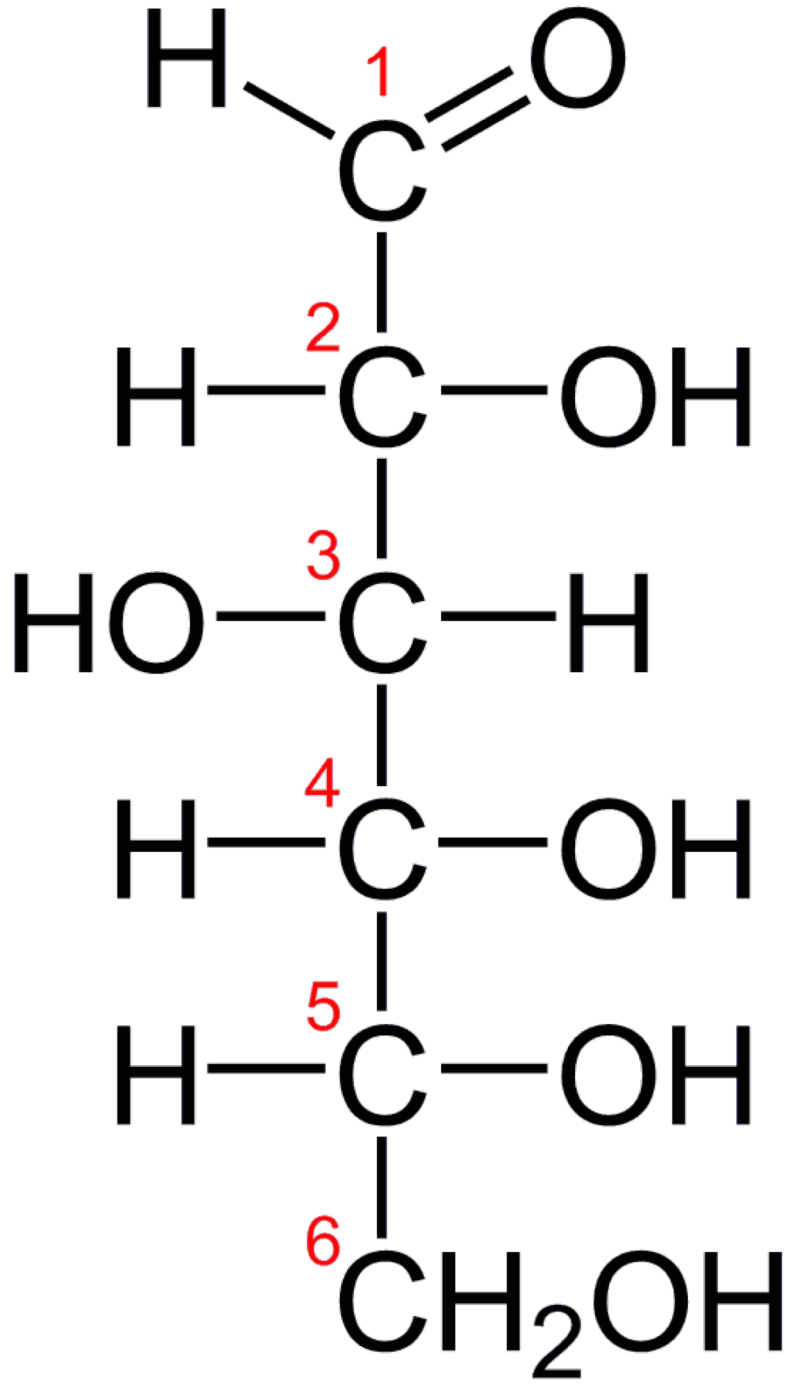
Chlorphyll

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

Enzymes

Photosynthesis - glucose

- Not actually the first product!
- Functions:
  1. Produce energy during respiration
  2. Lipid and starch formation
  3. Plant structure formation



Photosynthesis – the recipe

Chlorphyll

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

Enzymes

Photosynthesis – Oxygen and Water

- By products
- May be recycled or emitted as gas through leaves

Two phases of photosynthesis

1. Light-dependent reactions
2. Light-independent reactions
   (aka Dark reactions)

Light-dependent reactions

Light-dependent reactions - Steps

1. Photons of light are absorbed
2. Electrons are excited! (boosted to higher energy level)
3. Water is split
   - Releases electrons, hydrogen ions, and oxygen gas
4. Electrons flow down electron transport chain
5. ATP and NADPH are produced (stored energy)

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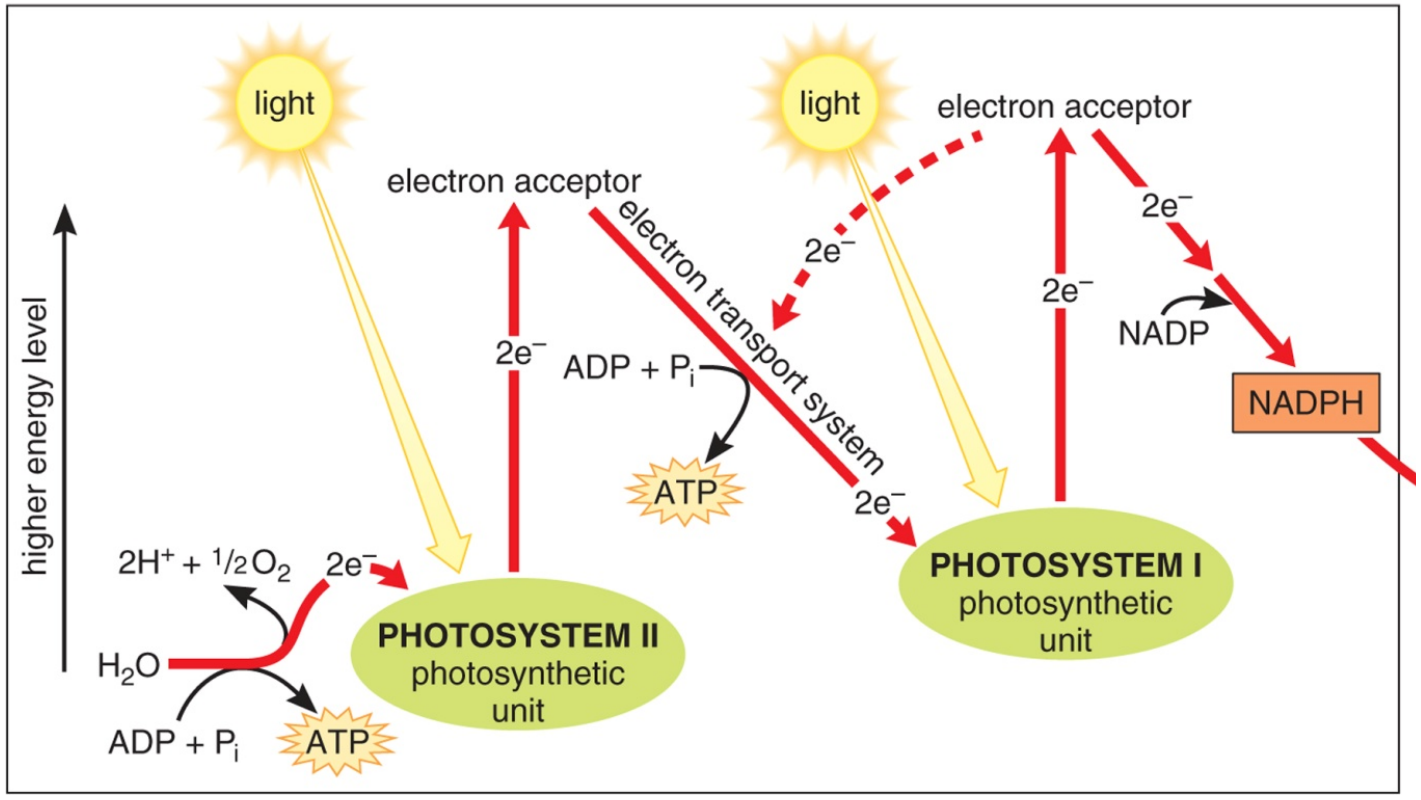
Light-dependent reactions

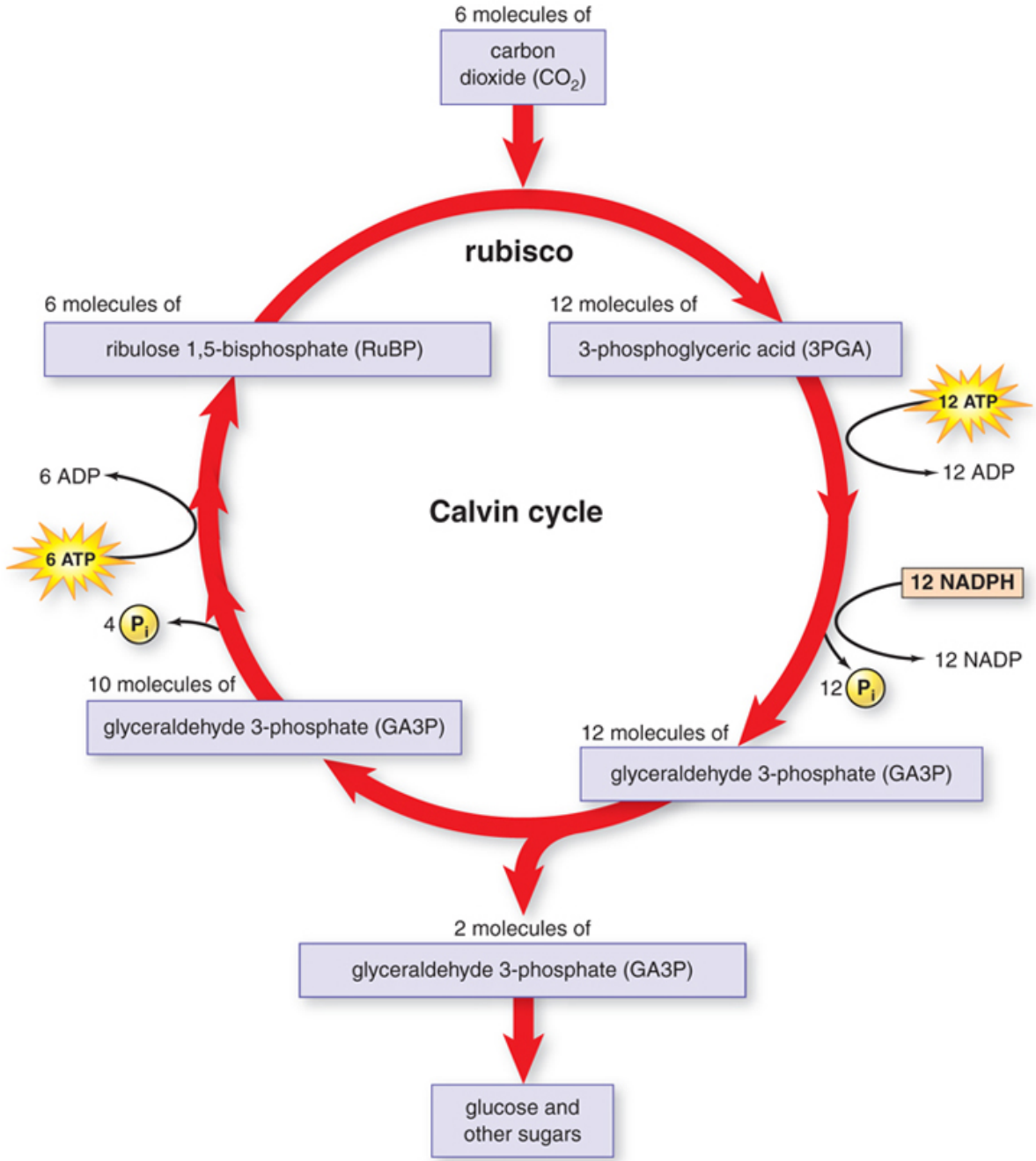
1. Ingredients
   - Light
   - H2O
   - NADP+
   - ADP
   - P
2. Outcomes
   - ATP
   - NADPH
   - O2
   - H+

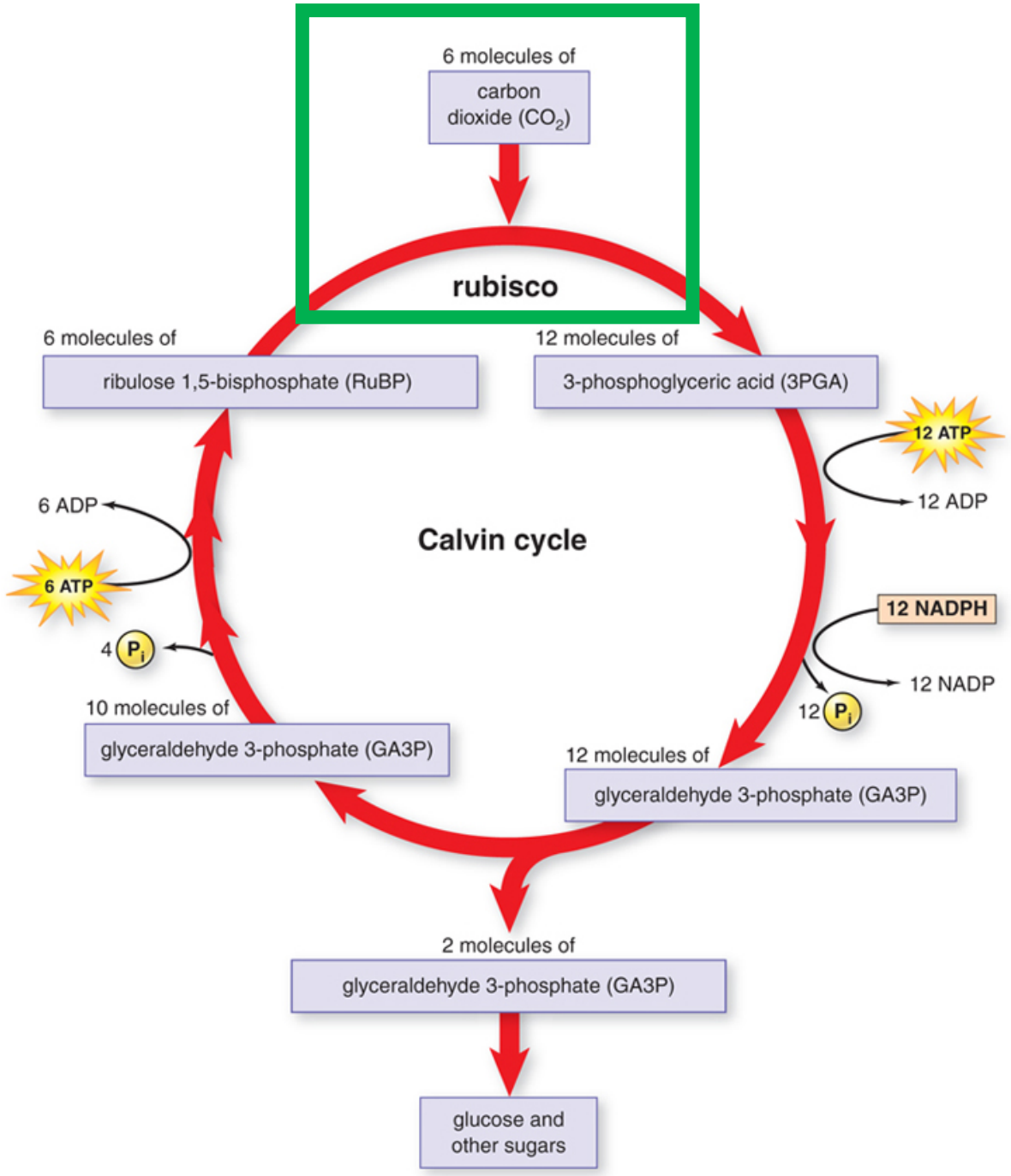


Light-independent reactions (“dark reactions”)

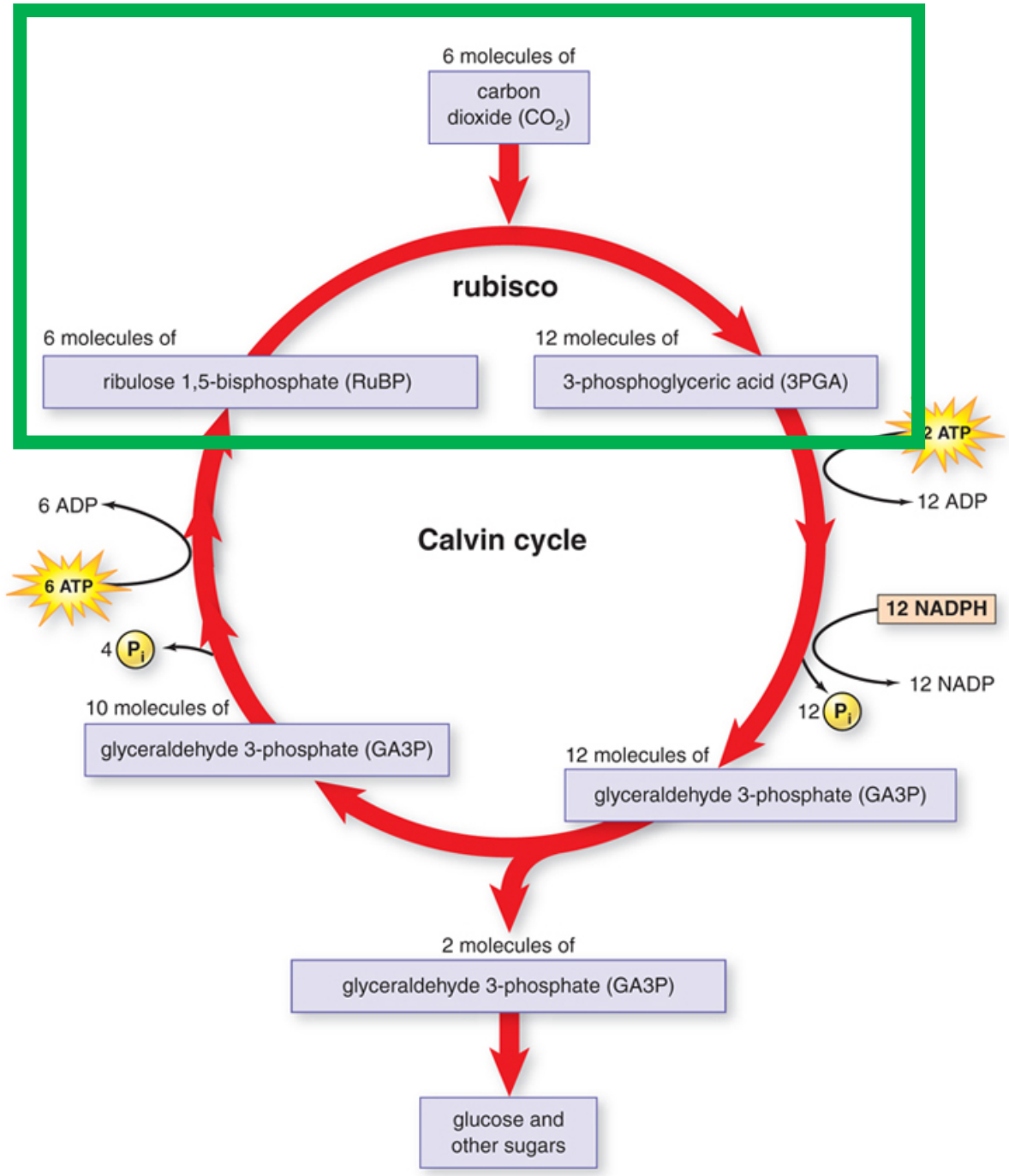
Light-independent reactions - Steps

1. Take ATP and NADPH from light-dependent reactions
2. Convert CO_2 into sugars
3. Restart the cycle

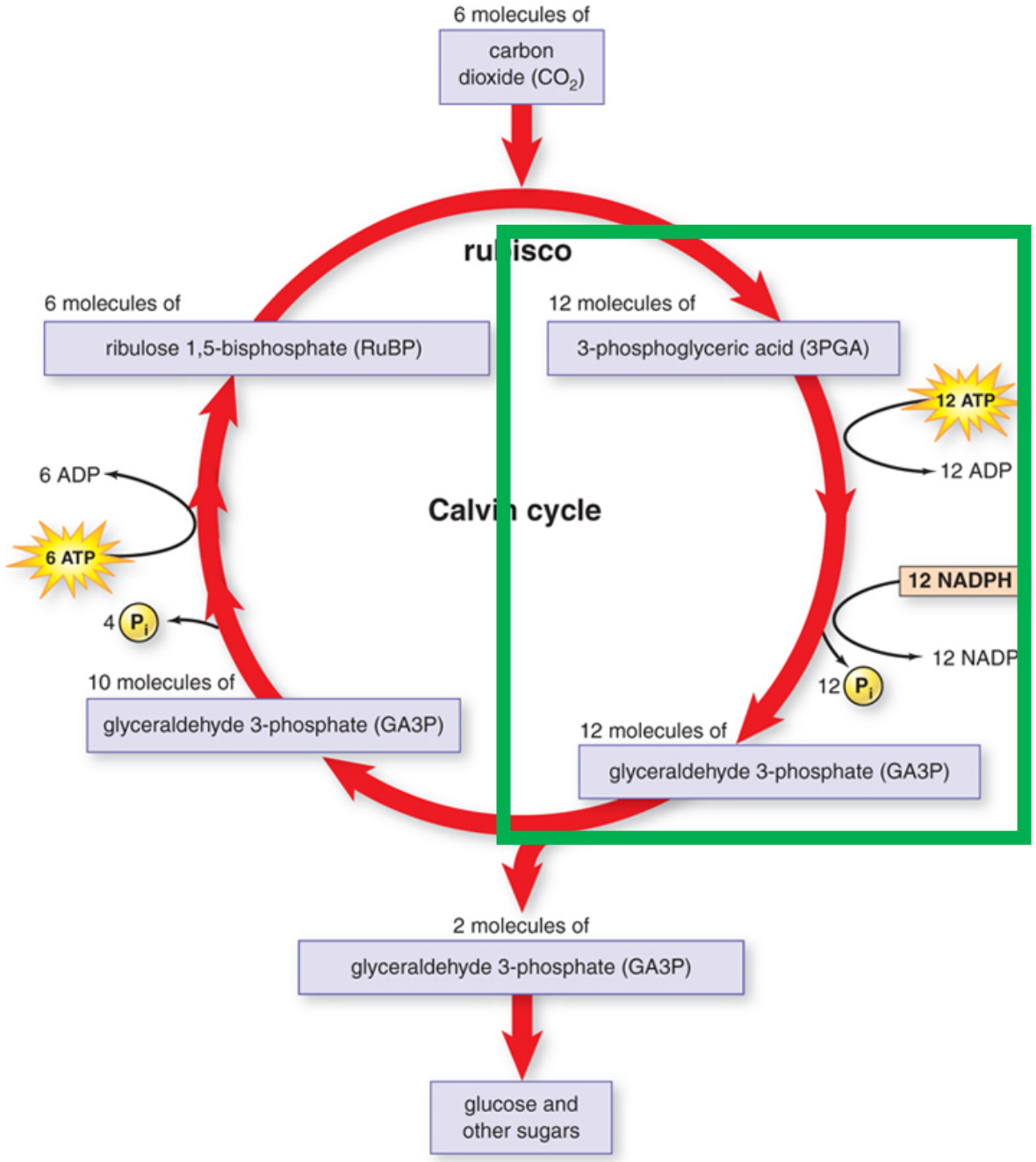

6 molecules of
carbon dioxide (CO_2)
rubisco
6 molecules of
ribulose 1,5-bisphosphate (RuBP)
12 molecules of
3-phosphoglyceric acid (3PGA)
12 ATP
12 ADP
6 ADP
Calvin cycle
6 ATP
12 NADPH
4 P_i
12 NADP
12 P_i
10 molecules of
glyceraldehyde 3-phosphate (GA3P)
12 molecules of
glyceraldehyde 3-phosphate (GA3P)
2 molecules of
glyceraldehyde 3-phosphate (GA3P)
glucose and other sugars



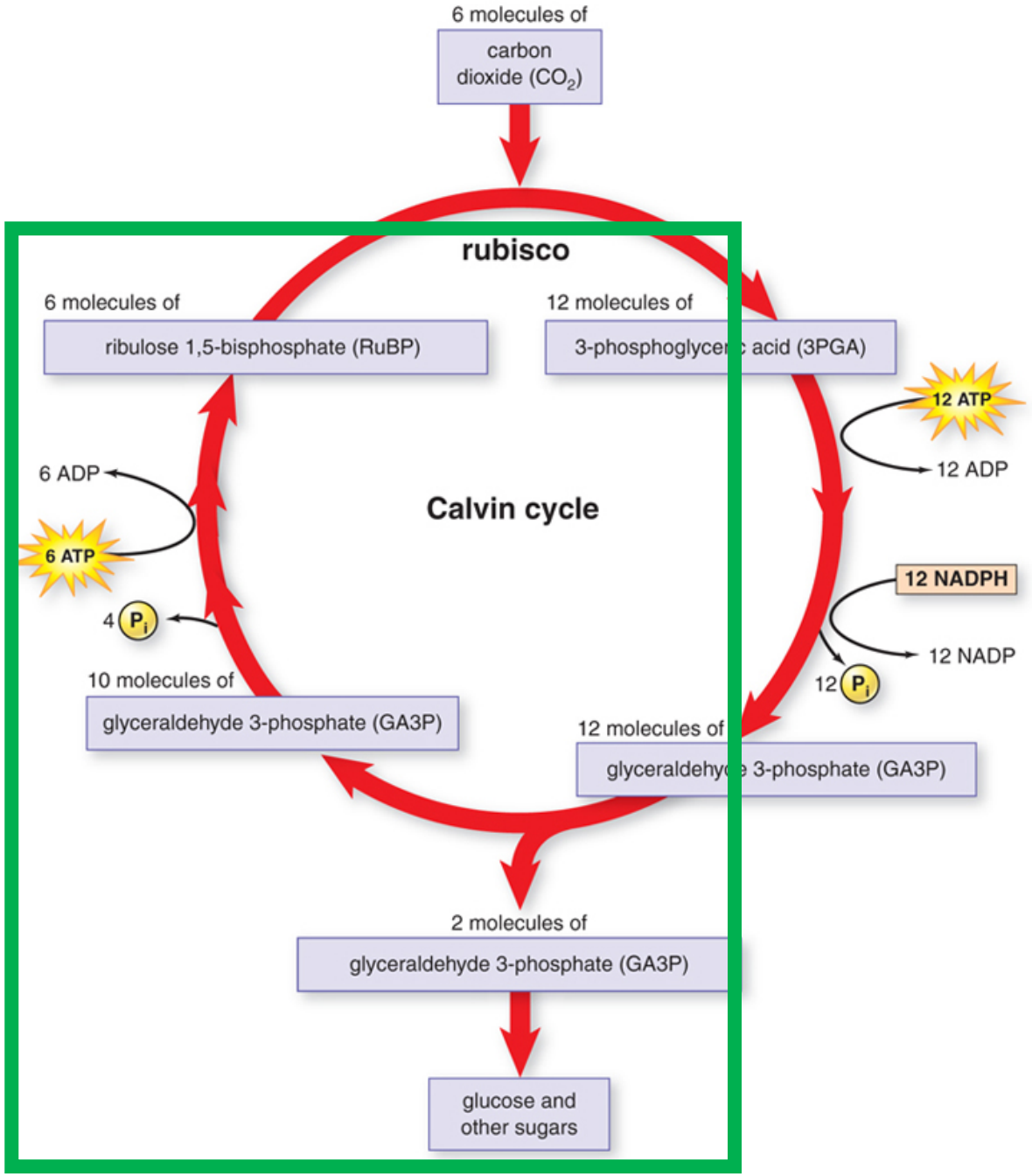
1. Rubisco grabs CO_2 (1 carbon)



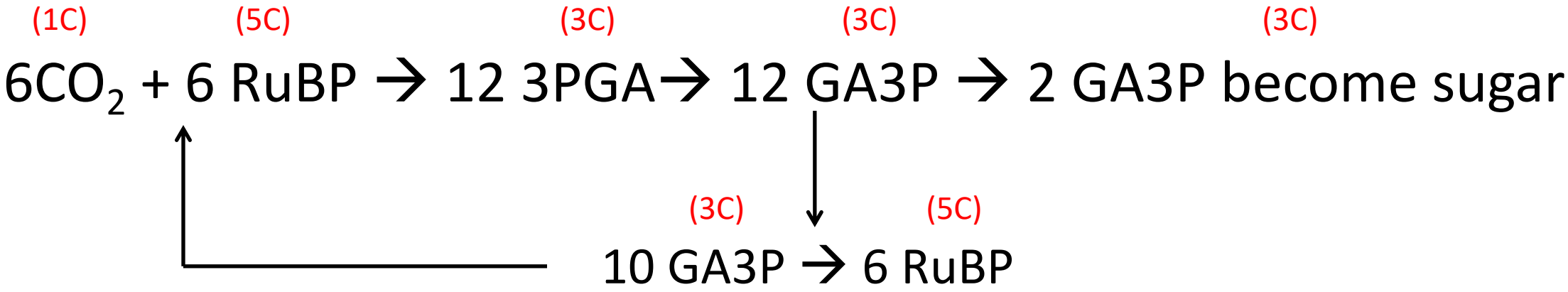
2. CO_2 (1 carbon) combines with RuBP (5 carbon)



2. GA3P (3 carbon) is produced

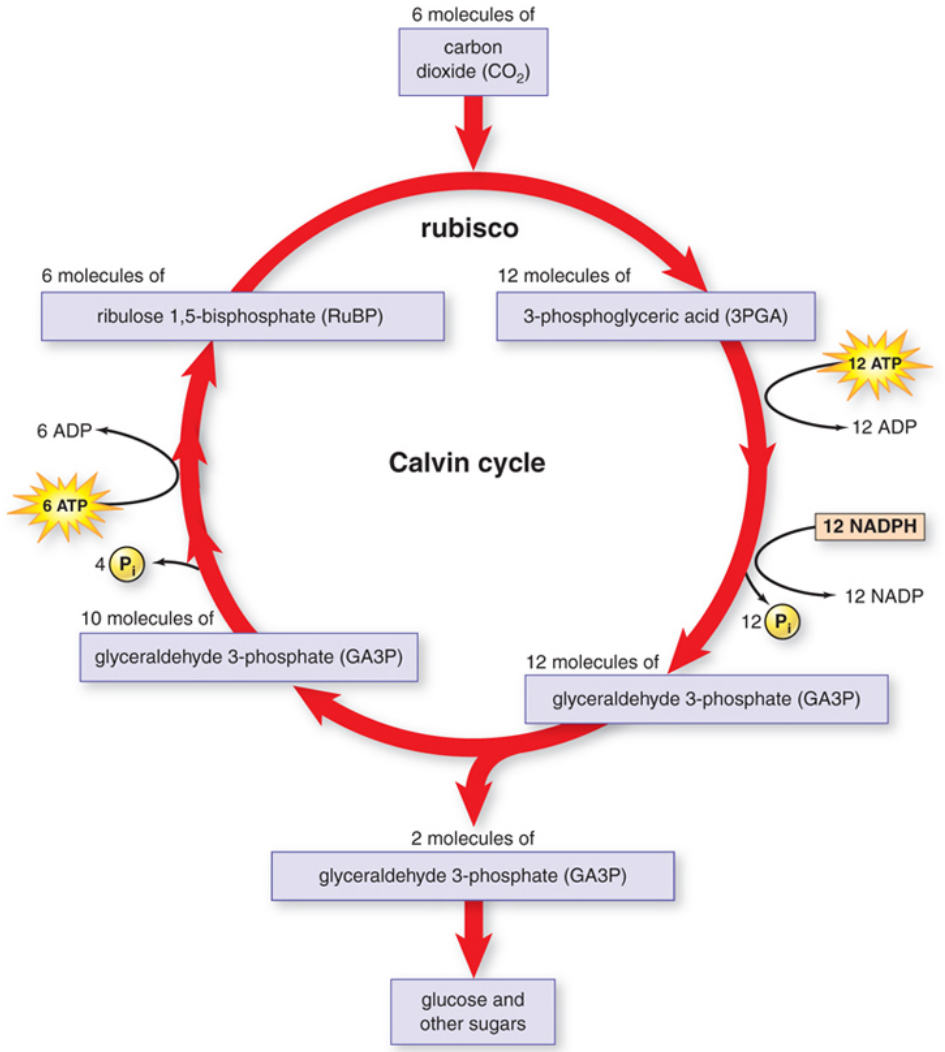


3. Some GA3P (3 carbon) are used for sugars, others restart the chain

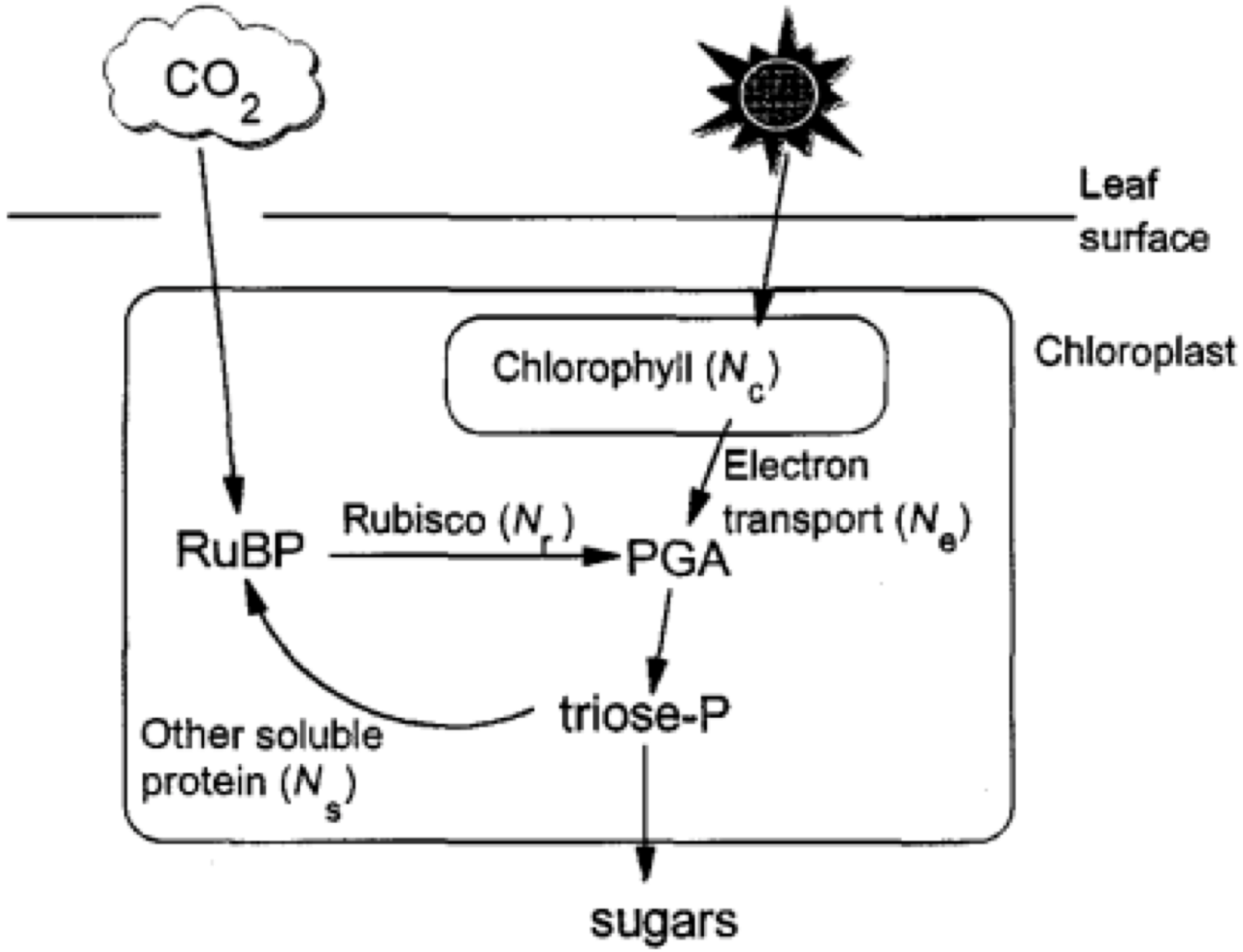

(1C)
(5C)
(3C)
(3C)
(3C)
6CO2 + 6 RuBP → 12 3PGA → 12 GA3P → 2 GA3P become sugar
(3C)
(5C)
10 GA3P → 6 RuBP

Light-independent reactions

1. Ingredients
   - CO_2
   - RuBP
   - NADPH
   - ATP
2. Outcomes
   - ADP
   - NADP
   - Sugars
   - RuBP



All together now!



Medlyn 1996

Photorespiration

Photorespiration

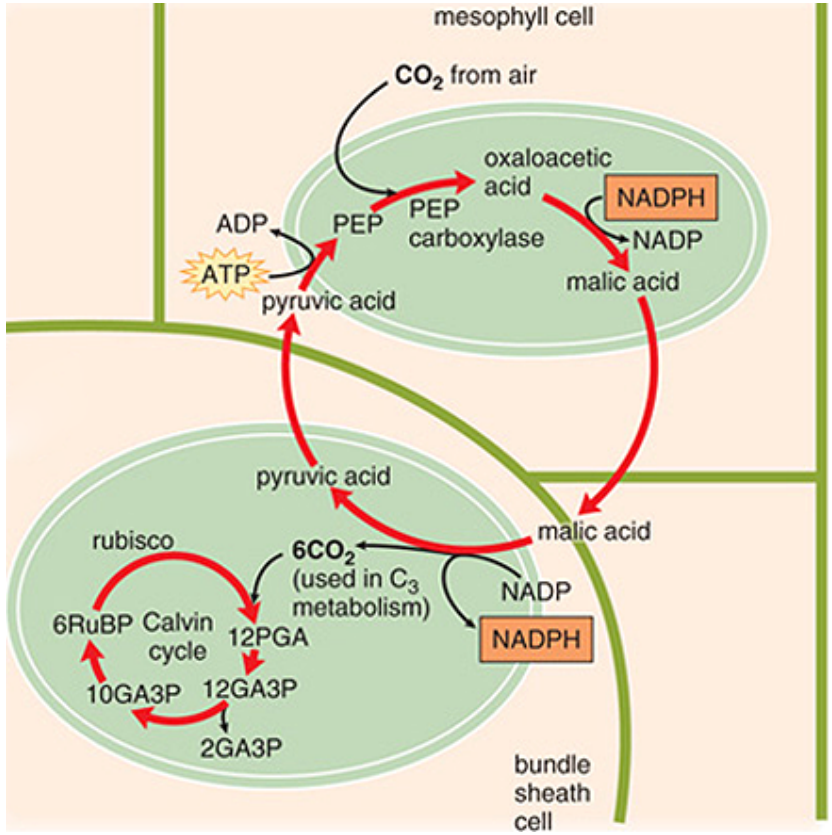
- Rubisco : RibUlose – 1,5 – BISphosphate Carboxylase and Oxygenase
- Catalyzes CO_2 and O_2
- Catalyzing O_2 leads to “wasteful” respiration (loss of CO_2)
- Increases as O_2 increases
- Increases with temperature

3 types of photosynthesis systems

- C_3: what we already covered
  - Most plants
- C_4: Separate carbon acquisition and sugar creation in space
  - Typically grasses
- CAM: Separate carbon acquisition and sugar creation in time
  - E.g., Cacti

C4 photosynthesis

- PEP carboxylase captures CO_2 and creates a 4 carbon sugar in mesophyll
- Moves sugar to bundle sheath, where CO2 is removed
  - Bundle sheath cells surround veins
- Calvin cycle progresses as normal
- “Costs” two extra ATPs



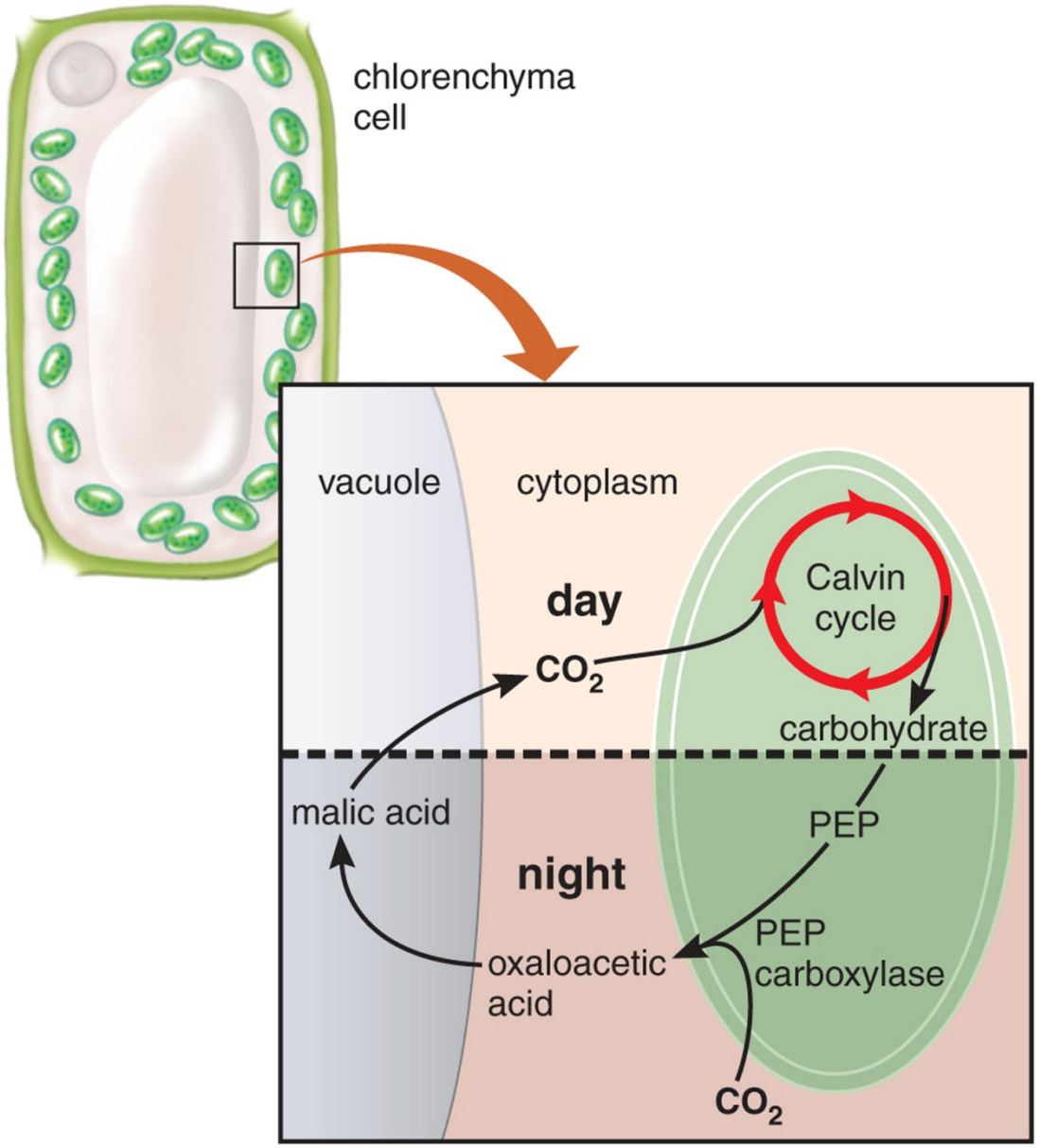
C4 photosynthesis - benefits

PEP carboxylase is not an oxygenase

- Good at capturing CO2
- Good in low CO2 environments
- Good in hot, dry environments
  - Can close stomata

CAM photosynthesis

- Opens stomata during the night
  - PEP carboxylase captures CO_2 and creates a 4 carbon sugar
- Closes stomata during the day
  - Calvin cycle

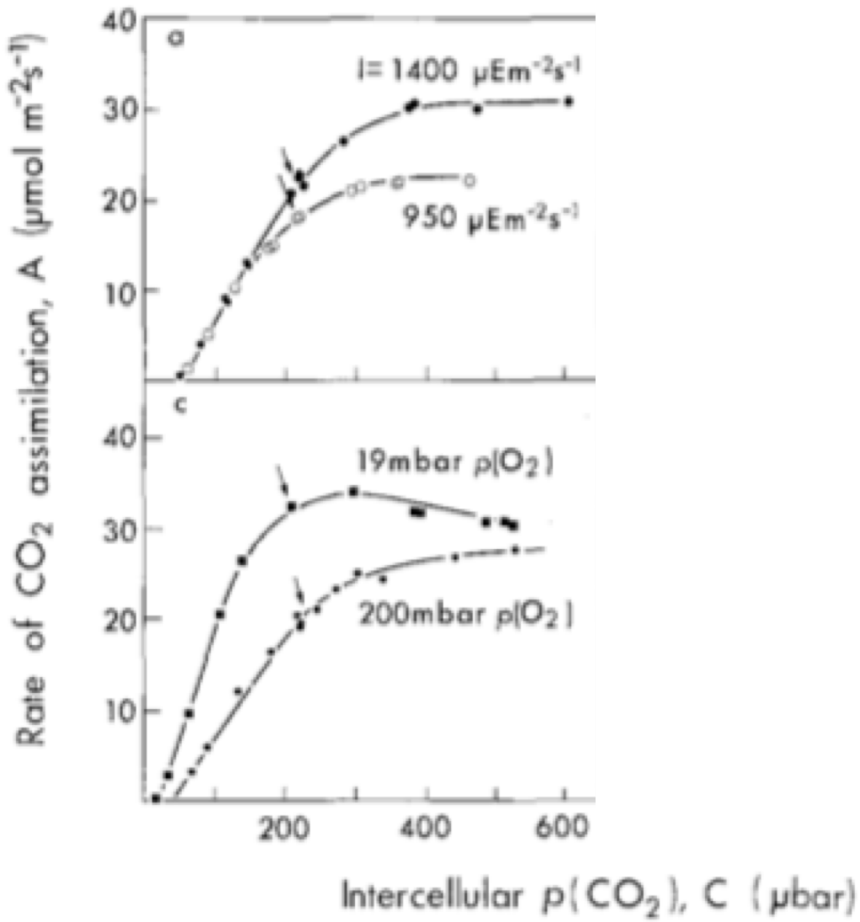


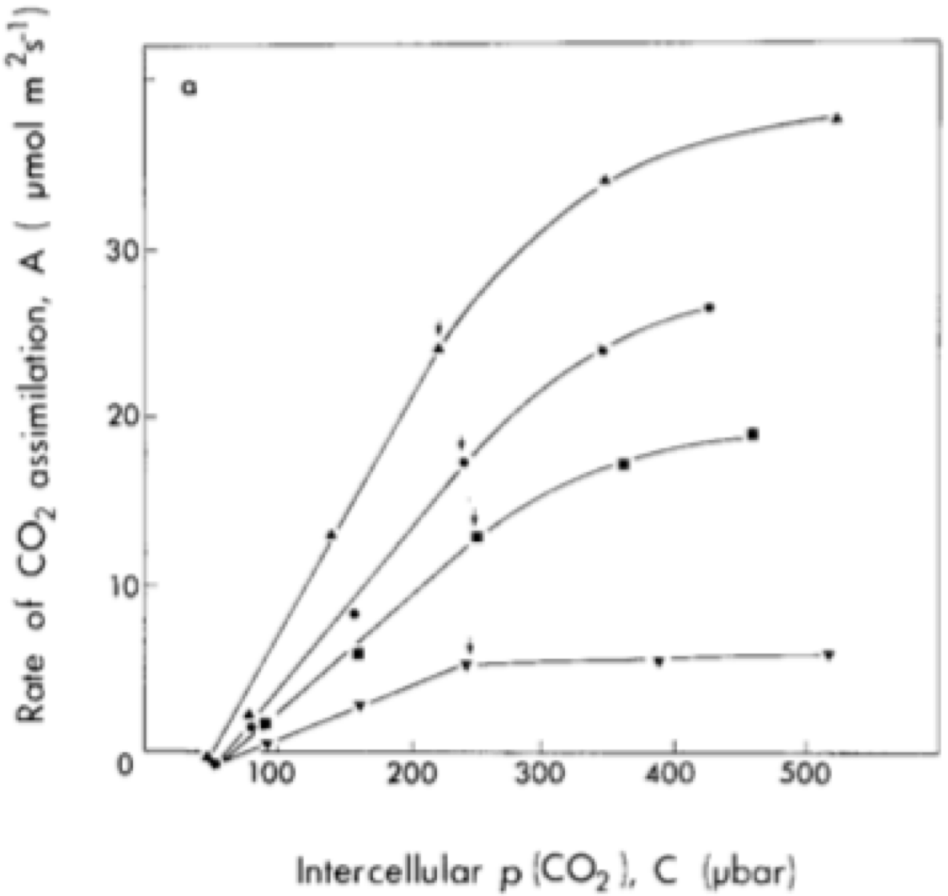
How is (C3) photosynthesis altered by the environment?

Von Caemmerer and Farquhar (1981)

Von Caemmerer and Farquhar – main points

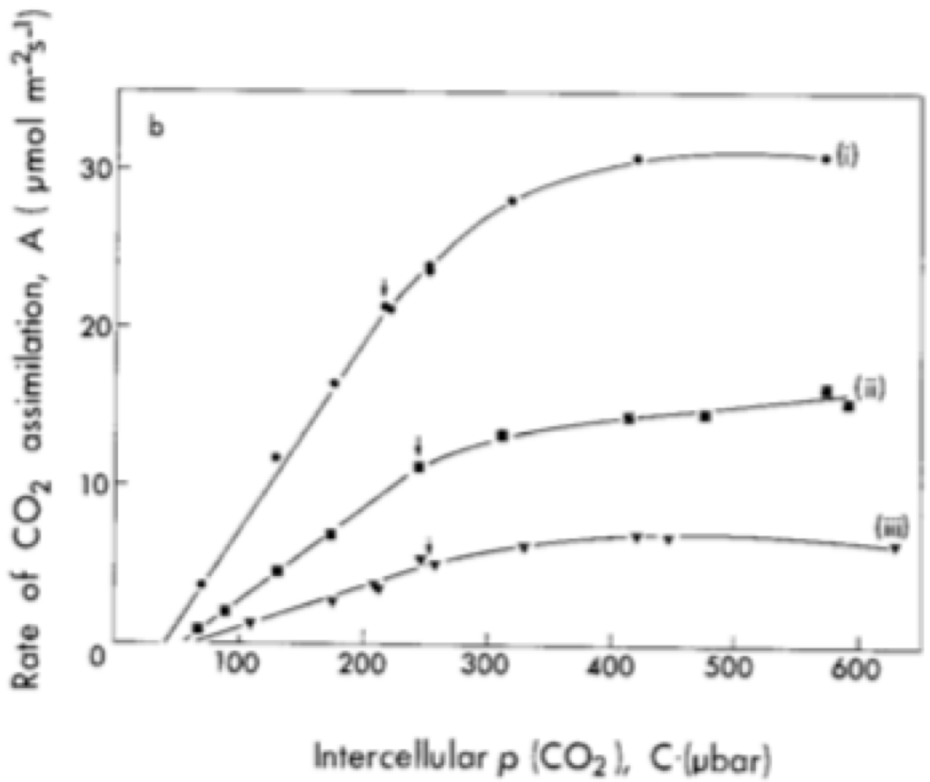
- Response of photosynthesis to environmental factors differs at low and high CO2
- Processes limiting photosynthesis differ at low and high CO2
- At low CO2, photosynthesis is limited by Rubisco carboxylation
- At high CO2, photosynthesis is limited by RuP2 regeneration
- Rates of biophysical processes can be extracted from gas exchange data and these match in vitro measurements
- Long-term response differs from the short-term response


a
I= 1400 µEm⁻²s⁻¹
950 µEm⁻²s⁻¹
c
19mbar p(O2)
200mbar p(O2)
40
30
20
10
200
400
600
Rate of CO2 assimilation, A (µmol m⁻²s⁻¹)
Intercellular p(CO2), C (µbar)


a
Rate of CO_2 assimilation, A (µmol $m^{-2}s^{-1}$)
0
10
20
30
100
200
300
400
500
Intercellular p (CO_2), C (µbar)

High N

Low N



High light

Low light