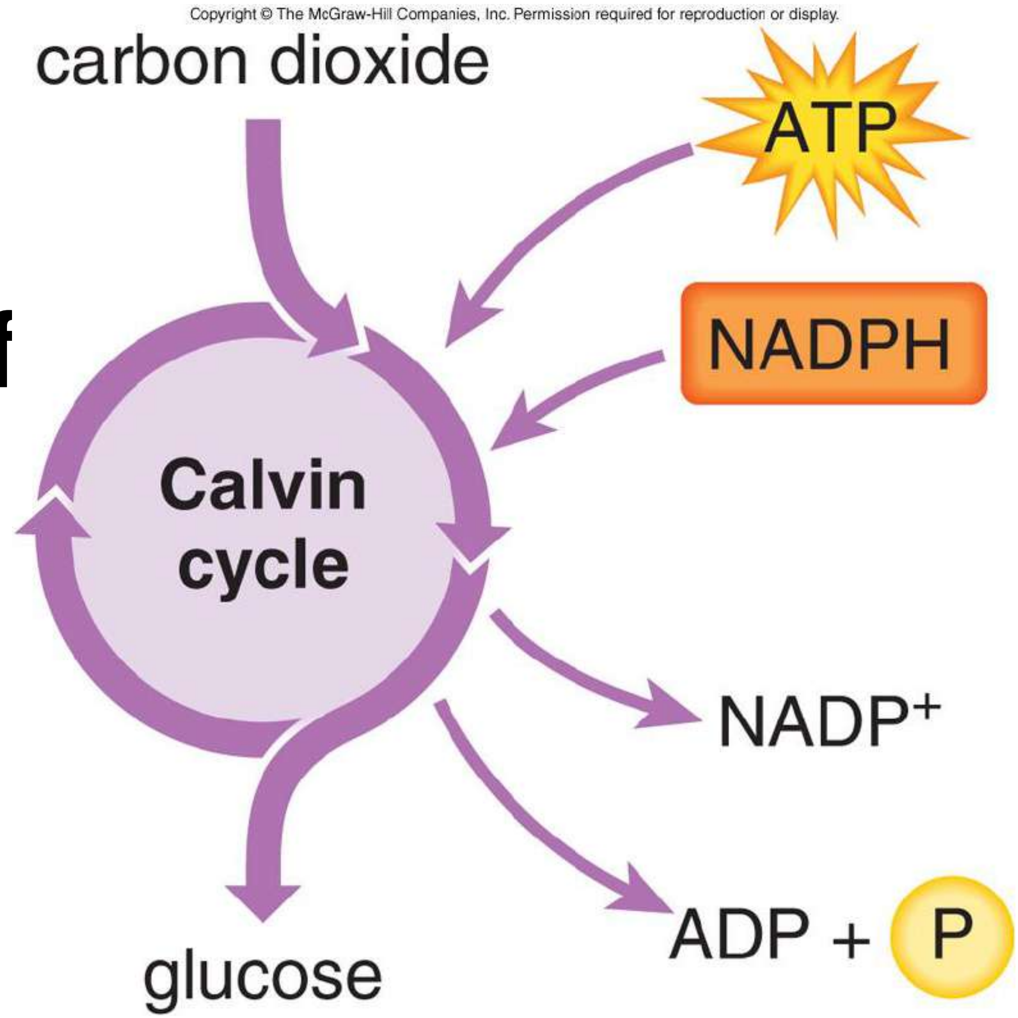
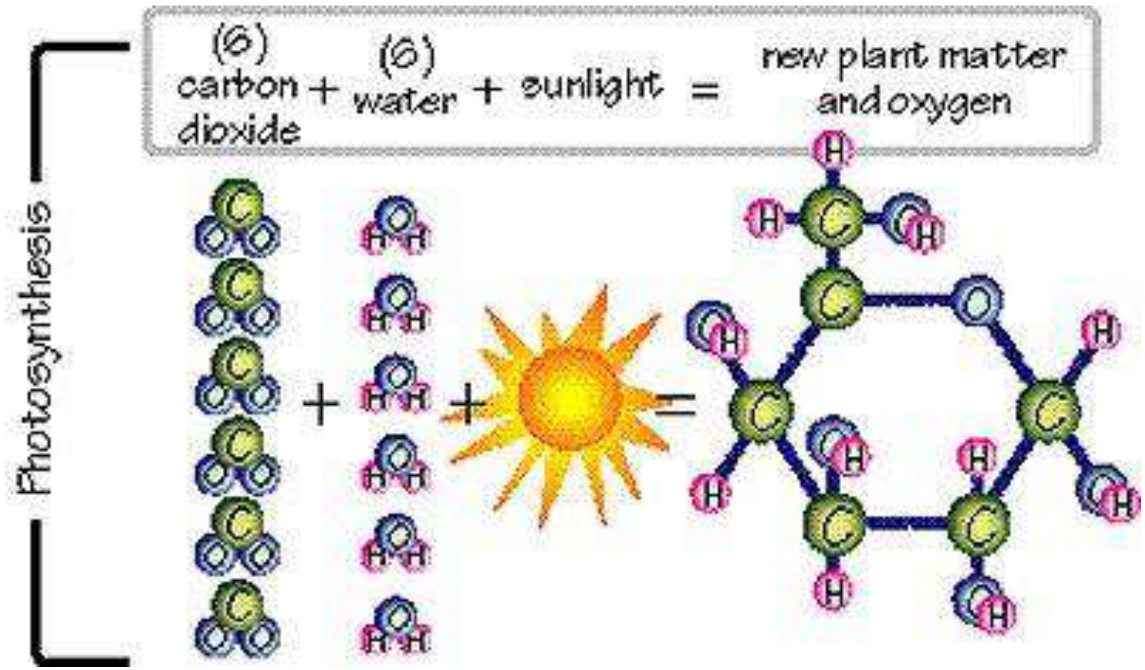
NOTES: CH 10, part 3 – Calvin Cycle (10.3) & Alternative Mechanisms of C-Fixation (10.4)



10.3 - The Calvin cycle uses ATP and NADPH to convert CO_2 to sugar

- The Calvin cycle, like the citric acid cycle, regenerates its starting material after molecules enter and leave the cycle
- The cycle builds sugar from smaller molecules by using ATP and the reducing power of electrons carried by NADPH

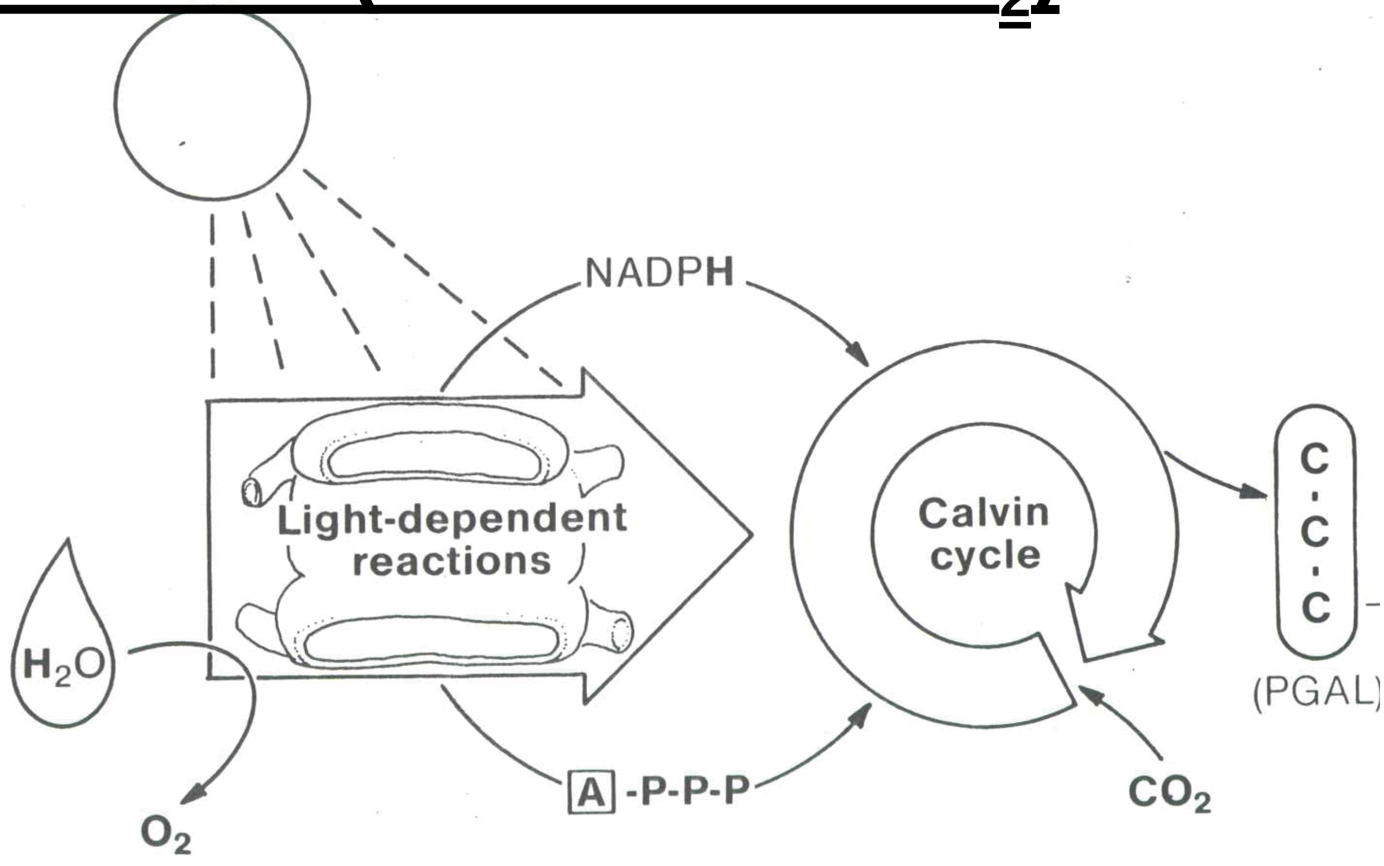
- Carbon enters the cycle in the form of CO_2 and leaves in the form of sugar ($C_6H_{12}O_6$)



- **<u>ATP and NADPH are consumed</u>**

- the carbohydrate produced is actually a 3-C sugar: **G3P**

- to make 1 molecule of G3P **the cycle occurs 3X (consumes 3CO_2)**



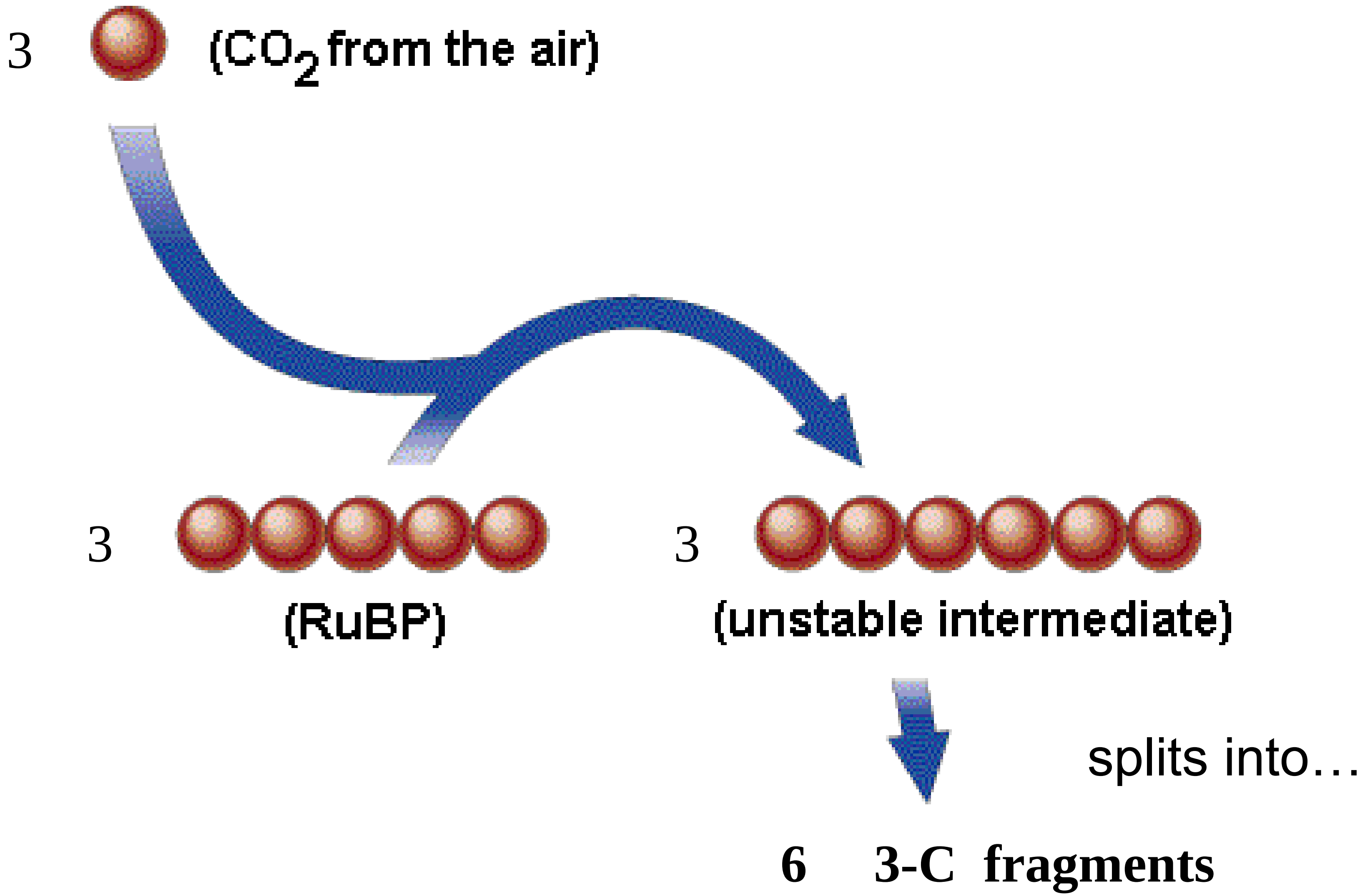
The Calvin Cycle can be divided into 3 phases:

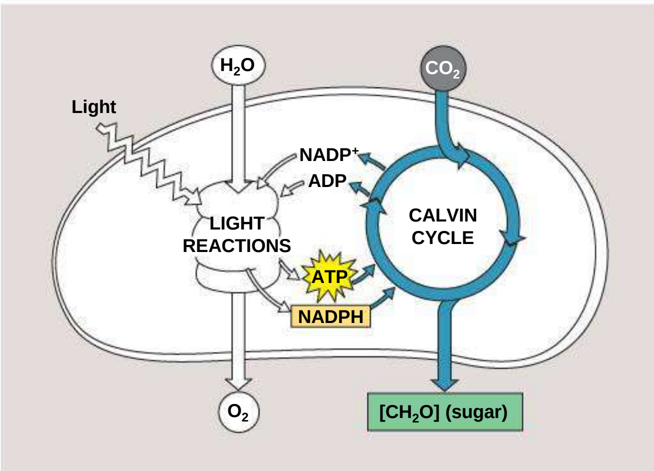
1) Carbon Fixation
2) Reduction
3) Regeneration of CO_2 acceptor (RuBP)

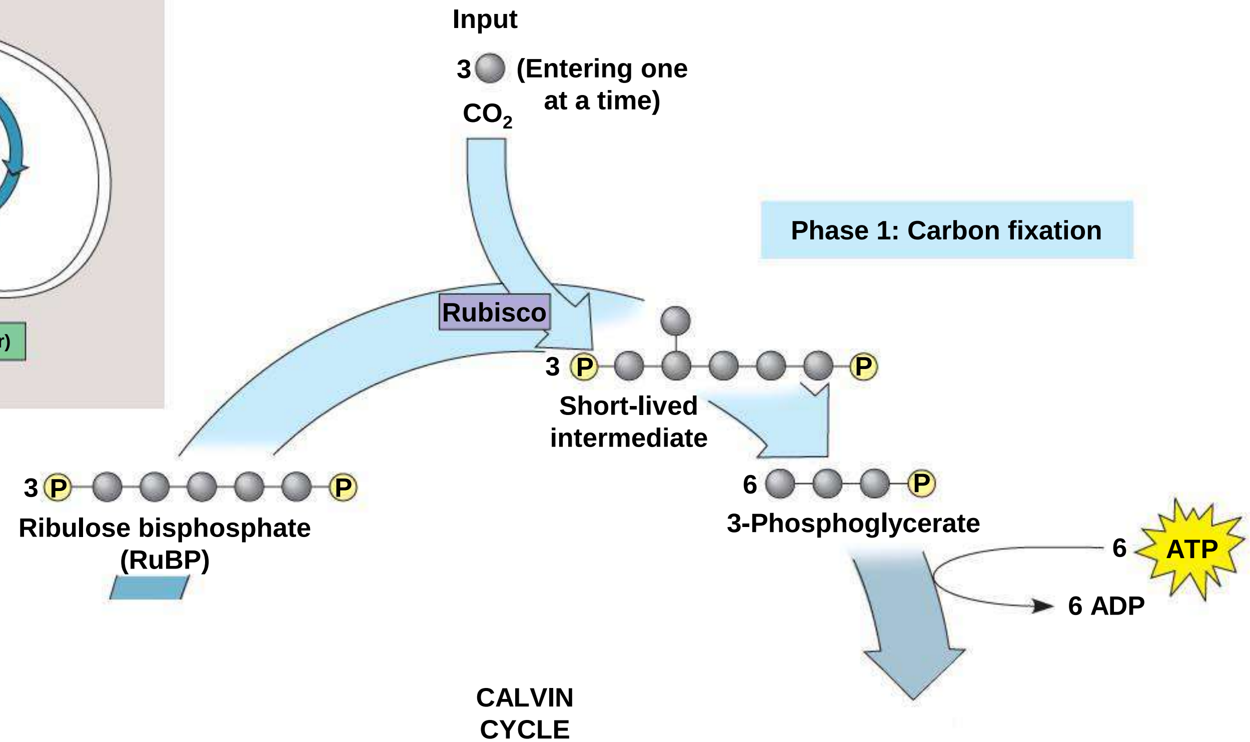
Phase 1: Carbon Fixation

- each CO_2 is attached to a 5-C sugar, **RuBP**, forming an unstable 6-C sugar which **immediately** splits into two 3-C molecules of 3-phosphoglycerate (this is done by the enzyme: **RUBISCO**)

Phase 1: Carbon Fixation



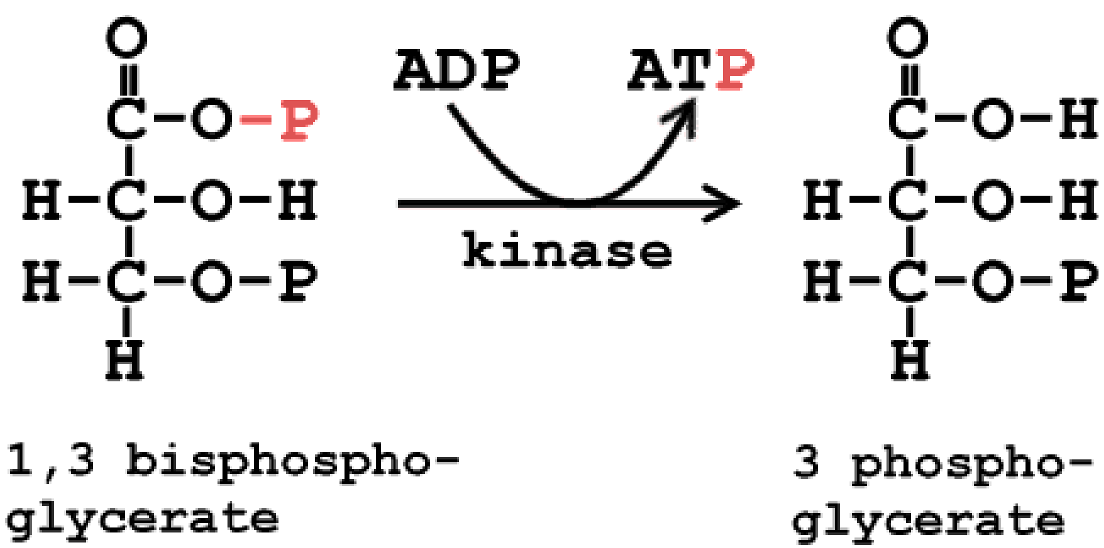

H2O
CO2
Light
NADP+
ADP
LIGHT REACTIONS
CALVIN CYCLE
ATP
NADPH
O2
[CH2O] (sugar)

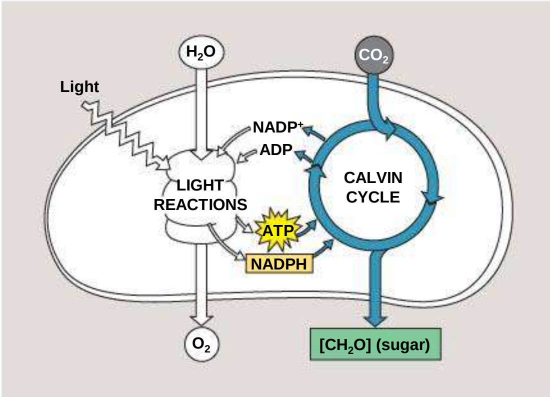

Input
3 (Entering one at a time)
CO2
Phase 1: Carbon fixation
Rubisco
3 P P
Short-lived intermediate
3 P P
Ribulose bisphosphate (RuBP)
6 P
3-Phosphoglycerate
6 ATP
6 ADP
CALVIN CYCLE

Phase 2: Reduction

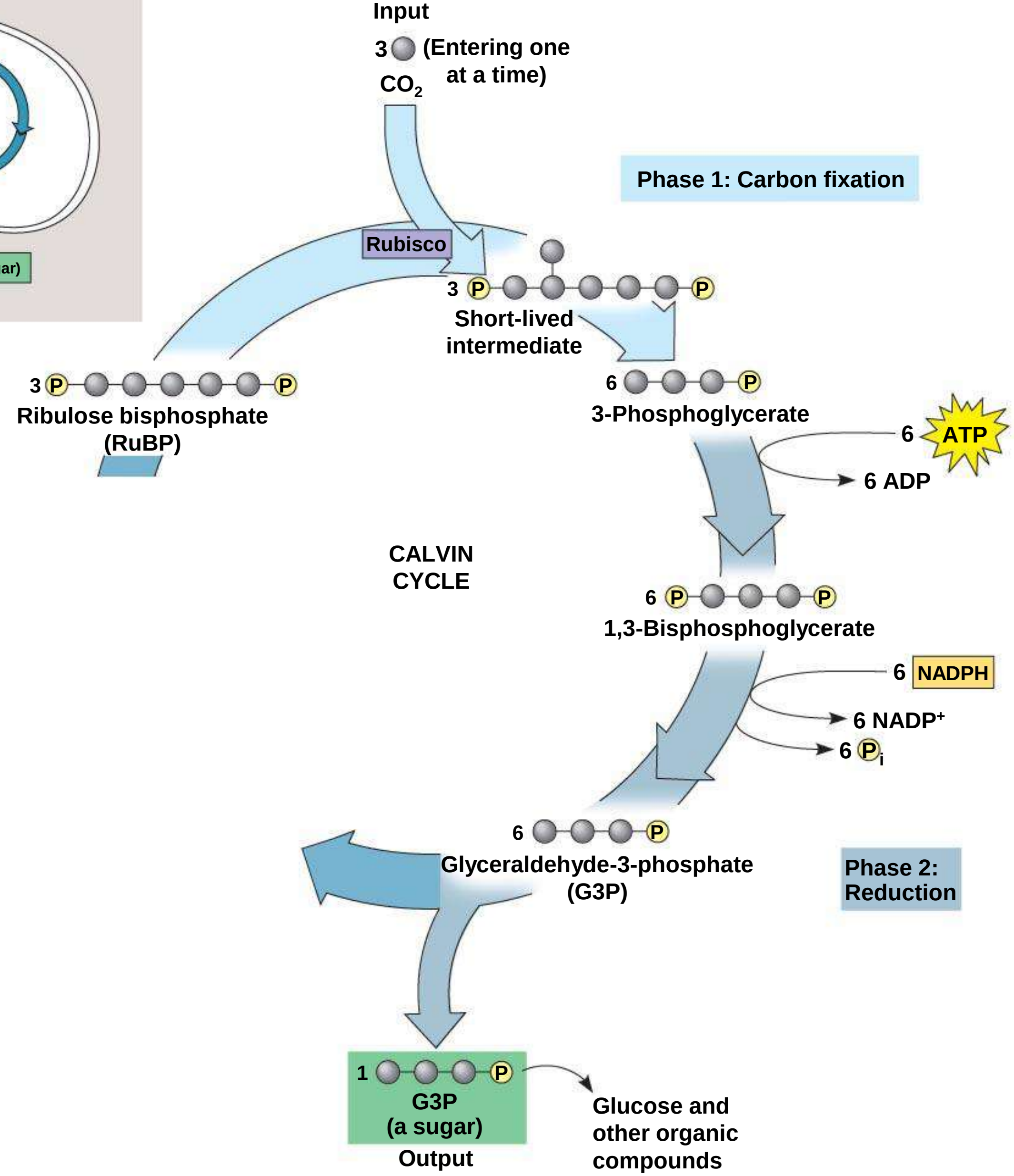
- each 3-phosphoglycerate receives an additional P_i from ATP, forming 1,3-bisphosphoglycerate
- Next, a pair of electrons from NADPH reduces the 1,3-bisphosphoblycerate to G3P

end product of Calvin Cycle!

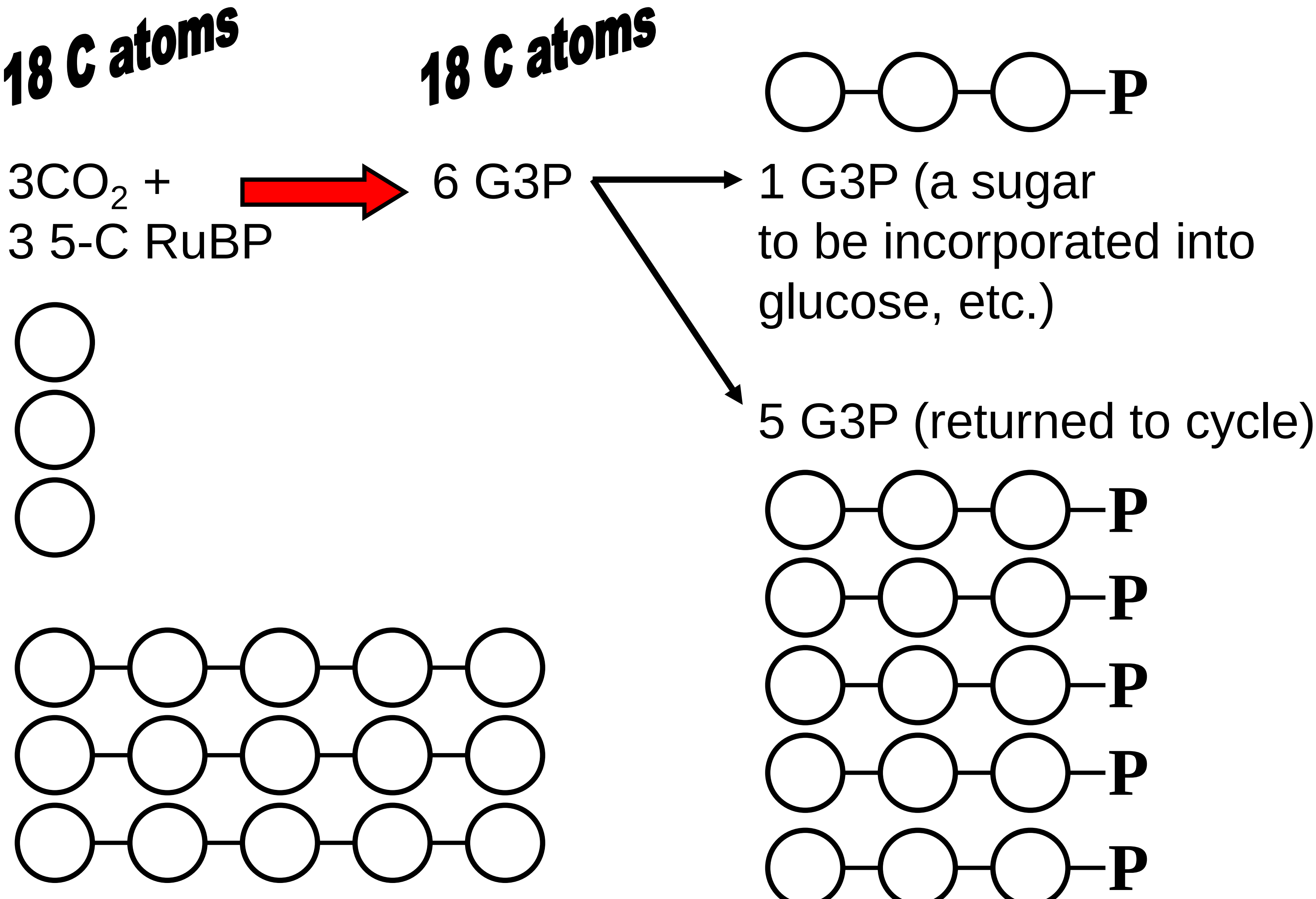




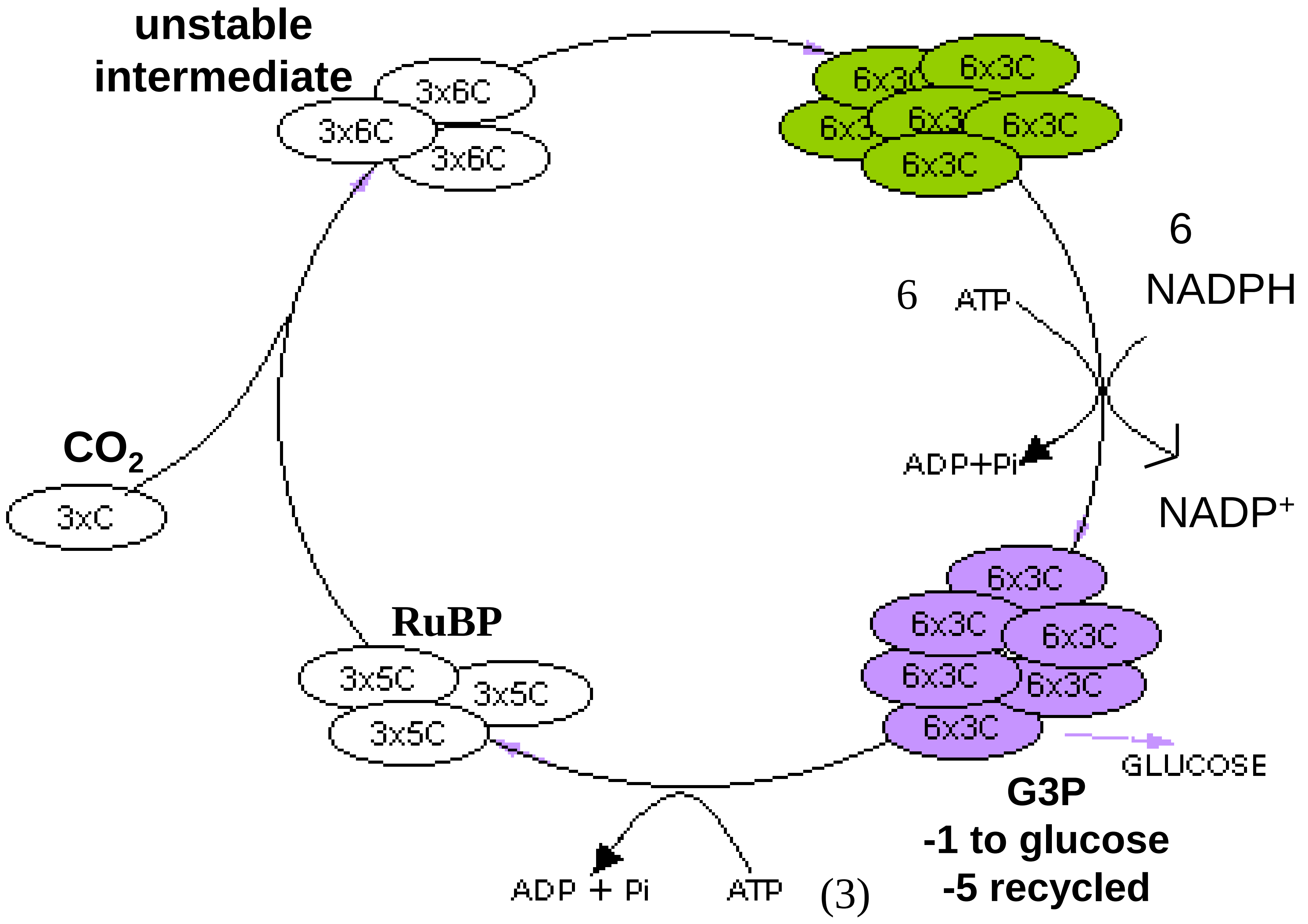
Light
H_2O
CO_2
$NADP^+$
ADP
LIGHT REACTIONS
CALVIN CYCLE
ATP
NADPH
O_2
$[CH_2O]$ (sugar)



Input
3 (Entering one at a time)
CO_2
Phase 1: Carbon fixation
Rubisco
3
Short-lived intermediate
6
3-Phosphoglycerate
6 ATP
6 ADP
3
Ribulose bisphosphate (RuBP)
CALVIN CYCLE
6
1,3-Bisphosphoglycerate
6 NADPH
6 $NADP^+$
6 P_i
6
Glyceraldehyde-3-phosphate (G3P)
Phase 2: Reduction
1
G3P (a sugar)
Output
Glucose and other organic compounds



18 C atoms
18 C atoms
$3CO_2$ +
3 5-C RuBP
6 G3P
1 G3P (a sugar to be incorporated into glucose, etc.)
5 G3P (returned to cycle)
P
P
P
P
P
P


unstable intermediate
3x6C
3x6C
3x6C
6x3C
6x3C
6x3C
6x3C
6x3C
6x3C
6
NADPH
6
ATP
ADP+Pi
NADP+
CO2
3xC
RuBP
3x5C
3x5C
3x5C
6x3C
6x3C
6x3C
6x3C
6x3C
6x3C
GLUCOSE
G3P
-1 to glucose
-5 recycled
ADP + Pi
ATP
(3)

<u>Phase 3: Regeneration of RuBP</u>

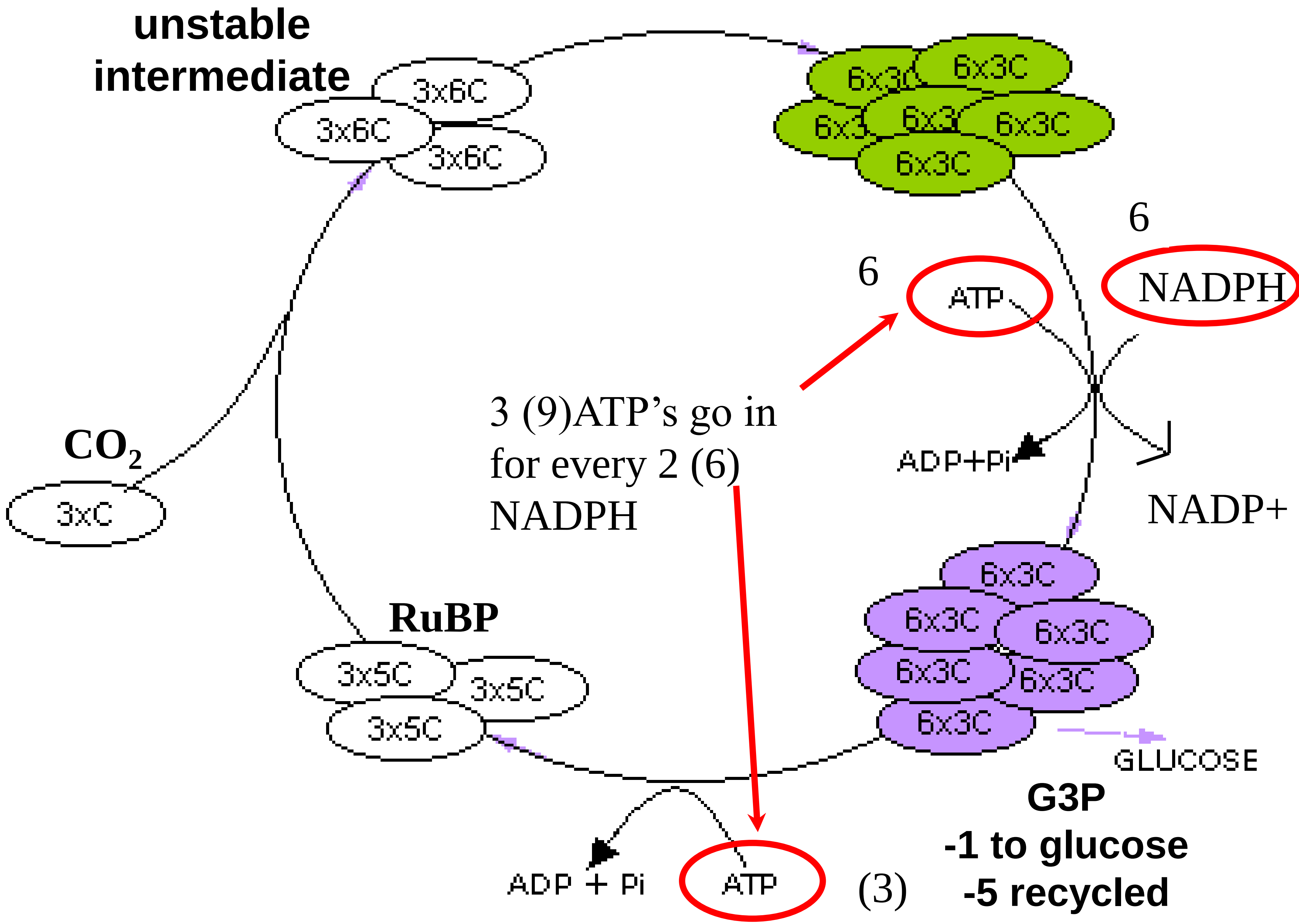
- the 5 molecules of G3P are rearranged through a series of reactions to regenerate RuBP (this uses <u>an additional 3 ATP</u>)

<u>Reason for Cyclic electron flow!!</u>**

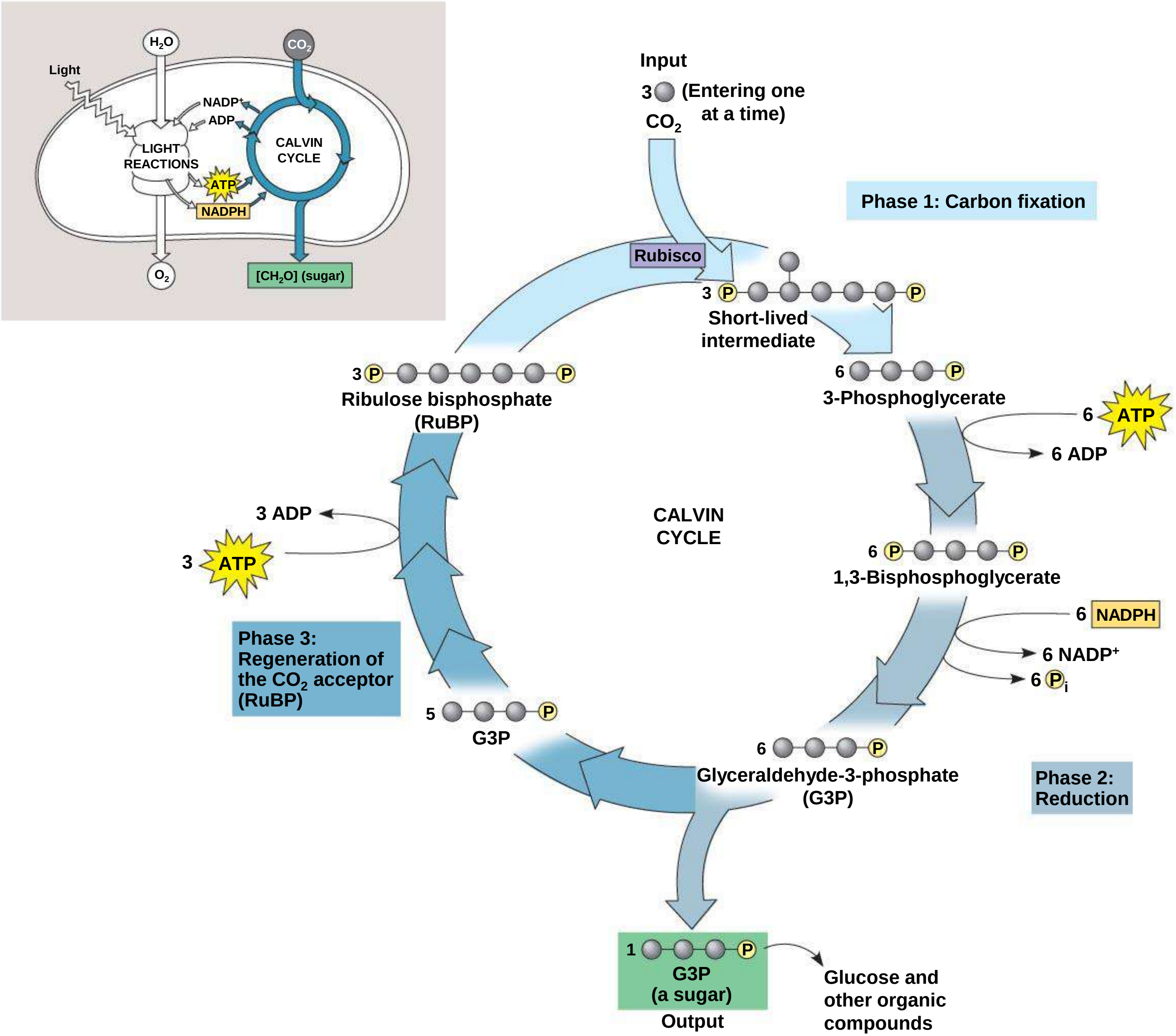
<u>Calvin cycle consumes:</u>

- **<u>9 ATP</u>**
- **<u>6 NADPH</u>**

Leads to negative feedback!



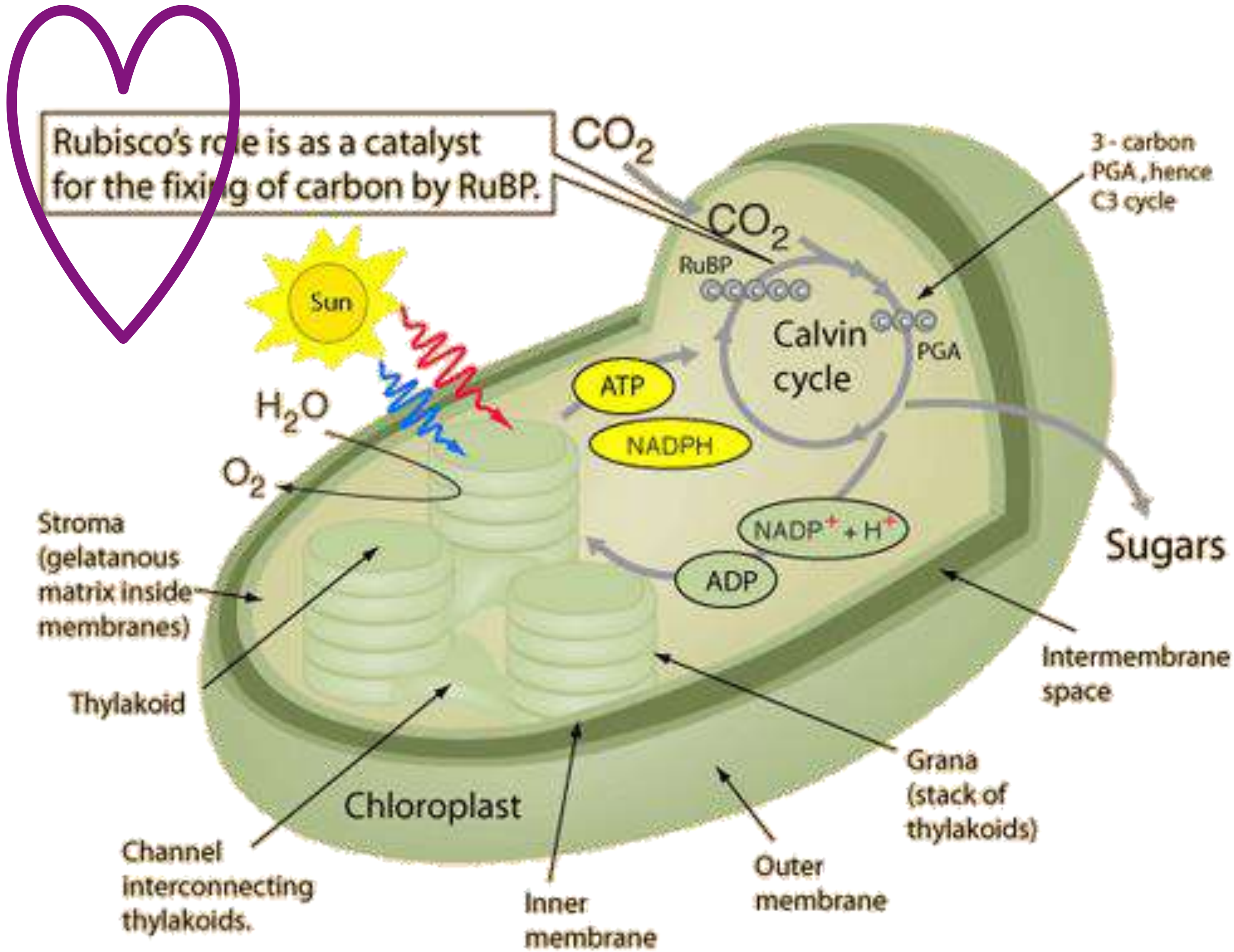
unstable intermediate
3x6C
3x6C
3x6C
6x3C
6x3C
6x3
6x3
6x3C
6x3C
6
6
ATP
NADPH
3 (9)ATP's go in for every 2 (6) NADPH
ADP+Pi
NADP+
CO_2
3xC
RuBP
3x5C
3x5C
3x5C
6x3C
6x3C
6x3C
6x3C
6x3C
6x3C
GLUCOSE
G3P
-1 to glucose
-5 recycled
ADP + Pi
ATP
(3)



H2O
CO2
Light
NADP+
ADP
LIGHT REACTIONS
CALVIN CYCLE
ATP
NADPH
O2
[CH2O] (sugar)
Input
3 (Entering one at a time)
CO2
Phase 1: Carbon fixation
Rubisco
3
Short-lived intermediate
6
3-Phosphoglycerate
6 ATP
6 ADP
3
Ribulose bisphosphate (RuBP)
CALVIN CYCLE
3 ADP
3 ATP
6
1,3-Bisphosphoglycerate
6 NADPH
6 NADP+
6 Pi
Phase 3: Regeneration of the CO2 acceptor (RuBP)
5
G3P
6
Glyceraldehyde-3-phosphate (G3P)
Phase 2: Reduction
1
G3P (a sugar)
Output
Glucose and other organic compounds

Thank you, RUBISCO!

P.S. my #6 most favorite term in bio! ☺



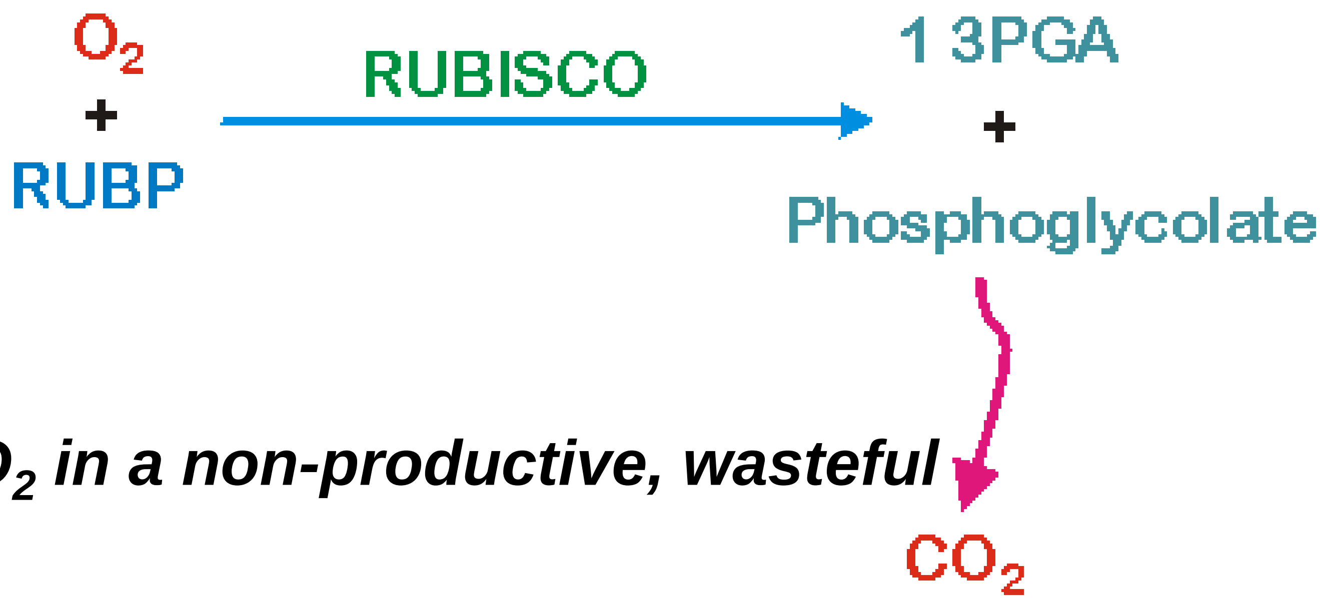
Net Equation for Photosynthesis :

$$6CO_2 + 6H_2O + \text{light energy} \xrightarrow{\textit{chloroplast}} C_6H_{12}O_6 + 6O_2$$

10.4 - Alternative mechanisms of carbon fixation have evolved in hot, arid climates

- **Dehydration** is a problem for plants, sometimes requiring tradeoffs with other metabolic processes, especially photosynthesis
- On hot, dry days, plants close stomata, which conserves water but also limits photosynthesis
- The closing of stomata reduces access to CO_2 and causes O_2 to build up
- These conditions favor a seemingly wasteful process called **PHOTORESPIRATION**

- **PHOTORESPIRATION**: consumes O_2, releases CO_2 into peroxisomes, generates no ATP, <u>decreases photosynthetic output</u>



O_2 replaces CO_2 in a non-productive, wasteful reaction;

Oxygen OUTCOMPETES CO_2 for the enzyme's active site!

Mechanisms of C-Fixation

- **C_3 Plants**: plants which combine CO_2 to RuBP, so that the first organic product of the cycle is the 3-C molecule 3-PGA (3-phosphoglycerate)

  what we've just discussed!

  -examples: rice, wheat, soybeans

  -produce less food when their stomata close on hot, dry days; this deprives the Calvin cycle of CO_2 and photosynthesis slows down

Photorespiration: An Evolutionary Relic?

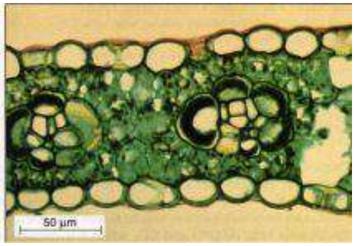
- In most plants (C_3 plants), initial fixation of CO_2, via rubisco, forms a three-carbon compound
- In photorespiration, rubisco adds O_2 to the Calvin cycle instead of CO_2
- Photorespiration consumes O_2 and organic fuel and releases CO_2 **without producing ATP or sugar**

Photorespiration: An Evolutionary Relic?

- Photorespiration may be an evolutionary relic because rubisco first evolved at a time when the atmosphere had far less O_2 and more CO_2
- In many plants, photorespiration is a problem because on a hot, dry day it can drain as much as 50% of the carbon fixed by the Calvin cycle

Alternative Mechanisms for C-Fixation

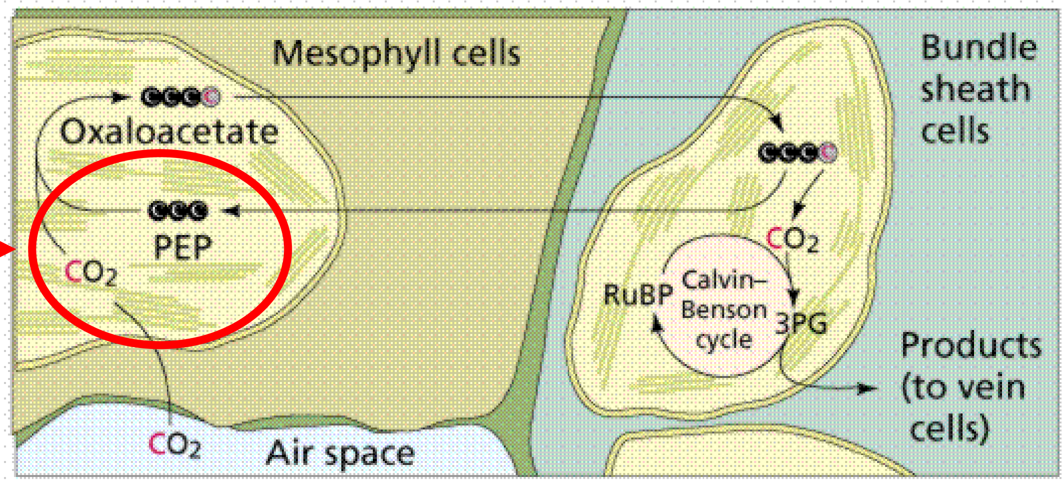
1. C_4 Plants: use an alternate mode of C-fixation which forms a 4-C compound as its first product



- examples: sugarcane, corn, grasses
- the 4-C product is produced in mesophyll cells
- it is then **exported** (through plasmodesmata! ☺) to bundle sheath cells (where the Calvin cycle occurs);

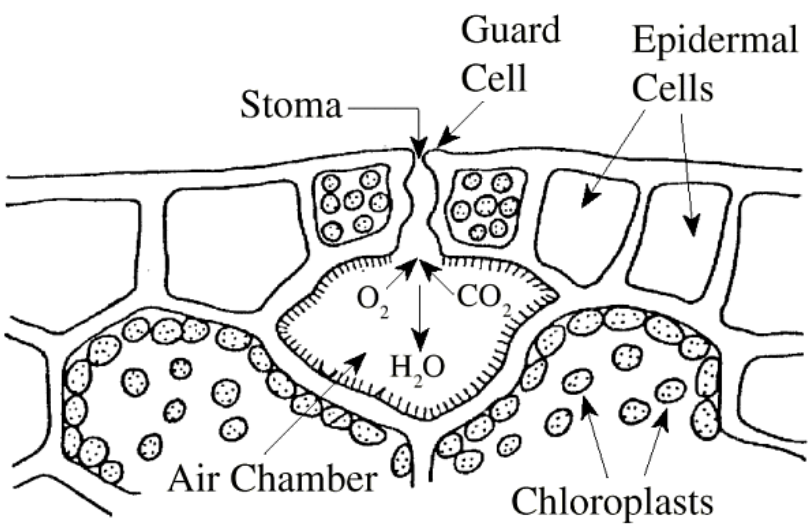
Has a higher affinity for CO_2 than RuBP does

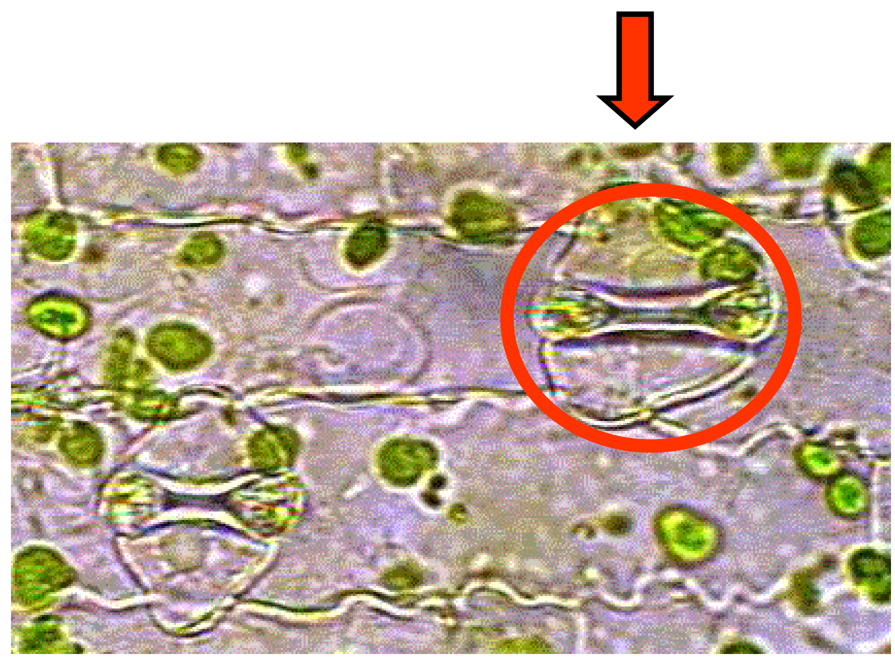
2 different cells!

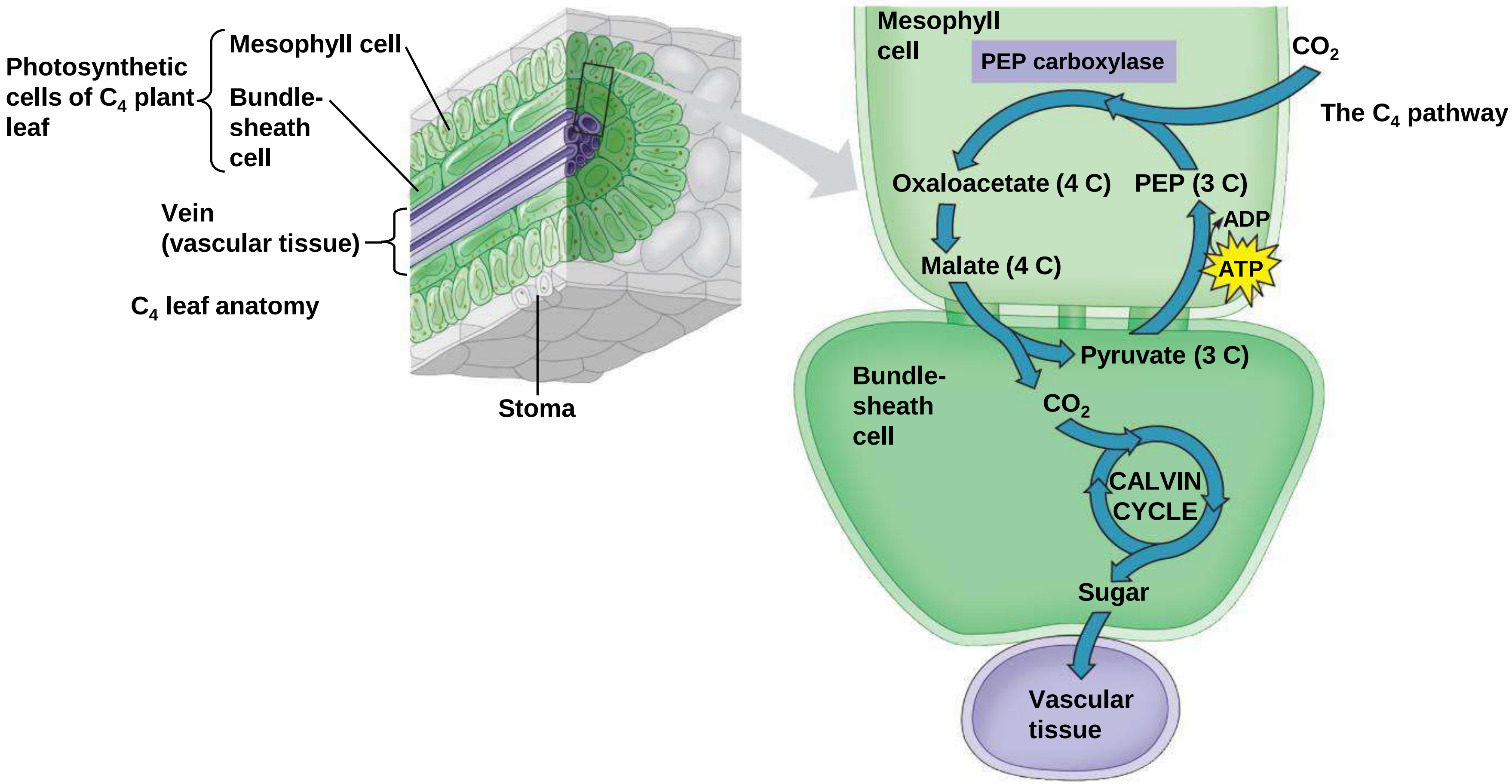


– once here, the 4-C product releases CO_2 which then enters the Calvin cycle to combine with RuBP (the enzyme rubisco catalyzes this step)

– this process keeps the levels of CO_2 sufficiently high inside the leaf cells, even on hot, dry days when the stomata close

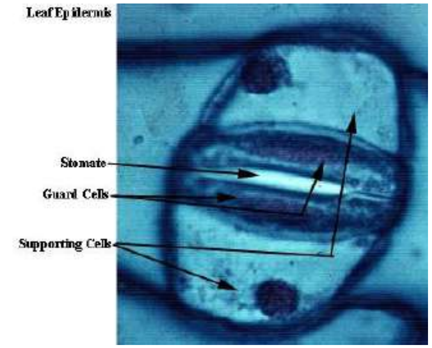


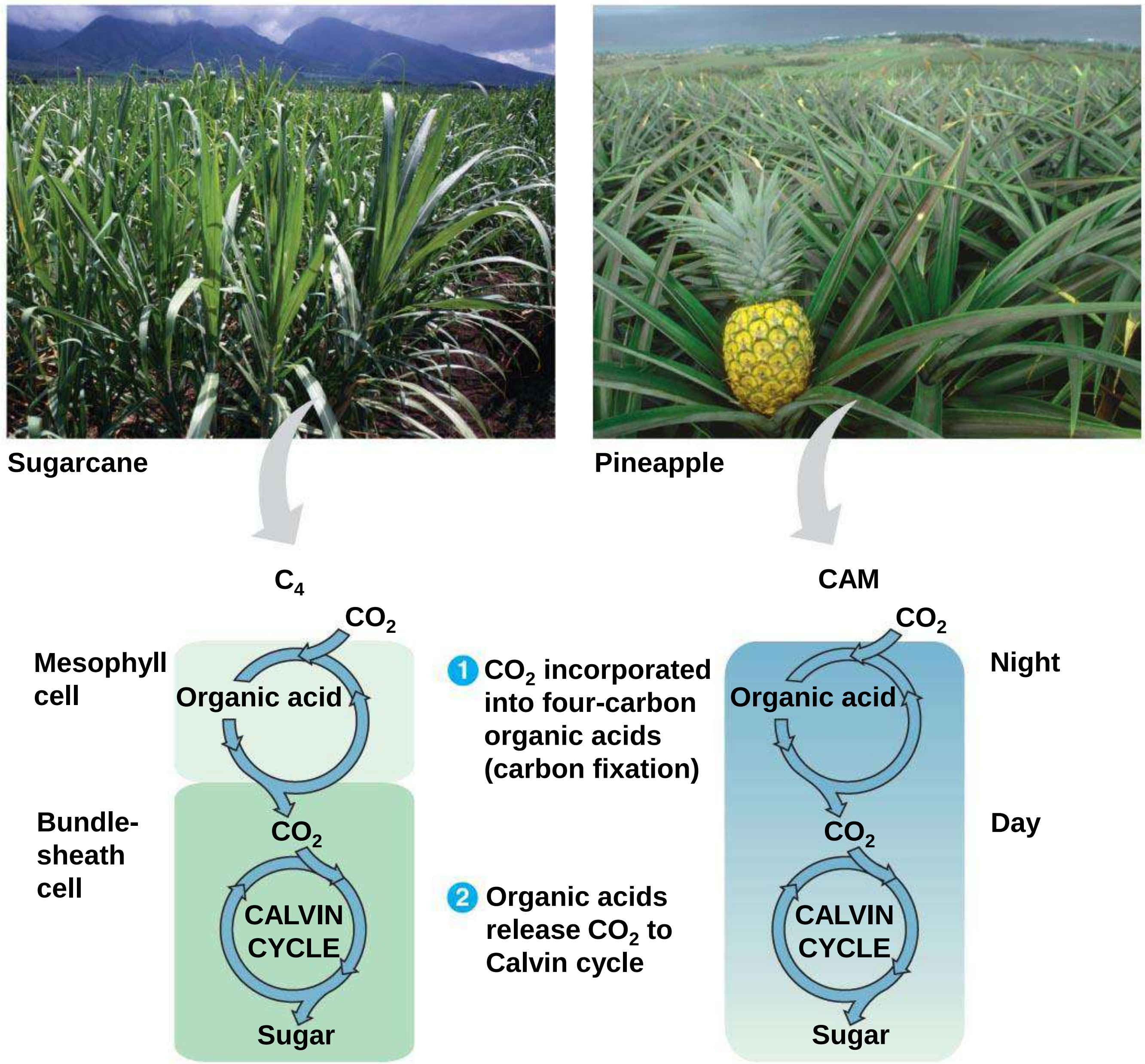



Photosynthetic cells of C_4 plant leaf
Mesophyll cell
Bundle-sheath cell
Vein (vascular tissue)
C_4 leaf anatomy
Stoma
Mesophyll cell
PEP carboxylase
CO_2
The C_4 pathway
Oxaloacetate (4 C)
PEP (3 C)
ADP
ATP
Malate (4 C)
Pyruvate (3 C)
Bundle-sheath cell
CO_2
CALVIN CYCLE
Sugar
Vascular tissue

2. CAM Plants: stomata are open at night, closed during day (this helps prevent water loss in hot, dry climates)

- at night, plants take up CO_2 and incorporate it into organic acids which are stored in the vacuoles until day;
- then CO_2 is released once the light reactions have begun again
- examples: cactus plants, pineapples





(a) Spatial separation of steps

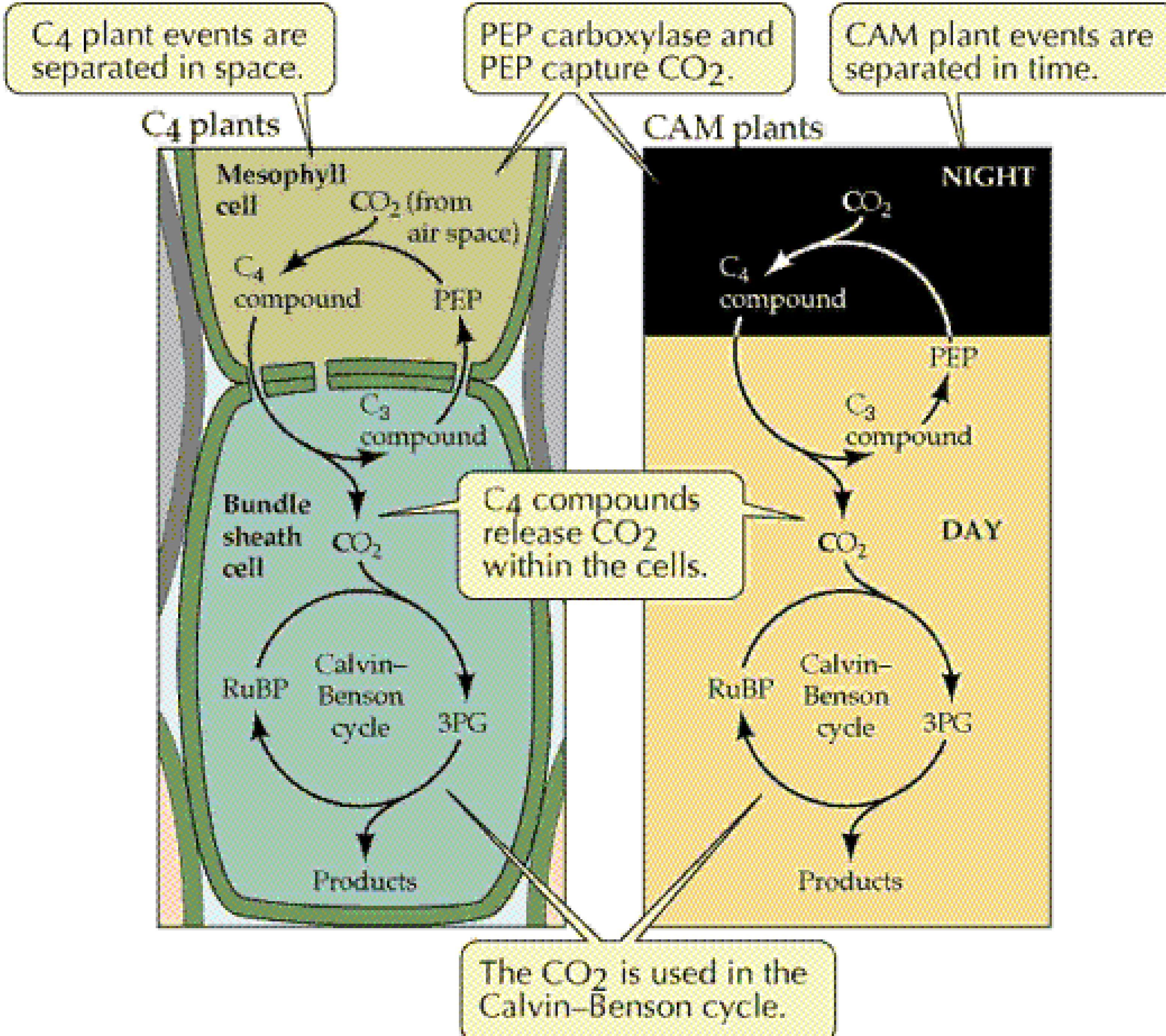
(b) Temporal separation of steps

C_4 and CAM Pathways are:

- ***Similar:*** in that CO_2 is first incorporated into organic intermediates before Calvin cycle
- ***Different:***

  -in C_4 plants the first and second steps are separated **spatially (different locations)**

  -in CAM plants the first and second steps are separated **temporally (occur at different times)**



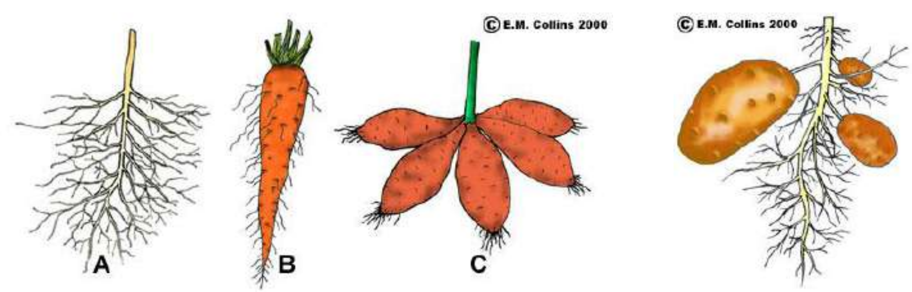
C4 plant events are separated in space.
PEP carboxylase and PEP capture CO2.
CAM plant events are separated in time.
C4 plants
CAM plants
Mesophyll cell
CO2 (from air space)
C4 compound
PEP
C3 compound
Bundle sheath cell
CO2
Calvin–Benson cycle
RuBP
3PG
Products
NIGHT
DAY
C4 compounds release CO2 within the cells.
The CO2 is used in the Calvin–Benson cycle.

What happens to the products of photosynthesis?

- O_2: **consumed during cellular respiration**
- 50% of **SUGAR** made by plant is consumed by plant in **cellular respiration**
- some is incorporated into polysaccharides:

  -**cellulose (cell walls)**

  -**starch (storage; in fruits, roots, tubers, seeds)**

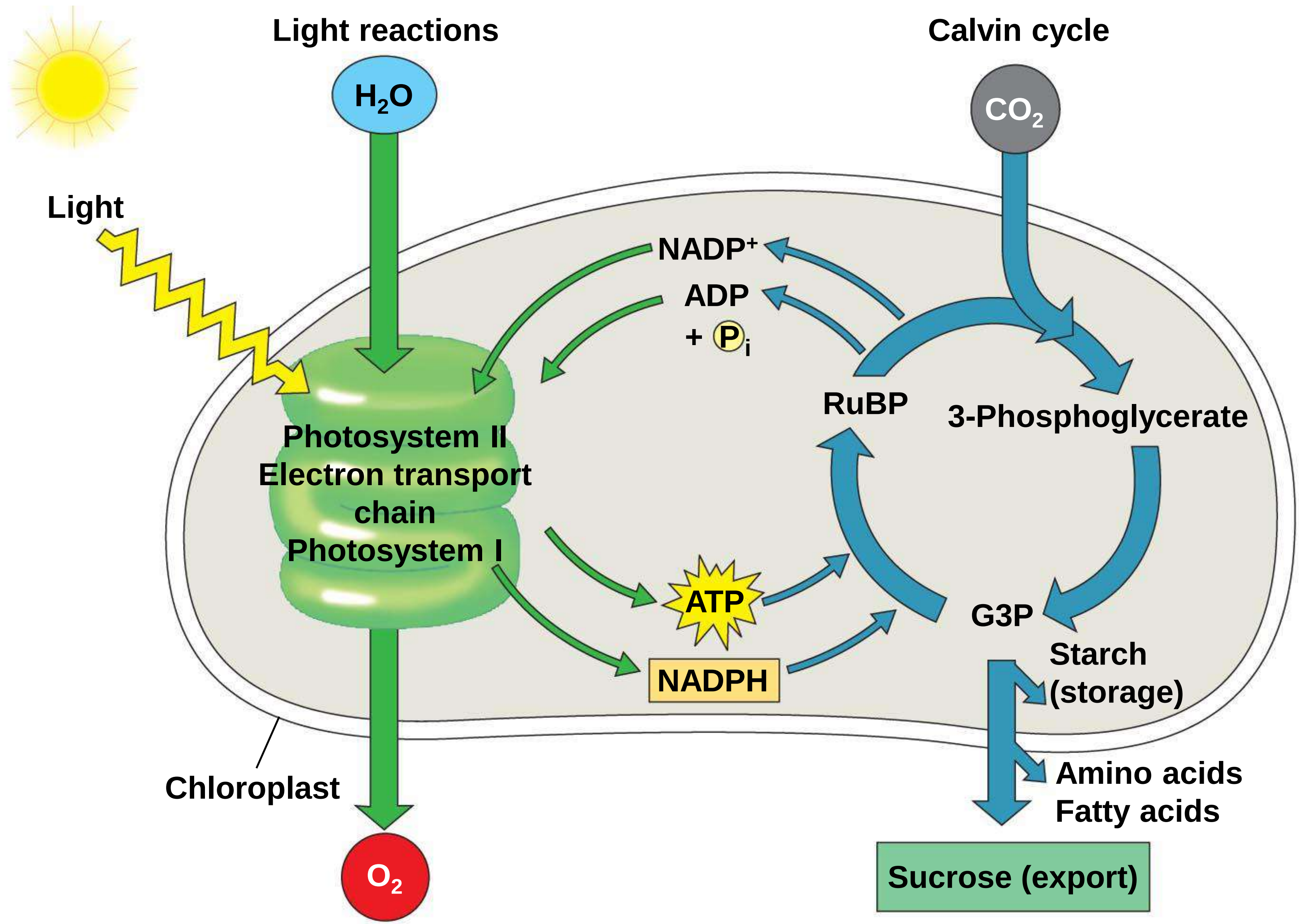


The Importance of Photosynthesis: *A Review*

- The energy entering chloroplasts as sunlight gets stored as chemical energy in organic compounds
- Sugar made in the chloroplasts supplies chemical energy and carbon skeletons to synthesize the organic molecules of cells
- In addition to food production, photosynthesis produces the oxygen in our atmosphere!!

The Importance of Photosynthesis: *A Review*

**no process is more important than photosynthesis to the welfare of life on Earth!...Thank you photosynthesis (& RUBISCO!). ☺


Light reactions
Calvin cycle
H_2O
CO_2
Light
$NADP^+$
ADP
+ P_i
RuBP
3-Phosphoglycerate
Photosystem II
Electron transport chain
Photosystem I
ATP
NADPH
G3P
Starch (storage)
Amino acids
Fatty acids
Chloroplast
O_2
Sucrose (export)