## Plant Growth

- Definition:
  – Size increase by cell division and enlargement, including synthesis of new cellular material and organization of subcellular organelles.

## Growth and Development

- Growth
  – Irreversible change in Mass
- Development
  – Irreversible change in State
    - Embryogenesis
    - Juvenile
    - Adult Vegetative
    - Adult Reproductive

# Growth

- Components
- 1. Cell Division
- 2. Cell Enlargement

# MEASURING GROWTH

- Increase in fresh weight
- Increase in dry weight
- Volume
- Length
- Height
- Surface area

# HOW PLANTS GROW

- Meristems
  - Dicots
    - Apical meristems – vegetative buds
      - shoot tips
      - axils of leaves
    - Cells divide/redivide by mitosis/cytokinesis
    - Cell division/elongation causes shoot growth
    - Similar meristematic cells at root tips

# HOW PLANTS GROW

- Meristems (cont)
    - Secondary growth in woody perennials
      - Increase in diameter
        - due to meristematic regions
      - vascular cambium
        - xylem to inside, phloem to outside
      - cork cambium
        - external to vascular cambium
        - produces cork in the bark layer

## Cell Division

- Meristematic Cells (Stem Cells)
- Primary
  - Shoot Apical Meristem (SAM)
  - Root Apical Meristem (RAM)
- Secondary
  - Axillary Buds
  - Vascular Cambium
  - Cork Cambium
  - Pericycle (root)

## Cell Enlargement

- Adjacent to Meristems
- Internode growth - Shoot
- Zone of Elongation - Root
- Turgor Pressure
  - $H_2O$ Uptake
  - Cell Wall Loosening
  - new cell walls

## Types of Growth

- 1. Determinant
  Terminal shoot apex flowers
- 2. Indeterminant
  Axillary buds flower
  Terminal buds vegetative
- 3. Monocarpic
  Flower once then die
- 4. Polycarpic
  Flower repeatedly over several seasons

## Types of Growth

- 5. Annual
  Monocarpic
  Flower in one season and then die
- 6. Biennial
  Monocarpic
  Flower in second season and then die

## Types of Growth

- 7. Herbaceous Perennial
- Polycarpic
- Determinant
  - Flower early and then go dormant
  - Flower Bulbs
- Indeterminant
- Flower throughout season
- Shoot dies in Fall

## Types of Growth

- 8. Woody Perennial
- Polycarpic
- Indeterminant
  - flower only once per year
- Biennial Bearing
  - flower and set fruit every other year
- Mast Flowering
  - more prolific in some years than in others

## ENVIRONMENTAL FACTORS INFLUENCING PLANT GROWTH

- Light
- Temperature
- Water
- Gases

## PLANT GROWTH REGULATORS

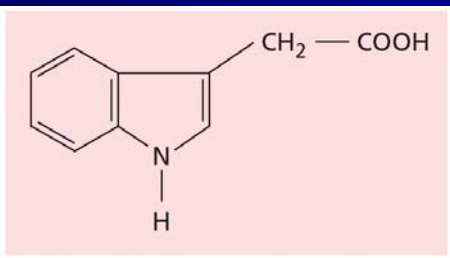
- 3. Hormone
  - a. Substance that acts in very low concentration (micro-molar or less)
  - b. Produced in one part of plant and act in another (translocatable)
  - c. Has the same response in many different plant species

## PLANT GROWTH REGULATORS

- 1. Auxins
- 2. Cytokinins
- 3. Gibberellins
- 4. Abscisic Acid
- 5. Ethylene

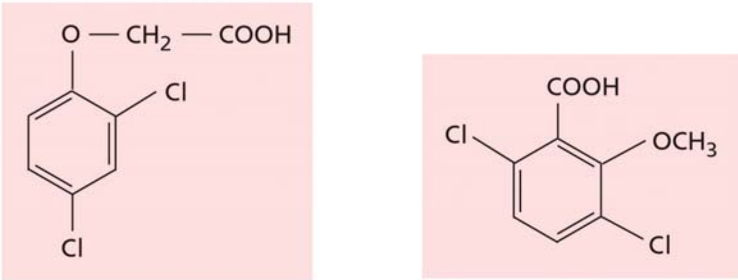
## Natural Auxin

- 1. Endogenous
- Indole Acetic Acid




Indole-3-acetic acid (IAA)

# Synthetic Auxins




2,4-Dichlorophenoxyacetic acid (2,4-D)

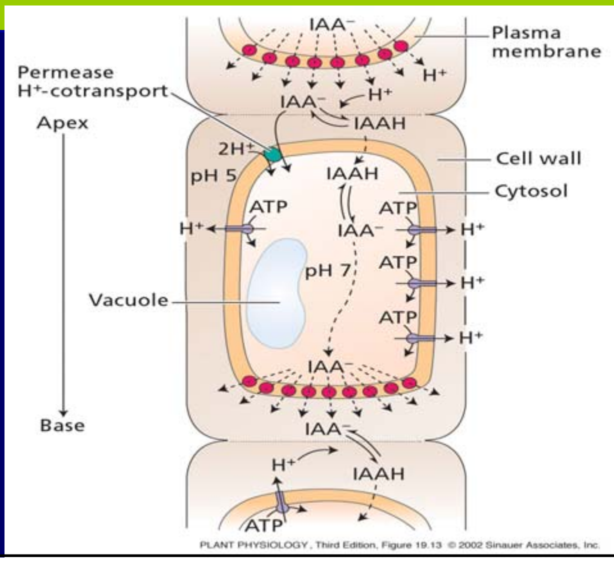
2-Methoxy-3, 6-dichlorobenzoic acid (dicamba)



# Auxin

- Synthesis
- a. Young developing leaves
- b. Terminal buds, growing axillary buds
- c. coleoptile tips
- Transport
- Basipetal
  away from tip

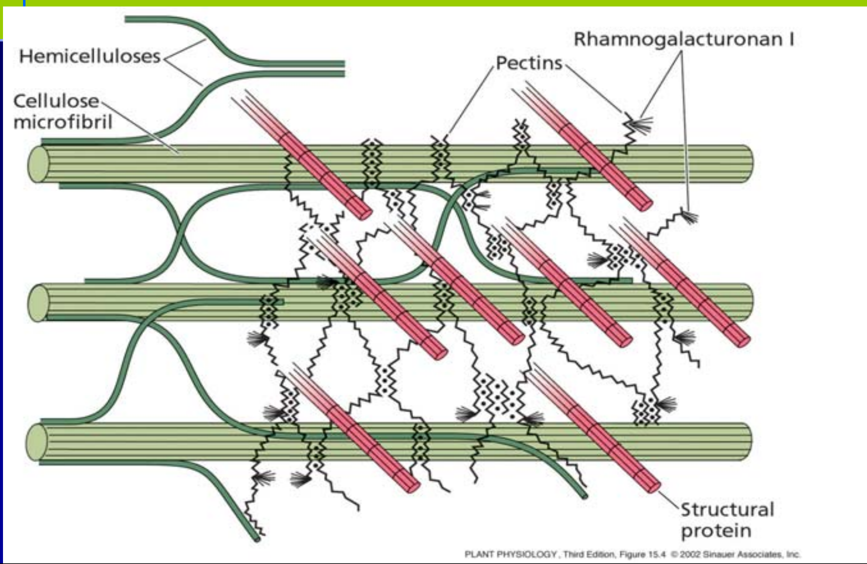
# Auxin Polar Transport



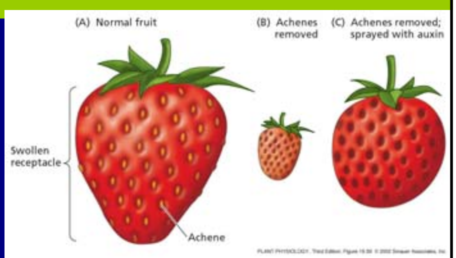

# Auxin Action

- Mechanism of Action
- a. Bind Receptor Protein Plasma membrane
- b. Transport into cell
- c. Activate ATPase in Plasma membrane
- d. H+ ion extrusion
- e. acidify cell wall
- f. break hemicellulose-pectin bonds
- g. cellulose microfibrils slide apart
- h. cell enlarges

# Auxin Cell Wall Loosening




# Auxin Responses

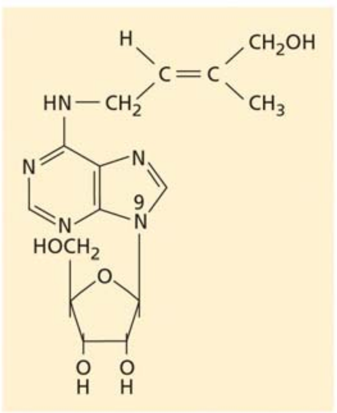



- Cell Enlargement
  - Shoot Growth
    - Internodes
    - Tubers
    - Bulbs
  - Root Growth
    - Storage Roots
    - Adventicious Roots
  - Fruit Growth
    - Strawberry - Receptacle enlargement
- Apical Dominance
  - Auxin:Cytokinin Ratio
    - High - Dormant Axillary Buds
    - Low - Axillary Bud Growth

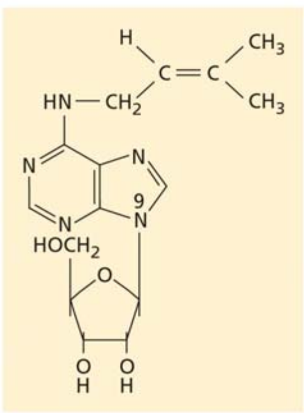
# Auxin Agricultural Uses

- Rooting of Cuttings
  - Propagation
  - Greenhouse and Nursery Crops
    - Hormodin, Rootone, etc.
    - Commercial preps of 2,4-D
- Herbicide
- High Concentration 2,4-D
- Dicots more sensitive
- Monocots less sensitive
- Weed control in cereal crop production
- Prevent Abscission of Leaves and Fruit
- Older leaves
- Ripe Fruit
- Endogenous production of IAA stops
- Replaced by exogenous NAA

# CYTOKININS



Ribosylzeatin (zeatin riboside)



$N^6$-($\Delta^2$-Isopentenyl)adenosine ([9R]iP) (IPA)

PLANT PHYSIOLOGY, Third Edition, Figure 21.2 © 2002 Sinauer Associates, Inc.

# Cytokinins

- Synthesis
  - Root Apex
- Transport
  - Upward in Xylem

# Cytokinins

- **Responses**
- Stimulate Cell Division
- Apical Dominance
- High Auxin in Shoot Apex
- High Cytokinin in Root Apex
- Gradient Between:
- High Auxin:Cytokinin
- Dormant Axillary Buds
- Low Auxin:Cytokinin
- Branch Growth

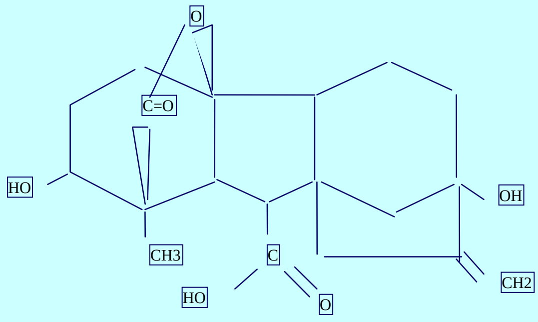
# Cytokinins

- Synthetic Cytokinins
- Kinetin
  - DNA degradation
- Benzyladenine (BA or 6-Benzyl amino purine)
- Agricultural Uses
- Limited
- Induction of Axillary Buds
  - Roses, Chrysanthemum
- Micropropagation
  - Shoot proliferation in Tissue Culture

# Gibberellins

- Family of more than 130 structures

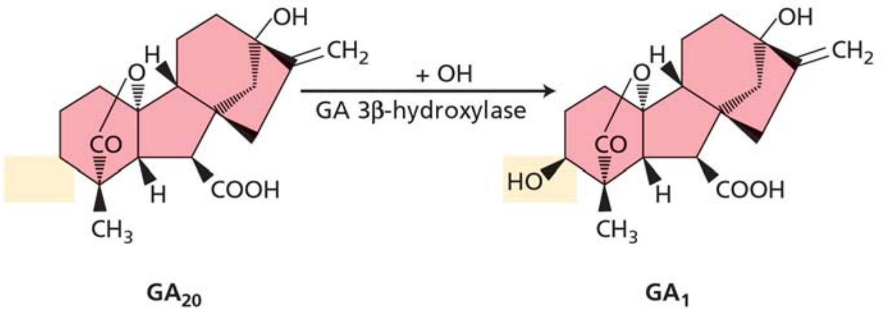
# Gibberellins




GA1

# Gibberellins

- Inactive Active

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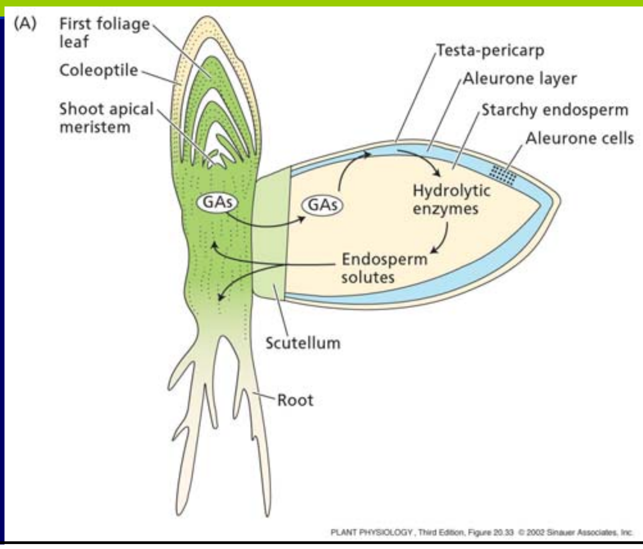
# Gibberellins

- Synthesis
- Tissue Localization
  – Immature seed embryo, Young Leaves, roots
- Transport
  – Phloem

# Gibberellins

- **Responses**
- Cell Elongation
- Dwarf cultivars
  eg. Peas (Little Marvel)
- Dwarfing rootstocks
  apples, pears, peaches
  height from roots
  fruit quality from scion
- Seed Dormancy
  High ABA
  Reversed by GA application
  Synthesis of GA by embryo

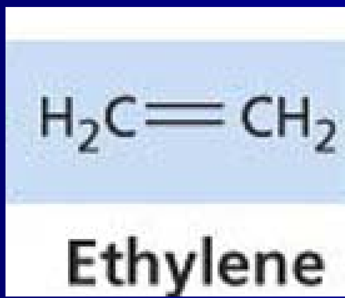
# Gibberellins




# Gibberellins

- **Agricultural Uses**
- 1. Thompson Seedless Grapes
  - Principal use
  - Parthenocarpic Fruit
- 2. Seed Germination
  - Malting Barley
  - Precocious germination
- 3. Male Flower production
  - Monoecious & Dioecious Plants
- 4. Chilling Requirement
  - Azaleas
  - Biennials
  - Biennial Bearing

# Ethylene




# Ethylene

- **$C_2H_4$**
- Gas at room temperature
- **Synthesis**

```
                                        |←Hemicellulose
            +ATP                        |
Methionine ---> SAM ---> ACC ---> Ethylene ---> PG
                 1          2           |            3
                                        |→Galactose
```

- 1. S-Adenosyl Methionine
- 2. Amino Cyclo Propane
- 3. Polygalacturonase

## Ethylene

- Agricultural Uses
  - Ethaphon - breaks down to form ethylene
- 1. Fruit Ripening

Tomato, Banana, Melon, etc.

Pick unripe and firm for shipping

Spray in store to "ripen"

Color development and softening

Field Spray

Uniform and synchronous ripening

Canning Tomatoes

Mechanical Harvest

## Ethylene

- 2. **Floral Development**

Bromeliads

Pineapple

Banana

Uniform development of inflorescence

- 3. **Sex Expression**

Female Flowers

Curcubits

opposite of GA action

- 4. **Degreening of Citrus**

Oranges, Lemons, Grapefruit

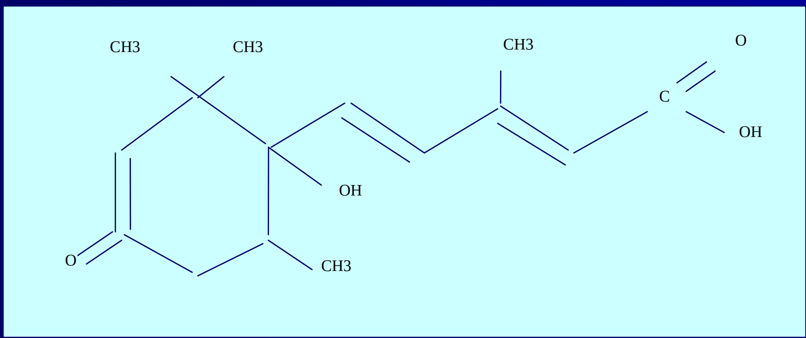
Break down Chlorophyll

Leaves Carotenoids

# Ethylene

- 5. Mechanical Harvesting
  - Formation of Abscission Zone
  - Stimulate Fruit Drop
    - Cherries, Walnuts, Pecans
- 6. Postharvest Shelf Life
  - block ethylene synthesis
    - AgNO3 or Silver Thiosulfate
    - delay senescence
    - Carnations

# Abscisic Acid



## Abscisic Acid

- Natural Plant Growth Retardant
  - Opposes action of GA and Auxin
- Synthesis
  - Chloroplasts
  - Breakdown product of Carotenoids

## Abscisic Acid

- Responses
- Dormancy Maintenance
  - high levels in dormant seed and buds
- Drought Resistance
  - causes stomatal closure
- Agricultural Uses
  - None

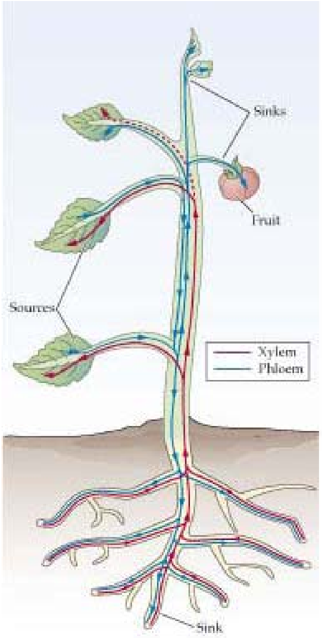
# Translocation in the Phloem

## Patterns of translocation: Source to Sink

**Metabolites move from source to sink.**

**SOURCE = area of supply**
- exporting organs: mature leaves
- storage organs: seed endosperm, storage root of second growing season beet

**SINK = areas of metabolism (or storage)**
- non-photosynthetic organs and organs that do not produce enough photosynthetic products to support their own growth or storage
- Example: roots, tubers, developing fruits/seeds, immature leaves

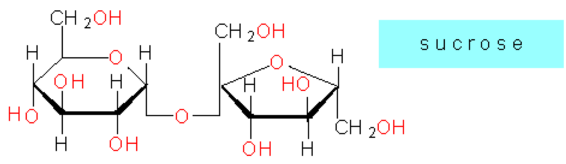


# Exactly what is transported in phloem?

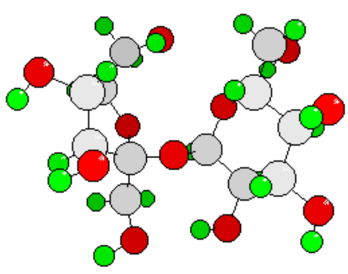
# Sucrose

The sugar that is most important in translocation is sucrose

Sucrose is a disaccharide, i.e., made up of two sugar molecules – an additional synthesis reaction is required after photosynthesis

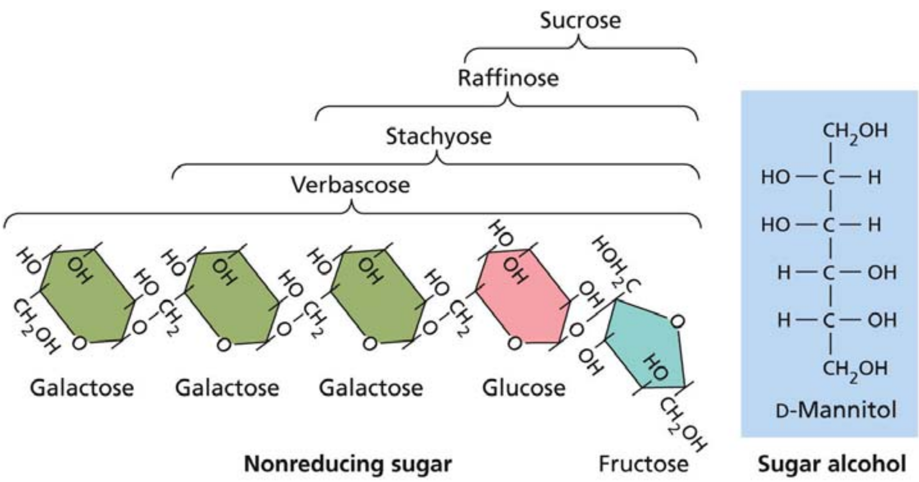



Sucrose - is not a rigid structure, but mobile in itself.



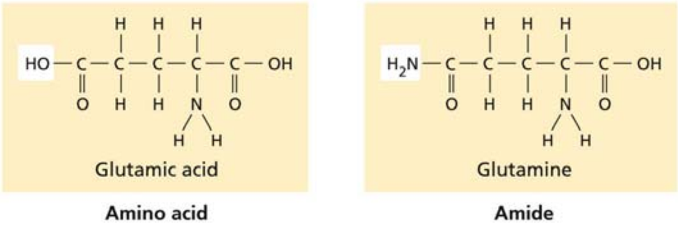
http://www.biologie.uni-hamburg.de/b-online/e16/16h.htm#sucr

## Compounds translocated in the phloem

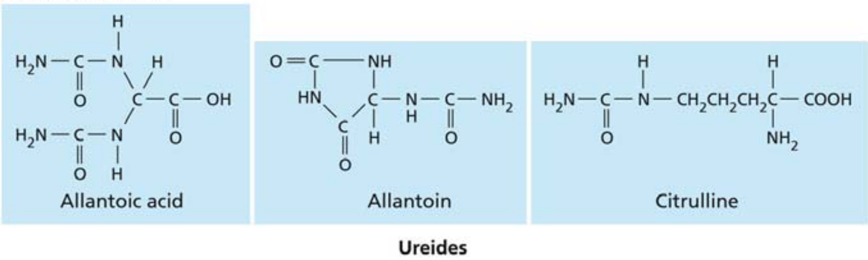



## Compounds translocated in the phloem

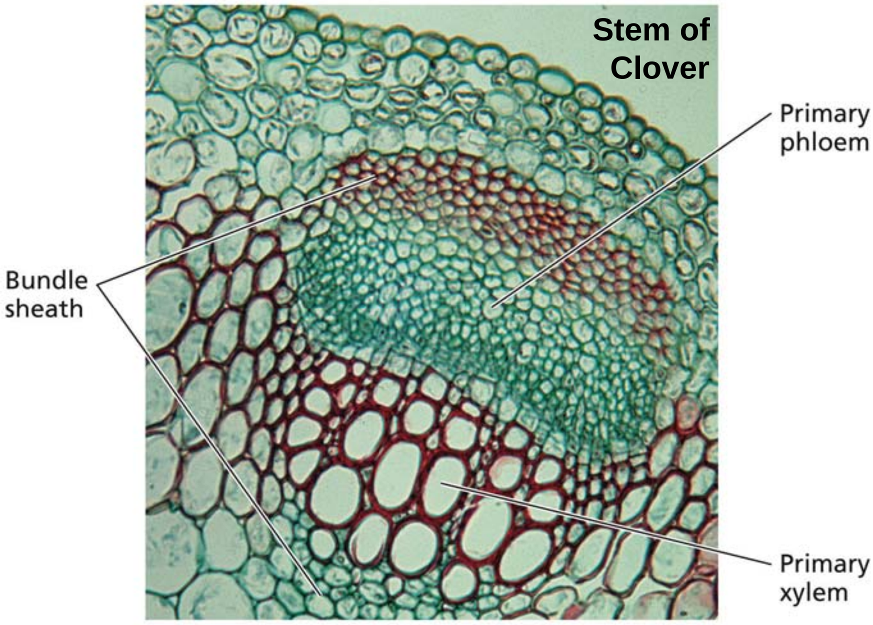
Glutamic acid, an amino acid, and glutamine, its amide, are important nitrogenous compounds in the phloem, in addition to aspartate and asparagine.




Species with nitrogen-fixing nodules also utilize ureides as transport forms of nitrogen.

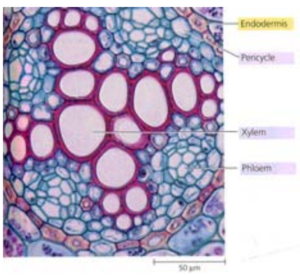


## Primary phloem and primary xylem

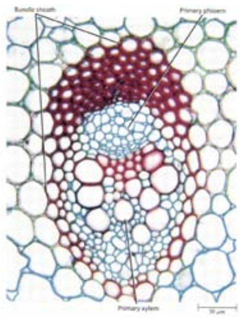



# Phloem Location

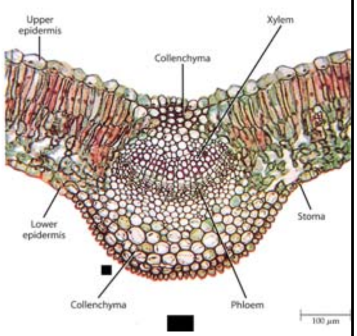
review




Root Stele



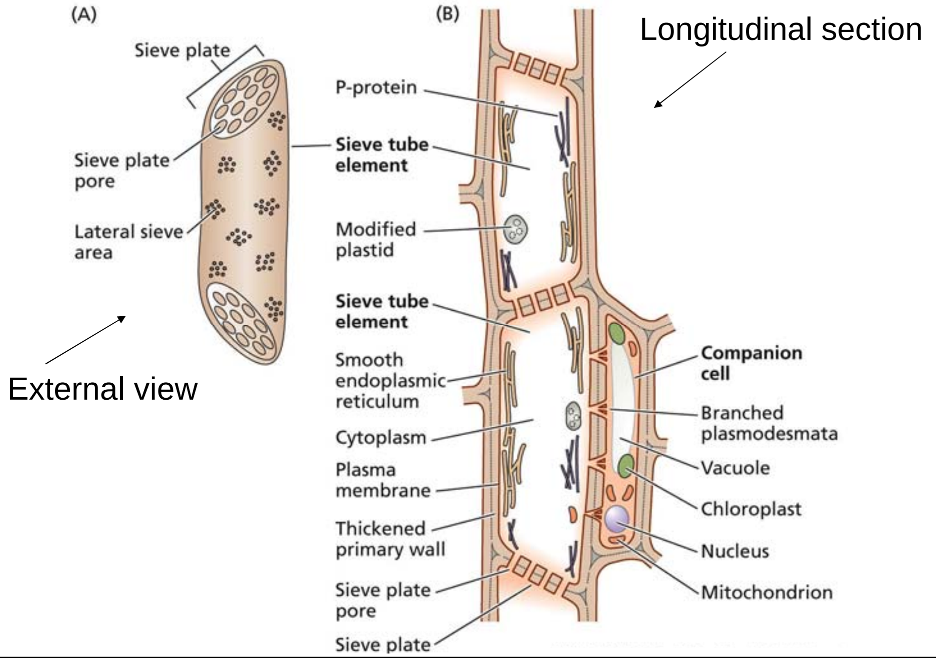

Stem Vascular Bundle



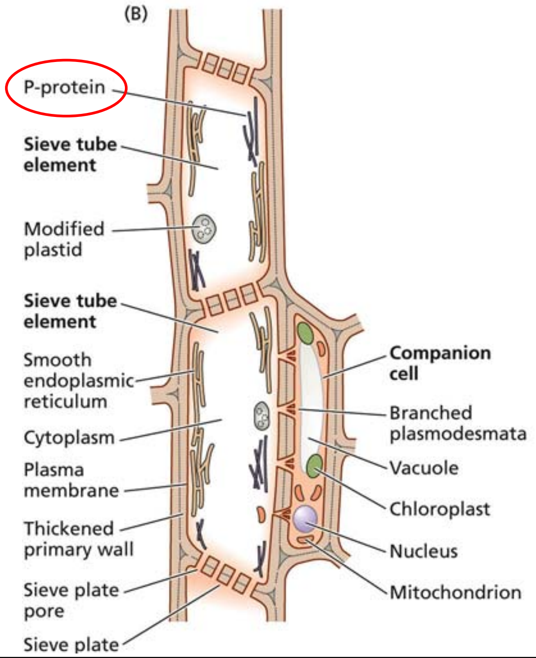

Leaf Midrib

Phloem is always in close proximity to xylem.

## Sieve elements are highly specialized for translocation




## Sieve elements are highly specialized for translocation



## Three different types of companion cells

**Ordinary companion cells**

- have chloroplasts
- few plasmodesmata between companion cell and surrounding cells, except for own sieve elements
- symplast of sieve element and its companion cell is relatively isolated from surrounding cells

**Transfer cells**

- similar to ordinary companion cells
- develop fingerlike wall ingrowths, particularly on walls that face away from sieve element
- wall ingrowths increase surface area of plasma membrane (increases potential for solute transfer across membrane)

**Intermediary cells**

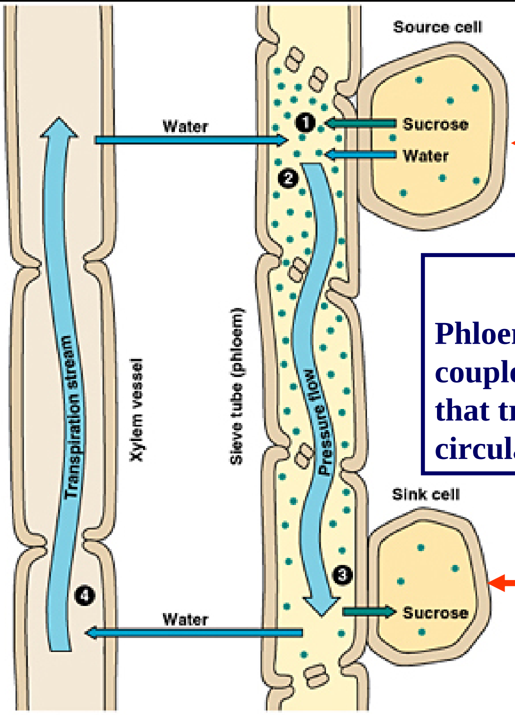
- have numerous plasmodesmata connecting them to bundle sheath cells
- have many small vacuoles
- poorly developed thylakoids and lack of starch grains

Phloem transport

Velocities ≈ 1 m $hour^{-1}$ , much faster than diffusion

*What is the mechanism of phloem transport?*

*What causes flow?, What's the source of energy?*



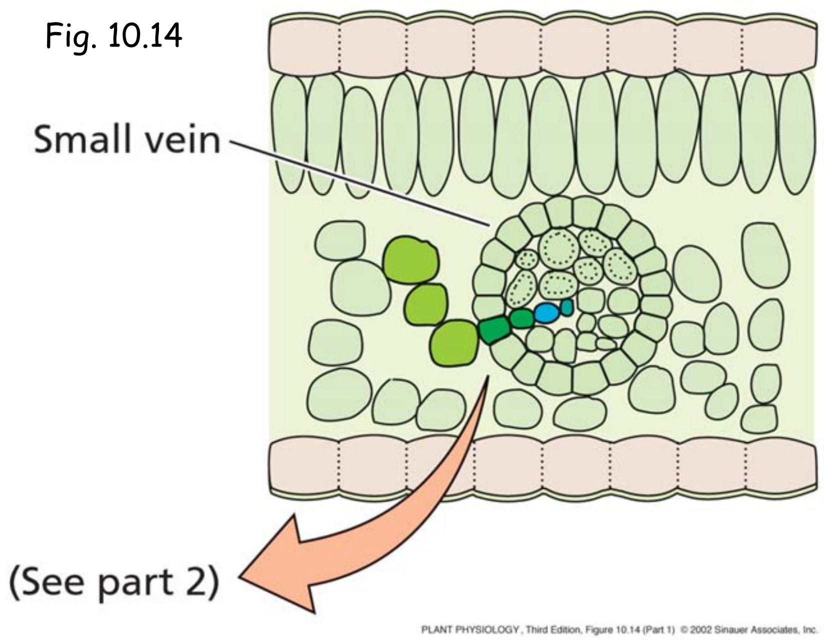

Physiological process of loading sucrose into the phloem

***Pressure-flow***

**Phloem and xylem are coupled in an osmotic system that transports sucrose and circulates water.**

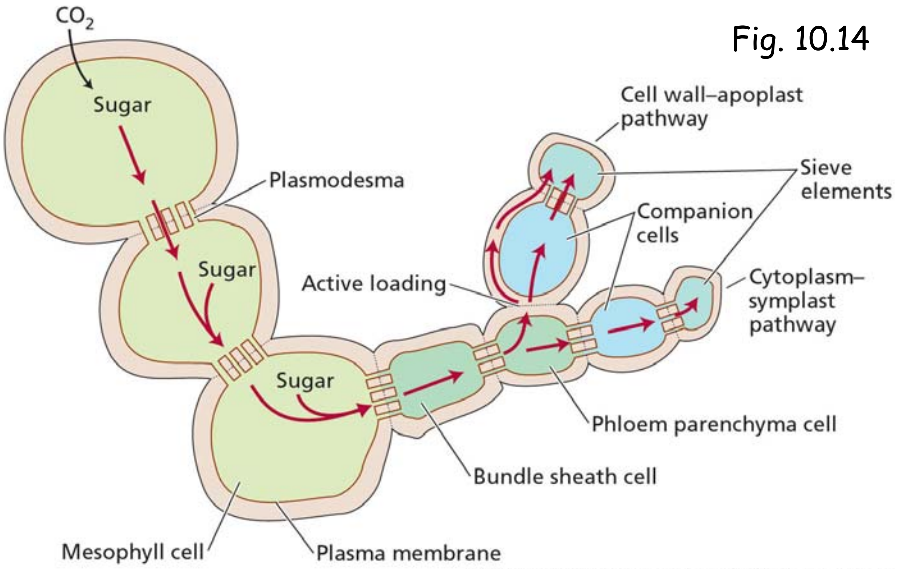
Physiological process of unloading sucrose from the phloem into the sink

Sugars are moved from photosynthetic cells and actively (energy) loaded into companion cells.



Sugars are moved from photosynthetic cells and actively (energy) loaded into companion & sieve cells.
*The concentrating of sugars in sieve cells drives the osmotic uptake of water.*

Fig. 10.14





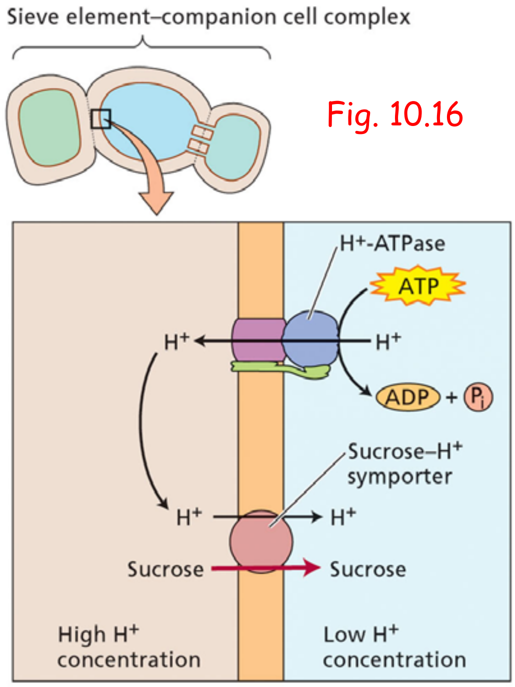
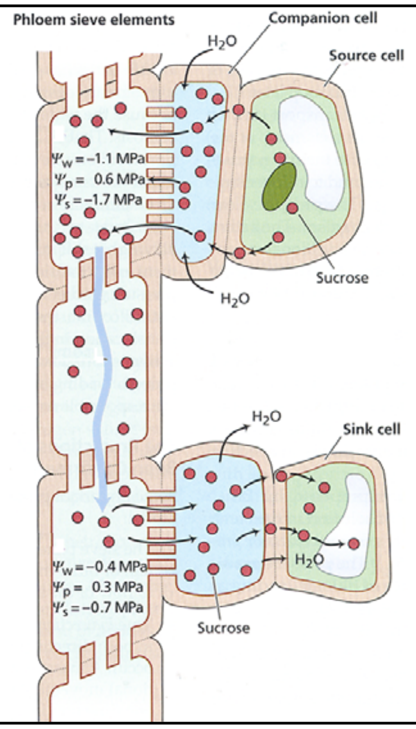






Fig. 10.16

Phloem loading uses a proton/sucrose symport.




# Pressure- Flow-Hypothesis

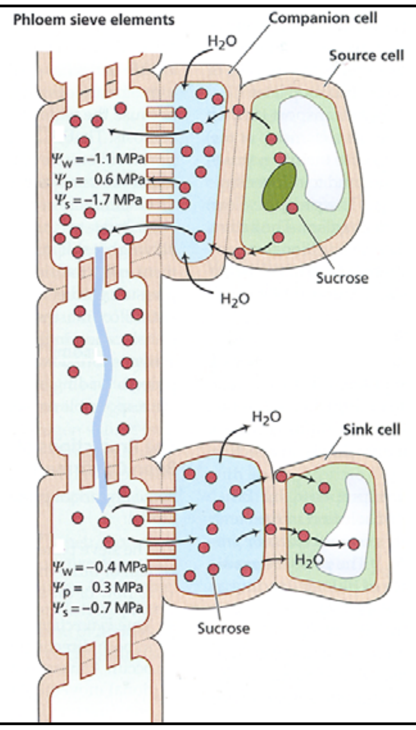
*Munch* Hypothesis

**Source**

- High concentration of sucrose, via photosynthesis,
  - Δ[sucrose] drives diffusion,
- Active $H^+$-ATPase,
  - electrochemical gradient drives **symporters**,
- - $\Psi_s$ builds, water enters the cell, + $\Psi_p$ builds.

**Sink**

- Low concentration of sucrose,
  - Δ[sucrose] drives diffusion,
- Active $H^+$-ATPase,
  - *electrochemical gradient drives **antiporters**,*
  - - $\Psi_s$ drops, water exits the cell, $\Psi_p$ drops.

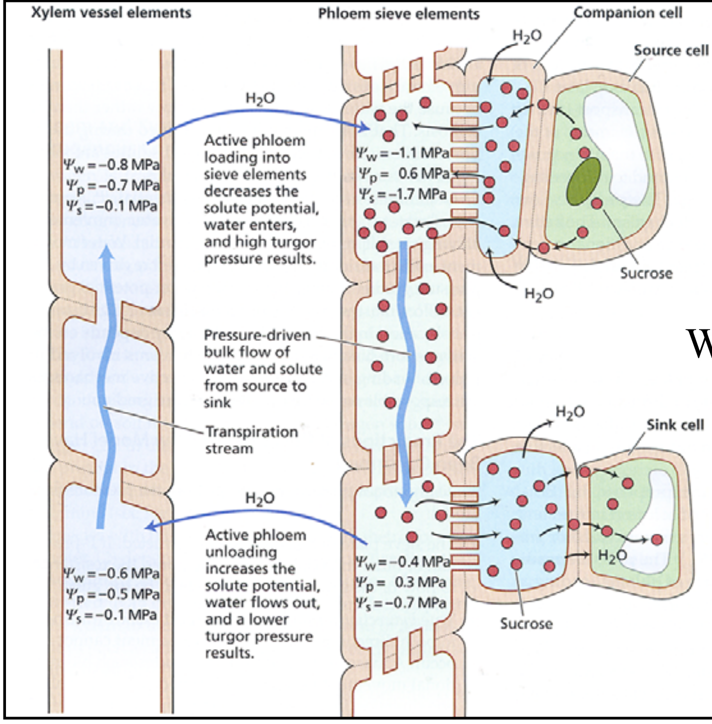



# **Pressure**-Flow-Hypothesis

$\Psi_p$

- Notice that the $\Psi_s$ at the **source** is ***more*** negative than at the sink!
- Why don't we expect water to flow toward the source?

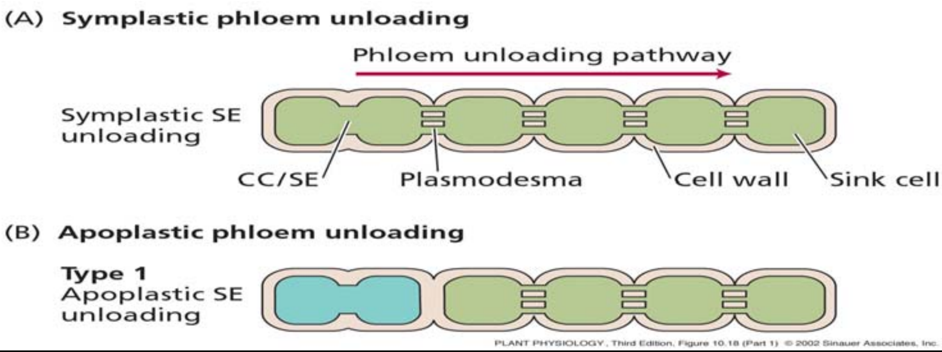
**Water, along with solutes moves down the pressure gradient, not the water potential gradient.**




Water Cycling

# Phloem unloading

- ***Apoplastic***: three types
- (1) [B] One step, transport from the sieve element-companion cell complex to successive sink cells, occurs in the apoplast.
- Once sugars are taken back into the symplast of adjoining cells transport is symplastic



## The pressure-flow model (Münch, 1930s)

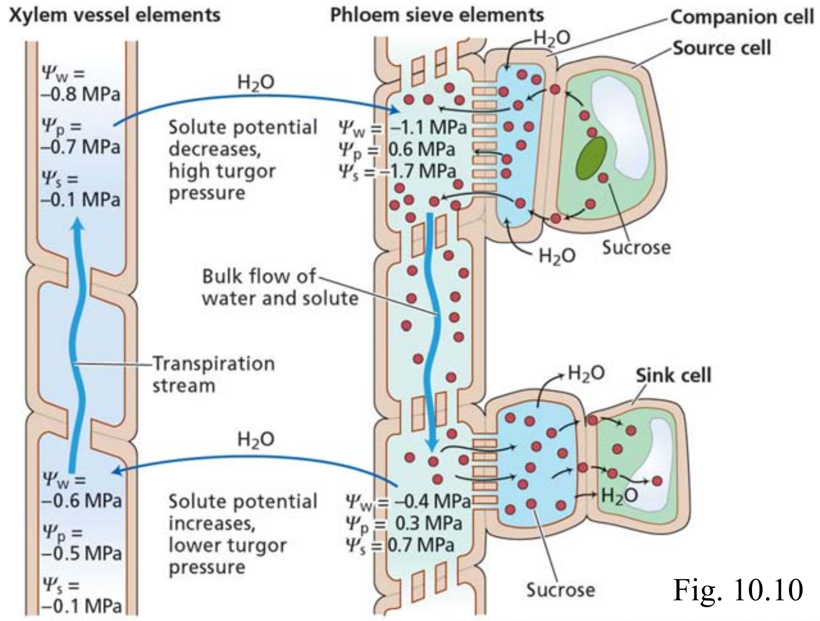



Fig. 10.10



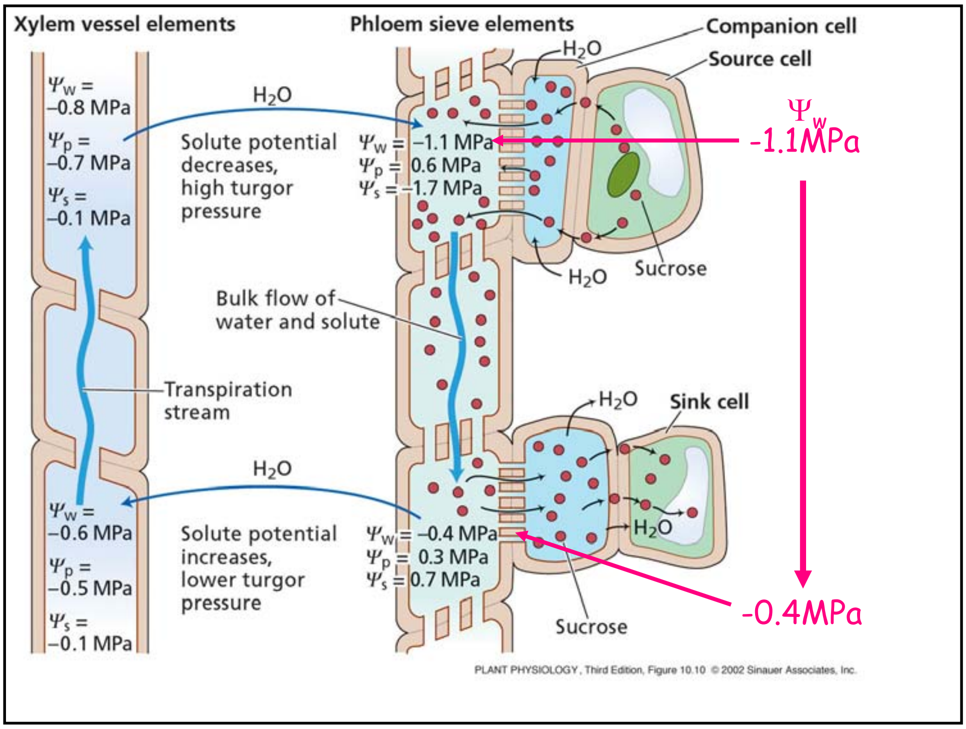
## The pressure-flow model of phloem translocation

At source end of pathway

- Active transport of sugars into sieve cells
- $\Psi_s$ and $\Psi_w$ decrease
- Water flows into sieve cells and turgor increases

At sink end of pathway

- Unloading of sugars
- $\Psi_s$ and $\Psi_w$ increase
- Water flows out of sieve cells and turgor decreases


Xylem vessel elements
Phloem sieve elements
Companion cell
Source cell
H2O
Ψw = −0.8 MPa
Ψp = −0.7 MPa
Ψs = −0.1 MPa
Solute potential decreases, high turgor pressure
Ψw = −1.1 MPa
Ψp = 0.6 MPa
Ψs = −1.7 MPa
Ψw
-1.1MPa
Sucrose
Bulk flow of water and solute
Transpiration stream
Sink cell
Ψw = −0.6 MPa
Ψp = −0.5 MPa
Ψs = −0.1 MPa
Solute potential increases, lower turgor pressure
Ψw = −0.4 MPa
Ψp = 0.3 MPa
Ψs = 0.7 MPa
-0.4MPa
PLANT PHYSIOLOGY, Third Edition, Figure 10.10 © 2002 Sinauer Associates, Inc.

## Photosynthesis Overview

Energy for all life on Earth ultimately comes from photosynthesis.

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

Oxygenic photosynthesis is carried out by:
cyanobacteria, 7 groups of algae,
all land plants

1

## Photosynthesis Overview

Photosynthesis is divided into:

**light-dependent reactions**

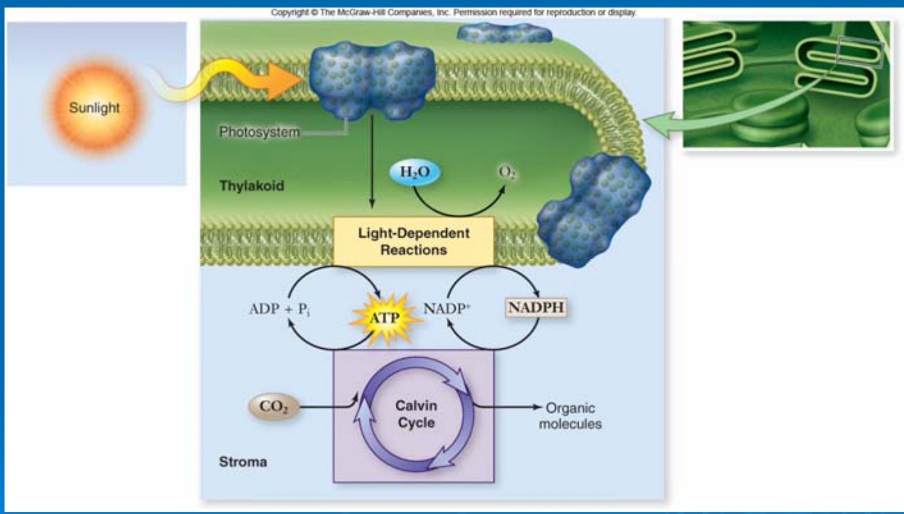
-capture energy from sunlight

-make ATP and reduce $NADP^+$ to NADPH

**carbon fixation reactions**

-use ATP and NADPH to synthesize organic molecules from $CO_2$

2




3

# Photosynthesis Overview

Photosynthesis takes place in chloroplasts.

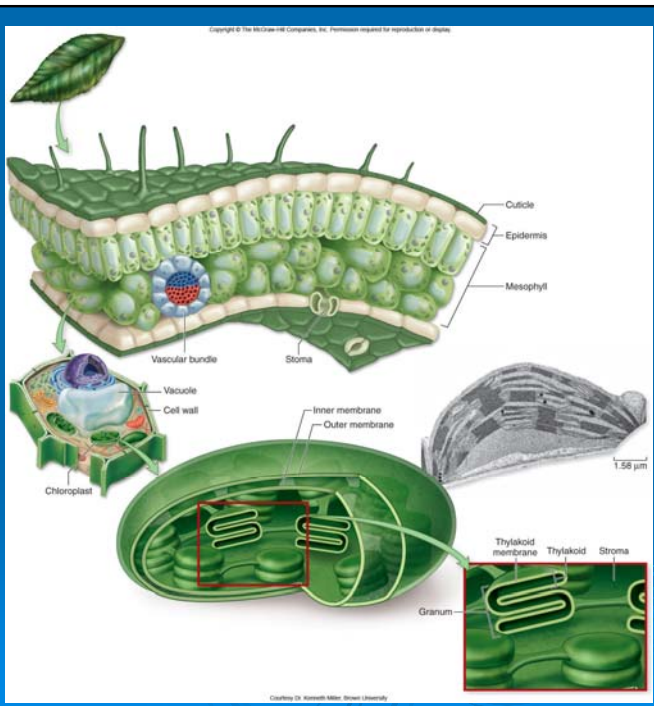
**thylakoid membrane** – internal membrane arranged in flattened sacs

-contain **chlorophyll** and other pigments

**grana** – stacks of thylakoid membranes

**stroma** – semiliquid substance surrounding thylakoid membranes

4




5

# Discovery of Photosynthesis

The work of many scientists led to the discovery of how photosynthesis works.

Jan Baptista van Helmont (1580-1644)
Joseph Priestly (1733-1804)
Jan Ingen-Housz (1730-1799)
F. F. Blackman (1866-1947)

6

## Discovery of Photosynthesis

C. B. van Niel, 1930's

-proposed a general formula:

$CO_2$+$H_2A$ + light energy → $CH_2O$ + $H_2O$ + 2A

where $H_2A$ is the electron donor

-van Niel identified water as the source of the $O_2$ released from photosynthesis

-Robin Hill confirmed van Niel's proposal that energy from the light reactions fuels carbon fixation

7

## Pigments

**photon**: a particle of light

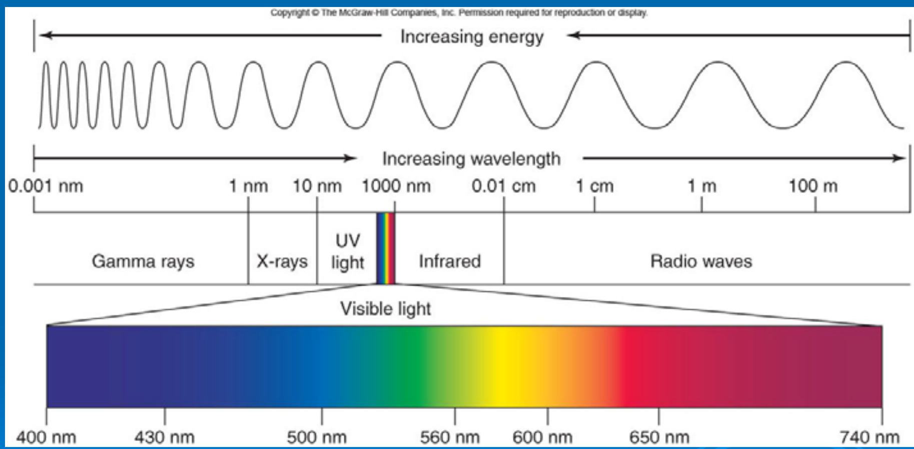
-acts as a discrete bundle of energy

-energy content of a photon is inversely proportional to the wavelength of the light

**photoelectric effect**: removal of an electron from a molecule by light

-occurs when photons transfer energy to electrons

8

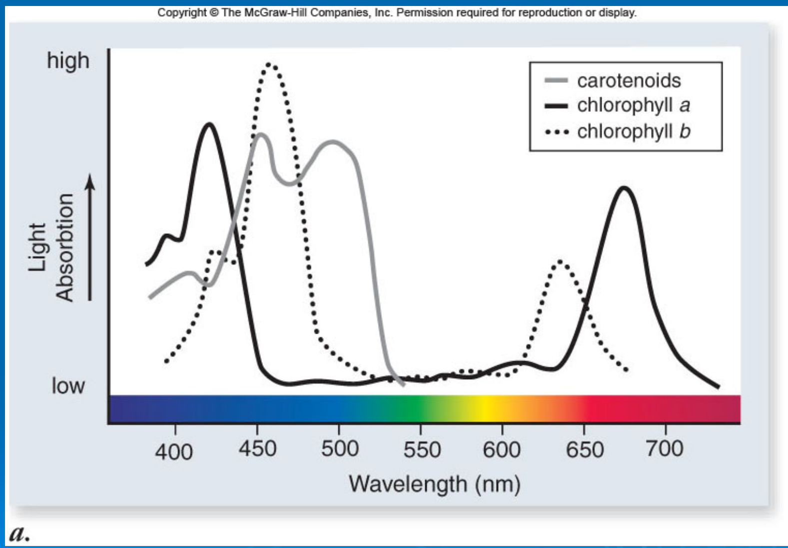





# Pigments

**Pigments**: molecules that absorb visible light

Each pigment has a characteristic **absorption spectrum**, the range and efficiency of photons it is capable of absorbing.




11

# Pigments

**chlorophyll a** – primary pigment in plants and cyanobacteria

-absorbs violet-blue and red light

**chlorophyll b** – secondary pigment absorbing light wavelengths that chlorophyll a does not absorb

12

# Pigments

Structure of pigments:

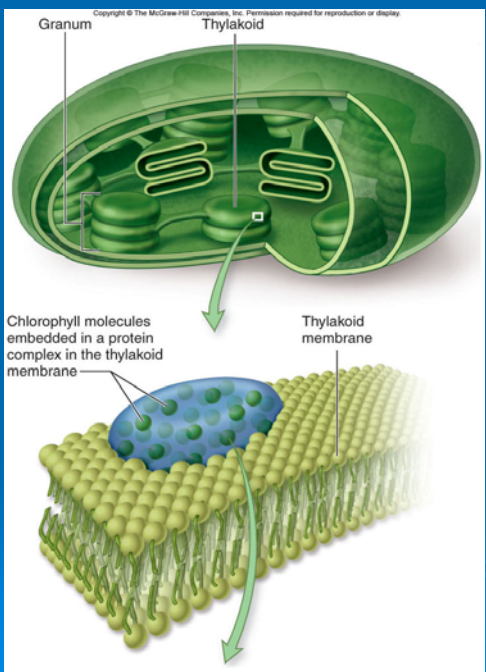
**porphyrin ring**: complex ring structure with alternating double and single bonds

-magnesium ion at the center of the ring

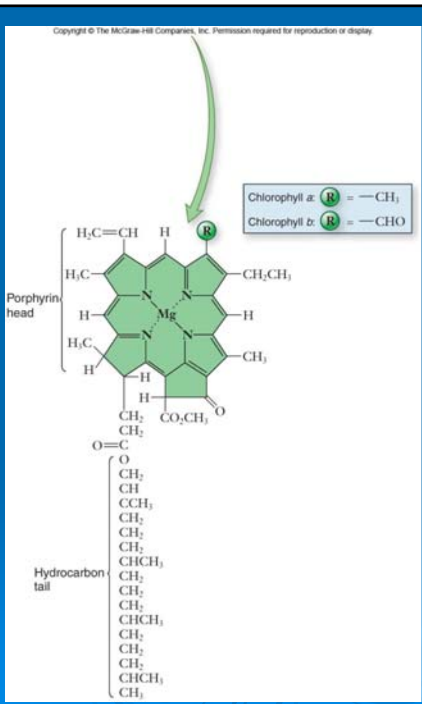
-photons excite electrons in the ring

-electrons are shuttled away from the ring

13




14




15

# Pigments

**accessory pigments**: secondary pigments absorbing light wavelengths other than those absorbed by chlorophyll a

-increase the range of light wavelengths that can be used in photosynthesis

-include: chlorophyll b, carotenoids, phycobiloproteins

-carotenoids also act as antioxidants

16

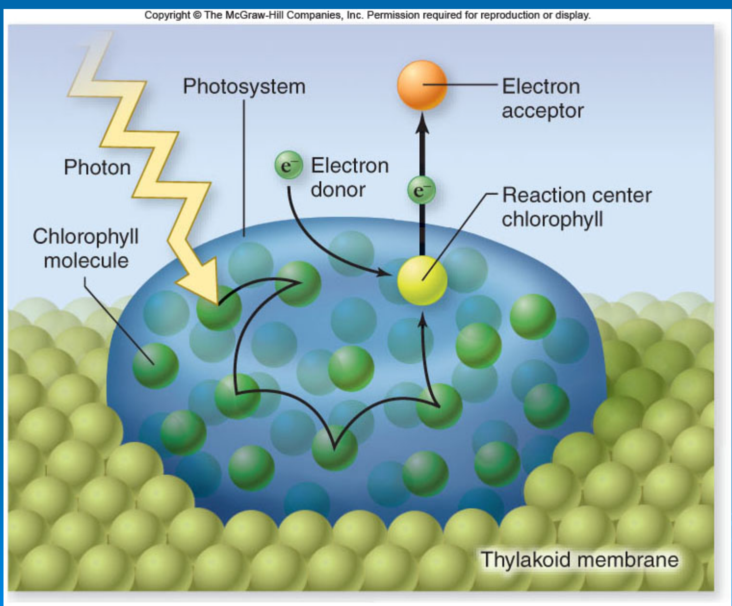
# Photosystem Organization

A **photosystem** consists of

1. an **antenna complex** of hundreds of accessory pigment molecules
2. a **reaction center** of one or more chlorophyll a molecules

Energy of electrons is transferred through the antenna complex to the reaction center.

17




18

## Photosystem Organization

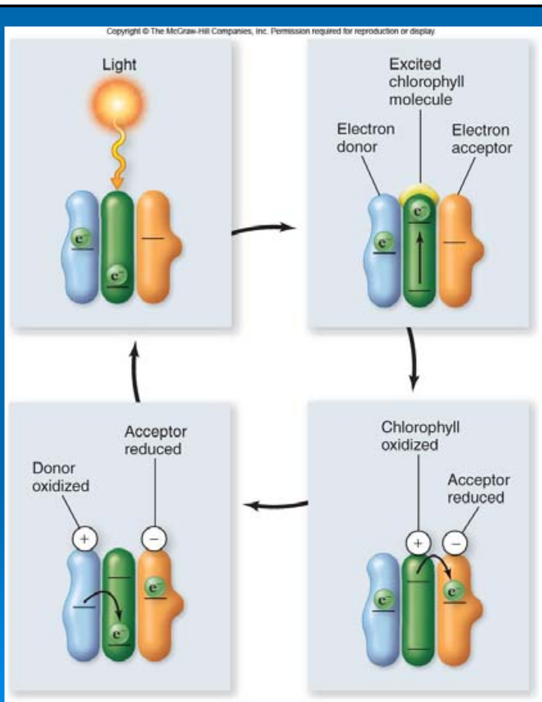
At the reaction center, the energy from the antenna complex is transferred to chlorophyll a.

This energy causes an electron from chlorophyll to become *excited.*

The excited electron is transferred from chlorophyll a to an electron acceptor.

Water donates an electron to chlorophyll a to replace the excited electron.

19




20

## Light-Dependent Reactions

Light-dependent reactions occur in 4 stages:

1. primary photoevent – a photon of light is captured by a pigment molecule
2. charge separation – energy is transferred to the reaction center; an excited electron is transferred to an acceptor molecule
3. electron transport – electrons move through carriers to reduce $NADP^+$
4. chemiosmosis – produces ATP

21

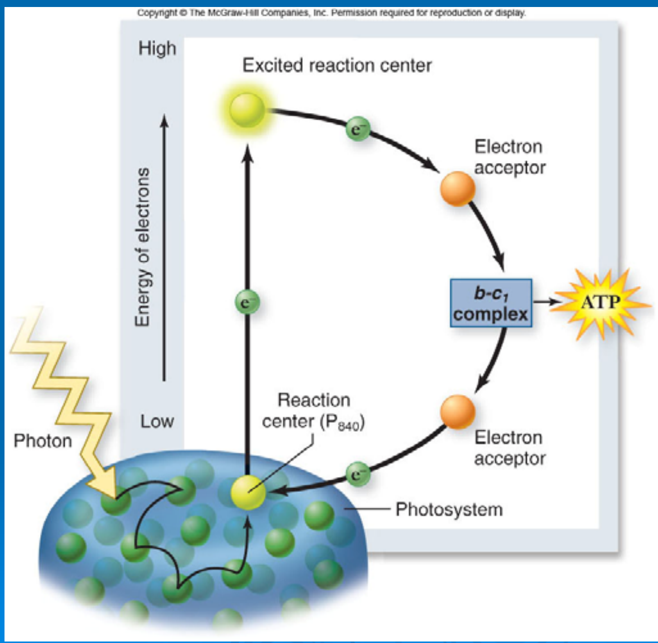
## Light-Dependent Reactions

In sulfur bacteria, only one photosystem is used for **cyclic photophosphorylation**

1. an electron joins a proton to produce hydrogen
2. an electron is recycled to chlorophyll

-this process drives the chemiosmotic synthesis of ATP

22




# Light-Dependent Reactions

In chloroplasts, two linked photosystems are used in **noncyclic photophosphorylation**

1. **photosystem I**

   -reaction center pigment ($P_{700}$) with a peak absorption at 700nm

2. **photosystem II**

   -reaction center pigment ($P_{680}$) has a peak absorption at 680nm

24

## Light-Dependent Reactions

Photosystem II acts first:

-accessory pigments shuttle energy to the $P_{680}$ reaction center

-excited electrons from $P_{680}$ are transferred to ***$b_6$-f* complex**

-electron lost from $P_{680}$ is replaced by an electron released from the splitting of water



## Light-Dependent Reactions

The ***$b_6$-f* complex** is a series of electron carriers.

-electron carrier molecules are embedded in the thylakoid membrane

-protons are pumped into the thylakoid space to form a proton gradient

## Light-Dependent Reactions

Photosystem I

-receives energy from an antenna complex

-energy is shuttled to $P_{700}$ reaction center

-excited electron is transferred to a membrane-bound electron carrier

-electrons are used to reduce $NADP^+$ to NADPH

-electrons lost from $P_{700}$ are replaced from the *$b_6$-f* complex

27

## Light-Dependent Reactions

ATP is produced via chemiosmosis.

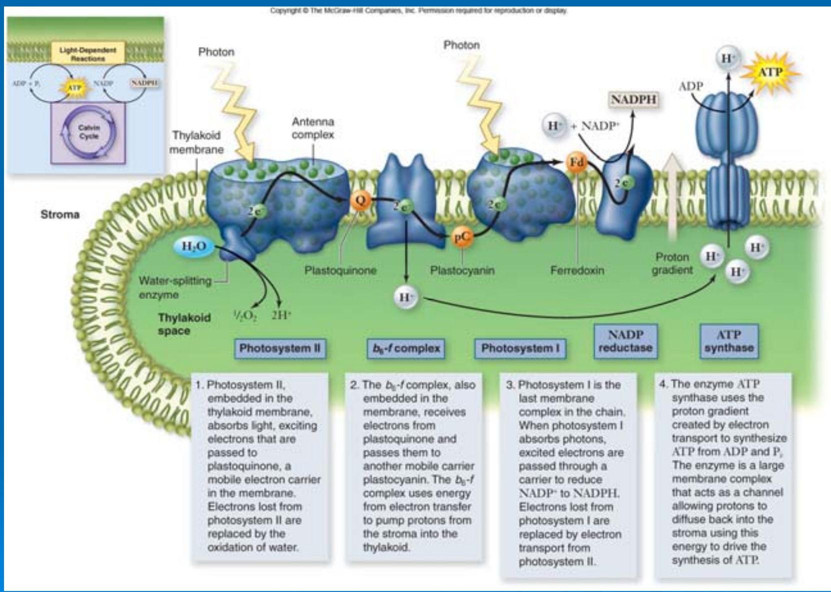
- **ATP synthase** is embedded in the thylakoid membrane

-protons have accumulated in the thylakoid space

-protons move into the stroma only through ATP synthase

-ATP is produced from ADP + $P_i$

28




29

# Carbon Fixation Reactions

To build carbohydrates, cells need:

1. energy
   -ATP from light-dependent reactions

2. reduction potential
   -NADPH from photosystem I

30

## Carbon Fixation Reactions

**Calvin cycle**

-biochemical pathway that allows for carbon fixation

-occurs in the stroma

-uses ATP and NADPH as energy sources

-incorporates $CO_2$ into organic molecules

31

## Carbon Fixation Reactions

**carbon fixation** – the incorporation of $CO_2$ into organic molecules

-occurs in the first step of the Calvin cycle

| ribulose-bis-phosphate | + $CO_2$ → | 2(PGA) |
|---|---|---|
| 5 carbons | 1 carbon | 3 carbons |

The reaction is catalyzed by **rubisco**.

32

# Carbon Fixation Reactions

The Calvin cycle has 3 phases:

1. carbon fixation

   RuBP + $CO_2$ ⟶ 2 molecules PGA

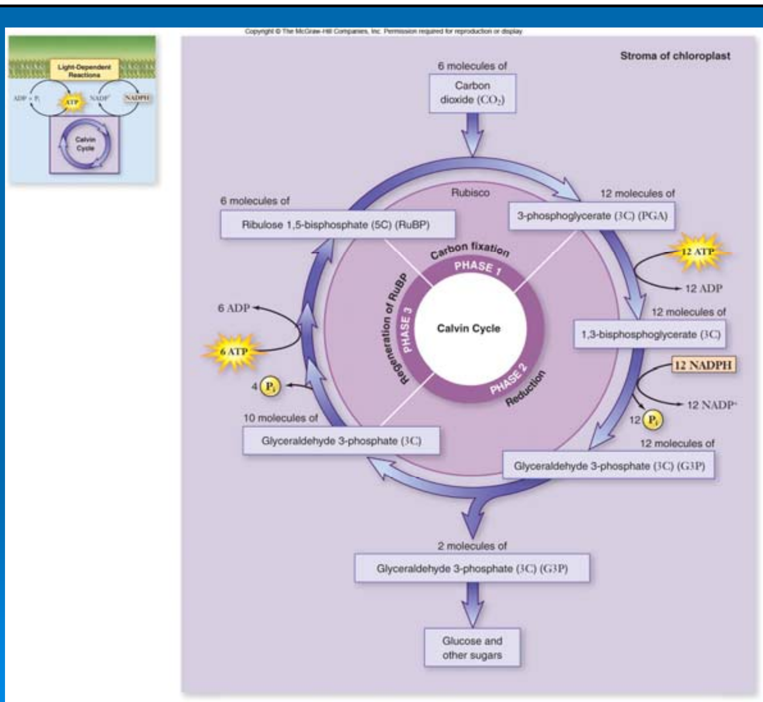
2. reduction

   PGA is reduced to G3P

3. regeneration of RuBP

   G3P is used to regenerate RuBP

33




34

## Carbon Fixation Reactions

Glucose is not a direct product of the Calvin cycle.

-2 molecules of G3P leave the cycle

-each G3P contains 3 carbons

-2 G3P are used to produce 1 glucose in reactions in the cytoplasm

35

## Carbon Fixation Reactions

During the Calvin cycle, energy is needed. The energy is supplied from:

- 18 ATP molecules
- 12 NADPH molecules

36

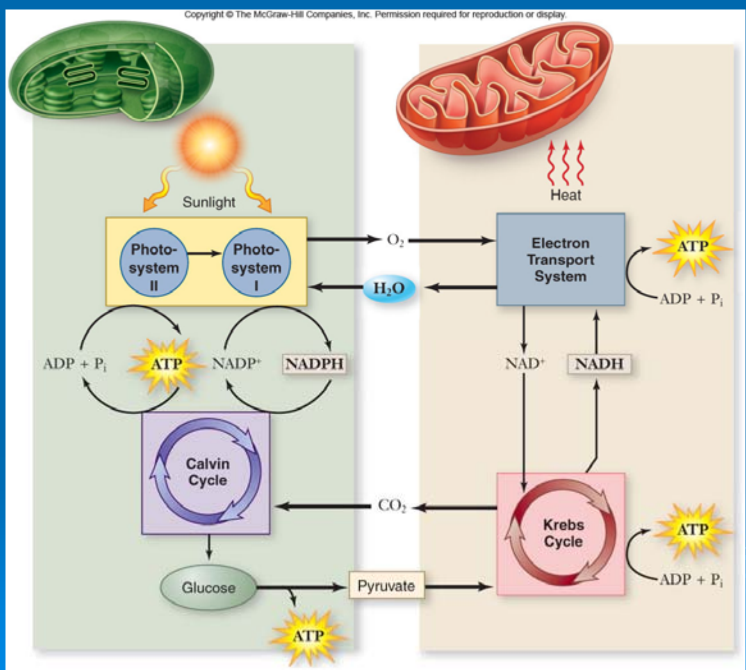
# Carbon Fixation Reactions

The energy cycle:

-photosynthesis uses the products of respiration as starting substrates

-respiration uses the products of photosynthesis as starting substrates

37




38

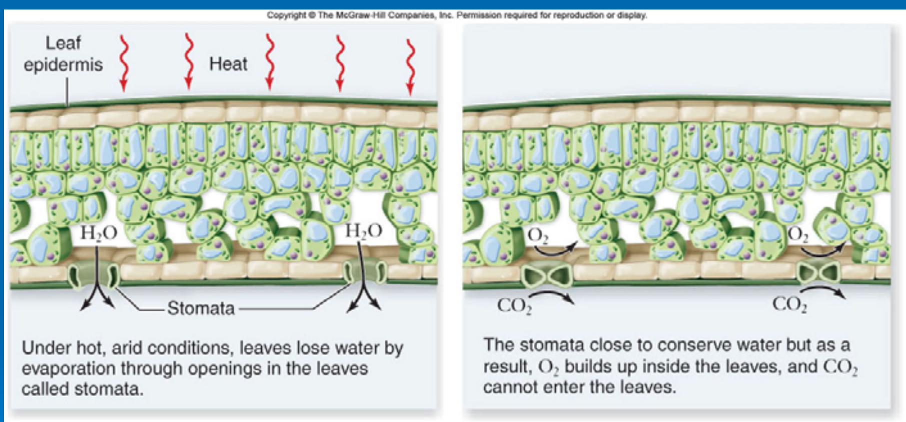
## Photorespiration

Rubisco has 2 enzymatic activities:

1. carboxylation – the addition of $CO_2$ to RuBP
   -favored under normal conditions
2. **photorespiration** – the oxidation of RuBP by the addition of $O_2$
   -favored in hot conditions

$CO_2$ and $O_2$ compete for the active site on RuBP.

39




40

## Photorespiration

Some plants can avoid photorespiration by using an enzyme other than rubisco.

-**PEP carboxylase**

-$CO_2$ is added to phosphoenolpyruvate (PEP)

-a 4 carbon compound is produced

-$CO_2$ is later released from this 4-carbon compound and used by rubisco in the Calvin cycle

41

## Photorespiration

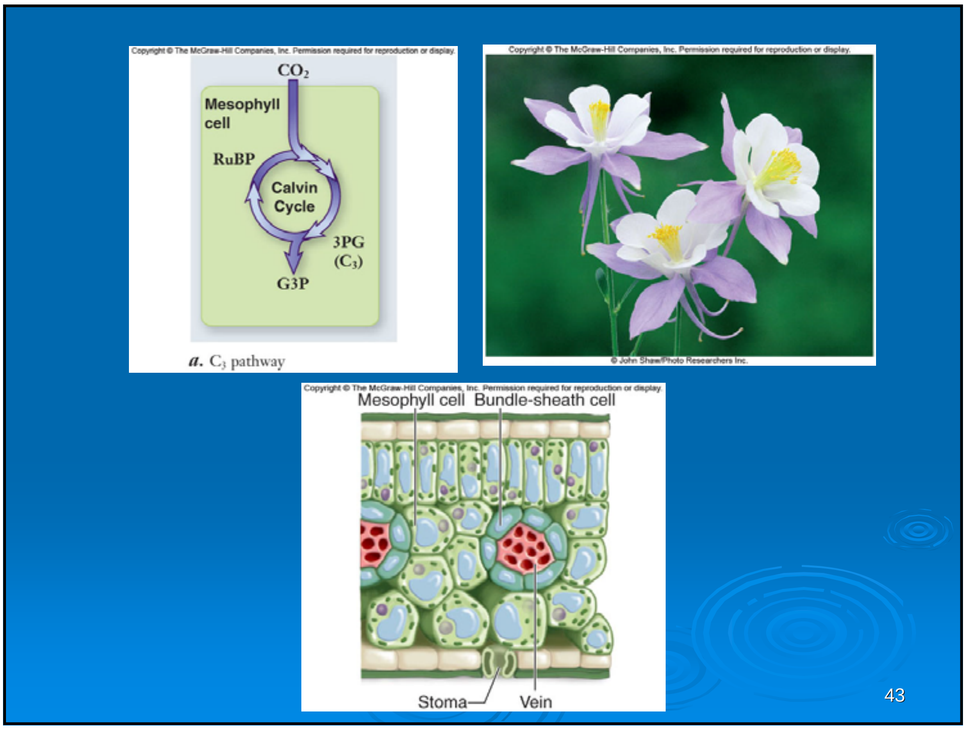
**$C_4$ plants**

-use PEP carboxylase to capture $CO_2$

-$CO_2$ is added to PEP in one cell type (mesophyll cell)

-the resulting 4-carbon compound is moved into a bundle sheath cell where the $CO_2$ is released and used in the Calvin cycle

42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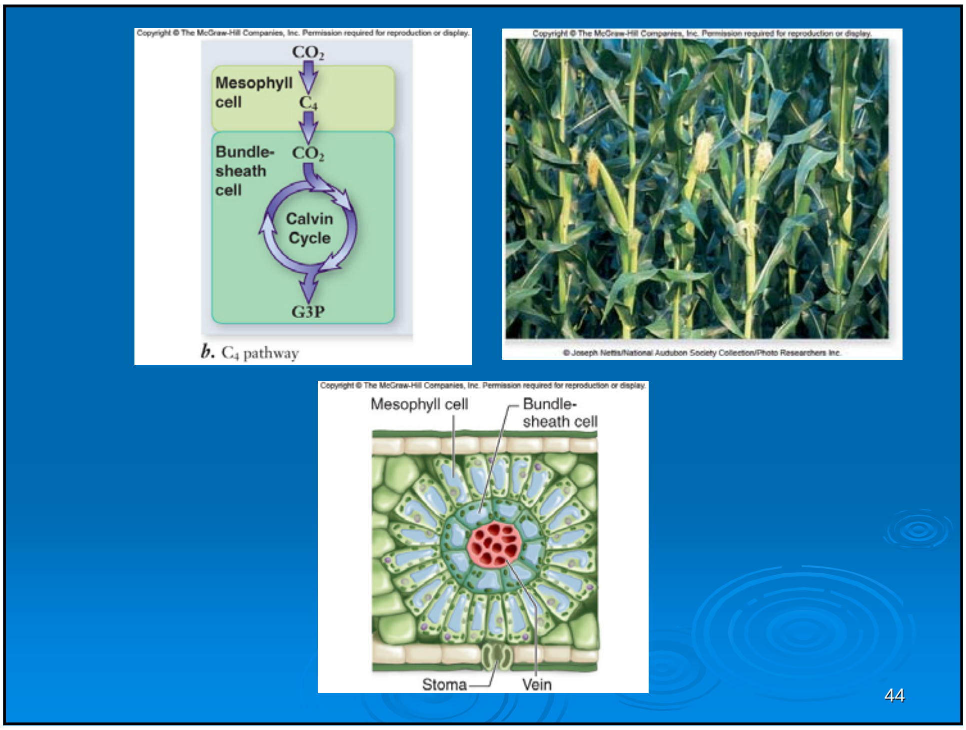
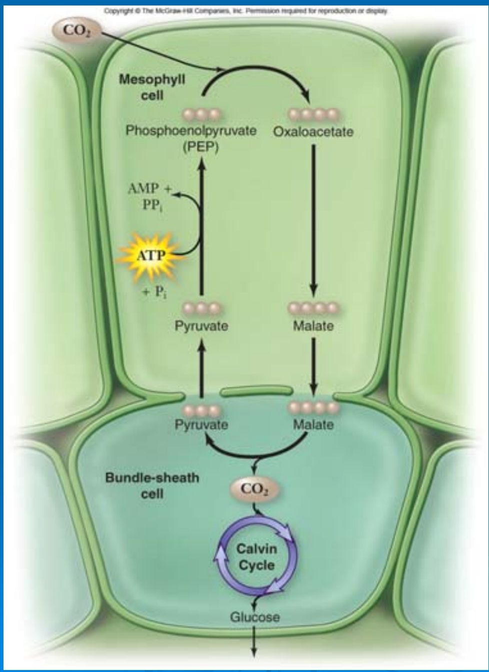
$CO_2$
Mesophyll cell
RuBP
Calvin Cycle
3PG ($C_3$)
G3P
*a.* $C_3$ pathway
© John Shaw/Photo Researchers Inc.
Mesophyll cell
Bundle-sheath cell
Stoma
Vein
43


Copyright © The McGraw-Hill Companies, Inc. Permission required for reproduction or display.
$CO_2$
Mesophyll cell
$C_4$
Bundle-sheath cell
$CO_2$
Calvin Cycle
G3P
*b.* $C_4$ pathway
© Joseph Nettis/National Audubon Society Collection/Photo Researchers Inc.
Mesophyll cell
Bundle-sheath cell
Stoma
Vein
44




45

# Photorespiration

**CAM plants**

-$CO_2$ is captured at night when stomata are open

-PEP carboxylase adds $CO_2$ to PEP to produce a 4 carbon compound

-this compound releases $CO_2$ during the day

-$CO_2$ is then used by rubisco in the Calvin cycle

46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night
$CO_2$
$C_4$
day
$CO_2$
Calvin Cycle
G3P
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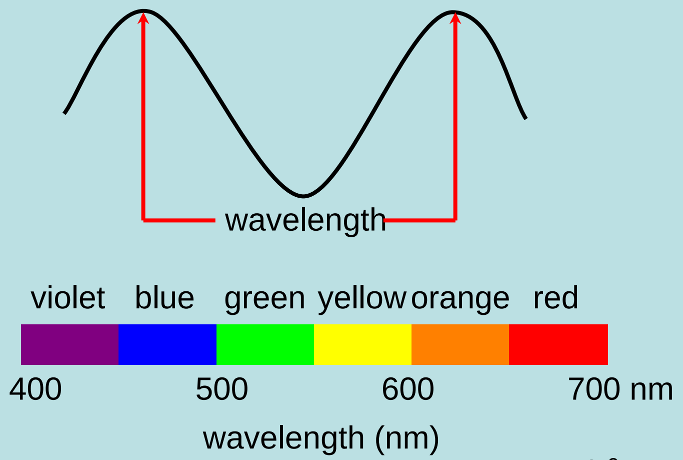
47

# Photosynthesis

The Source of most Biological Energy
Trapped in Photosynthesis
Energy Converted to Chemical Bonds

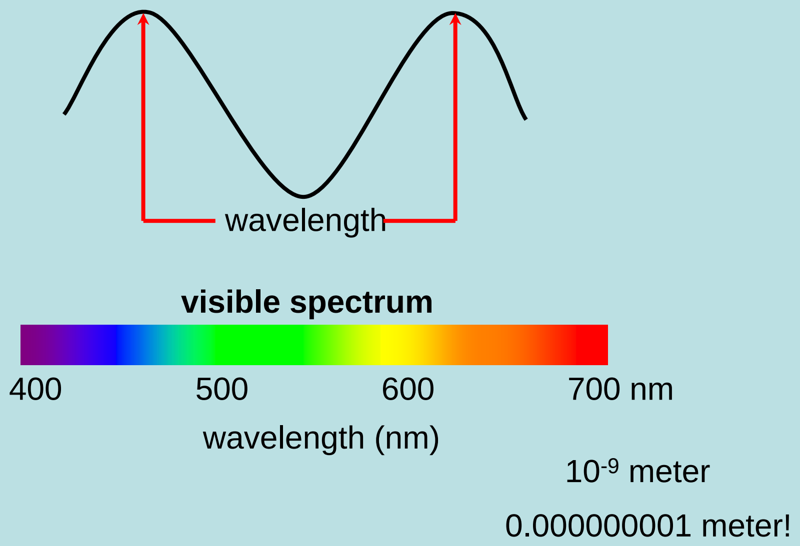
**Light:** An Energy Waveform With Particle Properties Too

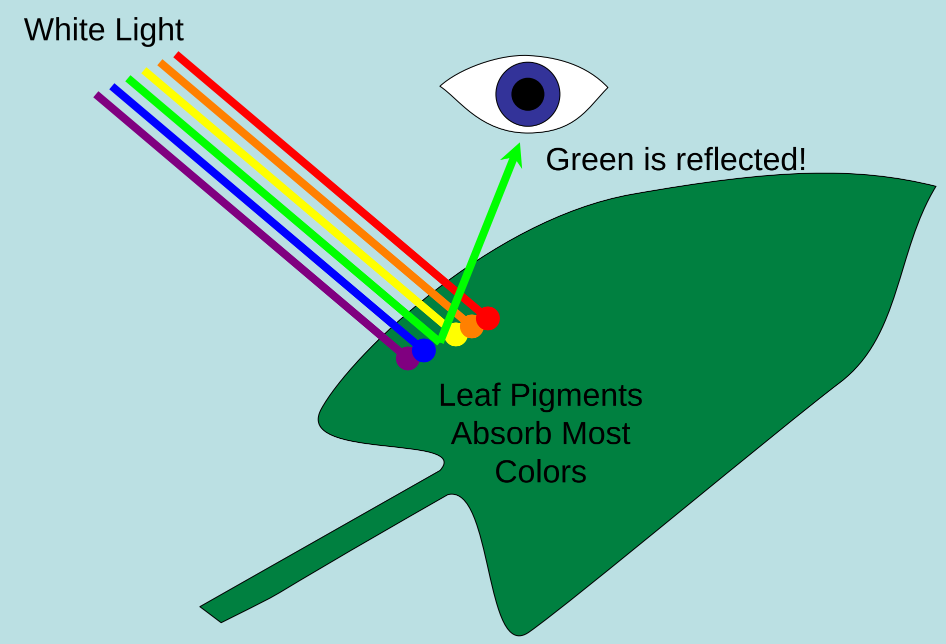



$10^{-9}$ meter

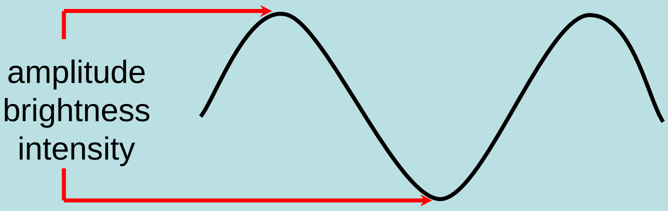
0.000000001 meter!

**Light:** An Energy Waveform With Particle Properties Too



**Light:** An Energy Waveform With Particle Properties Too




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

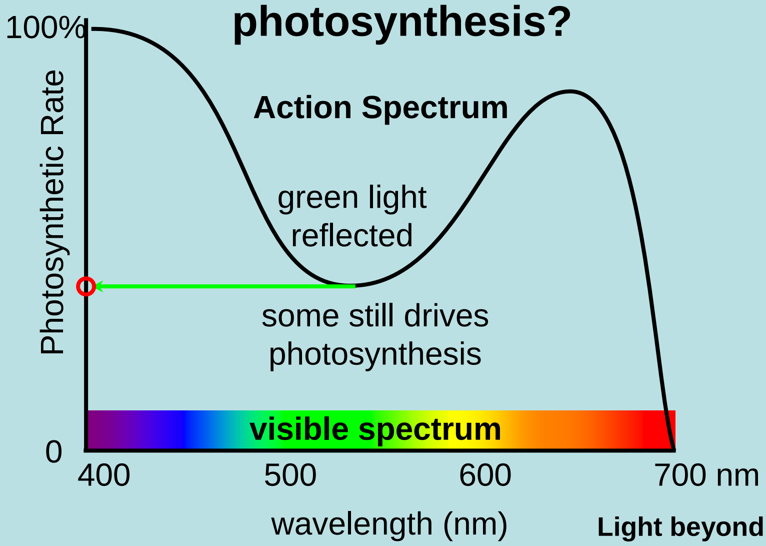
0 fc = darkness

100 fc = living room

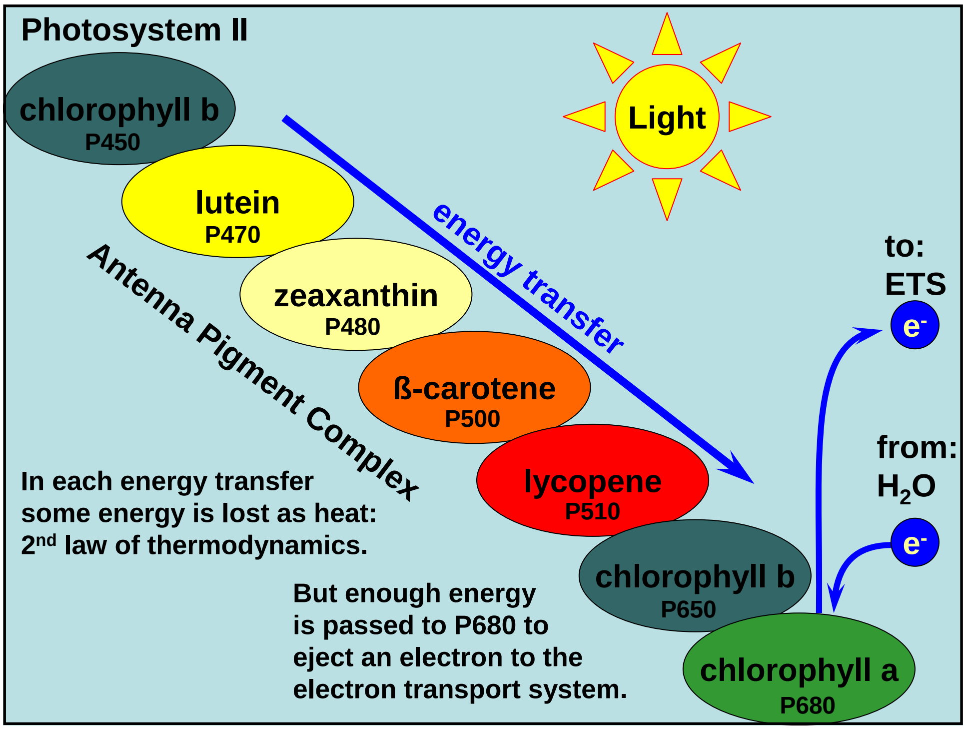
1,000 fc = CT winter day

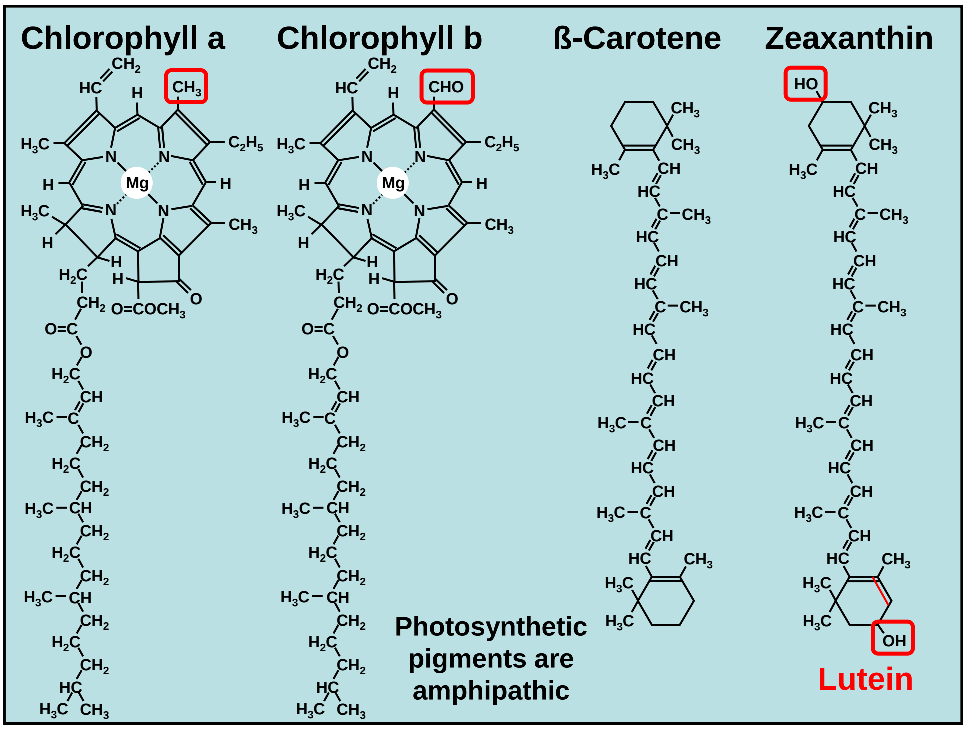
10,000 fc = June 21, noon, equator, 0 humidity

## What wavelengths of light drive photosynthesis?

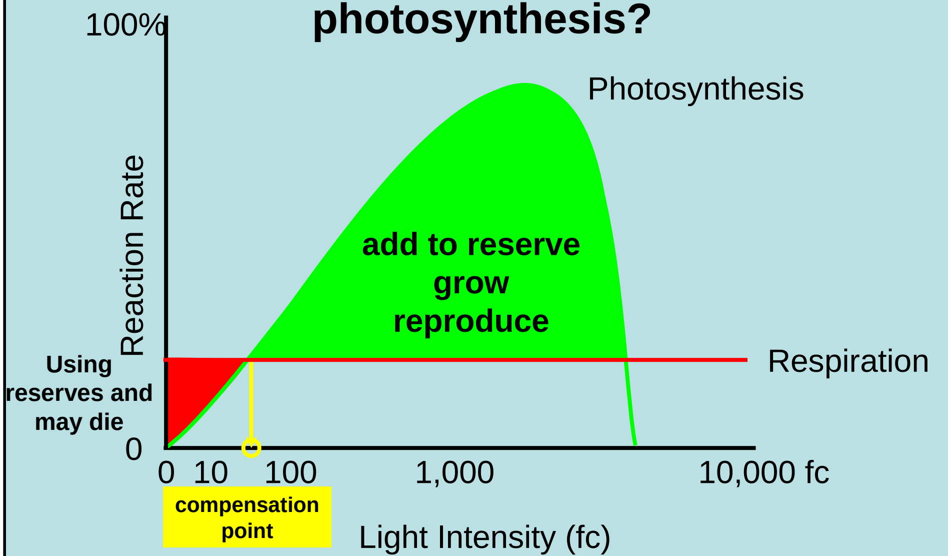



**Light beyond 700 nm has insufficient energy to drive photosynthesis**


Photosystem II
chlorophyll b
P450
lutein
P470
zeaxanthin
P480
ß-carotene
P500
lycopene
P510
chlorophyll b
P650
chlorophyll a
P680
Light
energy transfer
Antenna Pigment Complex
to:
ETS
e-
from:
H2O
e-
In each energy transfer
some energy is lost as heat:
2nd law of thermodynamics.
But enough energy
is passed to P680 to
eject an electron to the
electron transport system.

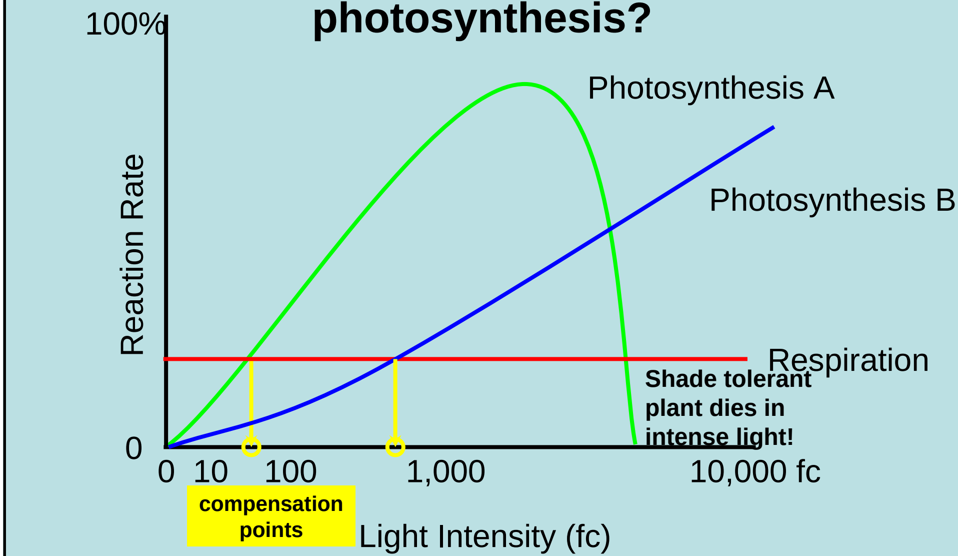

Chlorophyll a
Chlorophyll b
ß-Carotene
Zeaxanthin
Photosynthetic
pigments are
amphipathic
Lutein

## What intensities of light drive photosynthesis?



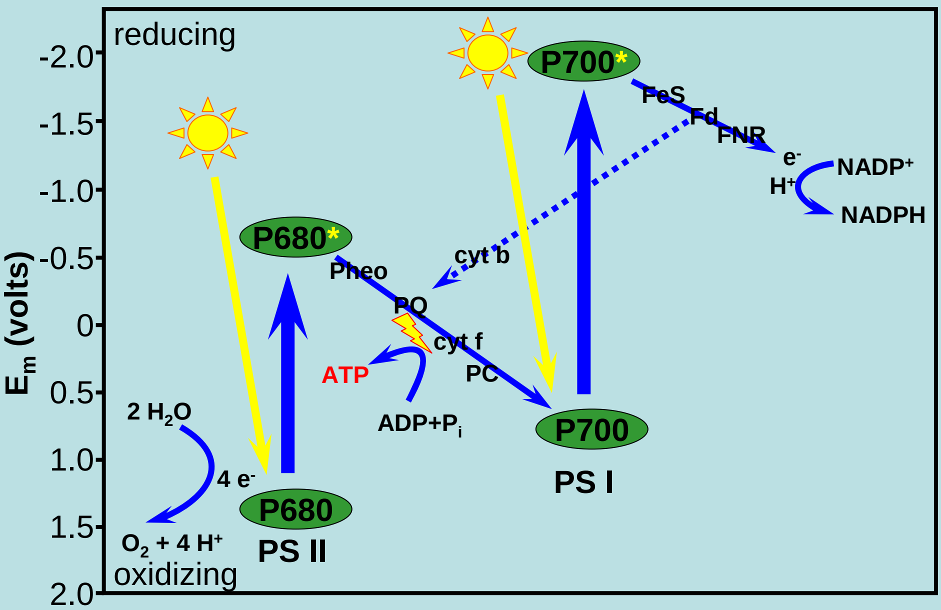

**The example plant shown here "breaks even" at an intensity we have in our homes…a house plant!**

## What intensities of light drive photosynthesis?

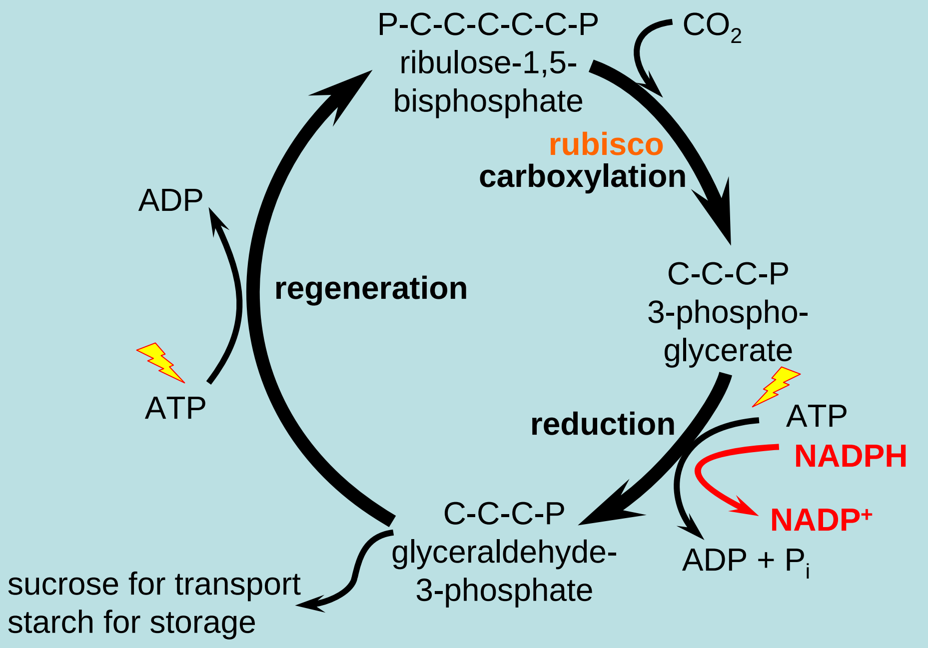


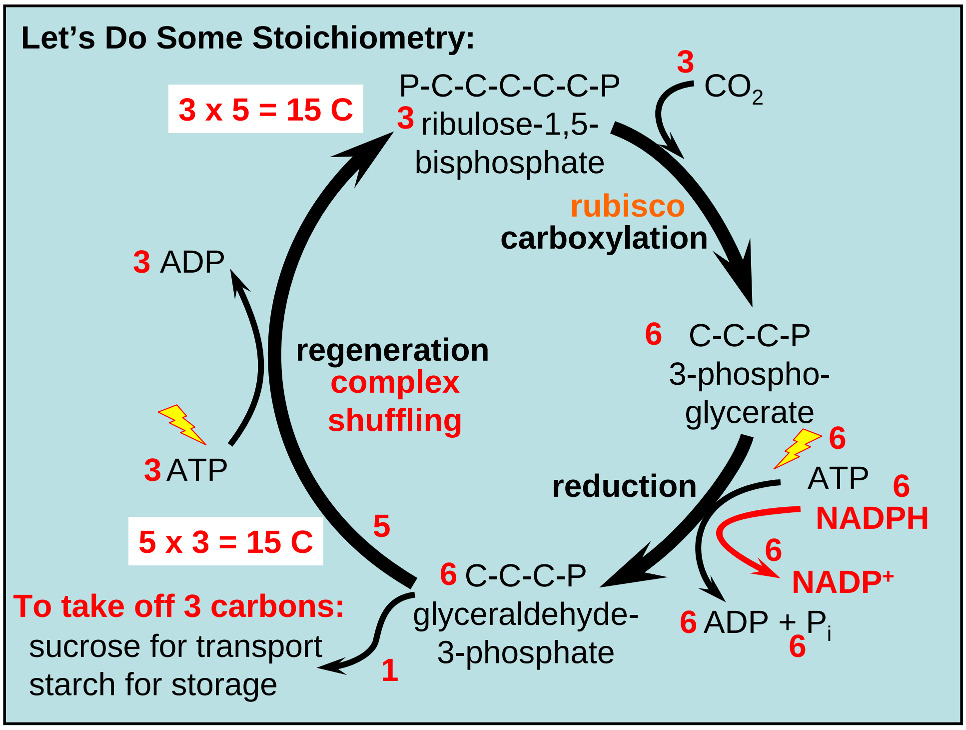

**The second example plant shown here cannot survive in our homes…it is a sun-loving crop plant!**

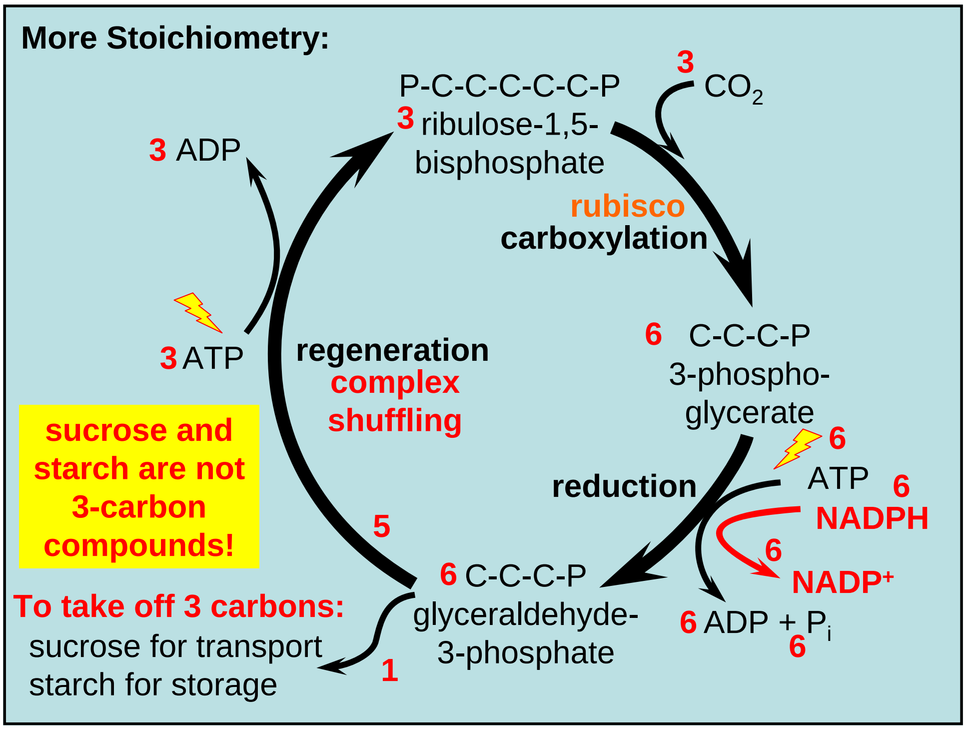
## The Light Reactions: An Energy Diagram



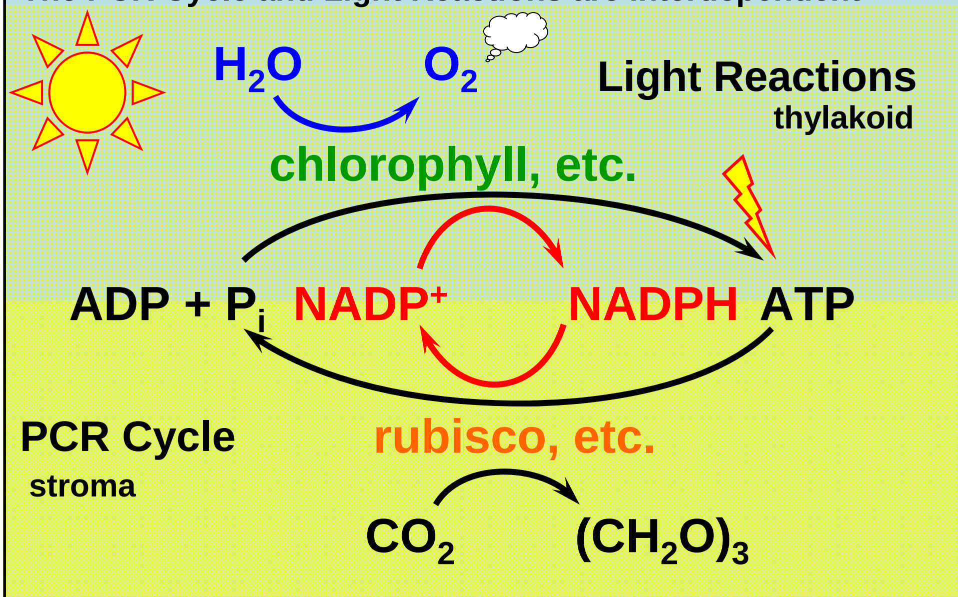

## The PCR Cycle has Three Phases




Let's Do Some Stoichiometry:
3 x 5 = 15 C
P-C-C-C-C-C-P
3 ribulose-1,5-bisphosphate
3 CO2
rubisco
carboxylation
6 C-C-C-P
3-phospho-glycerate
6 ATP
6 NADPH
6 NADP+
6 ADP + Pi
6
reduction
6 C-C-C-P
glyceraldehyde-3-phosphate
5
1
regeneration
complex
shuffling
3 ADP
3 ATP
5 x 3 = 15 C
To take off 3 carbons:
sucrose for transport
starch for storage

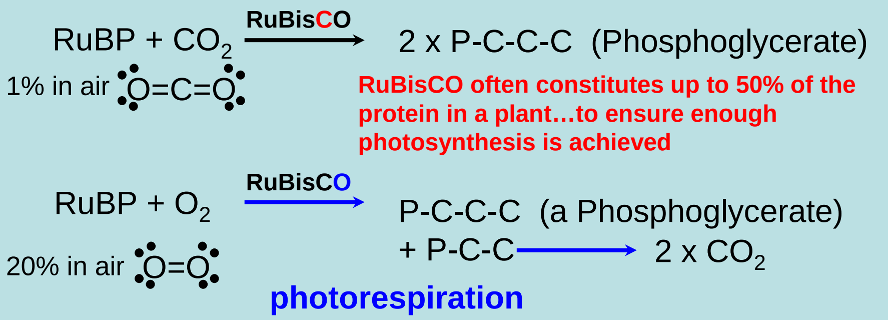

More Stoichiometry:
P-C-C-C-C-C-P
3 ribulose-1,5-bisphosphate
3 CO2
rubisco
carboxylation
6 C-C-C-P
3-phospho-glycerate
6 ATP
6 NADPH
6 NADP+
6 ADP + Pi
6
reduction
6 C-C-C-P
glyceraldehyde-3-phosphate
5
1
regeneration
complex
shuffling
3 ADP
3 ATP
sucrose and starch are not 3-carbon compounds!
To take off 3 carbons:
sucrose for transport
starch for storage

## The PCR Cycle and Light Reactions are interdependent

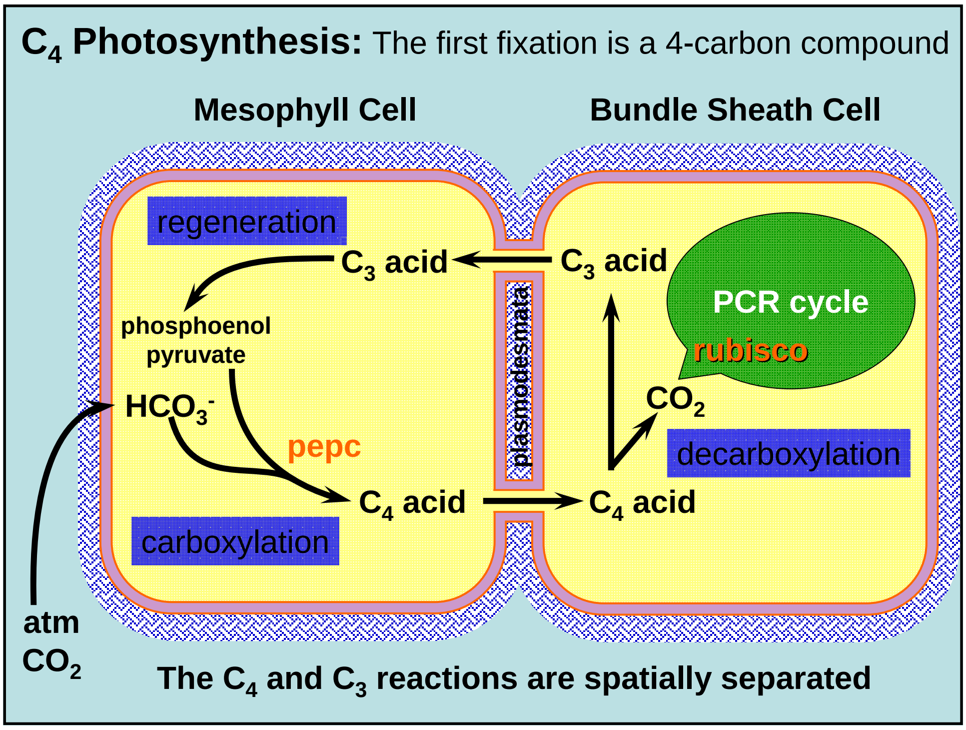


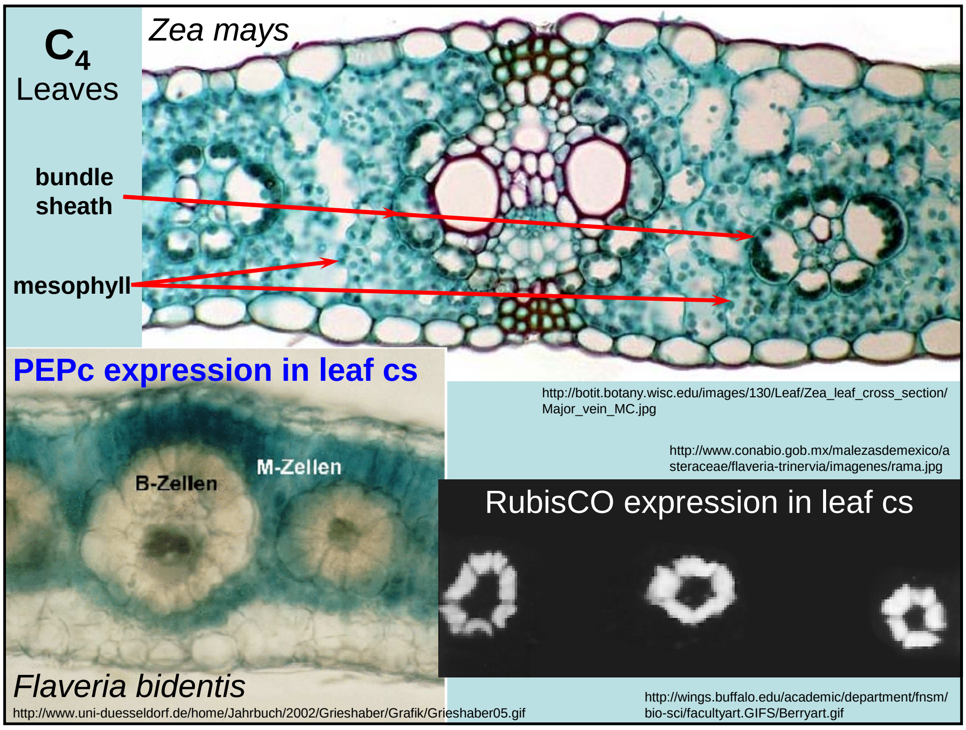

The PCR Cycle **cannot** operate in darkness!
"Dark Reactions?"

## RuBisCO: an ancient enzyme with a modern problem

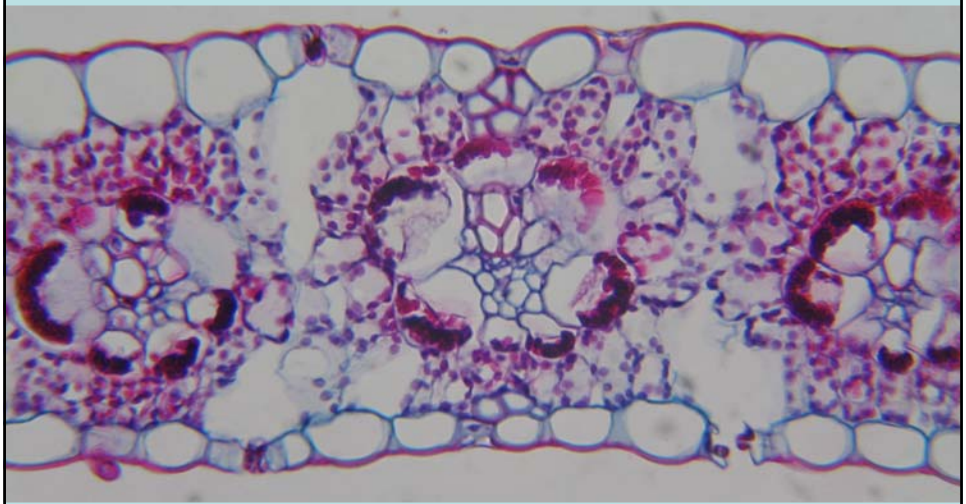



- Early in evolution of photosynthesis the atmosphere was anaerobic, so RuBisCo evolved without a problem.
- As photosynthesis was successful, competitive inhibition from oxygen was essentially a negative feedback.
- Evolution has not yet replaced RuBisCO.
- But several workarounds **have** evolved…


C4 Photosynthesis: The first fixation is a 4-carbon compound
Mesophyll Cell
Bundle Sheath Cell
regeneration
C3 acid
C3 acid
PCR cycle
rubisco
phosphoenol pyruvate
plasmodesmata
HCO3-
CO2
pepc
decarboxylation
C4 acid
C4 acid
carboxylation
atm CO2
The C4 and C3 reactions are spatially separated

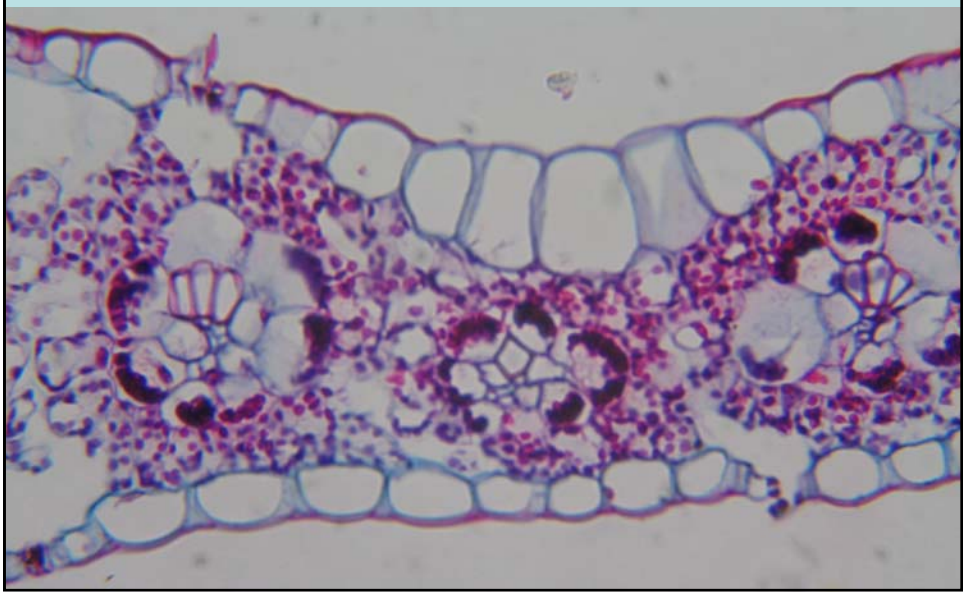

C4 Leaves
Zea mays
bundle sheath
mesophyll
PEPc expression in leaf cs
B-Zellen
M-Zellen
http://botit.botany.wisc.edu/images/130/Leaf/Zea_leaf_cross_section/Major_vein_MC.jpg
http://www.conabio.gob.mx/malezasdemexico/asteraceae/flaveria-trinervia/imagenes/rama.jpg
RubisCO expression in leaf cs
Flaveria bidentis
http://www.uni-duesseldorf.de/home/Jahrbuch/2002/Grieshaber/Grafik/Grieshaber05.gif
http://wings.buffalo.edu/academic/department/fnsm/bio-sci/facultyart.GIFS/Berryart.gif

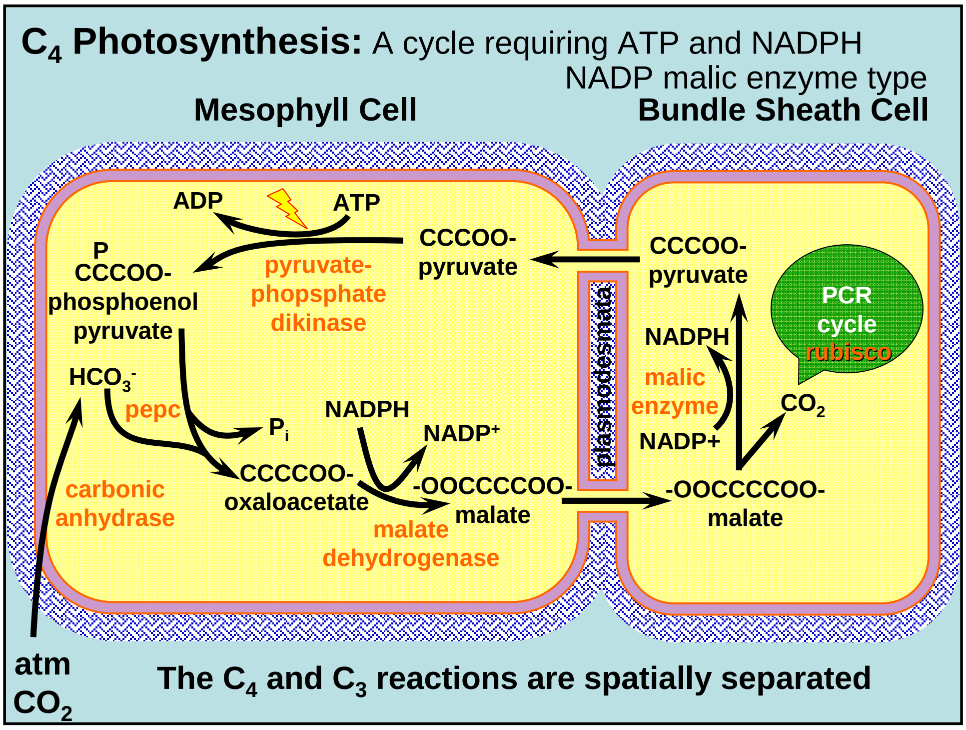
***Zea mays*** leaf cross section showing classic Kranz anatomy



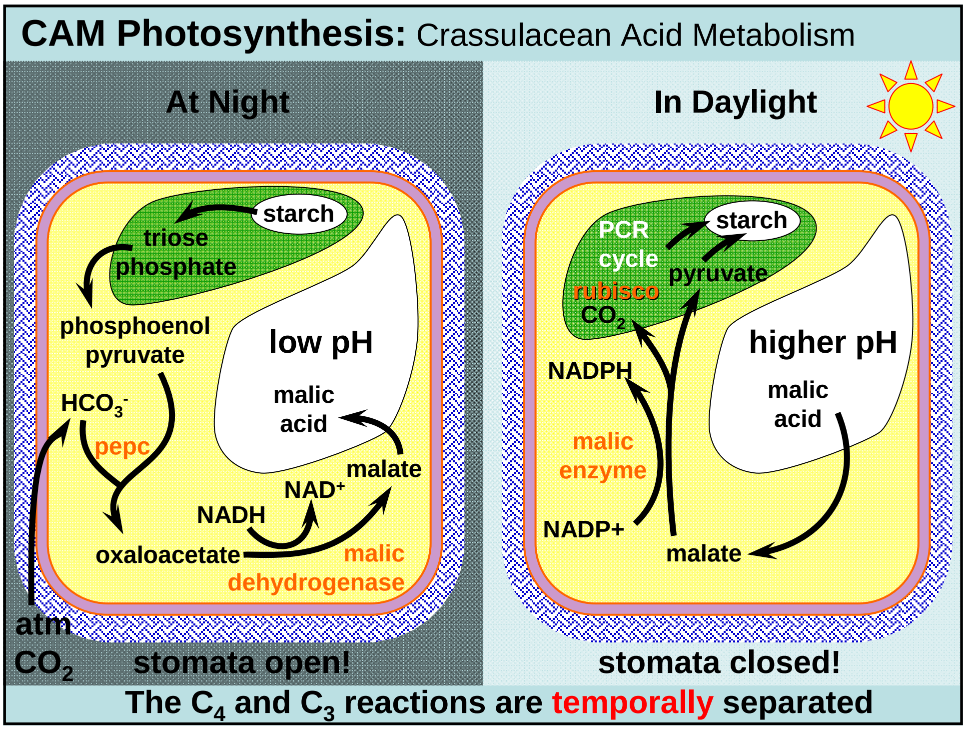
***Zea mays*** leaf cross section

These bulliform cells lose water and the leaf rolls…which way?



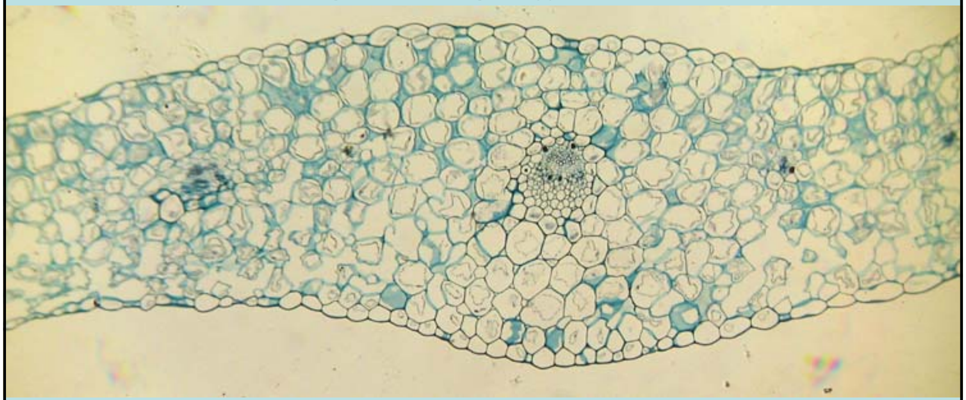


C4 Photosynthesis: A cycle requiring ATP and NADPH
NADP malic enzyme type
Mesophyll Cell
Bundle Sheath Cell
ADP
ATP
CCCOO-
pyruvate
P
CCCOO-
phosphoenol
pyruvate
pyruvate-
phopsphate
dikinase
CCCOO-
pyruvate
PCR
cycle
rubisco
NADPH
malic
enzyme
NADP+
CO2
plasmodesmata
HCO3-
pepc
Pi
NADPH
NADP+
CCCOO-
oxaloacetate
-OOCCCCOO-
malate
malate
dehydrogenase
-OOCCCCOO-
malate
carbonic
anhydrase
atm
CO2
The C4 and C3 reactions are spatially separated

CAM Photosynthesis: Crassulacean Acid Metabolism
At Night
In Daylight
starch
triose
phosphate
phosphoenol
pyruvate
low pH
malic
acid
HCO3-
pepc
malate
NAD+
NADH
oxaloacetate
malic
dehydrogenase
atm
CO2
stomata open!
PCR
cycle
rubisco
CO2
starch
pyruvate
higher pH
malic
acid
NADPH
malic
enzyme
NADP+
malate
stomata closed!
The C4 and C3 reactions are temporally separated

***Sedum*** leaf cross-section (a CAM plant) Note the lack of palisade/spongy differentiation



***Sedum*** leaf cross-section (a CAM plant) Note the lack of Kranz anatomy