Photosynthesis

Chapter 10

- Objectives
  - Describe the structure of a chloroplast, listing all membranes and compartments.
  - Write the chemically correct summary equation for photosynthesis, and, in general terms, explain the role of redox reactions in photosynthesis.
  - Describe the relationship between an action spectrum and an absorption spectrum.
  - Trace the movement of electrons in noncyclic and cyclic electron flow.

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- Describe the similarities and differences in chemiosmosis between oxidative phosphorylation in mitochondria and photophosphorylation in chloroplasts.
- Describe the major consequences of photorespiration.
- Describe two important photosynthetic adaptations that minimize photorespiration.

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Introduction

- Photosynthesis is the process that converts solar energy into chemical energy
- Plants and other autotrophs are the producers of the biosphere
  - autotroph-means self-feeding
    - applies to any organism that makes own food without eating, decomposing or absorbing other organisms or organic molecules

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- Photosynthetic autotrophs, or photoautotrophs, include plants, algae and photosynthetic bacteria
  - they use the energy of sunlight to make organic molecules from water and carbon dioxide

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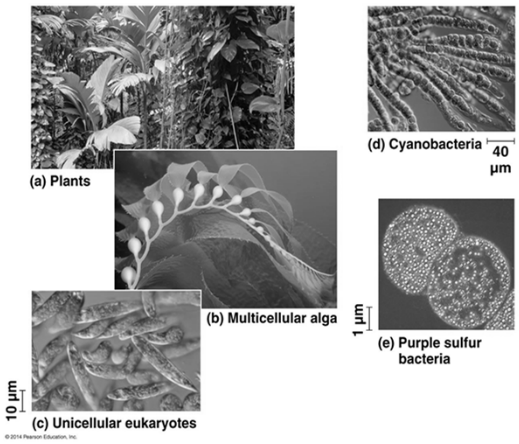

- Heterotrophs obtain their organic material from other organisms
  - they are the consumers of the biosphere

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Chloroplasts: The Sites of Photosynthesis in Plants

- Photosynthesis converts light energy to the chemical energy of food
- Photosynthesis occurs in chloroplasts in all photosynthetic organisms except bacteria

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- Leaves are the primary site of photosynthesis
- Chloroplasts are the organelles in which photosynthesis occurs
  - they contain a complex internal membrane system composed of thylakoids and grana
    - the light-absorbing pigment chlorophyll is located in protein complexes in the internal membranes of chloroplasts
    - sugars are assembled in stroma

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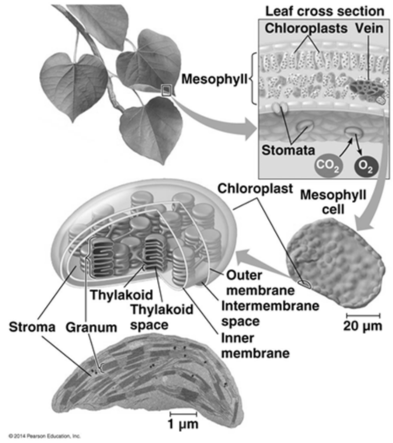

Tracking Atoms Through Photosynthesis

- Oxygen produced by splitting water
  - demonstrated using ^{18}O-labeled reactants
    - plant given $C^{18}O_2$ does not release $^{18}O_2$
    - plant given $H_2{}^{18}O$ does give off $^{18}O_2$

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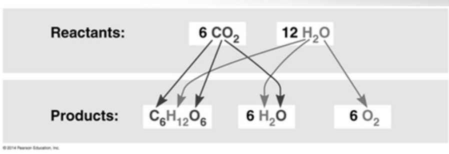

- Photosynthesis is summarized as

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

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Photosynthesis as a Redox Process

- Photosynthesis is redox process
  - H_2O oxidized → ½O_2 + $2H^+$ + $2e^-$
  - CO_2 reduced to glucose by addition of e^-'s and H^+'s
  - compare with respiration where glucose oxidized and O_2 reduced

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- In photosynthesis, electrons travel "uphill" from water to glucose, adding light energy captured by chlorophyll
  - In respiration, electrons travel "downhill" from glucose to water, releasing energy to ATP

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The Two Stages of Photosynthesis: A Preview

- Photosynthesis is a two-stage process
  - light-dependant reactions
    - occur in the thylakoid membranes
    - convert light energy to chemical energy
    - split water and release oxygen
    - produce energy shuttles ATP and NADPH
  - Calvin cycle
    - cyclic series of steps in the stroma that assemble organic molecules from CO_2 using ATP for energy and NADPH for reducing power

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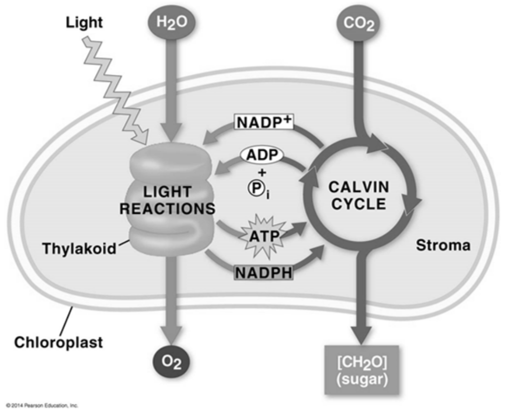
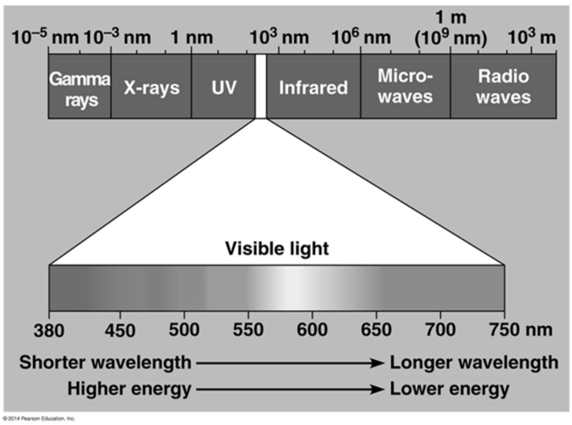


The Nature of Sunlight

- Light is a form of electromagnetic energy, which travels in waves
- Wavelength is the distance between the crests of waves
  - the wavelength determines the type of electromagnetic energy



- The visible light spectrum
  - includes the colors of light we can see
  - includes the wavelengths that drive photosynthesis
- Pigments are substances that absorb visible light
  - leaves absorb some wavelengths (red-orange and blue-violet) and reflects others (green)

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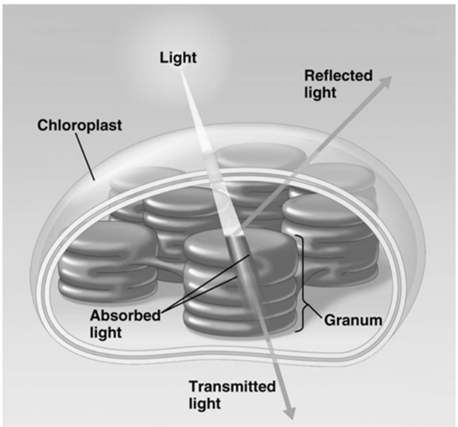

- The spectrophotometer is a machine that sends light through pigments and measures the fraction of light transmitted at each wavelength
- An absorption spectrum is a graph plotting light absorption versus wavelength

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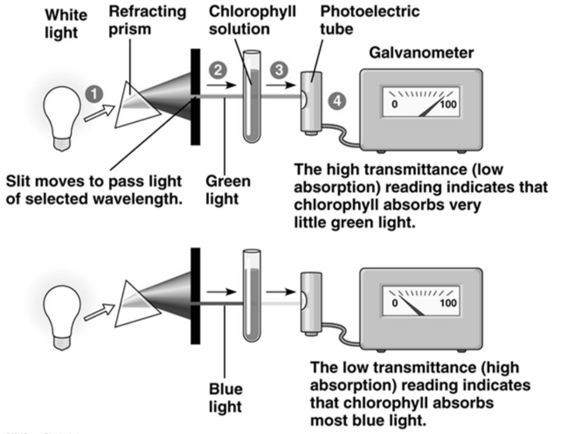

- The action spectrum for photosynthesis was first demonstrated by Theodor W. Engelmann
  - the action spectrum of a pigment profiles the relative effectiveness of different wavelengths of radiation in driving photosynthesis

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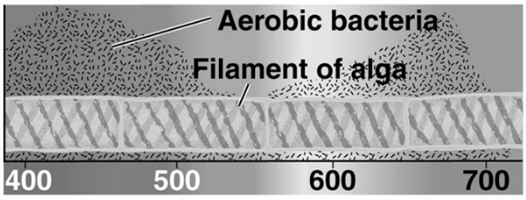

(c) Engelmann's experiment

- The absorption spectra of chloroplast pigments provide clues to the relative effectiveness of different wavelengths for driving photosynthesis

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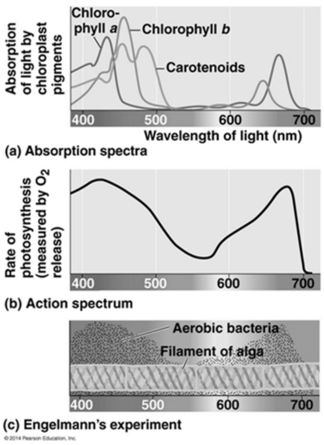

- In plants light is absorbed by chlorophyll a, chlorophyll b and carotenoids
  - only chlorophyll a directly involved in light reactions
- The other pigments act as “antenna” molecules to broaden range of energy absorbed
  - action spectrum demonstrates involvement of accessory pigments

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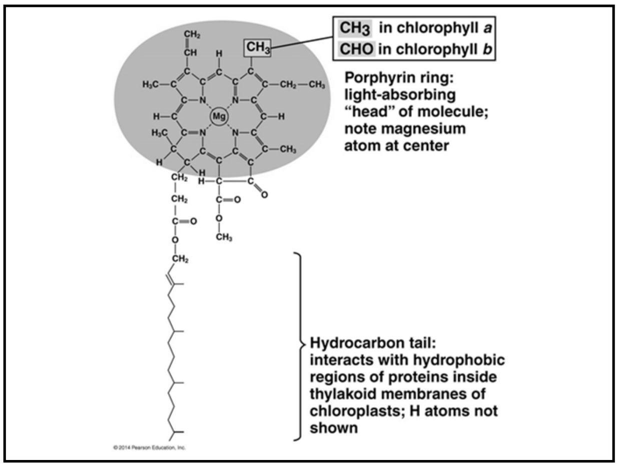

Excitation of Chlorophyll by Light

- Sometimes light behaves like a stream of particles
  - these particles are called photons
- When a pigment absorbs a photon the energy level of one electron is raised
  - The electron goes from the ground state (stable) to an excited state (unstable)

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- If pigment is isolated from its molecular environment the excited electron loses energy as heat or light and returns to the ground state
  - the release of energy is called fluorescence
- Isolated chlorophyll fluoresces red
  - chlorophyll in plants is found in large complexes that capture excited electrons before they can return to the ground state

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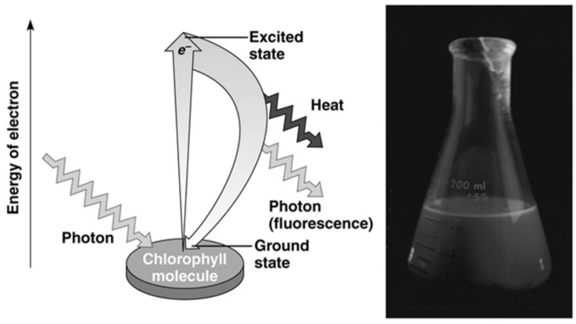

(a) Excitation of isolated chlorophyll molecule (b) Fluorescence

The Structure of a Photosystem

- A photosystem is composed of a reaction center surrounded by a number of light-harvesting complexes
  - in chloroplasts, 200-300 chlorophyll molecules grouped with proteins to form antenna assembly around two chlorophyll a molecules-reaction center chlorophylls

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- When a reaction-center chlorophyll molecule absorbs energy one of its electrons gets bumped up to a primary electron acceptor
- Excited electrons passed from antenna chlorophylls to reaction center chlorophylls then to primary electron acceptor
  - the passage of the electrons is a series of redox reactions
    - The final reaction is the oxidation of reaction center chlorophyll and reduction of primary electron acceptor

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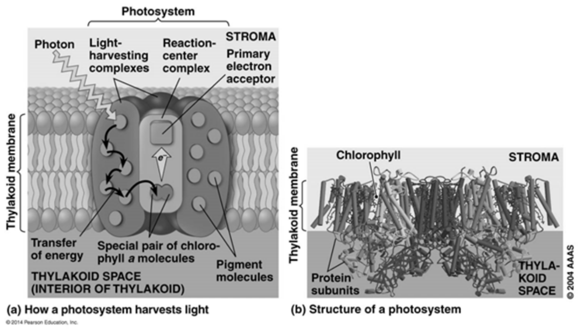

(a) How a photosystem harvests light
(b) Structure of a photosystem

- Two photosystems (reaction center+antenna assembly+primary electron acceptor) have been identified in thylakoid membranes
  - each absorbs light at different wavelengths
    - photosystem I-absorbs maximally at 700nm (P700)
    - photosystem II-absorbs maximally at 680nm (P680)

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Noncyclic Electron Flow

- Noncyclic electron flow is the primary pathway of energy transformation in the light reactions
  - Produces NADPH, ATP, and oxygen

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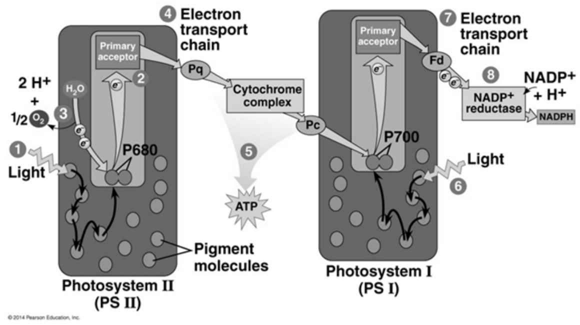

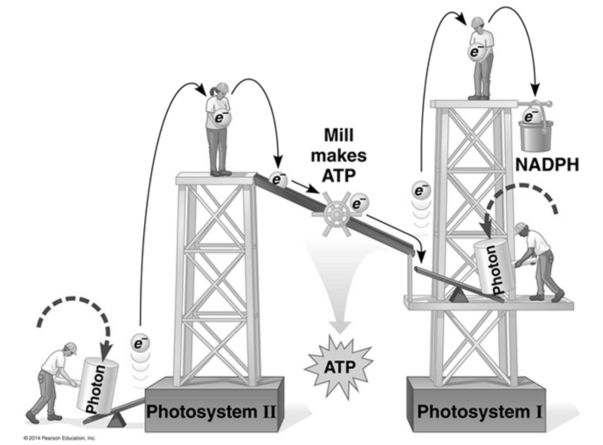

Cyclic Electron Flow

- Under certain conditions photoexcited electrons take an alternative path
- In cyclic electron flow only photosystem I is used and only ATP is produced
  - it is thought to be the earliest form of photosynthesis
    - the pathway is present in many “primitive” photosynthetic bacteria

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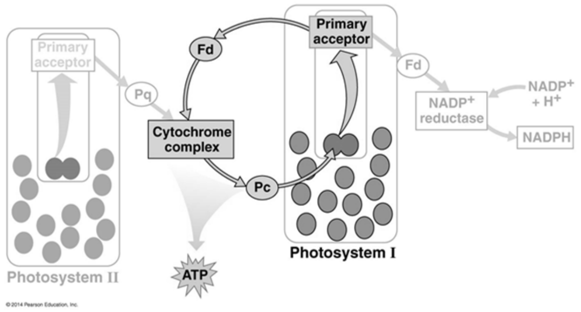

Chemical Energy Generation

- The electron transport chains generate ATP, NADPH and O_2
  - the kinetic energy of light excites electrons
  - the excited electrons are passed along the electron transport chain in a series of redox reactions
  - the released energy used to generate ATP, NADPH and O_2

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Oxygen Production

- The production of NADPH requires 2 electrons
  - these are supplied to NADP reductase by PS I
- PS I is briefly oxidized
  - PS I is reduced by electrons supplied by PS II
- PS II is briefly oxidized
  - PS II is reduced by electrons released by splitting water
  - $H_2O \rightarrow ½O_2 + 2H^+ + 2e^-$

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A Comparison of Chemiosmosis in Chloroplasts and Mitochondria

- Chloroplasts and mitochondria generate ATP by the same basic mechanism - chemiosmosis
  - each uses a different source of energy to accomplish this
- The spatial organization of chemiosmosis differs in chloroplasts and mitochondria

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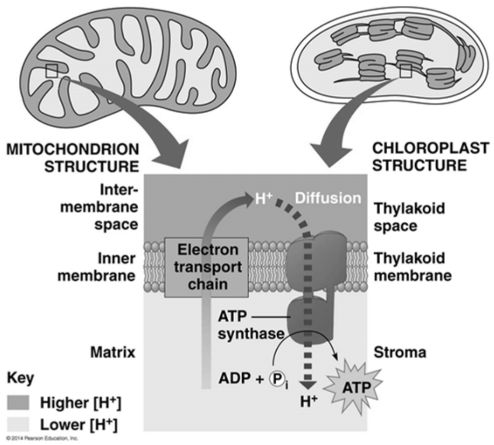

- In both organelles redox reactions of electron transport chains generate a H^+ gradient across a membrane
- ATP synthase uses this proton-motive force to make ATP

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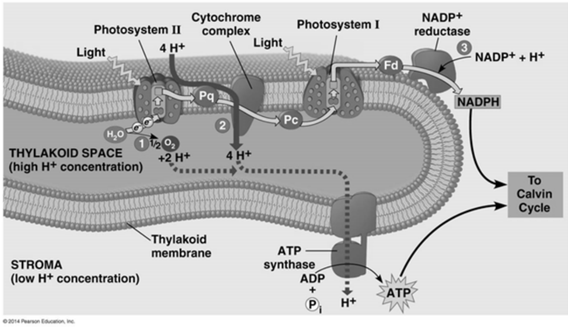

Carbon Fixation and the Calvin Cycle

- The Calvin cycle uses ATP and NADPH to convert CO_2 to sugar
- The Calvin cycle occurs in the stroma and has three phases
  - carbon fixation
  - reduction
  - regeneration of the CO_2 acceptor

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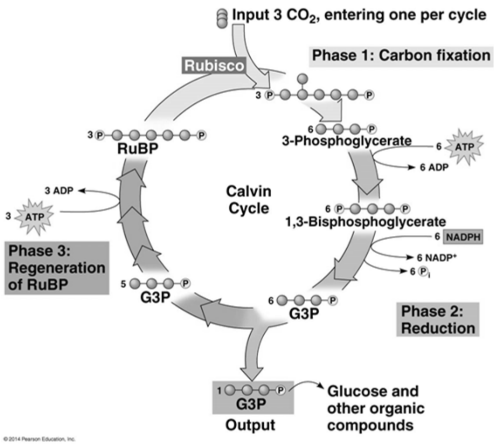

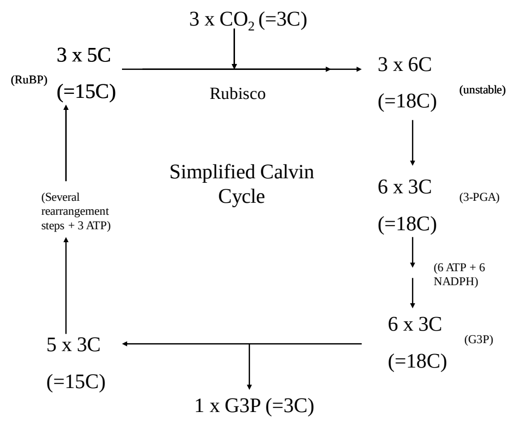

- The net result of the Calvin cycle is 3-carbon (3C) molecules from CO_2 using energy and electrons in ATP and NADPH from light-dependant reactions
- CO_2 is added to a 5-carbon (5C) intermediate called ribulose-1,5-bisphosphate (RuBP)
  - the reaction is catalyzed by RuBP carboxylase/oxygenase (rubisco)

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- A number of rearrangements occur in many steps, using energy in ATP and oxidation of NADPH
  - the last step in cycle regenerates RuBP
- All the steps occur simultaneously but ultimately regenerate starting reactants, hence a cycle

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- Three RuBP enter the cycle for each 3C molecule released from chloroplast
- The 3C molecules have two possible fates
  - they exported to cytoplasm and used to synthesize glucose and other organic molecules
  - they are retained in the chloroplast and stored as starch

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- Plants that use only the Calvin cycle to fix carbon are called C3 plants
  - the first identifiable product of carbon fixation is a 3C molecule

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Carbon-fixing Variations

- Alternative mechanisms of carbon fixation have evolved in hot, arid climates
- C3 plants conserve water by closing stomata
  - this allows buildup of O_2 in leaves
- Under these conditions Rubisco fixes O_2 rather than CO_2
  - The resulting series of reactions are called photorespiration

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- In photorespiration O_2 substitutes for CO_2 in the active site of the enzyme rubisco
  - The photosynthetic rate is reduced

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C4 Plants

- C4 plants minimize the cost of photorespiration and conserve water by incorporating CO_2 into four carbon compounds in mesophyll cells
- The 4C molecules diffuse into bundle sheath cells and CO_2 is released
  - The CO_2 enters Calvin cycle in bundle sheath chloroplasts

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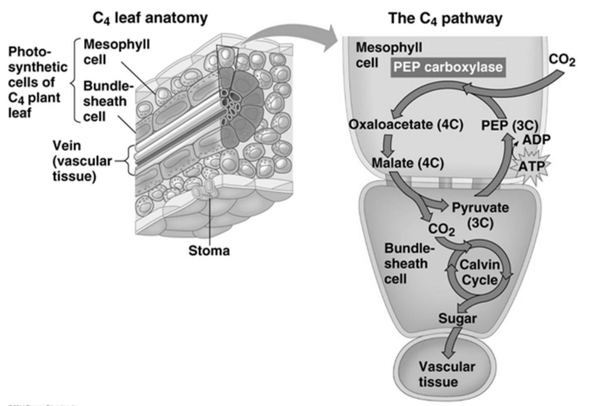
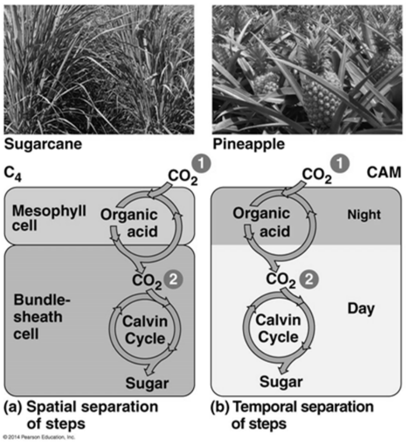
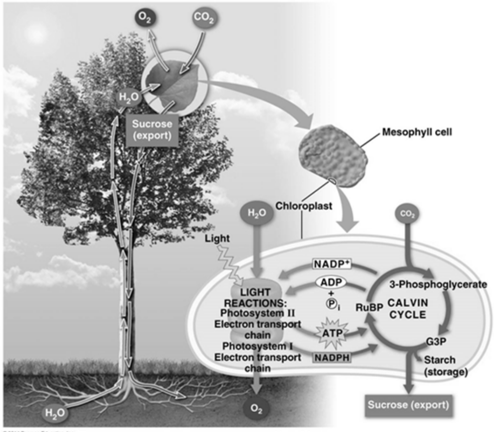


CAM Plants

- CAM (crassulacean acid metabolism) plants incorporate carbon during night
  - the stomata are open at night and closed during day
- CO_2 is incorporated in 4C molecules and stored in the vacuole at night
- During the day 4C molecules are exported into cytoplasm and CO_2 is released
  - the CO_2 enters the Calvin cycle
- The CAM pathway is similar to the C4 pathway



- C4 plants separate carbon incorporation and fixation spatially
  - separated by distance
- CAM plants separate carbon incorporation and carbon fixation temporally
  - separated by time



LIGHT REACTIONS	CALVIN CYCLE REACTIONS
• Are carried out by molecules in the thylakoid membranes • Convert light energy to the chemical energy of ATP and NADPH • Split H_2O and release O_2 to the atmosphere	• Take place in the stroma • Use ATP and NADPH to convert CO_2 to the sugar G3P • Return ADP, inorganic phosphate, and $NADP^+$ to the light reactions