Review Questions Chapter 5-7

These questions need full and complete answers. Typically this will require a paragraph or two. If you are not certain if your answer is complete, ASK.

2. What are the First and Second Laws of Thermodynamics? How do they impact growing complexity and decreasing entropy in living things?
3. Describe the process of photosynthesis. What is happening at a molecular and atomic level?
4. Compare and contrast exergonic and endergonic reactions and explain how they are related in coupled reactions.
5. Detail two coupled reactions involving ATP.
6. What are enzymes and how do they function?
7. What environmental factors effect enzyme function? How do they effect enzyme function?
8. Describe allosteric regulation and feedback inhibition.
9. How does photosynthesis convert solar energy into energy usable by cells? Be specific. What are the chemical reactions?
10. Describe the structure and location of chloroplasts within a leaf?
11. Describe PSI and PSII. How are they coupled?
13. What role does the color of photosynthetic pigments play in photosynthesis?
14. What is photorespiration? Why is it undesirable?
15. Compare and contrast photosynthesis and cellular respiration. Again be specific about reactions energy requirements etc.
16. How is cellular energy stored?
17. Describe in detail the processes of cellular metabolism. (glycolysis and cellular respiration)
18. Compare and contrast cellular respiration and fermentation. Once again be specific. What chemical processes are occurring in each and how are those similar and/or different?
5.1 What Is Energy?

- **Energy** is the capacity to do work.
  - Synthesizing molecules
  - Moving objects
  - Generating heat and light

- **Chemical energy** is the energy that powers life
  - The objects that move are electrons, which reposition during chemical reactions

- **Work** is force acting over distance.
  - Change in kinetic energy
What Is Energy?

- Two fundamental types of energy
  - **Kinetic energy** is the energy of movement
    - e.g. light, heat, electricity, moving objects
  - **Potential energy** is stored energy
    - e.g. chemical energy in bonds, electrical charge in a battery, a rock at the top of a hill

- The **laws of thermodynamics** describe the availability and usefulness of energy
The Laws of Thermodynamics

- First Law of Thermodynamics
  - Energy cannot be created nor destroyed, but it can change its form. (conservation of energy)
  - The total amount of energy within a given system remains constant unless energy is added or removed from the system.
  - Example: potential energy in gasoline can be converted to kinetic energy (and heat energy) in a car, but the energy is not lost.
The Laws of Thermodynamics

- **Second Law of Thermodynamics**
  - The amount of useful energy decreases when energy is converted from one form to another.
  - No process is 100% efficient, so no perpetual motion is possible.
  - The remaining energy is released in a less useful form as heat, but the total energy is constant.
The Laws of Thermodynamics

- Matter tends to become less organized.
  - **Entropy**: the spontaneous reduction in ordered forms of energy, and an increase in randomness and disorder.
  - Useful energy decreases as heat and other non-useful forms of energy increases.
  - Example:
    - gasoline is made up of an eight-carbon molecule that is highly ordered,
    - when broken down to single carbons in CO$_2$, it is less ordered and more random.
Energy of Sunlight

- In order to keep useful energy flowing in ecosystems where the plants and animals produce more random forms of energy, new energy must be brought in.
- Sunlight provides an continuous supply of new energy to power all molecular reactions in living organisms.
- Photosynthetic organisms use external solar energy to maintain orderly structure.
- Non-photosynthetic organisms use the stored chemical energy in other living things to counter increasing entropy.
Chemical Reactions

- Chemical reactions are processes that form or break chemical bonds between atoms
- Chemical reactions convert reactants to products

Reactants → Products
All chemical reactions require an initial energy input (activation energy) to begin

- Molecules need to be moving with sufficient collision speed
- The source of activation energy is the kinetic energy of movement when molecules collide.
- The electrons of an atom repel other atoms and inhibit bond formation
- Molecular collisions force electron shells of atoms to mingle and interact, resulting in chemical reactions.
Burning glucose (sugar): an exergonic reaction

Activation energy needed to ignite glucose

Energy released by burning glucose

Glucose + O₂ → CO₂ + H₂O

Progress of reaction
Chemical Reactions

- Reactions can be categorized as **exergonic** or **endergonic** based on energy gain or loss
Exergonic Reactions

- **Exergonic reactions** release energy
- Reactants contain more energy than products in exergonic reactions
Exergonic Reaction Example

- Burning of glucose
  - Sugar and oxygen contain more energy than the molecules of CO₂ and water.
  - The extra energy is released as heat.

\[
C_6H_{12}O_6 \quad + \quad O_2 \quad \rightarrow \quad 6 \text{ CO}_2 \quad + \quad 6 \text{ H}_2\text{O}
\]
Endergonic Reactions

- Endergonic reactions require an input of energy to begin and more energy to continue.
- Products contain more energy than reactants in endergonic reactions.

(b) Endergonic reaction

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Endergonic Reaction Example

- Photosynthesis
  - sunlight energy + CO₂ + H₂O → sugar and O₂
  - The sugar contains far more energy than the CO₂ and water used to form it.
Chemical Reactions

- Glucose respiration and photosynthesis are complementary exergonic and endergonic reactions

(a) Burning glucose (sugar): an exergonic reaction

(b) Photosynthesis: an endergonic reaction

Fig. 5-6
Coupled Reactions

- Exergonic reactions drive endergonic reactions
  - The product of an energy-yielding reaction fuels an energy-requiring reaction in a **coupled reaction**
- The exergonic and endergonic parts of coupled reactions often occur at different places within the cell
- **Energy-carrier molecules** are used to transfer the energy within cells
Coupled Reactions

- Exergonic reactions may be linked with endergonic reactions.
  - Endergonic reactions obtain energy from energy-releasing exergonic reactions in coupled reactions.
  - Example 1: the exergonic reaction of burning gasoline in a car provides the endergonic reaction of moving the car
  - Example 2: exergonic reactions in the sun release light energy used to drive endergonic sugar-making reactions in plants
5.3 How Is Energy Carried Between Coupled Reactions?

- Food energy cannot be used directly to power energy-requiring reactions.
- Energy carrier molecules act as intermediates to carry energy between exergonic and endergonic reactions.
- Energy carrier molecules are only used within cells because they are unstable.
ATP

- **Adenosine triphosphate (ATP)** is the primary energy carrying molecule within cells
  - ATP is composed of an adenosine molecule and three phosphates
ATP

- Energy is stored in the high-energy bond extending to the last phosphate.
- Heat is given off when ATP breaks into ADP (adenosine diphosphate) and P (phosphate).
ATP

- The energy released when ATP is broken down into ADP + P is transferred to endergonic reactions through coupling.
Energy Transfer in Coupled Reactions

- To summarize:
  - Exergonic reactions drive endergonic reactions
  - ATP moves to different parts of the cell and is broken down exergonically to liberate its energy to drive endergonic reactions.

- A biological example
  - Muscle contraction (an endergonic reaction) is powered by the exergonic breakdown of ATP.
  - During energy transfer in this coupled reaction, heat is given off, with overall loss of usable energy.
Energy Transfer in Coupled Reactions

- ATP breakdown is coupled with muscle contraction.

Exergonic reaction:  
\[ ATP \rightarrow 100 \text{ units energy released} + \text{ADP} + \text{P} \]

Endergonic reaction:  
\[ \text{relaxed muscle} + 20 \text{ units energy} \rightarrow \text{contracted muscle} \]

Coupled reaction:  
\[ \text{relaxed muscle} + \text{ATP} \rightarrow \text{contracted muscle} + 80 \text{ units energy released as heat} + \text{ADP} + \text{P} \]

Energy released from ATP breakdown exceeds the energy used for muscle contraction, so the overall coupled reaction is exergonic.

Fig. 5-10
Electron Carriers

- Electron carriers also transport energy within cells.
  - Carrier molecules other than ATP also transport energy within a cell.
  - Energy can be transferred to electrons in glucose metabolism and photosynthesis.
  - Electron carriers capture energetic electrons transferred by some exergonic reaction.
  - Energized electron carriers then donate these energy-containing electrons to endergonic reactions.
  - Energy can be transferred to electrons in glucose metabolism and photosynthesis.
Electron Carriers

- Two common electron carriers
  1. Nicotinamide adenine dinucleotide (NAD$^+$)
  2. Flavin adenine dinucleotide (FAD)
5.4 How Do Cells Control Their Metabolic Reactions?

- **Cellular metabolism**: the multitude of chemical reactions going on at any specific time in a cell

- **Metabolic pathways**: the sequence of cellular reactions (e.g., photosynthesis and glycolysis)
Overview of Metabolism

- Metabolic pathways proceed smoothly for three reasons:
  1. Endergonic reactions are coupled with exergonic reactions
  2. Energy-carrier molecules capture energy and transfer it between endergonic and exergonic reactions
  3. Chemical reactions are regulated through protein enzymes
Control of Metabolic Reactions

- At body temperature, many spontaneous reactions proceed too slowly to sustain life.
  - A reaction can be controlled by controlling its **activation energy**, the energy needed to start the reaction.
  - At body temperature, reactions occur too slowly because their activation energies are too high.
Spontaneous Reactions

- Reaction speed is generally determined by the activation energy required
  - Reactions with low activation energies proceed rapidly at body temperature
  - Reactions with high activation energies (e.g. sugar breakdown) move very slowly at body temperature, even if exergonic overall
Spontaneous Reactions

- **Enzyme** molecules are employed to **catalyze** (speed up) chemical reactions in cells.
- Catalysts speed up the rate of a chemical reaction without themselves being used up.
- Catalysts speed up spontaneous reactions by reducing activation energy.
Figure 6-14  Biology: Life on Earth, 8/e
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Catalyst Summary

- Four important principles about all catalysts
  - They speed up reactions that would occur anyway, if their activation energy could be surmounted.
  - Catalysts lower activation energy.
  - The lowered activation energy allows reactions to move forward more quickly.
  - Catalysts are not altered by the reaction.
Enzymes Are Biological Catalysts

- Almost all enzymes are proteins.
- Enzymes are highly specialized, generally catalyzing only a single reaction.
- In metabolic pathways each reaction is catalyzed by a different enzyme.
- Enzymes orient, distort, and reconfigure molecules in the process of lowering activation energy.
- Enzyme activity is often enhanced or suppressed by its reactants or product.
- Some enzymes require helper coenzymes (ex/ certain B vitamins)
Enzymes Are Biological Catalysts

- How does an enzyme catalyze a reaction?
  - Both substrates enter the enzyme’s active site, which is shaped specifically for those substrate molecules.
  - The shape of the active site makes it specific to one set of substrates.
  - The substrates in an enzyme’s active site change shape and conformation.
  - The chemical bonds are altered in the substrates, promoting the reaction.
  - The substrates change into a new form that no longer fits the active site, and so are released.
Enzyme Structure

- Enzymes have a pocket called an **active site**
- Reactants (substrates) bind to the active site
  - Distinctive shape of active site is complementary and specific to the substrate
  - Active site amino acids binds the substrate in a specific orientation
  - Upon binding, the substrates and enzyme change shape and distort bonds to facilitate a reaction
  - Products of the reaction leave the active site, leaving the enzyme ready for another catalysis
1 Substrates enter active site in a specific orientation.

2 Substrates and active site change shape, promoting reaction between substrates.

3 Substrates, bonded together, leave enzyme; enzyme ready for new set of substrates.

Figure 6-15 Biology: Life on Earth, 8/e
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Control of Metabolic Reactions

Metabolic pathways are controlled in several ways

1. Control of enzyme synthesis regulates availability
2. Some enzymes are inactive when created and must be “turned on” to be active
3. Small organic molecules can bind to enzymes and enhance/inhibit activity (allostERIC regulation)
4. Adequate amounts of formed product inhibit enzyme activity (feedback inhibition)
Allosteric Regulation

- Allosteric regulation can increase or decrease enzyme activity.
  - In allosteric regulation, an enzyme’s activity is modified by a regulator molecule.
  - The regulator molecule binds to a special regulatory site on the enzyme separate from the enzyme’s active site.
  - Binding of the regulator molecule modifies the active site on the enzyme, causing the enzyme to become more or less able to bind substrate.
  - Thus, allosteric regulation can either promote or inhibit enzyme activity.
(a) Enzyme structure

substrate
active site
enzyme

Many enzymes have both active sites and allostERIC regulatory sites.

allostERIC regulatory site

(b) Allosteric inhibition

An allostERIC regulator molecule causes the active site to change shape, so the substrate no longer fits.

table
Competitive Inhibition

- Competitive inhibition can be temporary or permanent.
- Some regulatory molecules temporarily bind directly to an enzyme’s active site, preventing the substrate molecules from binding.
- These molecules compete with the substrate for access to the active site, and control the enzyme by competitive inhibition.
A competitive inhibitor molecule occupies the active site and blocks entry of the substrate.
Feedback Inhibition

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Drugs and Poisons

- Drugs and poisons often inhibit enzymes by competing with the natural substrate for the active site (competitive inhibition)
- Some inhibitors bind permanently to the enzyme
Environmental Conditions

- The three-dimensional structure of an enzyme (protein) is sensitive to environmental conditions.
- Most enzymes function optimally only within a very narrow range of environmental conditions.
  - Enzyme structure is distorted and function is destroyed when pH is too high or low.
  - Salts in an enzyme’s environment can also destroy function by altering structure.
  - Temperature also affects enzyme activity.
    - Low temperatures slow down molecular movement.
    - High temperatures cause enzyme shape to be altered, destroying function.
**pH influences enzyme activity**

- **pepsin**
- **salivary amylase**

**Temperature influences enzyme activity**

- Enzyme activity increases as temperature approaches optimal.
- Maximum activity at optimal temperature.
- Activity reduced as high temperatures distort enzyme structure.
6.1 What Is Photosynthesis?

- Life on earth depends on photosynthesis.
  - **Photosynthesis** is the capturing and conversion of sunlight into chemical energy.
    - Virtually all life depends directly or indirectly on the energy captured by plants and stored as sugars.
  - Before photosynthesis, there was little oxygen on Earth, and therefore, no organisms that used oxygen.
    - All present-day organisms that use oxygen as their respiratory gas depend upon photosynthesis to generate new oxygen.
6.1 What Is Photosynthesis?

- Photosynthesis converts carbon dioxide and water to glucose.
  - The chemical reaction for photosynthesis:
    - \(6 \text{CO}_2 + 6 \text{H}_2\text{O} + \text{light energy} \rightarrow \text{C}_6\text{H}_{12}\text{O}_6 + 6 \text{O}_2\)
  - Plants, seaweeds, and single-celled organisms all show the basic aspects of photosynthesis.
6.1 What Is Photosynthesis?

- Plant photosynthesis takes place in leaves.
  - Leaves are the main location of photosynthesis.
    - Plants have thin leaves so sunlight can penetrate.
    - Plant leaves have a large surface area to expose them to the sun.
    - Plant leaves have pores to admit CO$_2$ and expel O$_2$, called stomata (singular, stoma).
6.1 What Is Photosynthesis?

- Leaf cells contain chloroplasts.
  - Photosynthesis occurs in chloroplasts, in layers of cells called the **mesophyll**.
  - The **stroma** contains sacs called **thylakoids** within which photosynthesis occurs.
6.1 What Is Photosynthesis?

- Photosynthesis consists of **light-dependent** and **light-independent** (dark) reactions.
  - These reactions occur at different locations in the chloroplast.
  - The two types of reactions are linked by the energy-carrier molecules adenosine triphosphatase (ATP) and nicotinamide adenine dinucleotide phosphate (NADPH).
6.1 What Is Photosynthesis?

- **Light-dependent reactions**
  - Occur in the membranes of the thylakoids
  - Light is captured here and stored in ATP and NADPH.
  - \( \text{H}_2\text{O} \) is consumed and \( \text{O}_2 \) is given off.
6.1 What Is Photosynthesis?

- **Light-independent reactions**
  - Enzymes in the stroma use ATP and NADPH produced by light-dependent reactions to make glucose and other molecules.
  - CO$_2$ is consumed in the process.
  - ATP and NADPH are converted to low-energy ADP and NADP$^+$.  
  - These low-energy molecules are re-charged to ATP and NADPH when recycled in light-dependent reactions.
6.1 What Is Photosynthesis?

- An overview of photosynthesis: light-dependent and light-independent reactions
The Energy in Visible Light

- The sun radiates **electromagnetic energy**
- Visible light is radiation falling between 400-750 nanometers of wavelength
- Packets of energy called **photons** have different energy levels depending on wavelength
  - Short-wavelength photons (indigo, UV, x-rays) are very energetic
  - Longer-wavelength photons have lower energies (red, infrared)
Light Captured by Pigments

- Action of light-capturing pigments
  - **Absorption** of certain wavelengths
    - light is “trapped”
    - “trapped” light it is no longer visible
  - **Reflection** of certain wavelengths
    - light bounces back
    - This light is visible on the same side as the light
  - **Transmission** of certain wavelengths
    - light passes through
    - This light is visible on the opposite side from the light source
Light Captured by Pigments

- Absorbed light is converted to chemical energy and drives biological processes
- Common pigments found in chloroplasts:
  - **Chlorophyll a and b**
    - absorb violet, blue, and red light
    - reflect green light (hence they appear green)
  - **Accessory pigments such as carotenoids**
    - Carotenoids absorb blue and green light
    - reflect yellow, orange, or red (hence they appear yellow-orange)
Figure 7-5  Biology: Life on Earth, 8/e
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Why Autumn Leaves Turn Color

- Both chlorophylls and carotenoids are present in leaves
  - Chlorophyll breaks down before carotenoids in dying autumn leaves revealing yellow colors
  - Red (anthocyanin) pigments are synthesized by some autumn leaves, producing red colors
6.2 How Is Light Energy Converted To Chemical Energy?

- Light is first captured by pigments in chloroplasts in light dependent reactions.
  - Membranes of chloroplast thylakoids contain **pigments** (light-absorbing molecules).
- Captured sunlight energy is stored as chemical energy in two carrier molecules in light-independent reactions
  - Adenosine triphosphate (ATP)
  - Nicotinamide adenine dinucleotide phosphate (NADPH)
6.2 How Is Light Energy Converted To Chemical Energy?

- The light-dependent reactions generate energy-carrier molecules.
  - Light-dependent reactions take place in two photosystems (PSI & PSII) found in the thylakoid membranes.
  - Each photosystem consists of an assemblage of proteins, chlorophyll, accessory pigment molecules, and a chain of electron-carriers.
6.2 How Is Light Energy Converted To Chemical Energy?

- Each photosystem consists of two major subsystems.
  - A **light-harvesting complex** collects light energy and passes it on to a specific chlorophyll molecule called the reaction center.
  - An **electron transport system** (ETS) transports energized electrons from one molecule to another.
6.2 How Is Light Energy Converted To Chemical Energy?

- Structures associated with the light-dependent reactions

![Diagram showing thylakoids, chloroplast, PS II, PS I, ETC, and reaction centers within thylakoid membrane.](image)
6.2 How Is Light Energy Converted To Chemical Energy?

- Photosystem II generates ATP.
  - Step 1: The light-harvesting complex passes light to the reaction center.
  - Step 2: Electrons of the reaction center become energized.
  - Step 3: The energized electrons jump to the ETS and jump from molecule to molecule, releasing energy at each step.
  - Step 4: The released energy powers reactions that synthesize ATP.
6.2 How Is Light Energy Converted To Chemical Energy?

- Photosystem I generates NADPH.
  - Step 5: The light-harvesting complex passes light to the reaction center.
  - Step 6: Activated electrons from the reaction center are passed to the ETS and are replaced by electrons coming from the ETS of photosystem II.
  - Step 7: Electrons jump from one molecule of the ETS to another, until they reach NADP⁺.
  - Step 8: Each molecule of NADP⁺ picks up two electrons, forming NADPH.
6.2 How Is Light Energy Converted To Chemical Energy?

• Step 9: The breakdown of H₂O provides the replacement electrons to keep the process continuing, through the reaction:

\[ \text{H}_2\text{O} \rightarrow \frac{1}{2} \text{O}_2 + 2\text{H}^+ + 2e^- \]

• The two electrons are donated to photosystem II.
• The hydrogen ions are used to convert NADP⁺ to NADPH.
• Oxygen atoms combine to form a molecule of oxygen gas (O₂), which is given off to the atmosphere.
sunlight

reaction center

photosystem II

energy level of electrons

electron transport chain

photosystem I

energy to drive

ATP synthesis

NADPH

NADP^+ + H^+

H_2O

2 H^+

1/2 O_2

Fig. 6-5
Maintaining Electron Flow Redux

- Electrons leaving PS II replaced when H₂O is split:
  - $\text{H}_2\text{O} \rightarrow \frac{1}{2}\text{O}_2 + 2\text{H}^+ + 2\text{e}^-$
  - Two electrons from water replace those lost when 2 photons boost 2 electrons out of PSII
  - Two hydrogen ions used to form NADPH
  - Oxygen atoms combine to form O₂
6.3 How Is Chemical Energy Stored in Glucose Molecules?

- The ATP and NADPH generated in light-dependent reactions are used in light-independent reactions to make molecules for long-term storage.
  - These reactions occur in the fluid stroma that surrounds the thalakoids, and do not require light.
  - In the stroma, ATP and NADPH are used with CO$_2$ and H$_2$O to synthesize the storage form of energy—glucose.
The C₃ cycle captures carbon dioxide.

- **Step 1**: CO₂ from air combines with a five-carbon sugar, ribulose biphosphate (RuBP), and H₂O to form phosphoglyceric acid (PGA).
- **Step 2**: PGA receives energy input from ATP and NADPH to form glyceraldehyde-3-phosphate (G₃P).
- **Step 3**: Two G₃P molecules (three carbons each) combine to form one molecule of glucose (six carbons).
- **Step 4**: 10 G₃P molecules powered by ATP are used to regenerate six molecules of RuBP to restart the cycle.
6.3 How Is Chemical Energy Stored in Glucose Molecules?

- **The C₃ cycle of carbon fixation**

![Diagram of the C₃ cycle](image)
6.4 What Is The Relationship Between Light-Dependent And Light-Independent Reactions?

- Photosynthesis includes two separate sets of reactions (light-dependent and light-independent) that are closely linked.
Light-Dependent And Light-Independent Reactions

- Light-dependent reactions capture solar energy; light-independent reactions use captured energy to make glucose.
  - Energy-carrier molecules provide the link between these two sets of reactions.
  - Light-dependent reactions of thylakoids use light to charge ADP and \( \text{NADP}^+ \) to make ATP and NADPH.
  - ATP and NADPH move to the stroma where they provide energy to synthesize glucose.
Light-Dependent And Light-Independent Reactions

- Two sets of reactions are connected in photosynthesis.
6.5 How Does the Need To Conserve Water Affect Photosynthesis?

- Photosynthesis requires carbon dioxide; porous leaves would allow the entry of CO$_2$, but would also result in the loss of H$_2$O.
- Evolution of the stomata resulted in pores that could open, letting in CO$_2$, but also to close, to restrict H$_2$O losses.
- Closing stomata to prevent H$_2$O loss also restricts the release of O$_2$, produced by photosynthesis, to the atmosphere.
Water Conservation and Photosynthesis

- When stomata are closed to conserve water, wasteful photorespiration occurs.
  - In hot, dry conditions, plant stomata are closed much of the time, reducing internal CO$_2$ concentrations and increasing O$_2$ concentrations.
  - Increased O$_2$ reacts with RuBP (instead of CO$_2$) in a process called photorespiration.
  - Photorespiration does not produce useful cellular energy, and prevents the C$_3$ synthesis of glucose.
Water Conservation and Photosynthesis

- Alternative pathways reduce photorespiration.
  - Some plants have evolved metabolic pathways that reduce photorespiration.
  - These plants can produce glucose even under hot and dry conditions.
  - The two most important alternative pathways are:
    - The C₄ pathway
    - Crassulacean acid metabolism (CAM)
6.5 How Does the Need To Conserve Water Affect Photosynthesis?

- Plants capture carbon and synthesize glucose in different places.
  - Typical plants (C\textsubscript{3} plants) fix carbon and synthesize glucose as a result of the C\textsubscript{3} cycle in mesophyll cells.
6.5 How Does the Need To Conserve Water Affect Photosynthesis

- The C₄ pathway includes two stages that take place in different parts of the leaf.
  - In the first stage, CO₂ is captured in mesophyll cells in the presence of high O₂, producing a four-carbon molecule.
  - The four-carbon molecule is transferred from mesophyll cells to the bundle-sheath cells where the four-carbon molecule is broken down to CO₂.
6.5 How Does the Need to Conserve Water Affect Photosynthesis

- C₄ plants capture carbon and synthesize glucose in different places.
  - In the sheath-bundle cells, the released CO₂ proceeds to the second stage of the pathway— the regular C₃ cycle—without excess O₂ interfering with the process.
  - Many C₄ plant species are grasses, and are agriculturally important species such as sugar cane, corn, and sorghum.
In a C₃ plant, carbon capture and glucose synthesis are in mesophyll cells (a) C₃ plant

In a C₄ plant, carbon capture is in mesophyll cells, but glucose is synthesized in bundle-sheath cells (b) C₄ plant
6.5 How Does the Need to Conserve Water Affect Photosynthesis

- CAM plants capture carbon and synthesize glucose at different times.
  - In CAM plants, photorespiration is reduced by fixing carbon in two stages that take place in the same cells but at different times of the day.
  - At night, with open stoma, reactions in mesophyll cells incorporate CO$_2$ into the organic acid molecules that are stored in vacuoles.
  - During the day, with stoma closed, the organic acids release their CO$_2$ and the regular C$_3$ cycle proceeds.
6.5 How Does the Need to Conserve Water Affect Photosynthesis

- Two ways to reduce photorespiration—in different places and times

(a) Steps in separate places

(b) Steps at separate times

Fig. 6-10
7.1 What Is The Source Of A Cell’s Energy?

- The energy for cellular activities is stored in bonds of molecules such as carbohydrates and fats.
- Stored energy is transferred to the bonds of energy-carrier molecules including ATP.
- Glucose is a key energy-storage molecule.
  - Nearly all cells metabolize glucose for energy
  - Glucose metabolism is fairly simple
  - Other organic molecules are converted to glucose for energy harvesting
Source Of Cellular Energy

- Photosynthesis is the ultimate source of cellular energy.
- Photosynthetic cells capture and store sunlight energy as glucose.
- This energy is later used by cells.
- These cells can be the photosynthetic organisms, or can be other organisms that consume photosynthetic organisms.
Source Of Cellular Energy

- Glucose metabolism and photosynthesis are complementary processes.
- The products of each reaction provide reactants for the other.
- The symmetry is visible in the equations that describe each process.
  - Photosynthesis:
    \[ 6 \text{CO}_2 + 6\text{H}_2\text{O} + \text{sunlight energy} \rightarrow \text{C}_6\text{H}_{12}\text{O}_6 + 6 \text{O}_2 \]
  - Glucose metabolism:
    \[ \text{C}_6\text{H}_{12}\text{O}_6 + 6\text{O}_2 \rightarrow 6 \text{CO}_2 + 6 \text{H}_2\text{O} + \text{ATP} + \text{heat energy} \]
7.2 How Do Cells Harvest Energy From Glucose?

- Glucose metabolism occurs in stages
  - 1st stage is **glycolysis**.
  - 2nd stage, **cellular respiration**
  - Under **anaerobic** (no O₂) conditions the 2nd stage of glucose metabolism is **fermentation**.
Fig. 7-1

**Glycolysis**

- **Glucose** → 2 **Pyruvate**
  - **Fermentation**:
    - 2 **Pyruvate** → 2 **Lactate** or 2 **Ethanol + CO₂**

**Cellular Respiration**

- **Pyruvate** → 2 **Acetyl CoA**
  - **Krebs Cycle**:
    - 4 **CO₂** → 2 **ATP**
  - **Electron Transport Chain**:
    - **H₂O** → 32 or 34 **ATP**
  - **Intermembrane Compartment**

**Electron Transport Chain**

- **O₂**
Overview of Glucose Breakdown

- Stage 1: Glycolysis.
  - Glycolysis occurs in the cytoplasm of cells.
  - Does not require oxygen
  - Glucose (6 C sugar) is split into two pyruvate molecules (3 C each).
  - Yields two molecules of ATP per molecule of glucose.
Overview of Glucose Breakdown

- **Stage 2: Cellular respiration**
  - Occurs in **mitochondria** (in eukaryotes)
  - Requires oxygen (**aerobic**)
  - Breaks down pyruvate into CO$_2$ and H$_2$O
  - Produces an additional 32 or 34 ATP molecules, depending on the cell type
Overview of Glucose Breakdown

- If oxygen is absent fermentation occurs
  - Pyruvate remains in the cytoplasm
  - Pyruvate may be converted into either lactate, or ethanol and CO\(_2\)
  - No ATP is produced
- If oxygen is present cellular respiration occurs
7.3 What Happens During Glycolysis?

- Glycolysis splits one molecule of glucose into two molecules of pyruvate.
- During glycolysis, one molecule of glucose yields two ATP and two molecules of nicotinamide adenine dinucleotide (NADH) an electron carrier.
- Glycolysis involves two major steps:
  - Glucose activation
  - Energy harvest
Glycolysis

1. Glucose activation phase
   • Glucose molecule converted into the highly reactive fructose bisphosphate
   • Two enzyme-catalyzed reactions drive the conversion
   • Yields 2 ATP molecules
Glycolysis

- Two ATP power the phosphorylation of glucose to form fructose bisphosphate.
Glycolysis

2. Energy harvesting phase
   - Fructose bisphosphate is split into two three-carbon molecules of glyceraldehyde 3 phosphate (G3P)
   - Each G3P molecule is converted into pyruvate, generating two ATPs per conversion (4 total ATPs)
   - Two ATPs were used to activate the glucose molecule so there is a net gain of two ATPs per glucose molecule
   - As each G3P is converted to pyruvate, two high-energy electrons and a hydrogen ion are added to an “empty” electron-carrier NAD+ to make the high-energy electron-carrier molecule NADH
   - Because two G3P molecules are produced per glucose molecule, two NADH carrier molecules are formed
Glycolysis Summary

- Energy harvest from glycolysis:
  - Each molecule of glucose is broken down to two molecules of pyruvate
  - A net of two ATP molecules and two NADH (high-energy electron carriers) are formed
7.4 What Happens During Cellular Respiration?

- Cellular respiration is the second stage of glucose metabolism.
- Only occurs in the presence of O$_2$ (aerobic).
- Occurs in the mitochondria.
- Converts pyruvate to CO$_2$ and H$_2$O.
- Large amounts of ATP are produced.
Cellular Respiration

- Steps of Cellular Respiration

1. Two molecules of pyruvate are transported into the matrix of a mitochondrion.

2. Each pyruvate is split into CO$_2$ and acetyl CoA, which enters the Krebs cycle.
   - The Krebs cycle produces one ATP from each pyruvate (total 2 per glucose) and donates electrons to NADH and FADH$_2$.

3. NADH and FADH$_2$ donate energized electrons to the electron transport chain of the inner membrane.
Cellular Respiration

- Steps of cellular respiration *(continued)*

4. In the electron transport chain, electron energy is used to transport protons *(H^+)* from the matrix to the intermembrane compartment.

5. Electrons combine with O₂ and H⁺ to form H₂O.

6. Hydrogen ions in the intermembrane compartment diffuse across the inner membrane down their concentration gradient.

7. The flow of ions into the matrix provides the energy to produce ATP from ADP.

8. ATP moves out of mitochondrion into the cytoplasm.
Fig. 7-3

**Glycolysis**
- Glucose → 2 pyruvate

**ATP-synthesizing enzyme**
- ATP

**Electron transport chain**
- NADH, FADH$_2$
- $2e^-$
- $1/2O_2$ → ATP
- $2H^+$ → ATP

**Krebs cycle**
- Acetyl CoA → CO$_2$, CO$_2$
- $2H^+$ → ATP
- $2e^-$ → ATP

**Mitochondrion**
- Inner membrane
- Intermembrane compartment
- Matrix
- Cristae

**Other components**
- Inner membrane
- Outer membrane
- Intermembrane compartment
- Cytoplasmic fluid
- Coenzyme A
- Oxygen (O$_2$)
- Water (H$_2$O)
- ATP, ADP, Pi
- ATP synthase
- Energized electron carriers: NADH, FADH$_2$
- Depleted carriers: NAD$, FAD$
Cellular Respiration

- The Krebs cycle breaks down pyruvate in the mitochondrial matrix.
  - Pyruvate produced by glycolysis reaches the matrix and reacts with coenzyme A, forming acetyl CoA.
  - During this reaction, two electrons and a H\(^+\) are transferred to NAD\(^+\) to form NADH.
  - Acetyl CoA enters the Krebs cycle and produces one ATP, one FADH\(_2\), and three NADH.
Cellular Respiration

- The reactions in the mitochondrial matrix

1. Formation of acetyl CoA

2. Krebs cycle

- CoA
- CO₂
- coenzyme A
- NAD⁺
- NADH

Fig. 7-4
Cellular Respiration

- Energetic electrons are carried to the electron transport chain.
  1. Energized carriers deposit their electrons in the electron transport chains (ETC) in the inner mitochondrial membrane.
  2. Electrons in the ETC move from one molecule to the next, transferring energy that is used to pump H\(^+\) out of the matrix and into the intermembrane compartment.
  3. At the end of the ETC, oxygen atoms combine with two H\(^+\) and two depleted electrons to form H\(_2\)O.
Cellular Respiration

- Energetic electrons are carried to the electron transport chain (*continued*).

4. Oxygen accepts electrons after they have passed through the ETC and given up most of their energy.

5. If $O_2$ is not present, electrons accumulate in the ETC, $H^+$ pumping out of the matrix stops, and cellular respiration ceases.
Cellular Respiration

- The electron transport chain in the mitochondrial matrix

![Diagram of electron transport chain in the mitochondrial matrix](image)

Fig. 7-5
Cellular Respiration

- Energy from a hydrogen-ion gradient is used to produce ATP.
  - Hydrogen ions accumulate in the intermembrane compartment and diffuse back into the matrix.
  - The energy released when hydrogen ions move down their concentration gradient is used to make ATP in a process called chemiosmosis.
  - During chemiosmosis, 32 to 34 molecules of ATP are produced from each molecule of glucose.
  - This ATP is transported from the matrix to the cytoplasm, where it is used to power metabolic reactions.
7.5 What Happens During Fermentation?

- Under anaerobic conditions (no $O_2$), glucose cannot be metabolized by cellular respiration; instead, fermentation takes place.

- Unlike cellular respiration, fermentation generates no ATP, but instead, regenerates $NAD^+$ that is used to generate ATP from glycolysis.
Fermentation

- In fermentation, pyruvate acts as an electron acceptor from the NADH produced during glycolysis.
- When pyruvate accepts electrons from NADH, it recycles the NAD$^+$ so that more glucose can be converted to pyruvate, generating a small amount of ATP in the process.
- When no $O_2$ is present, glycolysis becomes the main source of ATP and NADH production.
Fermentation

- There are two types of fermentation: one converts pyruvate to ethanol and CO₂, and the other converts pyruvate to lactate.
  - Alcoholic fermentation is the primary mode of metabolism in many microorganisms.
  - The reactions use hydrogen ions and electrons from NADH, thereby regenerating NAD⁺.
  - Alcoholic fermentation is responsible for the production of many economic products, such as wine, beer, and bread.
Fermentation

- Glycolysis followed by alcoholic fermentation

\[ \text{Glucose} \rightarrow \text{Pyruvate} \rightarrow \text{Ethanol} + \text{CO}_2 \]

\[ 2 \text{ATP} \rightarrow \text{ADP} \]

\[ \text{NAD}^+ \rightarrow \text{NADH} \rightarrow \text{NAD}^+ \]
Fermentation

- Other cells ferment pyruvate to lactate, and include microorganisms that produce yogurt, sour cream, and cheese.
- Lactate fermentation also occurs in aerobic organisms when cells are temporarily deprived of oxygen, such as muscle cells during vigorous exercise.
- These muscle cells ferment pyruvate to lactate, which uses $\text{H}^+$ and electrons from NADH to regenerate NAD$^+$. 
Fermentation

- Glycolysis followed by lactate fermentation
Fermentation

- Fermentation limits human muscle performance.
  - During a sprint muscles use more ATP than can be delivered by cellular respiration because \( O_2 \) cannot be delivered to muscles fast enough.
  - Glycolysis can deliver a small amount of ATP to rapidly contracting muscles, but toxic buildup of lactate will occur.
  - Long distance runners must therefore pace themselves so that cellular respiration can power their muscles for most of the race.
Fermentation

- Some microbes ferment pyruvate to other acids (as seen in making of cheese, yogurt, sour cream)
- Some microbes perform fermentation exclusively (instead of aerobic respiration)
- Yeast cells perform **alcoholic fermentation**
Summary of Glucose Breakdown

**Glycolysis**
- 2 ATP
- 2 pyruvate
- 2 NADH

**Krebs (Citric Acid) Cycle**
- 2 acetyl CoA
- 6 NADH
- 2 FADH₂
- 2 ATP
- 32 or 34 ATP

**Electron Transport Chain**
- Total of 36 or 38 ATP

**Fermentation**
- lactate or ethanol + CO₂

**Cellular Respiration**
- 2 CO₂
- 2 ATP
- 2 NADH
- 6 NADH
- 2 FADH₂
- 32 or 34 ATPs

*Figure 8-9 and Figure 8-10: Biology: Life on Earth, 8/e © 2006 Pearson Prentice Hall, Inc.*
Influence on How Organisms Function

- Metabolic processes in cells are heavily dependent on ATP generation (cyanide kills by preventing this)
- Muscle cells switch between fermentation and aerobic cell respiration depending on O$_2$ availability