TOPIC 1

The Chemistry of Life

Chapter 2: The Chemical Context of Life

WHAT'S IMPORTANT TO KNOW?
This chapter is considered prior knowledge for the AP Biology Examination. However, you will need to know this information to proceed with the required topics, so we include what is most important in this area.

YOU MUST KNOW

- The three subatomic particles and their significance.
- The types of chemical bonds, how they form, and their relative strengths.

Concept 2.1 Matter consists of chemical elements in pure form and in combinations called compounds

- **Matter** is anything that takes up space and has mass.
- An **element** is a substance that cannot be broken down to other substances by chemical reactions. *Examples*: gold, copper, carbon, and oxygen.
- A **compound** is a substance consisting of two or more elements combined in a fixed ratio. *Examples*: water (H_2O) and table salt (NaCl).
- **C, H, O, N** make up 96% of living matter. About 25 of the 92 natural elements are known to be essential to life.
- **Trace elements** are those required by an organism in only minute quantities. *Examples*: iron and iodine.

Concept 2.2 An element's properties depend on the structure of its atoms

- **Atoms** are the smallest unit of an element that still retains the property of the element. Atoms are made up of neutrons, protons, and electrons.
- **Protons** are positively charged particles. They are found in the nucleus and determine the element.
- **Electrons** are negatively charged particles that are found in electron shells around the nucleus. They determine the chemical properties and reactivity of the element.
- **Neutrons** are particles with no charge. They are found in the nucleus. Their number can vary in the same element, resulting in isotopes.

- **Isotopes** are forms of an element with differing numbers of neutrons. Example: ^{12}C and ^{14}C are isotopes of carbon. Both have 6 protons, but ^{12}C has 6 neutrons whereas ^{14}C has 8 neutrons.
- The **atomic number** is the number of protons an element possesses. This number is unique to every element. (See Figure 1.1.)
- The **mass number** of an element is the sum of its protons and neutrons.

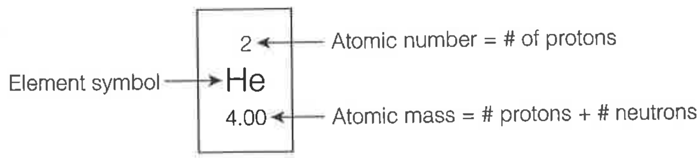


Figure 1.1 An element of the periodic table

Concept 2.3 The formation and function of molecules depend on chemical bonding between atoms

- **Chemical bonds** are defined as interactions between the valence electrons of different atoms. Atoms are held together by chemical bonds to form molecules.
- A **covalent bond** occurs when valence electrons are shared by two atoms.
  - **Nonpolar covalent bonds** occur when the electrons being shared are shared equally between the two atoms. *Examples*: O=O, H−H.
  - Atoms vary in their *electronegativity*, a tendency to attract electrons of a covalent bond. Oxygen is strongly electronegative.
  - In **polar covalent bonds**, one atom has greater electronegativity than the other, resulting in an unequal sharing of the electrons. *Example*: Refer to Figure 1.2 and note that within each molecule of H_2O the electrons are shared unequally, resulting in the region of the oxygen atom being slightly negative, whereas the regions about the hydrogen atoms are slightly positive.

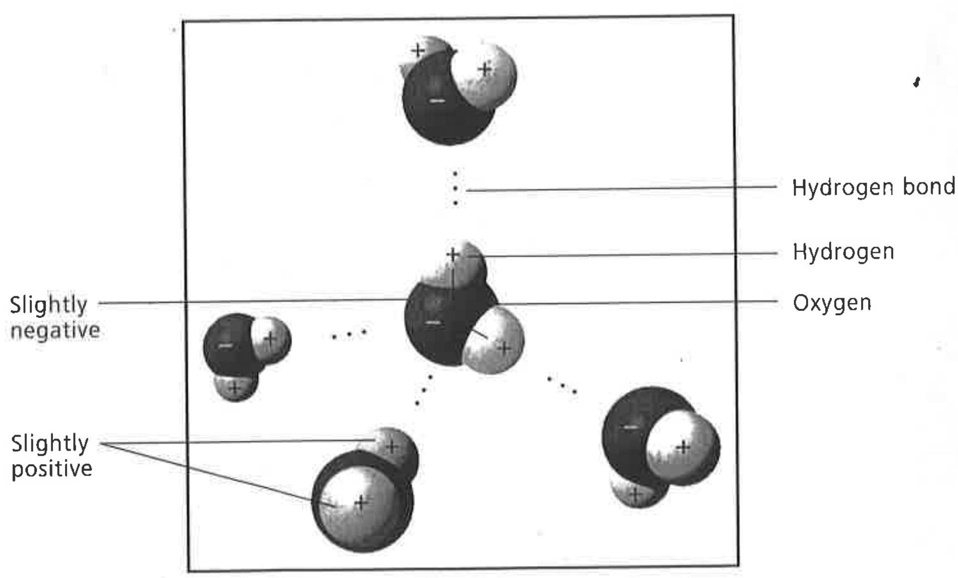


Figure 1.2 Hydrogen bonds between water molecules

- **Ionic bonds** are ones in which two atoms attract valence electrons so unequally that the more electronegative atom steals the electron away from the less electronegative atom.
  - An **ion** is the resulting charged atom or molecule.
  - **Ionic bonds** occur because these ions will be either positively or negatively charged, and will be attracted to each other by these opposite charges.
- **Hydrogen bonds** are relatively weak bonds that form between the partial positively charged hydrogen atom of one molecule and the strongly electronegative oxygen or nitrogen of *another* molecule.
- **Van der Waals interactions** are very weak, transient connections that are the result of asymmetrical distribution of electrons within a molecule. These weak interactions contribute to the three-dimensional shape of molecules.

Concept 2.4 Chemical reactions make and break chemical bonds

- A **chemical reaction** shows the **reactants**, which are the starting materials, an arrow to indicate their conversion into the **products**, the ending materials. *Example*: $6\ CO_2 + 6\ H_2O \longrightarrow C_6H_{12}O_6 + 6\ O_2$.
- The chemical reaction above also shows the number of molecules involved. This is the coefficient in front of each molecule. You will note that the number of atoms of each element is the same on each side of the reaction.
- Some chemical reactions are reversible, which is indicated with a double-headed arrow: $3\ H_2 + N_2 \rightleftharpoons 2\ NH_3$.
- **Chemical equilibrium** is the point at which the forward and reverse reactions offset one another exactly. Their concentrations have stabilized at a particular ratio, though they are not necessarily equal.

Chapter 3: Water and Life

YOU MUST KNOW

- The importance of hydrogen bonding to the properties of water.
- Four unique properties of water, and how each contributes to life on Earth.
- How to interpret the pH scale.
- How changes in pH can alter biological systems.
- The importance of buffers in biological systems.

Concept 3.1 Polar covalent bonds in water molecules result in hydrogen bonding

- The **structure of water** is the key to its special properties. Water is made up of one atom of oxygen and two atoms of hydrogen, bonded to form a molecule.
- Water molecules are **polar**. The oxygen region of the molecule has a partial negative charge, and each hydrogen has a partial positive charge.

- **Hydrogen bonds** form between water molecules. The slightly negative oxygen atom from one water molecule is attracted to the slightly positive hydrogen end of *another* water molecule.
- Each water molecule can form a maximum of four hydrogen bonds at a time.

Concept 3.2 Four emergent properties of water contribute to Earth's suitability for life

- **Hydrogen bonds** are the key to each of these properties. This is what makes water so unique.

1. **Cohesion.** Cohesion is the linking of like molecules. Think "water molecule joined to water molecule" and visualize a water strider walking on top of a pond due to the *surface tension* that is the result of this property.
   - **Adhesion** is the clinging of one substance to another. Think "water molecule attached to some other molecule" such as water droplets adhering to a glass windshield.
   - **Transpiration** is the movement of water molecules up the very thin xylem tubes and their evaporation from the stomata in plants. The water molecules cling to each other by *cohesion*, and to the walls of the xylem tubes by *adhesion*.
2. Moderation of temperature is possible because of water's high specific heat.
   - **Specific heat** is the amount of heat required to raise or lower the temperature of a substance by 1°C. Relative to most other materials, the temperature of water changes less when a given amount of heat is lost or absorbed. This high specific heat makes the temperature of Earth's oceans relatively stable and able to support vast quantities of both plant and animal life.
3. Insulation of bodies of water by floating ice.
   - Water is less dense as a solid than in its liquid state, whereas the opposite is true of most other substances. Because ice is less dense than liquid water, ice floats. This keeps large bodies of water from freezing solid and therefore moderates temperature.
4. Water is an important *solvent.* (The substance that something is dissolved in is called the *solvent*, whereas the substance being dissolved is the *solute.* Together they are called the *solution.*)
   - **Hydrophilic** substances are water-soluble. These include ionic compounds, polar molecules (e.g., sugars), and some proteins.
   - **Hydrophobic** substances such as oils are nonpolar and do not dissolve in water.

Concept 3.3 Acidic and basic conditions affect living organisms

- The **pH** scale runs between 0 and 14 and measures the relative acidity and alkalinity of aqueous solutions. (See Figure 1.3.)

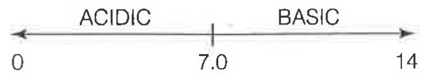


Figure 1.3 pH scale

- **Acids** have an excess of H^+ ions and a pH below 7.0. $[H^+] > [OH^-]$
- **Bases** have an excess of OH^- ions, and pH above 7.0. $[H^+] < [OH^-]$
- Pure water is neutral, which means it has a pH of 7. $[H^+] = [OH^-]$
- **Buffers** are substances that minimize changes in pH. They accept H^+ from solution when they are in excess and donate H^+ when they are depleted.
- **Carbonic acid (H_2CO_3)** is an important buffer in living systems. It moderates pH changes in blood plasma and the ocean.

Chapter 4: Carbon and the Molecular Diversity of Life

YOU MUST KNOW

- The properties of carbon that make it so important.

Concept 4.1 Organic chemistry is the study of carbon compounds

- The major elements of life are C, H, O, N, S, and P, sometimes recalled with the acronym for a person's name: ***P.S. COHN.***
- All ***organic compounds*** contain carbon, and most also contain hydrogen.
- Once thought to be made only in living cells, artificial synthesis of organic compounds is possible. A classic experiment done by Stanley Miller in 1953 showed that complex organic molecules could arise spontaneously. See the figure in your text, and note the conditions and compounds that might have been part of the early conditions on Earth.

Concept 4.2 Carbon atoms can form diverse molecules by bonding to four other atoms

- Carbon is unparalleled in its ability to form molecules that are large, complex, and diverse. Why?
  - It has 4 valence electrons.
  - It can form up to 4 covalent bonds.
  - These can be single, double, or triple covalent bonds.
  - It can form large molecules.
  - These molecules can be chains, ring-shaped, or branched.
- **Isomers** are molecules that have the same molecular formula but differ in their arrangement of these atoms. These differences can result in molecules that are very different in their biological activities. *Examples*: glucose and fructose (both have the molecular formula of $C_6H_{12}O_6$).

Concept 4.3 ***A few chemical groups are key to the functioning of biological molecules***

- **Functional groups** attached to the carbon skeleton have diverse properties. The behavior of organic molecules is dependent on the identity of their functional groups.
- Some common functional groups are listed below:

Functional Group Name/Structure	Organic Molecules with the Functional Group and Items of Note about Functional Group
Hydroxyl, —OH	Alcohols such as ethanol, methanol; helps dissolve molecules such as sugars
Carboxyl, —COOH	Carboxylic acids such as fatty acids and sugars; acidic properties because it tends to ionize; source of H^+ ions
Carbonyl, ⟨CO	Ketones and aldehydes such as sugars
Amino, —NH_2	Amines such as amino acids
Phosphate, PO_3	Organic phosphates, including ATP, DNA, and phospholipids
Sulfhydryl, —SH	This group is found in some amino acids; forms disulfide bridges in proteins
Methyl, —CH_3	Addition of a methyl group affects expression of genes

Chapter 5: The Structure and Function of Large Biological Molecules

YOU MUST KNOW

- The role of **dehydration reactions** in the formation of organic compounds and **hydrolysis** in the digestion of organic compounds.
- How to recognize the four biologically important organic compounds (carbohydrates, lipids, proteins, and nucleic acids) by their structural formulas.
- The cellular functions of the four groups of organic compounds.
- The four structural levels of proteins and how changes at any level can affect the activity of the protein.
- How proteins reach their final shape **(conformation)**, the **denaturing** impact that heat and pH can have on protein structure, and how these changes may affect the organism.

Concept 5.1 ***Macromolecules are polymers, built from monomers***

- **Polymers** are long chain molecules made of repeating subunits called **monomers**. *Examples*: Starch is a polymer composed of glucose monomers. Proteins are polymers composed of amino acid monomers. (See Figure 1.4.)

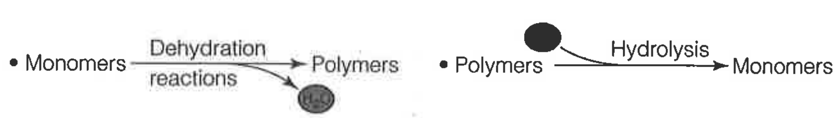


Figure 1.4 Synthesis and breakdown of polymers

- **Dehydration reactions** create polymers from monomers. Two monomers are joined by removing one molecule of water. *Example*: $C_6H_{12}O_6 + C_6H_{12}O_6 \rightarrow H_{22}O_{11} + H_2O$.
- **Hydrolysis** occurs when water is added to split large molecules. This occurs in the reverse of the above reaction.

Concept 5.2 Carbohydrates serve as fuel and building material

- **Carbohydrates** include both simple sugars (glucose, fructose, galactose, etc.) and polymers such as starch made from these and other subunits. All carbohydrates exist in a ratio of 1 carbon: 2 hydrogen: 1 oxygen or CH_2O.
- **Monosaccharides** are the monomers of carbohydrates. *Examples*: glucose ($C_6H_{12}O_6$) and ribose ($C_5H_{10}O_5$). Notice the 1:2:1 ratio discussed above.
- **Polysaccharides** are polymers of monosaccharides. *Examples*: starch, cellulose, and glycogen.
- Two functions of polysaccharides are **energy storage** and **structural support.**

  1. **Energy-storage polysaccharides**
     - **Starch** is a storage polysaccharide found in plants (e.g., potatoes).
     - **Glycogen** is a storage polysaccharide found in animals, vertebrate muscle cells, and liver cells.
  2. **Structural support polysaccharides**
     - **Cellulose** is a major component of plant cell walls.
     - **Chitin** is found in the exoskeleton of arthropods, such as lobsters and insects and the cell walls of fungi. It gives cockroaches their "crunch."

Concept 5.3 Lipids are a diverse group of hydrophobic molecules

- Lipids are all **hydrophobic.** They aren't polymers, as they are assembled from a variety of components. *Examples*: **waxes, oils, fats,** and **steroids.**
- **Fats** (also called triglycerides) are made up of a **glycerol** molecule and three **fatty acid** molecules.
- **Fatty acids** include hydrocarbon chains of variable lengths. These chains are nonpolar and therefore hydrophobic.
  - **Saturated fatty acids**
    - have no double bonds between carbons
    - tend to pack solidly at room temperature
    - are linked to cardiovascular disease
    - are commonly produced by animals
    - *Examples*: butter and lard
  - **Unsaturated fatty acids**
    - have some C=C (carbon double bonds); this results in kinks
    - tend to be liquid at room temperature

- are commonly produced by plants
- *Examples*: corn oil and olive oil

- **Functions of lipids**
  - *Energy storage*. Fats store twice as many calories/gram as carbohydrates!
  - *Protection* of vital organs and *insulation*. In humans and other mammals, fat is stored in **adipose cells**.

- **Phospholipids** make up cell membranes. They
  - have a glycerol backbone (head), which is hydrophilic.
  - have two fatty acid tails, which are hydrophobic.
  - are arranged in a bilayer in forming the cell membrane, with the hydrophilic heads pointing toward the watery cytosol or extracellular environment, and hydrophobic tails sandwiched in between (see Figure 1.5).

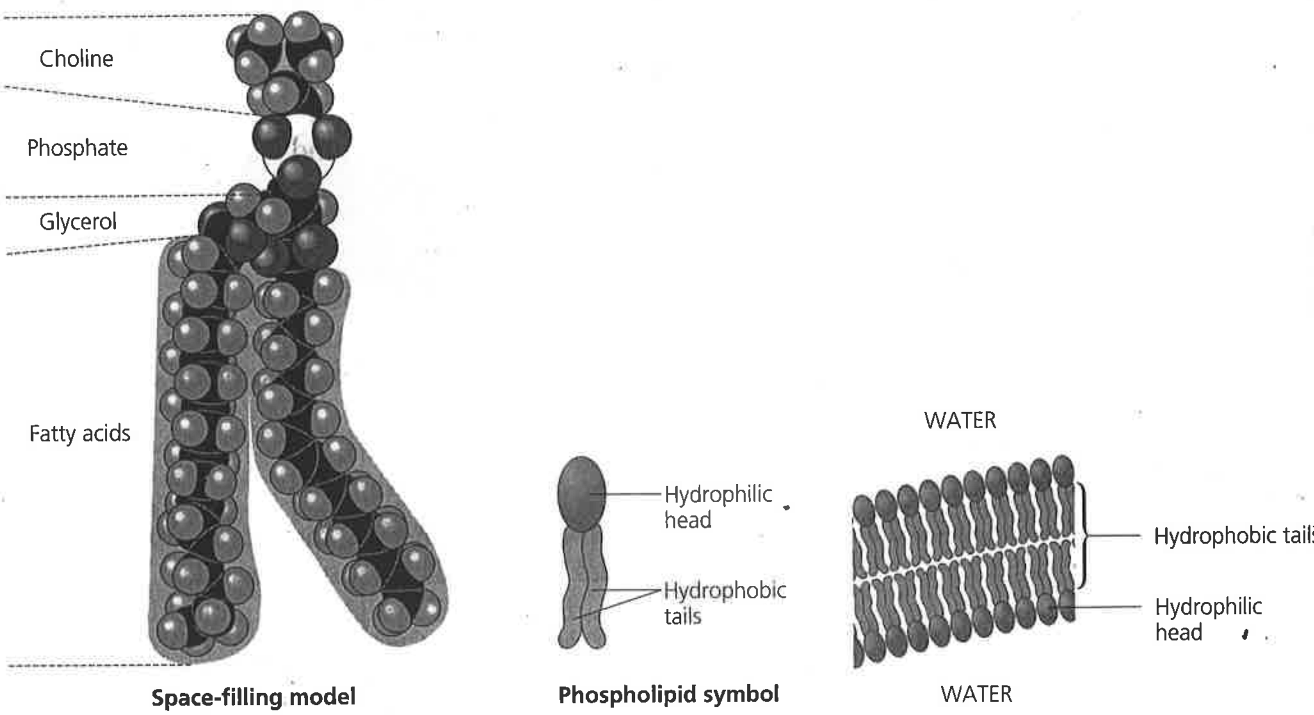


Figure 1.5 The structure of a phospholipid

- **Steroids** are made up of four rings that are fused together.
  - **Cholesterol** is a steroid. It is a common component of cell membranes.
  - **Estrogen** and **testosterone** are steroid hormones.

Concept 5.4 Proteins include a diversity of structures, resulting in a wide range of functions

- **Proteins** are polymers made up of amino acid monomers.
- **Amino acids** contain a central carbon bonded to a carboxyl group, an amino group, a hydrogen atom, and an R group (variable group or side chain). (See Figure 1.6.)

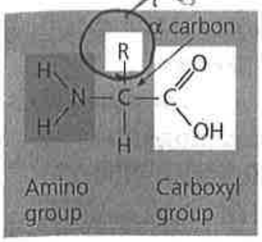


Figure 1.6 The structure of an amino acid

- **Peptide bonds** link amino acids. They are formed by dehydration synthesis.
- **There are four levels of protein structure** (see Figure 1.7):
  - **Primary structure** is the unique sequence in which amino acids are joined.
  - **Secondary structure** refers to one of two three-dimensional shapes that are the result of hydrogen bonding.
    - **Alpha (α) helix** is a coiled shape, much like a slinky.
    - **Beta (β) pleated sheet** is an accordion shape.
  - **Tertiary structure** results in a complex globular shape, due to interactions between R groups, such as hydrophobic interactions, van der Waals interactions, hydrogen bonds, and disulfide bridges.
    - Globular proteins such as enzymes are held in position by these R group interactions.
  - **Quaternary structure** refers to the association of two or more polypeptide chains into one large protein. Hemoglobin is a globular protein with quaternary structure, as it is composed of four chains.

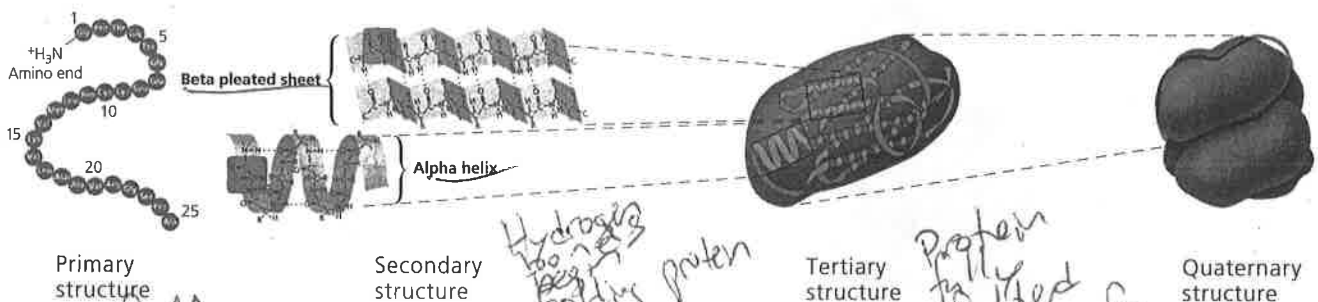


Figure 1.7 Levels of protein structure

- **Protein shape is crucial to protein function.** When a protein does not fold properly, its function is changed. This can be the result of a single amino acid substitution, such as that seen in the abnormal hemoglobin typical of sickle-cell disease.
- **Chaperonins** are protein molecules that assist in the proper folding of proteins within cells. They provide an isolating environment in which a polypeptide chain may attain final conformation.
- A protein is **denatured** when it loses its shape and ability to function due to **heat**, a **change in pH**, or some other disturbance.

Concept 5.5 Nucleic acids store, transmit, and help express hereditary information

- **DNA** (deoxyribonucleic acid) and **RNA** (ribonucleic acid) are the two nucleic acids. Their monomers are nucleotides.
- **Nucleotides** are made up of three parts (see Figure 1.8):
  - **Nitrogenous base** (adenine, thymine, cytosine, guanine, and uracil)
  - **Pentose** (5-carbon) sugar (deoxyribose in DNA or ribose in RNA)
  - **Phosphate group**

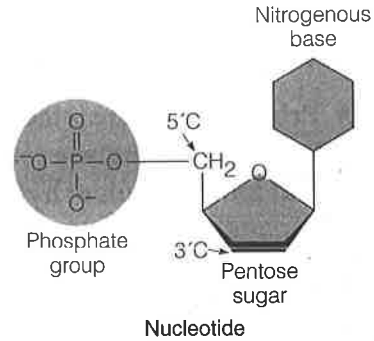


Figure 1.8 The components of nucleic acids

- **DNA** is the molecule of heredity.
  - It is double-stranded helix.
  - Its nucleotides are adenine, thymine, cytosine, and guanine.
  - Adenine nucleotides will hydrogen bond to thymine nucleotides, and cytosine to guanine.
- **RNA** is single-stranded. Its nucleotides are adenine, uracil, cytosine, and guanine. Note that it does not have thymine.

SUMMARY TABLE

Macromolecules/Polymers	Monomers/Components	Examples	Functions
Carbohydrates	Monosaccharides	Sugars, starch, glycogen, cellulose	Energy, energy storage; structural
Lipids	Fatty acids and glycerol	Fats, oils	Important energy source; insulation
Proteins	Amino acids	Hemoglobin, pepsin	Enzymes, movement
Nucleic Acids	Nucleotides (sugar, phosphate group, nitrogenous base)	DNA, RNA	Heredity; code for amino acid sequence

Level 1: Knowledge/Comprehension Questions

1. Which list of components characterizes RNA?
   (A) a PO_3 group, deoxyribose, and uracil
   (B) a PO_3 group, ribose, and uracil
   (C) a PO_3 group, ribose, and thymine
   (D) a PO_2 group, deoxyribose, and uracil
   (E) a PO_2 group, deoxyribose, and thymine

2. Which of the following molecules would contain a polar covalent bond?
   (A) Cl_2
   (B) NaCl
   (C) H_2O
   (D) CH_4
   (E) $C_6H_{12}O_6$

3. Which of the following statements regarding carbon is *false*?
   (A) Carbon has a tendency to form covalent bonds.
   (B) Carbon has the ability to bond with up to four other atoms.
   (C) Carbon has the capacity to form single and double bonds.
   (D) Carbon has the ability to bond together to form extensive, branched, or unbranched "carbon skeletons."
   (E) Carbon has the capacity to form polar bonds with hydrogen.

4. Three terms associated with the travel of water from the roots up through the vascular tissues of plants are
   (A) adhesion, cohesion, and translocation.
   (B) adhesion, cohesion, and transcription.
   (C) cohesion, hybridization, and transpiration.
   (D) cohesion, adhesion, and transpiration.
   (E) transpiration, neutralization, and adhesion.

Directions: The group of questions below consists of five lettered choices followed by a list of numbered phrases or sentences. For each numbered phrase or sentence, select the one choice that is most closely related to it. Each choice may be used once, more than once, or not at all.

Questions 5–9
   (A) Lipids
   (B) Peptide bonds
   (C) Alpha helix
   (D) Unsaturated fatty acids
   (E) Cellulose

5. Contain one or more double bonds which "kink" the carbon backbone

6. The major class of biological molecules that are not polymers

7. Linkages between the monomers of proteins

8. A secondary structure of proteins

9. A structural carbohydrate found in plants

10. The process by which protein conformation is lost or broken down is
   (A) dehydration synthesis.
   (B) translation.
   (C) denaturation.
   (D) hydrolysis.
   (E) protein synthesis.

11. An organic compound that is composed of carbon, hydrogen, and oxygen in a 1:2:1 ratio is known as a
   (A) lipid.
   (B) carbohydrate.
   (C) salt.
   (D) nucleic acid.
   (E) protein.

12. If three molecules of a fatty acid that has the formula $C_{16}H_{22}O_2$ are joined to a molecule of glycerol ($C_3H_8O_3$), then the resulting molecule would have the formula
   (A) $C_{48}H_{96}O_6$.
   (B) $C_{48}H_{98}O_8$.
   (C) $C_{51}H_{68}O_6$.
   (D) $C_{51}H_{106}O_8$.
   (E) $C_{51}H_{104}O_9$.

13. Which of the macromolecules below could be structural parts of the cell, enzymes, or involved in cell movement or communication?
   (A) nucleic acids
   (B) proteins
   (C) lipids
   (D) carbohydrates
   (E) minerals

14. Which macromolecule is the main component of all cell membranes?
   (A) DNA
   (B) phospholipids
   (C) carbohydrates
   (D) steroids
   (E) glucose

15. The partial negative charge at one end of a water molecule is attracted to a partial positive charge of another water molecule. What is this type of attraction called?
   (A) a polar covalent bond
   (B) an ionic bond
   (C) a hydration shell
   (D) a hydrogen bond
   (E) a hydrophobic bond

16. Polymers of carbohydrates and proteins are all synthesized from monomers by
    (A) the joining of monosaccharides.
    (B) hydrolysis.
    (C) dehydration reactions.
    (D) ionic bonding of monomers.
    (E) cohesion.

17. If the pH of a solution is decreased from 7 to 6, it means that the
    (A) concentration of H^+ has decreased to 1/10 of what it was at pH 7.
    (B) concentration of H^+ has increased 10 times what it was at pH 7.
    (C) concentration of OH^- has increased 10 times what it was at pH 7.
    (D) concentration of OH^- has increased by 1/7 of what it was.
    (E) solution has become more basic.

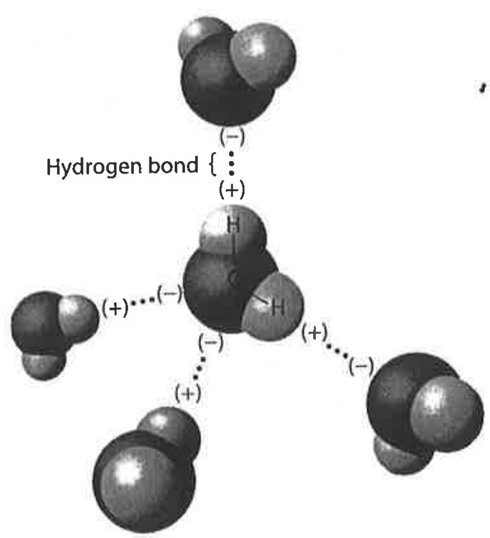
18. Which of the following is NOT considered to be an emergent property of water?
    (A) cohesion
    (B) transpiration
    (C) moderation of temperature
    (D) insulation of bodies of water by floating ice
    (E) a versatile solvent

19. Which two functional groups are always found in amino acids?
    (A) amine and sulfhydryl
    (B) carbonyl and carboxyl
    (C) carboxyl and amine
    (D) alcohol and aldehyde
    (E) ketone and amine

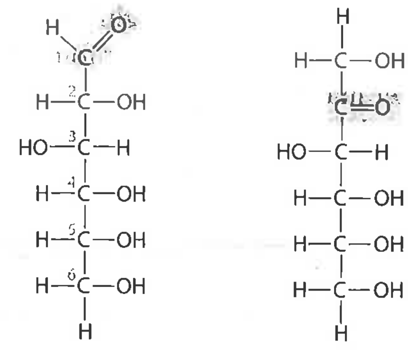
20. Hydrolysis is involved in which of the following?
    (A) formation of starch
    (B) hydrogen bond formation between nucleic acids
    (C) peptide bond formation of proteins
    (D) the hydrophilic interactions of lipids
    (E) the digestion of maltose to glucose

Level 2: Application/Analysis/Synthesis Questions

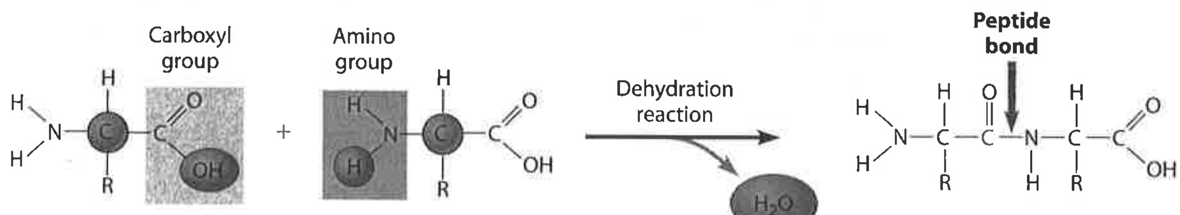
1. The hydrogen bonds shown in this figure are each
    (A) between two hydrogen atoms.
    (B) between two oxygen atoms.
    (C) between an oxygen and a hydrogen atom of the same water molecule.
    (D) between an oxygen and a hydrogen atom of different water molecules.



2. These two molecules are structural isomers and can be predicted to have different functions. What is the difference between them?
   (A) the number of carbon atoms
   (B) the number of oxygen atoms
   (C) the number of hydrogen atoms
   (D) the location of a double-bonded oxygen atom



Questions 3 and 4 refer to the following art.



3. How are these two amino acids attached together?
   (A) amino group to amino group
   (B) amino group to carboxylic acid group
   (C) carboxylic acid group to carboxylic acid group
   (D) carbon atom to carbon atom

4. If the dipeptide above were to be digested, how would it be reduced to amino acids?
   (A) by a dehydration reaction
   (B) by reduction in digestive fluid pH
   (C) through removal of functional groups
   (D) through a hydrolysis reaction

After reading the following paragraph, answer questions 5 and 6.

You're the manager of a factory that produces enzyme-washed blue jeans (the enzymes lighten the color of the denim, giving a faded appearance). When the most recent batch of fabric came out of the enzyme wash, however, the color wasn't light enough to meet your standards.

Your quality control laboratory wants to do some tests to determine why the wash enzymes didn't perform as expected.

5. Which hypothesis is most likely to be productive for their initial investigation?
   (A) The nucleotide chain of the enzymes may be incorrectly formed.
   (B) The dye in the fabric may have hydrolyzed the fatty acids in the enzymes.
   (C) The polysaccharides in the enzymes may have separated in the wash water.
   (D) The three-dimensional structure of the proteins may have been altered.

6. Based on your understanding of enzyme structure, which of the following would you recommend that they also investigate?
   (A) the temperature of the liquid in the washing vat
   (B) the pH of the liquid in the washing vat
   (C) the manufacturer of the fabric
   (D) both A and B

7. The molecular formula for glucose is $C_6H_{12}O_6$. What would be the molecular formula for a polymer made by lining ten glucose molecules together by dehydration reactions?
(A) $C_{60}H_{120}O_{60}$
(B) $C_6H_{12}O_6$
(C) $C_{60}H_{102}O_{51}$
(D) $C_{60}H_{100}O_{50}$

8. Which of the following pairs of base sequences could form a short stretch of a normal double helix of DNA?
(A) 5′-purine-pyrimidine-purine-pyrimidine-3′ with 3′-purine-pyrimidine-purine-pyrimidine-5′
(B) 5′-AGCT-3′ with 5′-TCGA-3′
(C) 5′-GCGC-3′ with 5′-TATA-3′
(D) 5′-ATGC-3′ with 5′-GCAT-3′

Free-Response Question

1. *The selectively permeable plasma membrane is composed of phospholipids and protein, which allow for its unique functions.*

   (a) Describe the structure and properties of phospholipids and *explain* the important roles of phospholipids in the plasma membrane.
   (b) Explain why proteins are an important component of the cell membrane, based on their structure and properties.

TOPIC 2

The Cell

Chapter 6: A Tour of the Cell

YOU MUST KNOW

- Three differences between prokaryotic and eukaryotic cells.
- The structure and function of organelles common to plant and animal cells.
- The structure and function of organelles found only in plant cells or only in animal cells.

Concept 6.2 Eukaryotic cells have internal membranes that compartmentalize their functions

- The table below organizes the major characteristics of prokaryotic and eukaryotic cells.

Characteristics	Prokaryotic Cells	Eukaryotic Cells
Plasma membrane	yes	yes
Cytosol with organelles	yes	yes
Ribosomes	yes	yes
Nucleus	no	yes
Size	1 µm–10 µm	10 µm–100 µm
Internal membranes	no	yes

- Prokaryotic cells are found in the domains Bacteria and Archaea. Eukaryotic cells belong to the domain Eukarya and include animals, fungi, plants, and protists.
- Three key details to remember about prokaryotes include
  - Chromosomes are grouped together in a region called the nucleoid, but there is no nuclear membrane and therefore no true nucleus.
  - No membrane-bounded organelles are found in the cytosol. (Ribosomes are found, but they are not membrane bound.)
  - From the table above, notice how much smaller prokaryotes are than eukaryotes.

TOPIC 2

The Cell

Chapter 6: A Tour of the Cell

YOU MUST KNOW

- Three differences between prokaryotic and eukaryotic cells.
- The structure and function of organelles common to plant and animal cells.
- The structure and function of organelles found only in plant cells or only in animal cells.

Concept 6.2 Eukaryotic cells have internal membranes that compartmentalize their functions

- The table below organizes the major characteristics of prokaryotic and eukaryotic cells.

Characteristics	Prokaryotic Cells	Eukaryotic Cells
Plasma membrane	yes	yes
Cytosol with organelles	yes	yes
Ribosomes	yes	yes
Nucleus	no	yes
Size	1 μm–10 μm	10 μm–100 μm
Internal membranes	no	yes

- Prokaryotic cells are found in the domains Bacteria and Archaea. Eukaryotic cells belong to the domain Eukarya and include animals, fungi, plants, and protists.
- Three key details to remember about prokaryotes include
  - Chromosomes are grouped together in a region called the nucleoid, but there is no nuclear membrane and therefore no true nucleus.
  - No membrane-bounded organelles are found in the cytosol. (Ribosomes are found, but they are not membrane bound.)
  - From the table above, notice how much smaller prokaryotes are than eukaryotes.

7. The molecular formula for glucose is $C_6H_{12}O_6$. What would be the molecular formula for a polymer made by lining ten glucose molecules together by dehydration reactions?
(A) $C_{60}H_{120}O_{60}$
(B) $C_6H_{12}O_6$
(C) $C_{60}H_{102}O_{51}$
(D) $C_{60}H_{100}O_{50}$

8. Which of the following pairs of base sequences could form a short stretch of a normal double helix of DNA?
(A) 5′-purine-pyrimidine-purine-pyrimidine-3′ with 3′-purine-pyrimidine-purine-pyrimidine-5′
(B) 5′-AGCT-3′ with 5′-TCGA-3′
(C) 5′-GCGC-3′ with 5′-TATA-3′
(D) 5′-ATGC-3′ with 5′-GCAT-3′

Free-Response Question

1. *The selectively permeable plasma membrane is composed of phospholipids and protein, which allow for its unique functions.*
   (a) Describe the structure and properties of phospholipids and *explain* the important roles of phospholipids in the plasma membrane.
   (b) Explain why proteins are an important component of the cell membrane, based on their structure and properties.

- Three corresponding details about eukaryotic cells:
  - A membrane-enclosed nucleus contains the cell's chromosomes.
  - Many membrane-bounded organelles are found in the cytoplasm.
  - On average, eukaryotes are much larger than prokaryotes.
- Use Figures 2.1 and 2.2 to locate each component of a plant or animal cell as they are reviewed.
- The **plasma membrane** forms the boundary for a cell. It is selectively permeable and permits the passage of materials into and out of the cell.
- The plasma membrane is made up of *phospholipids*, *proteins*, and associated *carbohydrates*.
- The *surface area to volume ratio* becomes less favorable as a cell increases in size. The total volume grows proportionately more than the surface area. Since a cell acquires resources through the plasma membrane, cell size is limited.

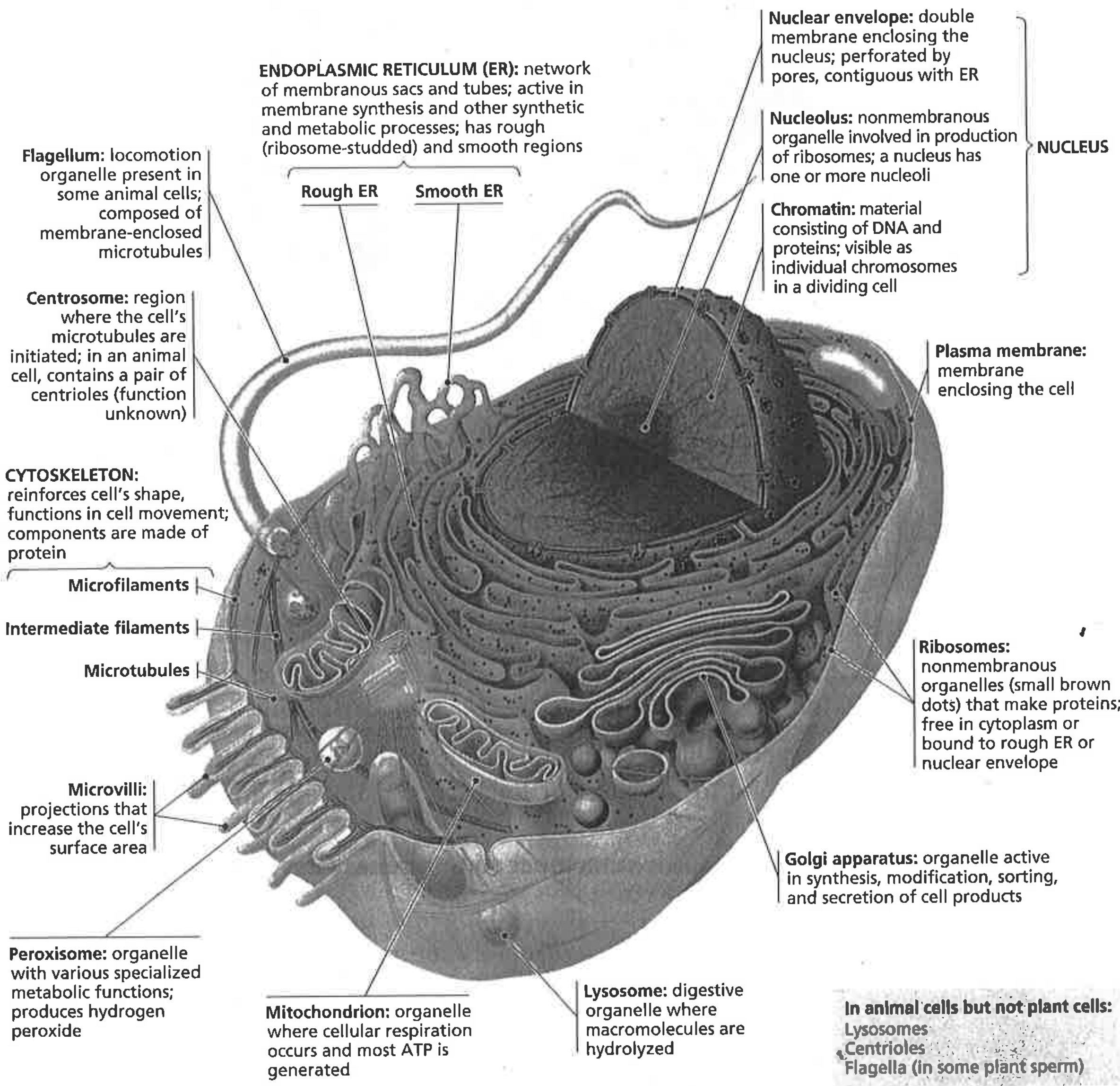


Figure 2.1 Animal cell structure

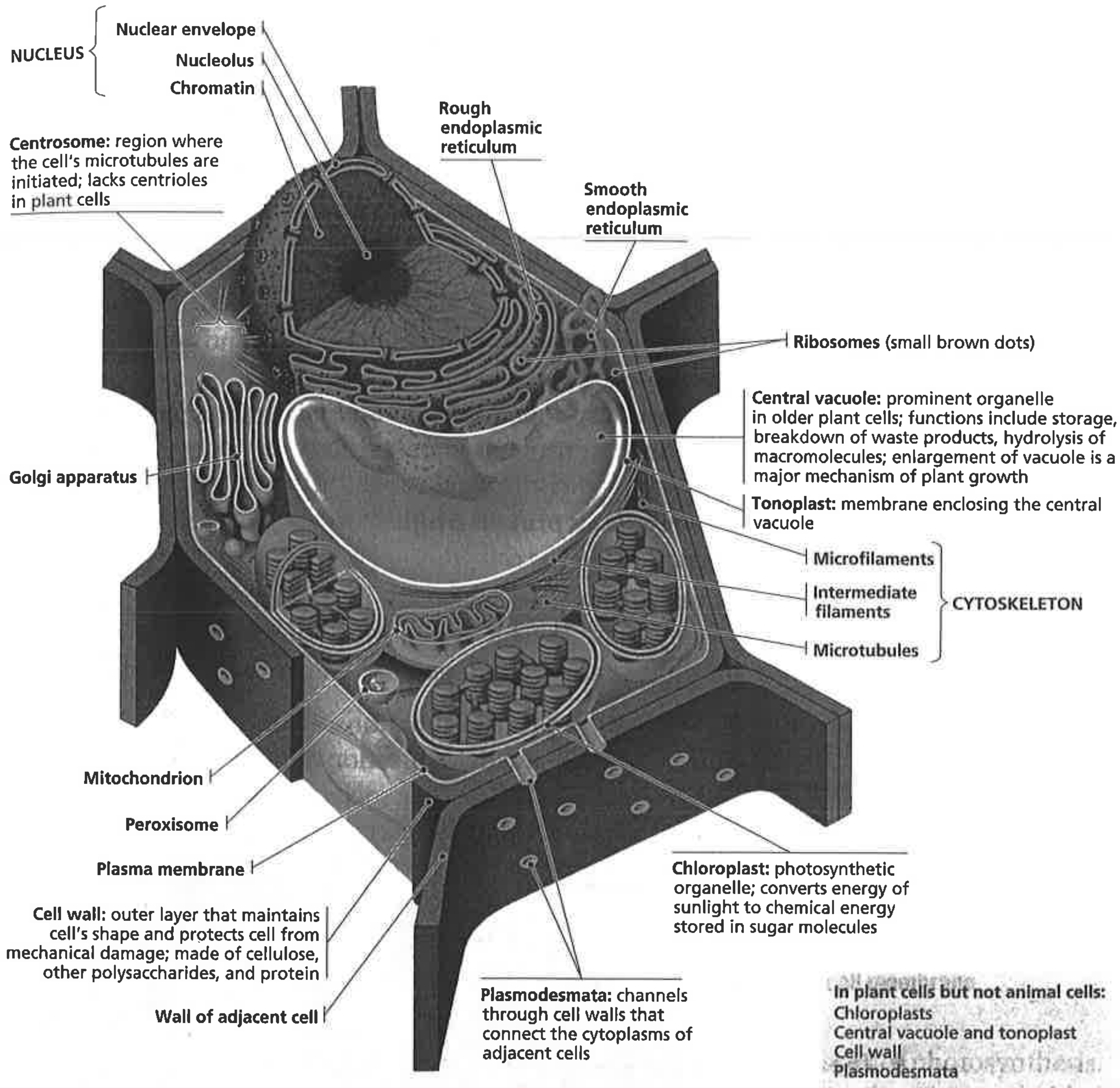


Figure 2.2 Plant cell structure

Concept 6.3 The eukaryotic cell's genetic instructions are housed in the nucleus and carried out by the ribosomes

- The **nucleus** has the following key characteristics:
  - The nucleus contains most of the cell's DNA. It is in the nucleus where DNA is used as the template to make messenger RNA (mRNA), which contains the code to produce a protein. Because the nucleus contains the genetic information, it is referred to as the control center of the cell.
  - The nucleus is the most noticeable organelle in the cell because of its large relative size. The nucleus is surrounded by a double membrane, the **nuclear envelope.** Note that the nuclear envelope is continuous with the rough endoplasmic reticulum. The nuclear envelope contains **nuclear pores** that control what may enter or leave the nucleus.

- **Chromatin** is the complex of DNA and protein housed in the nucleus that makes up the chromosomes. As a cell gets ready for cell division, the diffuse threads of chromatin condense into visible chromosomes.
- The **nucleolus** is a region of the nucleus where ribosomal RNA (rRNA) complexes with proteins to form ribosomal subunits.

- **Ribosomes** are protein factories. They are composed of rRNA and protein, and are sites of protein synthesis in the cell. Each ribosome consists of a large and small subunit.
  - *Free ribosomes* are found floating in the cytosol and generally produce proteins that are used within the cell.
  - *Bound ribosomes* are attached to the endoplasmic reticulum, and make proteins destined for export from the cell.

Concept 6.4 The endomembrane system regulates protein traffic and performs metabolic functions in the cell

- **Endoplasmic reticulum (ER)** makes up more than half the total membrane structure in many cells. The ER is a network of membranes and sacs whose internal area is called the *cisternal space*. There are two types of ER:
  - **Smooth ER** has three primary functions: synthesis of lipids, metabolism of carbohydrates, and detoxification of drugs and poisons.
  - **Rough ER** is so called because its associated ribosomes make the structure appear rough under the microscope. Ribosomes associated with ER synthesize proteins that are generally secreted by the cell. As the proteins are produced by the ER-bound ribosomes, the polypeptide chains travel across the ER membrane and into the cisternal space. Within the cisternal space the proteins are packaged into *transport vesicles,* which bud off the ER and move toward the Golgi apparatus.
- The **Golgi apparatus** operates something like the postal system—proteins from the transport vesicles are modified, stored, and shipped. As Figures 2.1 and 2.2 show, the Golgi apparatus consists of flattened sacs of membranes, again called cisternae, arranged in stacks. Golgi stacks have polarity—the *cis* face receives vesicles, whereas the *trans* face ships vesicles.
- **Lysosomes** are membrane-bound sacs of hydrolytic enzymes that can digest large molecules, including proteins, polysaccharides, fats, and nucleic acids. They have digestive enzymes that break down macromolecules to organic monomers that are released into the cytosol and thus recycled by the cell. The digestive or hydrolytic enzymes work best in the acidic environment found in lysosomes. If a lysosome breaks open or leaks, the enzymes are not very active in the neutral pH of the cell. This is a good example of the importance of cell compartmentalization.
- **Vacuoles** are membrane-bound vesicles. *Food vacuoles* such as those formed by phagocytosis of protists are one example, as are the *contractile vacuoles* that maintain water balance in *Paramecia* and other protists.

- **Central vacuoles** in plant cells may concentrate and contain compounds not found in the cytosol. A large central vacuole is one of the striking differences between plant and animal cells. In plants, a vacuole can make up as much as 80% of the cell.

Concept 6.5 Mitochondria and chloroplasts change energy from one form to another

- **Mitochondria** are the sites of cellular respiration, the metabolic process that uses oxygen to generate ATP by extracting energy from sugars, fats, and other fuels. Study Figure 2.3 to learn the structure.
  - Mitochondria consist of an *outer* and *inner membrane.* The inner membrane is highly folded. These *cristae* (folds) increase the surface area, enhancing the productivity of cellular respiration.
  - The inner compartment, the *mitochondrial matrix*, is fluid-filled.

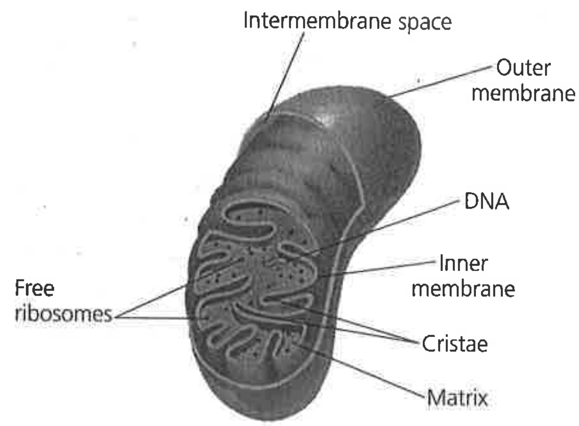


Figure 2.3 Detailed structure of animal cell membrane

- **Chloroplasts**, found in plants and algae, are the sites of photosynthesis.
- The *endosymbiont theory* proposes that both mitochondria and chloroplasts share a similar origin. This theory states that these organelles descended from prokaryotic cells once engulfed by ancestors of eukaryotic cells. There are several lines of evidence for this:
  - Both organelles have a double-membrane structure.
  - Both organelles have their own ribosomes and DNA.
  - Both reproduce independently within the cell.
- **Peroxisomes** are single-membrane-bound compartments in the cell responsible for various metabolic functions that involve the transfer of hydrogen from compounds to oxygen, producing hydrogen peroxide (H_2O_2). Peroxisomes break down fatty acids to be sent to the mitochondria for fuel and detoxify alcohol by transferring hydrogen from the poison to oxygen.
- This is an excellent example of how the cell's compartmental structure is crucial to its functions: The enzymes that produce hydrogen peroxide and those that dispose of this toxic compound are separate from other cellular components that could be damaged.

WHAT'S IMPORTANT TO KNOW?

Concepts 6.6 and 6.7 are not part of the Essential Knowledges for the AP Biology Exam, though your teacher may select illustrative examples from this material.

Concept 6.6 The cytoskeleton is a network of fibers that organizes structures and activities in the cell

- The **cytoskeleton** is a network of protein fibers that runs throughout the cytoplasm, where it is responsible for support, motility, and regulating some biochemical activities. Three types of fibers make up the cytoskeleton:
    - **Microtubules**, made of the protein tubulin, are the largest of the cytoskeleton fibers. Microtubules shape and support the cell and also serve as tracks along which organelles equipped with *motor molecules* can move. They also separate chromosomes during mitosis and meiosis (forming the spindle) and are the structural components of cilia and flagella (found primarily in animal cells).
    - **Microfilaments** are composed of the protein actin. Much smaller than microtubules, microfilaments function in smaller-scale support. When coupled with the motor molecule *myosin*, microfilaments can be involved with movement. *Examples*: amoeboid movement, cytoplasmic streaming, and contraction of muscle cells.
    - **Intermediate filaments** are slightly larger than microfilaments and smaller than microtubules. Intermediate fibers are more permanent fixtures in the cell, where they are important in maintaining the shape of the cell and fixing the position of certain organelles.
- **Centrosomes** are a region located near the nucleus, from which microtubules grow (the area is also called the microtubule-organizing center). Centrosomes contain centrioles in animal cells.
- **Centrioles** are located within the centrosomes of animal cells, where they replicate before cell division.
- A specialized arrangement of microtubules is responsible for the beating of flagella and cilia.
    - **Flagella** are usually long and few in number. Many unicellular eukaryotic organisms are propelled through the water by flagella, as are the sperm of animals, algae, and some plants.
    - **Cilia** are usually much shorter and more numerous than flagella. Cilia can also be used in locomotion or, when held in place as part of a tissue layer, they can move fluid over the surface of the tissue. For example, the lining of the trachea moves mucus-trapped debris out of the lungs in this manner.
- Though different in length, number per cell, and beating pattern, cilia and flagella share a common ultrastructure. Nearly all eukaryotic cilia and flagella have nine pairs of microtubules surrounding a central core of two microtubules. This arrangement is referred to as the "9 + 2" pattern.
- **Extracellular matrix (ECM)** of animal cells is situated just external to the plasma membrane; it is composed of glycoproteins secreted by the cell (most

prominent of which is collagen). The ECM greatly strengthens tissues and serves as a conduit for transmitting external stimuli into the cell, which can turn genes on and modify biochemical activity.

- Animal cells have three types of intercellular junctions:
  - **Tight junctions** are sections of animal cell membrane where two neighboring cells are fused, making the membranes watertight.
  - **Desmosomes** fasten adjacent animal cells together, functioning like rivets to fasten cells into strong sheets.
  - **Gap junctions** provide channels between adjacent animal cells through which ions, sugars, and other small molecules can pass.

Concept 6.7 Extracellular components and connections between cells help coordinate cellular activities

- The **cell wall** of a plant protects the plant and helps maintain its shape. The primary component of cell walls is the carbohydrate *cellulose*.
- **Plasmodesmata** are channels that perforate adjacent plant cell walls and allow the passage of some molecules from cell to cell. gap junctions for plants
- To help you summarize structures that are found in either plant cells or animal cells, study the following chart.

Cellular Structure	
Plant Cells Only	**Animal Cells Only**
Central vacuoles	Lysosomes
Chloroplasts	Centrioles
Cell wall of cellulose	Flagella, cilia
Plasmodesmata	Extracellular matrix
	Desmosomes, tight and gap junctions

STUDY TIP Know the structure and function of each organelle and whether it is found in a plant cell, animal cell, or both. Be able to predict and justify how a change in a cellular organelle would affect the function of the entire cell or organism.

Chapter 7: Membrane Structure and Function

YOU MUST KNOW

- Why membranes are selectively permeable.
- The role of phospholipids, proteins, and carbohydrates in membranes.
- How water will move if a cell is placed in an isotonic, hypertonic, or hypotonic solution and be able to predict the effect of different environments on the organism.
- How electrochemical gradients are formed and function in cells.

Concept 7.1 Cellular membranes are fluid mosaics of lipids and proteins

- The cell or **plasma membrane** is **selectively permeable**; that is, it allows some substances to cross it more easily than others.
- Membranes are predominantly made of phospholipids and proteins held together by weak interactions that cause the membrane to be fluid. The *fluid mosaic model* of the cell membrane describes the membrane as fluid, with proteins embedded in or associated with the phospholipid bilayer. Figure 2.4 shows the current model of an animal cell's plasma membrane. Find each part of the membrane as the three primary organic molecules of the membrane are described:

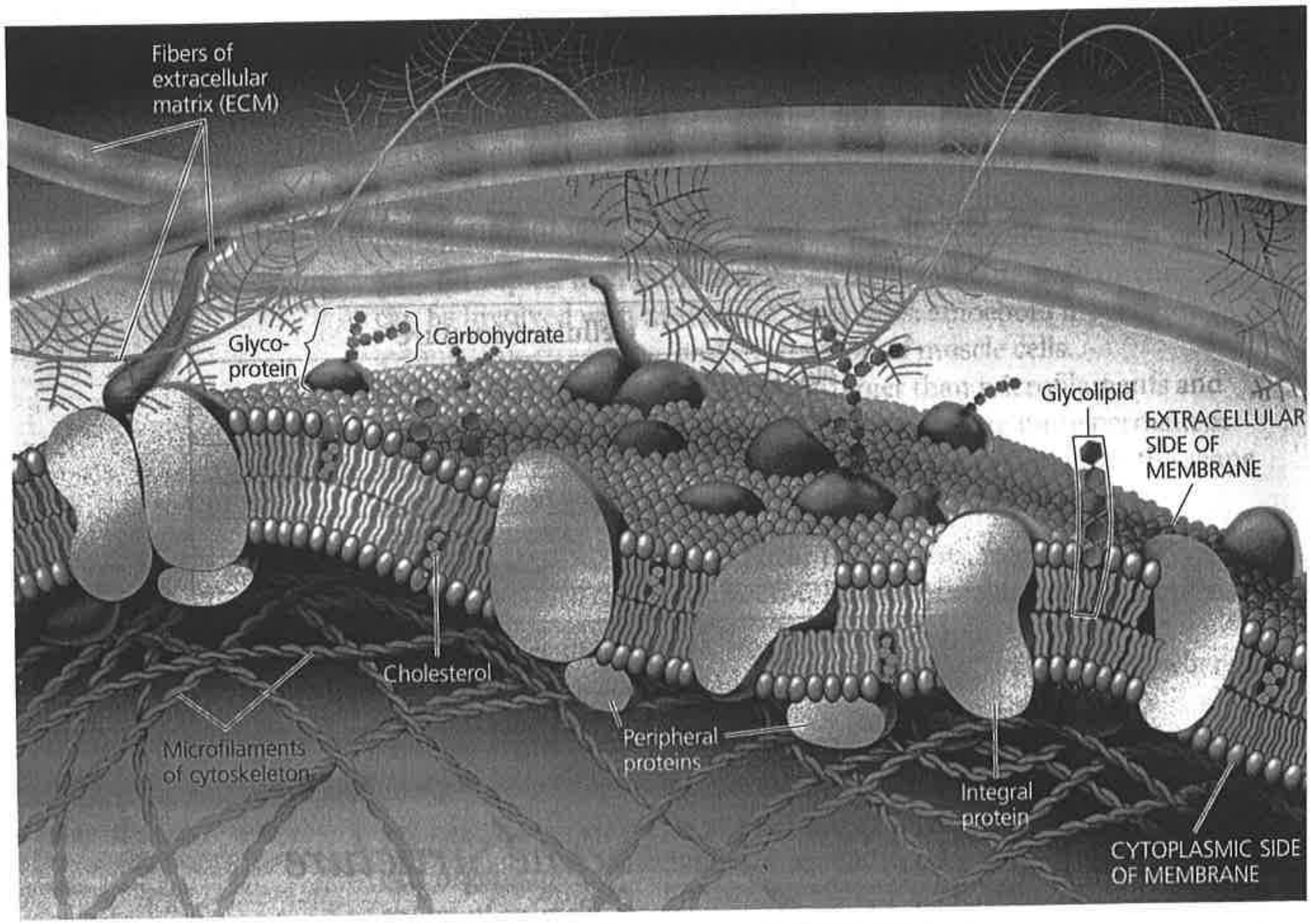


Figure 2.4 Structure of an animal cell's plasma membrane

- The **phospholipids** in the membrane provide a hydrophobic barrier that separates the cell from its liquid environment. Hydrophilic molecules cannot easily enter the cell, but hydrophobic molecules can enter much more easily; hence, the selectively permeable nature of the membrane.
- There are both integral proteins and peripheral proteins in the cell membrane. **Integral proteins** are those that are completely embedded in the membrane, some of which are transmembrane proteins that span the membrane completely. **Peripheral proteins** are loosely bound to the membrane's surface.

- **Carbohydrates** on the membrane are crucial in cell-cell recognition (which is necessary for proper immune function) and in developing organisms (for tissue differentiation). Cell-surface carbohydrates vary from species to species and are the reason that blood transfusions must be type-specific.

Concept 7.2 Membrane structure results in selective permeability

- Nonpolar molecules—such as hydrocarbons, carbon dioxide, and oxygen—are hydrophobic and can dissolve in the phospholipid bilayer and cross the membrane easily.
- The hydrophobic core of the membrane impedes the passage of ions and polar molecules, which are hydrophilic. However, hydrophilic substances can avoid the lipid bilayer by passing through **transport proteins** that span the membrane (see Figure 2.4).
- Perhaps the most important molecule to move across the membrane is water. Water moves through special transport proteins termed **aquaporins**. Aquaporins greatly accelerate the speed (3 billion water molecules per aquaporin per second!) at which water can cross membranes.

Concept 7.3 Passive transport is diffusion of a substance across a membrane with no energy investment

- In **passive diffusion,** a substance travels from where it is more concentrated to where it is less concentrated, diffusing down its **concentration gradient**. Hydrocarbons, carbon dioxide, and oxygen are hydrophobic substances that can pass easily across the cell membrane by passive diffusion. This type of diffusion requires that no work be done, and it relies only on the thermal motion energy intrinsic to the molecule in question. It is called "passive" because the cell expends no energy in moving the substances.
- The diffusion of water across a selectively permeable membrane is **osmosis**. A cell has one of three water relationships with the environment around it.
  - In an **isotonic solution** there will be no net movement of water across the plasma membrane. Water crosses the membrane, but at the same rate in both directions.
  - In a **hypertonic solution** the cell will lose water to its surroundings. The *hyper-* prefix refers to more solutes in the water around the cell; hence, the movement of water to the higher (hyper-) concentration of solutes. In this case the cell loses water to the environment, will shrivel, and may die.
  - In a **hypotonic solution** water will enter the cell faster than it leaves. The *hypo-* prefix refers to fewer solutes in the water around the cell; hence, the movement of water into the cell where solutes are more heavily concentrated. In this case the cell will swell and may burst.
  - Because plant cells have walls, you can observe changes in firmness as water moves in or leaves. A plant cell that is limp is said to be *flaccid*, one that has lost water and is shriveled is *plasmolyzed*, and cells that have full vacuoles and are very firm are *turgid*.

> ***STUDY TIP*** It is likely that you will do an investigation or lab that focuses on osmosis and diffusion. Work with these ideas until you can predict the direction of water movement based on the concentration of solutes inside and outside the cell.

- **Ions** and **polar molecules** cannot pass easily across the membrane. The process by which ions and hydrophilic substances diffuse across the cell membrane with the help of transport proteins is called **facilitated diffusion**. Transport proteins are specific (like enzymes) for the substances they transport. They work in one of two ways:
  - They provide a hydrophilic channel through which the molecules in question can pass.
  - They bind loosely to the molecules in question and carry them through the membrane.

Concept 7.4 Active transport uses energy to move solutes against their gradients

- In **active transport**, substances are moved against their concentration gradient—that is, from the region where they are *less* concentrated to the region where they are *more* concentrated. This type of transport requires energy, usually in the form of ATP.
- A common example of active transport is the **sodium-potassium pump**. This transmembrane protein pumps sodium out of the cell and potassium into the cell. The sodium-potassium pump is necessary for proper nerve transmission and is a major energy consumer in your body as you read this.
- The inside of the cell is negatively charged compared with outside the cell. The difference in electric charge across a membrane is expressed in voltage and termed the **membrane potential**. Because the inside of the cell is negatively charged, a positively charged ion on the outside, like sodium, is attracted to the negative charges inside the cell. Thus, two forces drive the diffusion of ions across a membrane:
  - *A chemical force*, which is the ion's concentration gradient.
  - *A voltage gradient* across the membrane, which attracts positively charged ions and repels negatively charged ions.

  This combination of forces acting on an ion forms an **electrochemical gradient**.
- A transport protein that generates voltage across the membrane is called an **electrogenic pump**. The sodium-potassium pump and the proton pump are examples of electrogenic pumps.

> ***STUDY TIP*** Both photosynthesis and cellular respiration, the topics of two upcoming chapters, utilize electrochemical gradients as potential energy sources to generate ATP. By carefully studying electrochemical gradients now, you will be in a good position to understand more complex processes later.

- In **cotransport**, an ATP pump that transports a specific solute indirectly drives the active transport of other substances. In this process, the substance that was initially pumped across the membrane—an H^+ pumped by a proton pump, for example—can do work as it moves back across the membrane by diffusion and brings with it a second compound, like sucrose, against its gradient. This process is analogous to water that has been pumped uphill and performs work as it flows back down. Figure 2.5 will help you visualize the process. Note that this process has generated an electrochemical gradient, a source of potential energy that performs cell work.

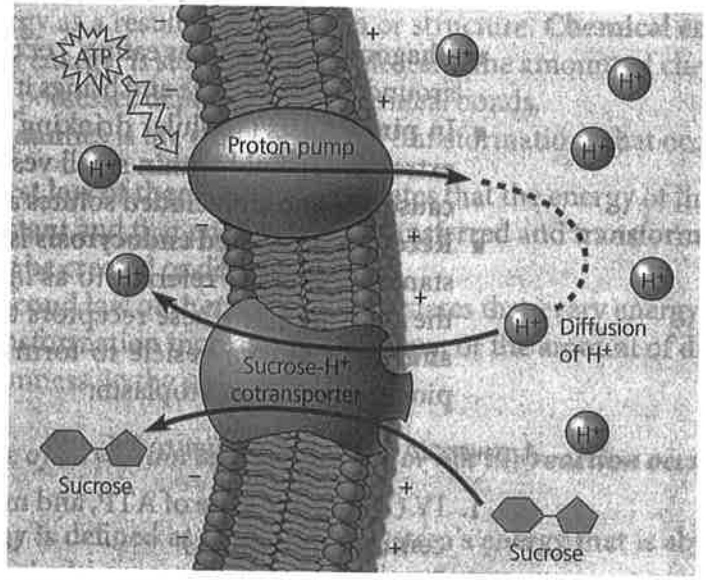


Figure 2.5 Cotransport

To review transport, try your hand at the following questions using Figure 2.6.

1. Which figure represents *active transport*? There are two ways you should be able to tell.
2. Which section shows *simple diffusion*?
3. Which section shows *facilitated diffusion* with a *carrier protein*?
4. Which section shows *facilitated diffusion* with a *channel protein*?

(Answers are at the end of this section.)

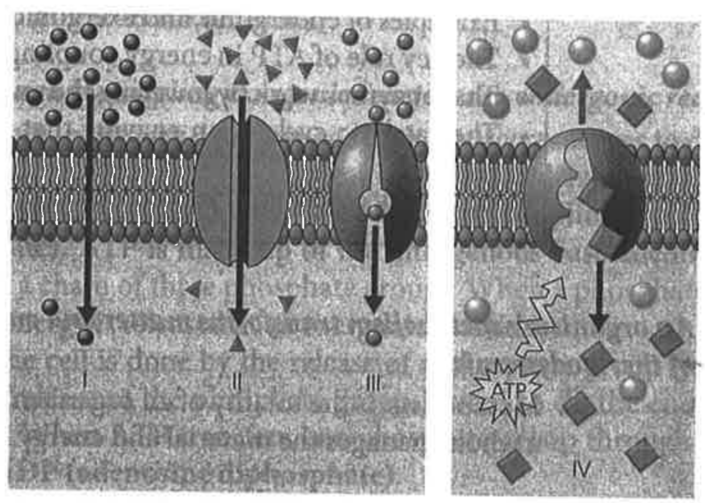


Figure 2.6 Passive and active transport

Concept 7.5 ***Bulk transport across the plasma membrane occurs by exocytosis and endocytosis***

- Large molecules are moved across the cell membrane through exocytosis and endocytosis.
  - In **exocytosis**, vesicles from the cell's interior fuse with the cell membrane, expelling their contents.
  - In **endocytosis**, the cell forms new vesicles from the plasma membrane; this is basically the reverse of exocytosis, and this process allows the cell to take in macromolecules. There are three types of endocytosis:
    - **Phagocytosis** ("cellular eating") occurs when the cell wraps pseudopodia around a solid particle and brings it into the cell.
    - In **pinocytosis** ("cellular drinking"), the cell takes in small droplets of extracellular fluid within small vesicles. Pinocytosis is not specific, because any and all included solutes are taken into the cells.
    - **Receptor-mediated endocytosis** is a very specific process. Certain substances (generally referred to as *ligands*) bind to specific receptors on the cell's surface (these receptors are usually clustered in coated pits), and this causes a vesicle to form around the substance and then to pinch off into the cytoplasm.

Answers to questions for Figure 2.6:

1. IV (It shows the use of ATP, and molecules being moved against a concentration gradient.)
2. I
3. III
4. II

Chapter 8: An Introduction to Metabolism

YOU MUST KNOW

- Examples of endergonic and exergonic reactions.
- The key role of ATP in energy coupling.
- That enzymes work by lowering the energy of activation.
- The catalytic cycle of an enzyme that results in the production of a final product.
- Factors that influence enzyme activity.

Concept 8.1 ***An organism's metabolism transforms matter and energy, subject to the laws of thermodynamics***

- **Metabolism** is the totality of an organism's chemical reactions. Metabolism as a whole manages the material and energy resources of the cell.

- A **catabolic pathway** leads to the release of energy by the breakdown of complex molecules to simpler compounds. *Example*: Catabolic pathways occur when your digestive enzymes break down food and release energy.
- **Anabolic pathways** consume energy to build complicated molecules from simpler ones. *Example*: Anabolic pathways occur when your body links together amino acids to form muscle protein in response to physical exercise.

- **Energy** is defined as the capacity to do work. Anything that is moving is said to possess **kinetic energy**. An object at rest can possess **potential energy** if it has stored energy as a result of its position or structure. **Chemical energy**, a form of potential energy, is stored in molecules, and the amount of chemical energy a molecule possesses depends on its chemical bonds.
- **Thermodynamics** is the study of energy transformations that occur in matter.
  - The **first law of thermodynamics** states that the energy of the universe is constant and that energy *can* be transferred and transformed, but it *cannot* be created or destroyed.
  - The **second law of thermodynamics** states that every energy transfer or transformation increases the **entropy**, or the amount of disorder or randomness, in the universe.

Concept 8.2 The free-energy change of a reaction tells us whether or not the reaction occurs spontaneously

- **Free energy** is defined as the part of a system's energy that is able to perform work when the temperature of a system is uniform.
- ΔG is a symbol for a change in free energy.
  - An **exergonic reaction** is one in which energy is released. Exergonic reactions occur spontaneously (that does not necessarily mean quickly) and release free energy to the system. $\Delta G < 0$.
  - An **endergonic reaction** is one that requires energy in order to proceed. Endergonic reactions absorb free energy; that is, they require free energy from the system. $\Delta G > 0$.
  - Is the breakdown of glucose in cellular respiration exergonic or endergonic? (ΔG is –686 kcal/mol.)

Concept 8.3 ATP powers cellular work by coupling exergonic reactions to endergonic reactions

- A key feature in the way cells manage their energy resources to do cell work is **energy coupling**, the use of an exergonic process to drive an endergonic one.
- The primary source of energy for cells in energy coupling is **ATP (adenosine triphosphate)**. ATP is made up of the nitrogenous base adenine, bonded to ribose and a chain of three phosphate groups. When a phosphate group is hydrolyzed, energy is released in an exergonic reaction.
- Work in the cell is done by the release of a phosphate group from ATP. The exergonic release of the phosphate group is used to do the endergonic work of the cell. When ATP transfers one phosphate group through hydrolysis, it becomes **ADP (adenosine diphosphate)**.

Concept 8.4 Enzymes speed up metabolic reactions by lowering energy barriers

- **Catalysts** are substances that can change the rate of a reaction without being altered in the process.
- **Enzymes** are macromolecules that are biological catalysts. In this chapter all enzymes considered are proteins; however, in Chapters 17 and 25, RNA enzymes—termed *ribozymes*—are discussed.
- The **activation energy** of a reaction is the amount of energy it takes to start a reaction—the amount of energy it takes to break the bonds of the reactant molecules. Enzymes speed up reactions *by lowering the activation energy* of the reaction—but without changing the free-energy change of the reaction. The reactant that the enzyme acts on is called a **substrate**. Figure 2.7 graphically depicts how enzymes function.
- The **active site** is the part of the enzyme that binds to the substrate. The enzyme and substrate form a complex called an **enzyme-substrate complex** that is generally held together by weak interactions. The substrate is then converted into **products**, and the products are released from the enzyme. Use Figure 2.8 to locate each step in the catalytic cycle of an enzyme.

> ***STUDY TIP*** Enzymes are a key topic in biology. It is likely that you will do an investigation with enzymes. Focus on factors that affect enzyme action, and be able to pose a question about enzyme function, design an experiment to test this question, predict results, and analyze data from an enzyme experiment.

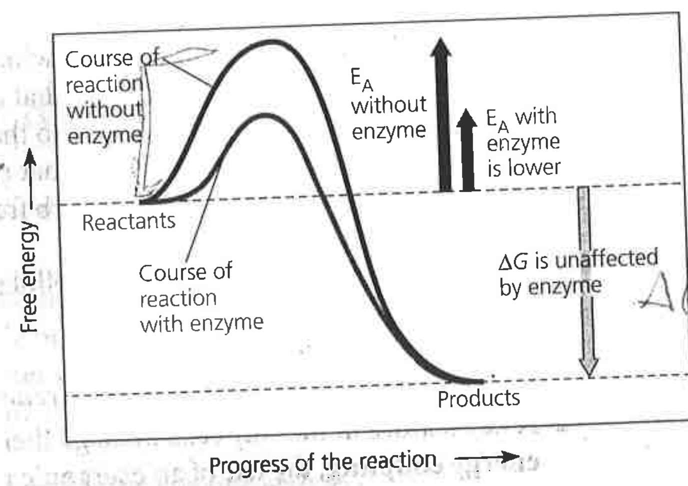


Figure 2.7 Effect of an enzyme on reaction rate

- The activity of an enzyme can be affected by several factors:
  - Protein enzymes have complicated three-dimensional shapes that are dramatically affected by changes in **pH** and **temperature.** Changes in the precise shape of an enzyme usually mean the enzyme will not be as effective. Note how the rate of the reaction is altered in the graphs in Figure 2.9 when temperature and pH are not optimal.

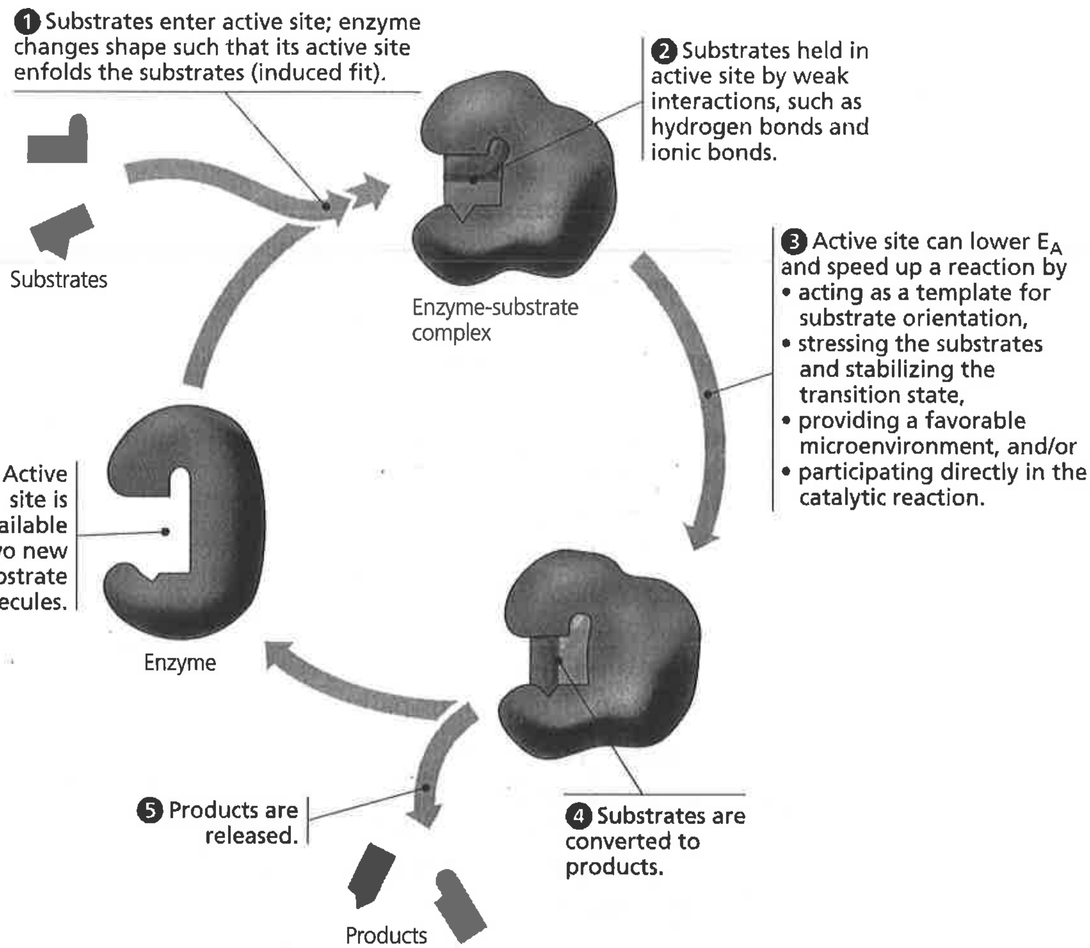


Figure 2.8 The active site and catalytic cycle of an enzyme

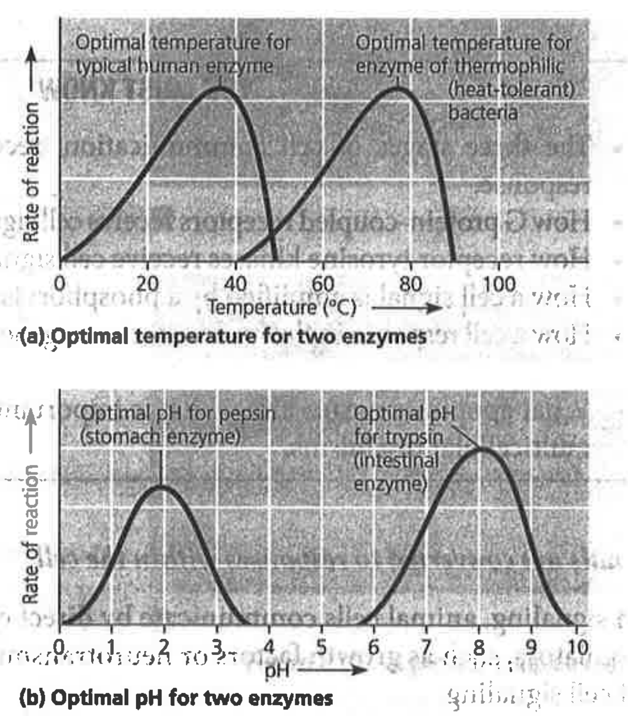


Figure 2.9 Environmental factors affecting enzyme activity

- Many enzymes require nonprotein helpers, termed **cofactors**, to function properly. Cofactors include metal ions like zinc, iron, and copper and function in some crucial way to allow catalysis to occur. If the cofactor is organic, it is more properly referred to as a coenzyme. **Coenzymes** are organic cofactors; vitamins are examples of coenzymes.
- **Competitive inhibitors** are reversible inhibitors that *compete with the substrate for the active site* on the enzyme. Competitive inhibitors are often chemically very similar to the normal substrate molecule and reduce the efficiency of the enzyme as it competes for the active site.
- **Noncompetitive inhibitors** do not directly compete with the substrate molecule; instead, they impede enzyme activity by binding to another part of the enzyme. This causes the enzyme to change its shape, rendering the active site nonfunctional.

Concept 8.5 Regulation of enzyme activity helps control metabolism

- Many enzyme regulators bind to an **allosteric** site on the enzyme, which is a specific binding site, but not the active site. Once bound, the shape of the enzyme is changed, and this can either stimulate or inhibit enzyme activity.
- The end product on an enzymatic pathway can switch off its pathway by binding to the allosteric site of an enzyme in the pathway. This type of allosteric inhibition is termed **feedback inhibition**. Feedback inhibition increases the efficiency of the pathway by turning it off when the end product accumulates in the cell.

Chapter 11: Cell Communication

YOU MUST KNOW

- The three stages of cell communication: reception, transduction, and response.
- How G protein-coupled receptors receive cell signals and start transduction.
- How receptor tyrosine kinases receive cell signals and start transduction.
- How a cell signal is amplified by a phosphorylation cascade.
- How a cell response in the nucleus turns on genes, whereas in the cytoplasm it activates enzymes.
- What apoptosis means and why it is important to normal functioning of multicellular organisms.

Concept 11.1 External signals are converted to responses within the cell

- In signaling, animal cells communicate by direct contact or by secreting local regulators, such as growth factors or neurotransmitters. There are three stages of cell signaling.

- **Reception**—The target cell's detection of a signal molecule coming from outside the cell.
- **Transduction**—The conversion of the signal to a form that can bring about a specific cellular response.
- **Response**—The specific cellular response to the signal molecule.

Concept 11.2 Reception: A signaling molecule binds to a receptor protein, causing it to change shape

- The binding between a signal molecule **(ligand)** and a **receptor** is highly specific. A conformational change in a receptor is often the initial transduction of the signal. Receptors are found in two places.
  - *Intracellular receptors* are found inside the plasma membrane in the cytoplasm or nucleus. The signal molecule must cross the plasma membrane and therefore must be hydrophobic, like the steroid testosterone, or very small, like nitric oxide (NO).
  - *Plasma membrane receptors* bind to water-soluble ligands.
- A **G protein-coupled receptor** is a membrane receptor that works with the help of a **G protein**. Follow Figure 2.10 to review how these receptors work.
  - Step 1: The ligand or signaling molecule has bound to the G protein-coupled receptor. This causes a conformational change in the receptor so that it may now bind to an inactive G protein, causing a GTP to displace the GDP. This activates the G protein.

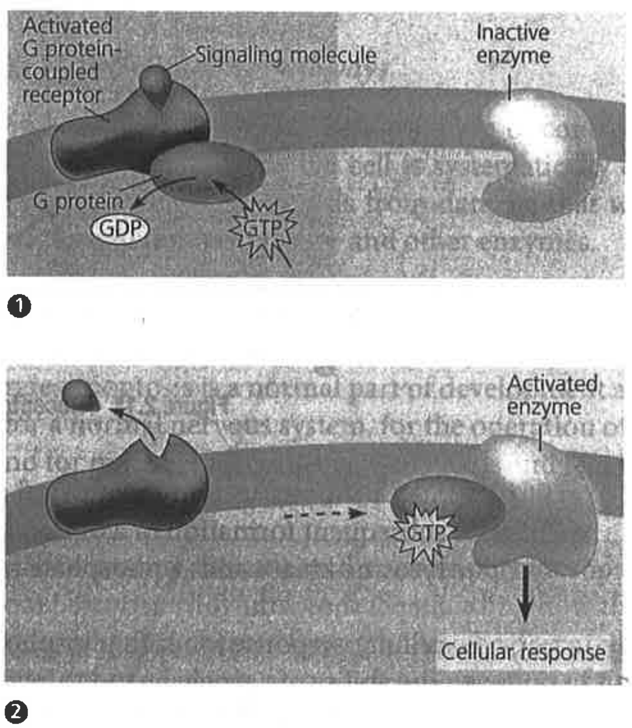


Figure 2.10 G protein-coupled receptor

- Step 2: The G protein binds to a specific enzyme and activates it. When the enzyme is activated, it can trigger the next step in a pathway leading to a cellular response. All the molecular shape changes are temporary. To continue the cellular response, new signal molecules are required.

- The **receptor tyrosine kinases** are a second type of membrane protein. Follow Figure 2.11 to review how they function.

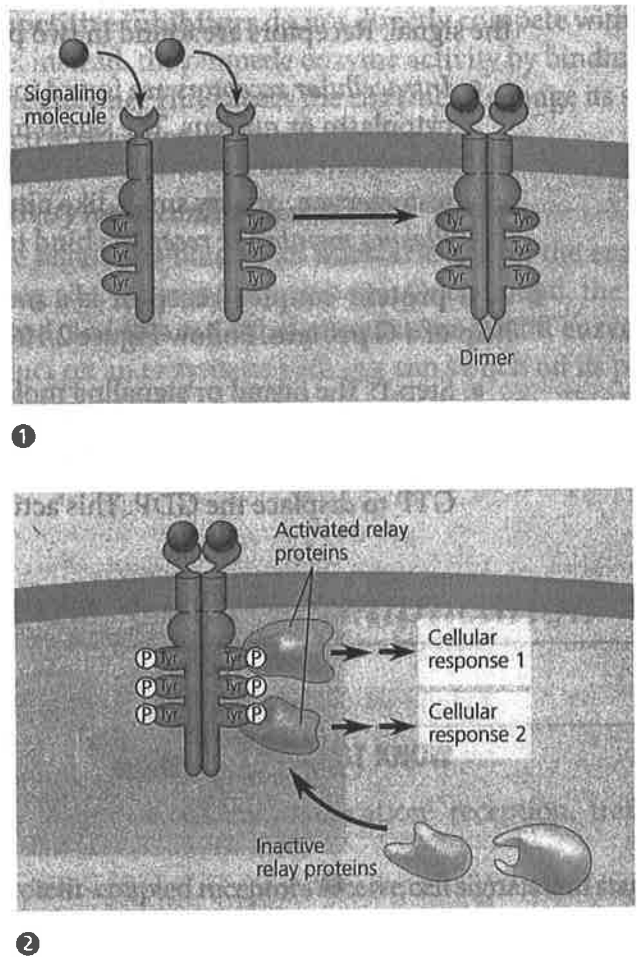


Figure 2.11 Receptor tyrosine kinase

  - Step 1 shows the binding of signal molecules to the receptors and the subsequent formation of a dimer. In the dimer configuration each tyrosine kinase adds a phosphate from an ATP molecule.
  - Step 2 shows the fully activated receptor protein as it initiates a unique cellular response for each phosphorylated tyrosine.
  - The ability of a single ligand to activate multiple cellular responses is a key difference between G protein-coupled receptors and receptor tyrosine kinases.

- Specific signal molecules cause **ligand-gated ion channels** in a membrane to open or close, regulating the flow of specific ions.

Concept 11.3 ***Transduction: Cascades of molecular interactions relay signals from receptors to target molecules in the cell***

- Signal transduction pathways often involve a **phosphorylation cascade**. Because the pathway is usually a multistep one, the possibility of greatly amplifying the signal exists. At each step enzymes called **protein kinases** phosphorylate and thereby activate many proteins at the next level. This cascade of phosphorylation greatly enhances the signal, allowing for a large cellular response.
- **Protein phosphatases** are enzymes that remove phosphate groups and inactive protein kinases. Thus, the signal can be turned on by kinases, and off by phosphatases.
- Not all components of signal transduction pathways are proteins. Many signaling pathways involve small, nonprotein water-soluble molecules or ions called **second messengers**. *Calcium ions* and *cyclic AMP* are two common second messengers. The second messengers, once activated, can initiate a phosphorylation cascade resulting in a cellular response.

Concept 11.4 ***Response: Cell signaling leads to regulation of transcription or cytoplasmic activities***

- Many signaling pathways ultimately regulate protein synthesis, usually by turning specific genes on or off in the nucleus. Often, the final activated molecule in a signaling pathway functions as a transcription factor.
- In the cytoplasm, signaling pathways often regulate the activity of proteins rather than their synthesis. For example, the final step in the signaling pathway may affect the activity of enzymes or cause cytoskeleton rearrangement.

Concept 11.5 ***Apoptosis integrates multiple cell-signaling pathways***

- An elaborate example of cell signaling is a program of controlled cell suicide called **apoptosis**. During apoptosis the cell is systematically dismantled and digested. This protects neighboring cells from damage that would occur if a dying cell merely leaked out its digestive and other enzymes.
  - Apoptosis is triggered by signals that activate a cascade of "suicide" proteins in the cells.
  - In vertebrates apoptosis is a normal part of development and is essential for a normal nervous system, for the operation of the immune system, and for normal morphogenesis of hands and feet in humans.

> ***STUDY TIP*** Cell signaling has emerged as an important topic that explains cell interactions. Devote study time to understanding how the two types of receptors discussed in this chapter function. Also be prepared to explain the role of apoptosis in specific instances, such as formation of fingers and toes, or cancer.

Chapter 12: The Cell Cycle

YOU MUST KNOW

- The structure of the duplicated chromosome.
- The cell cycle and stages of mitosis.
- The role of kinases and cyclin in the regulation of the cell cycle.
- The role of mitosis in the distribution of genetic information.

Concept 12.1 Most cell division results in genetically identical daughter cells

- The **cell cycle** is the life of a cell from the time it is first formed from a dividing parent cell until its own division into two cells.
- A cell's endowment of DNA, its genetic information, is called its **genome**. Before the cell can divide, the cell's genome must be copied.
  - All eukaryotic organisms have a characteristic number of chromosomes in their cell nuclei. As an example, human **somatic cells** (all body cells except gametes) have 46 chromosomes, which is the diploid chromosome number. *Mitosis* is the process by which somatic cells divide, forming daughter cells that contain the same chromosome number as the parent cell.
  - Human **gametes**—sperm and egg cells—are haploid and have half the number of chromosomes as a diploid cell. Human gametes have 23 chromosomes. A special type of cell division called meiosis (the topic of Chapter 13) results in gametes.
- When the chromosomes are replicated, each duplicated chromosome consists of two **sister chromatids** attached by a **centromere**. Figure 2.12 will help you visualize this arrangement.
  - The two sister chromatids have identical DNA sequences.
  - Later, in the process of cell division, the two sister chromatids will separate and move into two new cells. Once the sister chromatids separate, they are considered individual chromosomes.
- **Mitosis** is the division of the cell's nucleus. It may be followed by **cytokinesis** which is the division of the cell's cytoplasm. Where there was one cell, there are now two, each the genetic equivalent of the parent cell.

Concept 12.2 The mitotic phase alternates with interphase in the cell cycle

- The primary events of **interphase**, which is 90% of the cell cycle, follow:
  - In **G_1 phase** the cell grows while carrying out cell functions unique to its cell type.
  - In **S phase** the cell continues to carry out its unique functions but does one other important process—it duplicates its chromosomes. This means it faithfully makes a copy of the DNA that makes up the cell's chromosomes.

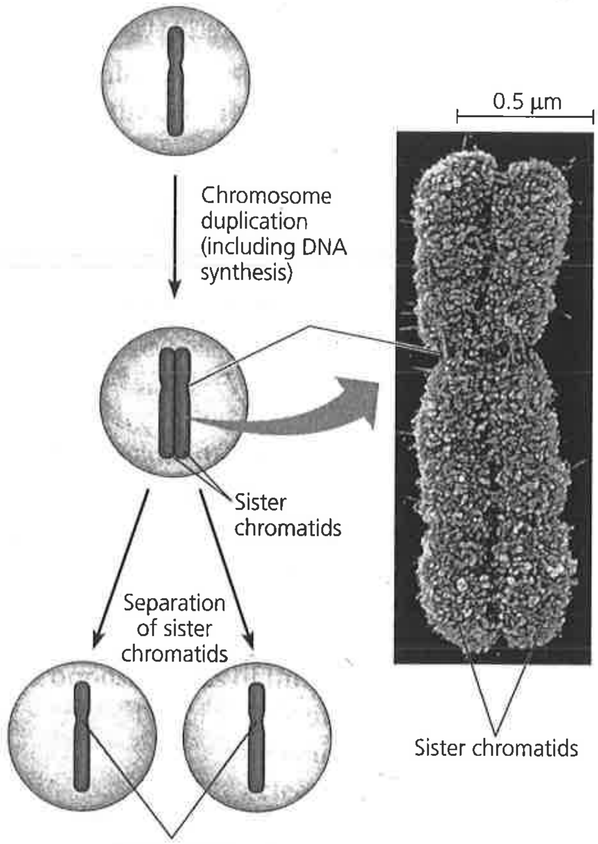


Figure 2.12 Chromosomes and chromatids

- The G_2 **phase** is the gap after the chromosomes have been duplicated and just before mitosis.

> **WHAT'S IMPORTANT TO KNOW?**
> The Curriculum Framework says that you do not have to know the specific phases of mitosis. However, many students find it useful to organize their understanding of the process.

- Mitosis can be broken down into five phases, not including cytokinesis. At each stage, find the specific references in Figure 2.13. You may be asked to identify stages by diagrams on the AP Biology Exam. To simplify your studying, key features of each phase are given.
  - **Prophase:**
    1. The chromatin becomes more tightly coiled into discrete chromosomes.
    2. The nucleoli disappear.
    3. The mitotic spindle (consisting of microtubules extending from the two centrosomes) begins to form in the cytoplasm.

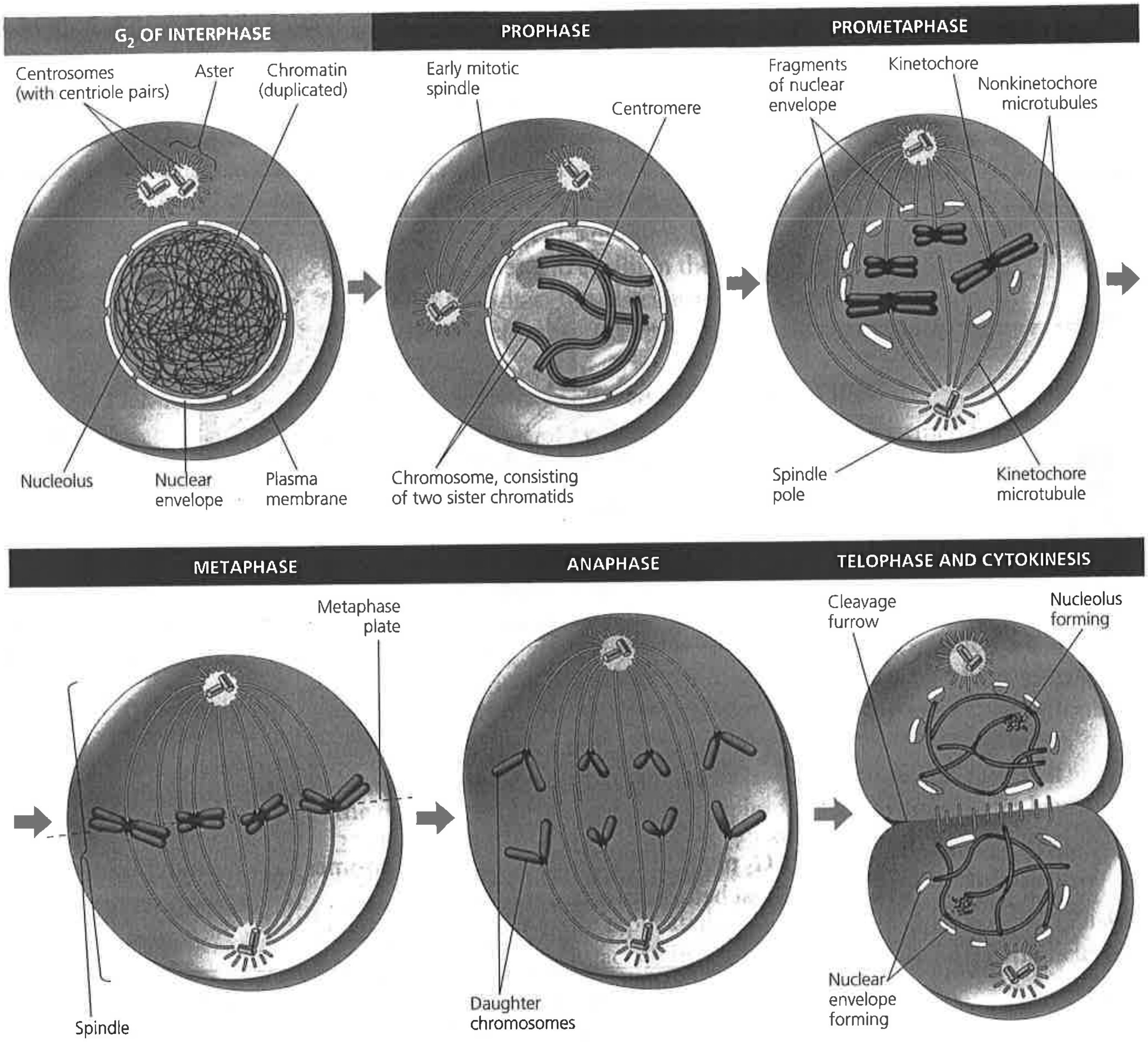


Figure 2.13 The mitotic division of an animal cell

- **Prometaphase:**
  1. The nuclear envelope begins to fragment, allowing the microtubules tc attach to the chromosomes.
  2. The two chromatids of each chromosome are held together by protein kinetochores in the centromere region.
  3. The microtubules will attach to the kinetochores.

- **Metaphase:**

  1. The microtubules move the chromosomes to the metaphase plate at the equator of the cell. The microtubule complex is referred to as the *spindle.*
  2. The centrioles have migrated to opposite poles in the cell, riding along on the developing spindle.

- **Anaphase:**

  1. Sister chromatids begin to separate, pulled apart by motor molecules interacting with kinetochore microtubules.
  2. The cell elongates, as the nonkinetochore microtubules ratchet apart, again with the help of motor molecules.
  3. By the end of anaphase, the opposite ends of the cell both contain complete and equal sets of chromosomes.

- **Telophase:**

  1. The nuclear envelopes re-form around the sets of chromosomes located at opposite ends of the cell.
  2. The chromatin fiber of the chromosomes becomes less condensed.
  3. **Cytokinesis** begins, during which the cytoplasm of the cell is divided. In animal cells, a **cleavage furrow** forms that eventually divides the cytoplasm; in plant cells, a **cell plate** forms that divides the cytoplasm.
  4. Prokaryotes replicate their genome by **binary fission** rather than mitosis.

Concept 12.3 The eukaryotic cell cycle is regulated by a molecular control system

- The steps of the cycle are controlled by a **cell cycle control system.** This control system moves the cell through its stages by a series of **checkpoints,** during which signals tell the cell either to continue dividing or to stop.
- The major cell cycle checkpoints include the **G_1 phase checkpoint, G_2 phase checkpoint,** and **M phase checkpoint.**
- The **G_1 phase checkpoint** seems to be most important. If the cell gets the go-ahead signal at this checkpoint, it usually completes the whole cell cycle and divides. If it does not receive the go-ahead signal, it enters a nondividing phase called the *G_0 phase.*
- **Kinases** are the protein enzymes that control the cell cycle. They exist in the cells at all times but are active only when they are connected to **cyclin** proteins. Thus, they are called **cyclin-dependent kinases (Cdks).** Specific kinases give the go-ahead signals at the G_1 and G_2 checkpoints.
- As a specific example, cyclin molecules combine with Cdk molecules producing enough molecules of **MPF** to pass the G_2 checkpoint and initiate the events of mitosis.

- How does the cell stop cell division? During anaphase, MPF switches itself off by starting a process that leads to the destruction of cyclin molecules. Without cyclin molecules Cdk molecules become inactive, bringing mitosis to a close.
- Normal cell division has two key characteristics:
  - **Density-dependent inhibition**—The phenomenon in which crowded cells stop dividing.
  - **Anchorage dependency**—Normal cells must be attached to a substratum, like the extracellular matrix of a tissue, to divide.
- Cancer cells exhibit neither density-dependent inhibition nor anchorage dependency. Cancer is covered in more depth in Concept 18.5, but several important points are made in this chapter.
  - **Transformation** is the process that converts a normal cell to a cancer cell.
  - A **tumor** is a mass of abnormal cells within otherwise normal tissue. If the abnormal cells remain at the original site, the lump is called a **benign tumor**. A **malignant tumor** becomes invasive enough to impair the functions of one or more organs. An individual with a malignant tumor is said to have cancer.
  - **Metastasis** occurs when cells separate from a malignant tumor and enter blood or lymph vessels and travel to other parts of the body.

For Additional Review

Compare the process of meiosis with the process of mitosis. In your comparison, include a study of the change in chromosomal number through the cell, the purposes of each process within an organism, and the starting material and product for each. *Note:* The details of meiosis are covered in Chapter 13, Unit 3 of the text.

Level 1: Knowledge/Comprehension Questions

1. Which structure could you observe with a light microscope?
   (A) a ribosome
   (B) a Golgi apparatus
   (C) a nucleus
   (D) an endoplasmic reticulum
   (E) a peroxisome

2. Prokaryotic and eukaryotic cells have all of the following structures in common EXCEPT
   (A) a plasma membrane.
   (B) DNA.
   (C) a nucleoid region.
   (D) ribosomes.
   (E) cytoplasm.

Directions: Questions 3–7 consist of five lettered choices followed by a list of numbered phrases or sentences. For each numbered phrase or sentence, select the one choice that is most closely related to it. Each choice may be used once, more than once, or not at all in each group.

Questions 3–7

(A) Peroxisomes
(B) Golgi apparatus
(C) Lysosomes
(D) Endoplasmic reticulum
(E) Mitochondria

3. An organelle that is characterized by extensive, folded membranes and is often associated with ribosomes

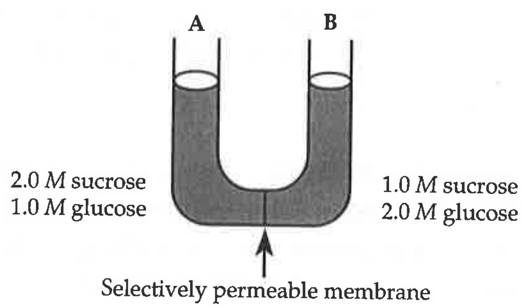
4. An organelle with a *cis* and *trans* face, which acts as the packaging and secreting center of the cell

5. The sites of cellular respiration

6. Single-membrane structures in the cell that perform many metabolic functions and produce hydrogen peroxide in the process

7. Large membrane-bound structures that contain hydrolytic enzymes and that are found predominantly in animal cells

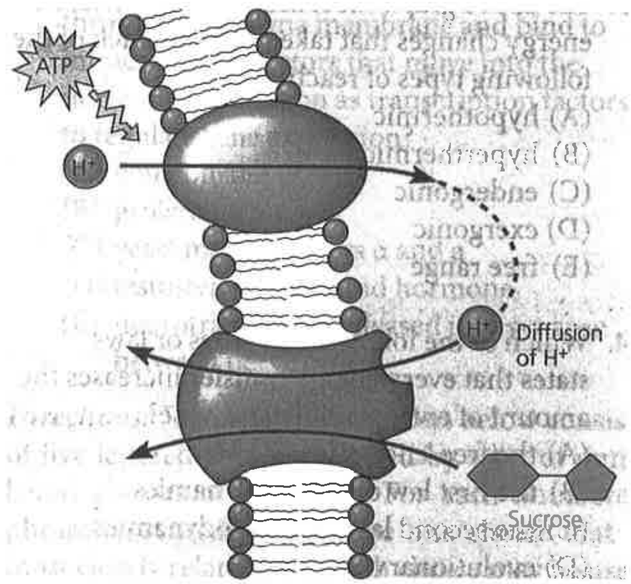
8. Which of the following molecules is a typical component of an animal cell membrane?
(A) starch
(B) glucose
(C) nucleic acids
(D) carbohydrates
(E) vitamin K



U-Tube Setup

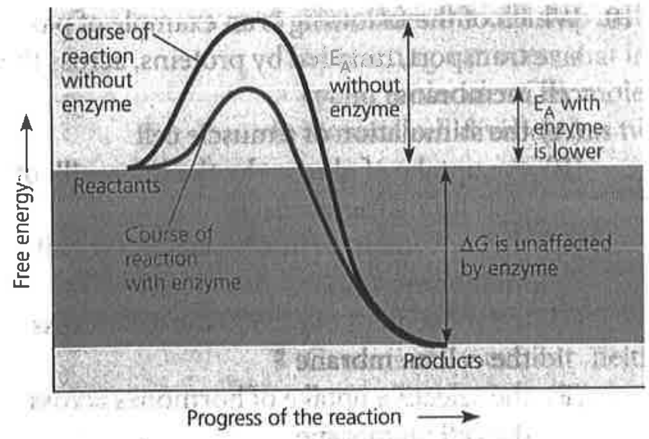
9. The drawing above shows two solutions of glucose and sucrose in a U-tube containing a semipermeable membrane (which allows the passage of sugars). Which of the following accurately describes what will take place next?
(A) Glucose will diffuse from side A to side B.
(B) Sucrose will diffuse from side B to side A.
(C) No net movement of molecules will occur.
(D) Glucose will diffuse from side B to side A.
(E) There will be a net movement of water from side B to side A.

10. Which of the following is an example of passive transport, unaided by proteins, across the cell membrane?
(A) the stimulation of a muscle cell
(B) the uptake of glucose by the microvilli of cells lining the stomach
(C) the movement of insulin across the cell membrane
(D) the movement of carbon dioxide across the cell membrane
(E) the selective uptake of hormones across the cell membrane



11. The figure above illustrates the process of
(A) cotransport.
(B) passive diffusion.
(C) receptor-mediated endocytosis.
(D) phagocytosis.
(E) pinocytosis.

12. Large molecules are moved out of the cell by which of the following processes?
(A) pinocytosis
(B) phagocytosis
(C) receptor-mediated endocytosis
(D) cytokinesis
(E) exocytosis



13. The above graph most accurately depicts the energy changes that take place in which of the following types of reactions?
    (A) hypothermic
    (B) hyperthermic
    (C) endergonic
    (D) exergonic
    (E) free range

14. Which of the following theories or laws states that every energy transfer increases the amount of entropy in the universe?
    (A) the free-energy law
    (B) the first law of thermodynamics
    (C) the second law of thermodynamics
    (D) evolutionary theory
    (E) the law of increased chaos

15. Catalysts speed up chemical reactions by
    (A) decreasing the free-energy change of the reaction.
    (B) increasing the free-energy change of the reaction.
    (C) degrading the competitive inhibitors in a reaction.
    (D) lowering the activation energy of the reaction.
    (E) raising the activation energy of the reaction.

Directions: The following group of questions consists of five lettered choices followed by a list of numbered phrases or sentences. For each numbered phrase or sentence, select the one choice that is most closely related to it. Each choice may be used once, more than once, or not at all.

Questions 16–20
(A) Allosteric interactions
(B) Feedback inhibition
(C) Competitive inhibitor
(D) Noncompetitive inhibitor
(E) Cooperativity

16. Describes interactions by an enzyme that is capable of either activating or inhibiting an enzymatic reaction

17. A reversible inhibitor that looks similar to the normal substrate and competes for the active site of the enzyme

18. The process by which the binding of the substrate to the enzyme triggers a favorable conformation change, which causes a similar change in all of the proteins' subunits

19. The process by which a metabolic pathway is shut off by the product it produces

20. Binds to the enzyme at a site other than the active site, causing the enzyme to change shape and be unable to bind substrate

21. Which of the following processes could result in the net movement of a substance into a cell, if the substance is more concentrated in the cell than in the surroundings?
    (A) active transport
    (B) facilitated diffusion
    (C) diffusion
    (D) osmosis
    (E) passive transport

22. The activation of receptor tyrosine kinases is characterized by
(A) channel protein shape change.
(B) IP_3 binding.
(C) a phosphorylation cascade.
(D) dimerization and phosphorylation.
(E) GTP hydrolysis.

23. In cell signaling, how is the flow of specific ions regulated?
(A) opening and closing of ligand-gated ion channels
(B) transduction
(C) cytoskeleton rearrangement
(D) endocytosis
(E) phosphorylation cascades

24. What is a G protein?
(A) a specific type of membrane receptor protein
(B) a protein on the cytoplasmic side of a membrane that becomes activated by a receptor protein
(C) a membrane-bound enzyme that converts ATP to cAMP
(D) a tyrosine kinase relay protein
(E) a guanine nucleotide that converts between GDP and GTP to activate and inactivate relay proteins

25. Which of the following can activate a protein by transferring a phosphate group to it?
(A) cAMP
(B) G protein
(C) phosphodiesterase
(D) protein kinase
(E) protein phosphatase

26. Many signal transduction pathways use second messengers to
(A) transport a signal through the lipid bilayer portion of the plasma membrane.
(B) relay a signal from the outside to the inside of the cell.
(C) relay the message from the inside of the membrane throughout the cytoplasm.
(D) amplify the message by phosphorylating proteins.
(E) dampen the message once the signal molecule has left the receptor.

27. Which of the following signal molecules pass through the plasma membrane and bind to intracellular receptors that move into the nucleus and function as transcription factors to regulate gene expression?
(A) epinephrine
(B) growth factors
(C) yeast mating factors α and **a**
(D) testosterone, a steroid hormone
(E) neurotransmitter released into synapse between nerve cells

Directions: The group of questions below consists of five lettered choices followed by a list of numbered phrases or sentences. For each numbered phrase or sentence, select the one choice that is most closely related to it. Each choice may be used once, more than once, or not at all in each group.

Questions 28–32
(A) Telophase
(B) Interphase
(C) Cytokinesis
(D) Prometaphase
(E) Anaphase

28. Cytokinesis begins during this final stage of mitosis.

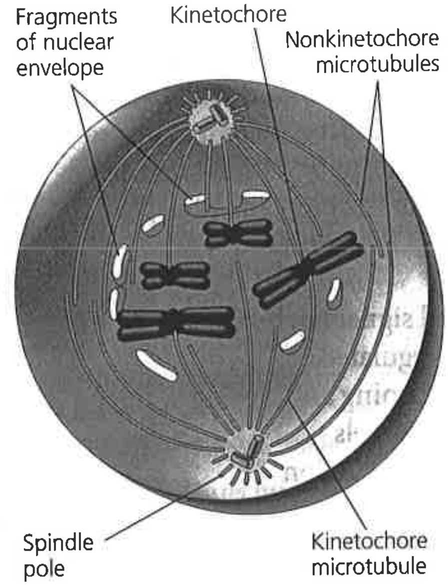
29. Division of the cytoplasm of the cell.

30. Sister chromatids begin to separate.

31. The genetic material of the cell replicates to prepare for cell division.

32. Microtubules begin to attach to the centromeres of the sister chromatids.

33. What stage of mitosis is represented in the figure to the right?
    (A) prophase
    (B) prometaphase
    (C) metaphase
    (D) anaphase
    (E) telophase



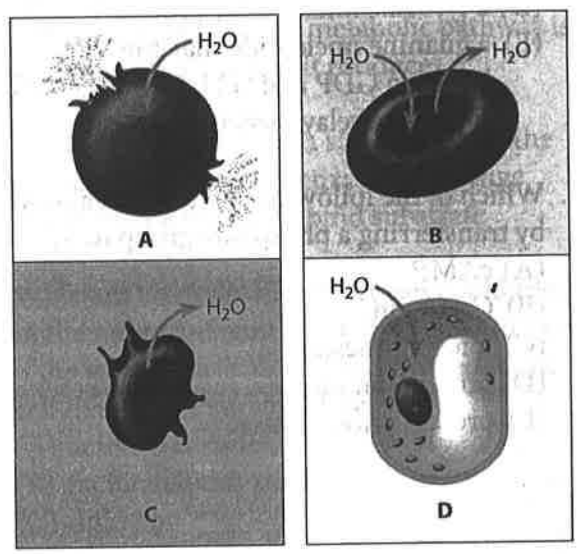
34. After which of the following checkpoints in the cell cycle is the cell first committed to divide?
    (A) G_2 phase checkpoint
    (B) M phase checkpoint
    (C) interphase checkpoint
    (D) G_1 phase checkpoint
    (E) MPF checkpoint

Level 2: Application/Analysis/Synthesis Questions

1. Cells of the pancreas will incorporate radioactively labeled amino acids into proteins. This "tagging" of newly synthesized proteins enables a researcher to track their location. In this case, we are tracking an enzyme secreted by pancreatic cells. What is its most likely pathway?
    (A) ER → lysosomes → vesicles that fuse with plasma membrane
    (B) Golgi → ER → lysosome
    (C) nucleus → ER → Golgi
    (D) ER → Golgi → vesicles that fuse with plasma membrane

2. If the S phase were eliminated from the cell cycle, the daughter cells would
    (A) have half the genetic material found in the parent cell.
    (B) be generally identical to each other.
    (C) be genetically identical to the parent.
    (D) synthesize the missing genetic material on their own.

3. Which figure depicts an animal cell placed in a solution hypotonic to the cell?



    (A) cell A
    (B) cell B
    (C) cell C
    (D) cell D

4. Which two figures show a cell that is hypertonic to its environment?
   (A) cells A and B
   (B) cells A and C
   (C) cells A and D
   (D) cells C and D

After reading the paragraph, answer the question(s) that follow.

Americans spend up to $100 billion annually for bottled water (41 billion gallons). The only beverages with higher sales are carbonated soft drinks. Recent news stories have highlighted the fact that most bottled water comes from municipal water supplies (the same source as your tap water), although it may undergo an extra purification step called reverse osmosis.

Imagine two tanks that are separated by a membrane that is permeable to water, but not to the dissolved minerals present in the water. Tank A contains tap water and Tank B contains the purified water. Under normal conditions, the purified water would cross the membrane to dilute the more concentrated tap water solution. In the reverse osmosis process, pressure is applied to the tap water tank to force the water molecules across the membrane into the pure water tank.

5. After the reverse osmosis system has been operating for 30 minutes, the solution in Tank A would
   (A) be hypotonic to Tank B.
   (B) be isotonic to Tank B.
   (C) be hypertonic to Tank B.
   (D) move by passive transport to Tank B.

6. If you shut the system off and pressure was no longer applied to Tank A, you would expect
   (A) the water to flow from Tank A to Tank B.
   (B) the water to reverse flow from Tank B to Tank A.
   (C) the water to flow in equal amounts in both directions.
   (D) the water to flow against the concentration gradient.

7. Earl Sutherland received the Nobel Prize for his discovery of cAMP as a second messenger. Which observation suggested to Sutherland the involvement of a second messenger in epinephrine's effect on liver cells?
   (A) Enzymatic activity was proportional to the amount of calcium added to a cell-free extract.
   (B) Receptor studies indicated that epinephrine was a ligand.
   (C) Glycogen breakdown was observed only when epinephrine was administered to intact cells.
   (D) Glycogen breakdown was observed when epinephrine and glycogen phosphorylase were combined.

8. Protein phosphorylation is commonly involved with all of the following EXCEPT
   (A) regulation of transcription by extracellular signaling molecules.
   (B) enzyme activation.
   (C) activation of G protein-coupled receptors.
   (D) activation of receptor tyrosine kinases.

Free-Response Question

1. *Prokaryotic and eukaryotic cells are physiologically different in many ways, but both represent functional, evolutionarily successful cells.*
   (a) It has been theorized that the organelles of eukaryotic cells evolved from prokaryotes living symbiotically within a larger cell. **Compare** and **contrast** the structure of the prokaryotic cell with eukaryotic cell organelles, and make an argument for or against this theory. Be sure to justify your position with factual information.
   (b) **Create** a model to show the path of a protein in a eukaryotic cell from its formation to its secretion from the cell.

TOPIC 3

Respiration and Photosynthesis

Chapter 9: Cellular Respiration and Fermentation

YOU MUST KNOW

- The summary equation of cellular respiration.
- The difference between fermentation and cellular respiration.
- The role of glycolysis in oxidizing glucose to two molecules of pyruvate.
- The process that brings pyruvate from the cytosol into the mitochondria and introduces it into the citric acid cycle.
- How the process of chemiosmosis utilizes the electrons from NADH and $FADH_2$ to produce ATP.

Oxidation-reduction reactions, fermentation, cellular respiration, and photosynthesis are among the most technically challenging sections of the course. Here, we will focus on the major steps of each of the processes, as well as the results. Questions on the AP Biology Exam are likely to focus on the net results of photosynthesis and respiration—not on the exact reactions that create the products, nor are you expected to know the names of the enzymes involved in the process. As you work through these chapters, compare and contrast the two fundamental cell processes.

Concept 9.1 Catabolic pathways yield energy by oxidizing organic fuels

- **Catabolic pathways** occur when molecules are broken down and their energy is released. You should know these two catabolic pathways:
  - **Fermentation** is the partial degradation of sugars that occurs without the use of oxygen.
  - **Cellular respiration** is the most prevalent and efficient catabolic pathway. It is also termed **aerobic respiration** as oxygen is required along with organic fuel.

- Carbohydrates, fats, and proteins can all be broken down to release energy i cellular respiration. However, glucose is the primary nutrient molecule that i used in cellular respiration. The standard way of representing the process o cellular respiration shows glucose being broken down in the following reaction

$$C_6H_{12}O_6 + 6\ O_2 \rightarrow 6\ CO_2 + 6\ H_2O + \text{Energy (686 kcal/mol of glucose)}$$

- The exergonic release of energy from glucose is used to phosphorylate ADP t ATP. Life processes constantly consume ATP; cellular respiration burns fuel and uses the energy to regenerate ATP.
- The reactions of cellular respiration are of a type termed **oxidation-reductio (redox)** reactions. In redox reactions electrons are transferred from one reac tant to another.
    - The loss of one or more electrons from a reactant is called **oxidation**. When a reactant is *oxidized*, it loses electrons and, consequently, energy.
    - The gain of one or more electrons is **reduction**. When a reactant is *reduced*, it gains electrons and, therefore, energy.
- At key steps in cellular respiration, electrons are stripped from glucose. Eac electron travels with a proton, thereby forming a hydrogen atom. The hydro gen atoms are not transferred directly to oxygen, as the formula might sugges but instead are usually passed to an electron carrier, the coenzyme **NAD** (a derivative of the B vitamin niacin). Within the cell **NAD^+** accepts two elec trons, plus the stabilizing hydrogen ion, to form **NADH**. Note that NADH ha been reduced and therefore has gained energy.
- Figure 3.1 shows the three stages of cellular respiration. Each stage is sepa rately featured in the next three concepts. Use this figure to begin to develo an overall concept of the process of cellular respiration.

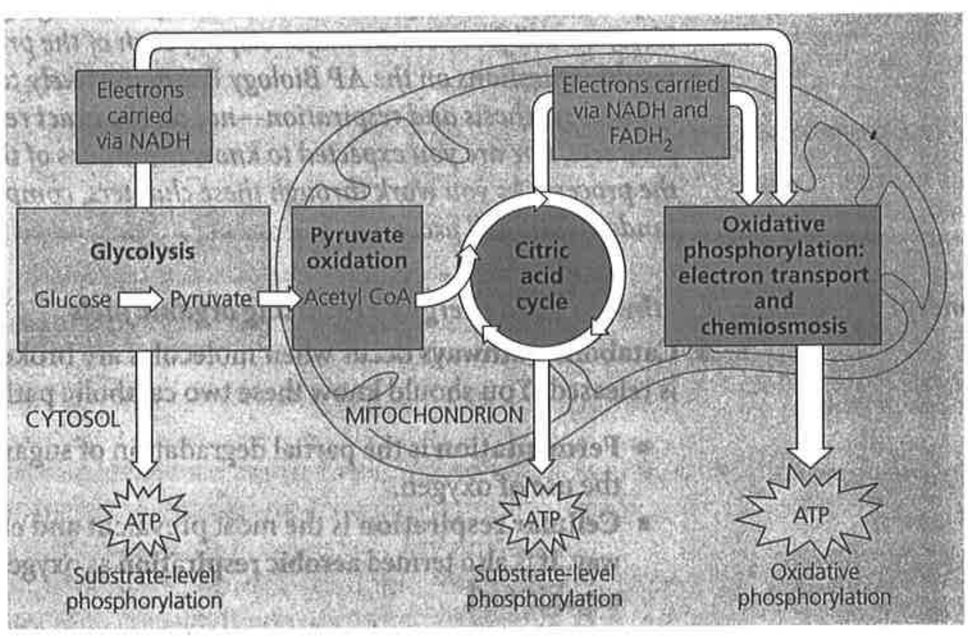


Figure 3.1 An overview of cellular respiration

Concept 9.2 Glycolysis harvests chemical energy by oxidizing glucose to pyruvate

- In **glycolysis** (which occurs in the cytosol), the degradation of glucose begins as it is broken down into two pyruvate molecules. The six-carbon glucose molecule is split into two three-carbon sugars through a long series of steps.

> *STUDY TIP* Use Figure 3.2 as a guide to the important features of glycolysis. It is not necessary to know the enzymes and reactions for each step in glycolysis.

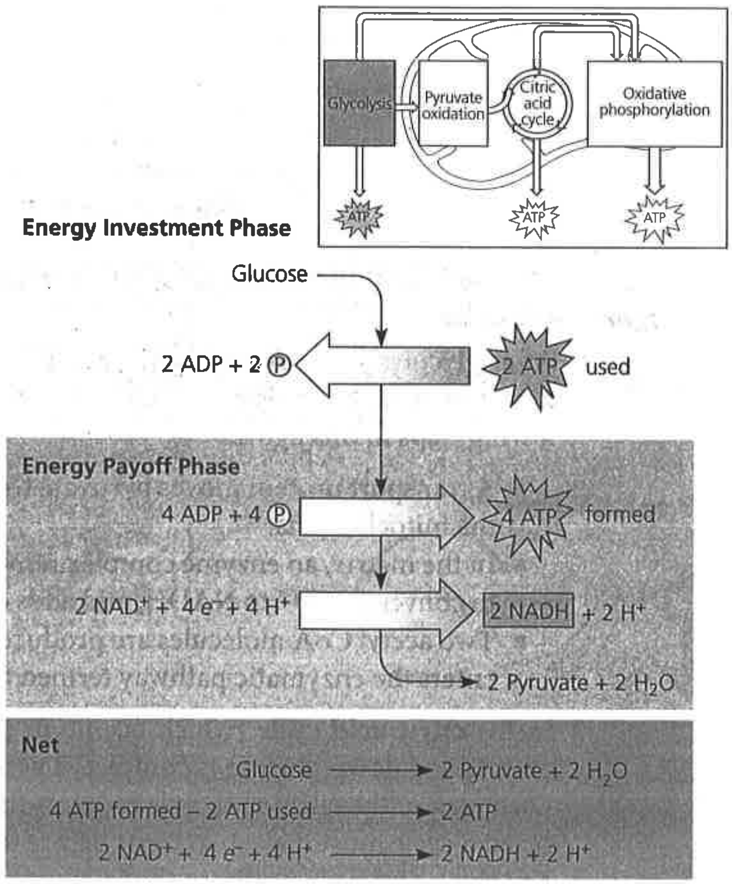


Figure 3.2 Energy input and output of glycolysis

- In the course of glycolysis, there is an ATP-consuming phase and an ATP-producing phase. In the ATP-consuming phase, two ATP molecules are consumed, which helps destabilize glucose and make it more reactive. Later in glycolysis, 4 ATP molecules are produced; thus, glycolysis results in a net gain of 2 ATP. Two NADH are also produced, which will be utilized in the electron transport system (see Figure 3.1) to produce ATP.
- Notice the *net* energy gain in glycolysis as indicated in Figure 3.2—2 ATP molecules and 2 NADH molecules. Most of the potential energy of the glucose molecule still resides in the two remaining pyruvates, which will now feed into the citric acid cycle, as discussed in the next concept.

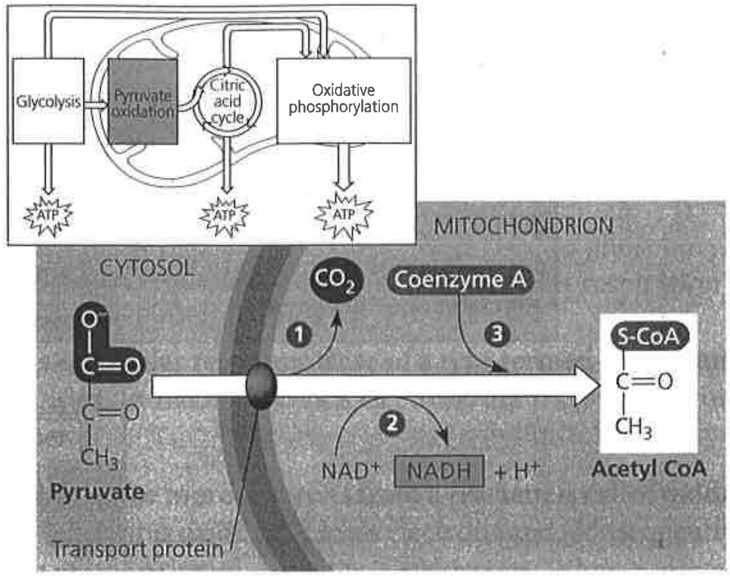


Figure 3.3 Pyruvate oxidation

Concept 9.3 After pyruvate is oxidized, the citric acid cycle completes the energy-yielding oxidation of organic molecules

- After glycolysis, **pyruvate is oxidized to acetyl CoA**. This junction between glycolysis and the citric acid cycle is shown above in Figure 3.3. Note the following steps in this figure:
  - A transport protein moves pyruvate from the cytosol into the matrix of the mitochondria.
  - In the matrix, an enzyme complex removes a CO_2, strips away electrons to convert NAD^+ to NADH, and adds coenzyme A to form acetyl CoA.
  - Two acetyl CoA molecules are produced per glucose. Acetyl CoA now enters the enzymatic pathway termed the citric acid cycle.
- In the **citric acid cycle** (which occurs in the mitochondrial matrix), the job of breaking down glucose is completed with CO_2 released as a waste product. Each turn of the citric acid cycle requires the input of one acetyl CoA. The citric acid cycle must make two turns before the glucose is completely oxidized.
- The citric acid cycle results in the following:
  - Each turn of the citric acid cycle produces **2 CO_2, 3 NADH, 1 $FADH_2$,** and **1 ATP**.
  - Because each glucose yields *two* pyruvates, the *total* products of the citric acid cycle are usually listed as the result of two cycles:

4 CO_2, 6 NADH, 2 $FADH_2$, and **2 ATP**

- Note that at the end of the citric acid cycle the six original carbons in glucose have been released as CO_2. (You are exhaling this gas as you study.) Only 2 ATP molecules, however, have been produced. Where is all the energy? The energy is held in the electrons in the electron carriers, NADH and $FADH_2$. These electrons will by utilized by the electron transport system, explained in the next concept.

Concept 9.4 ***During oxidative phosphorylation, chemiosmosis couples electron transport to ATP synthesis***

- Use Figure 3.4 as a map to understand the process of electron transport.

1. The electron transport chain is embedded in the inner membrane of the mitochondria. Notice that it is composed of three transmembrane proteins that work as hydrogen pumps and two carrier molecules that transport electrons between hydrogen pumps. There are thousands of such electron transport chains in the inner mitochondrial membrane.

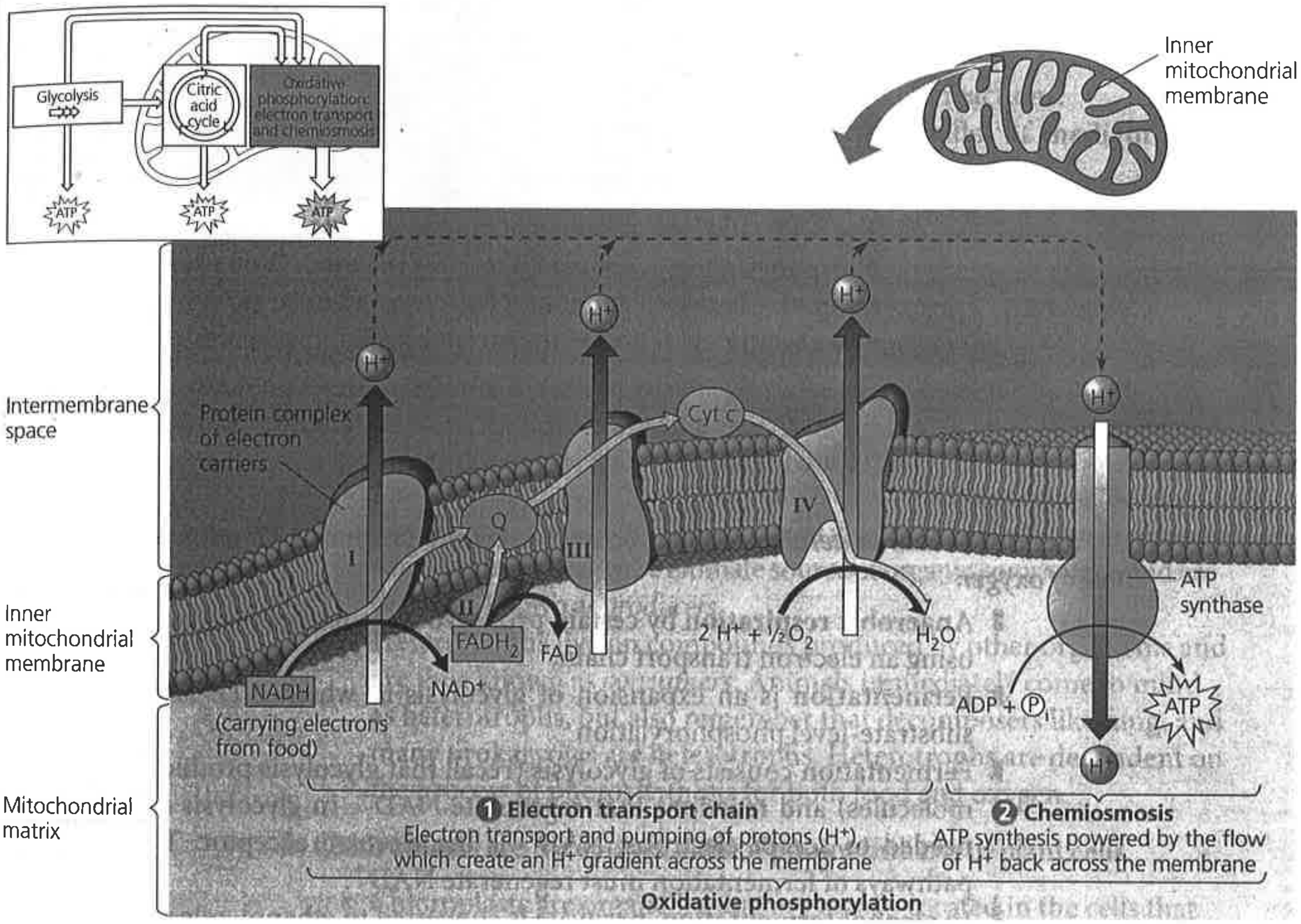


Figure 3.4 ATP production by chemiosmosis

2. The electron transport chain is powered by electrons from the electron carrier molecules NADH and $FADH_2$ ($FADH_2$ is also a B vitamin coenzyme that functions as an electron acceptor in the citric acid cycle). As the electrons flow through the electron chain, the loss of energy by the electrons is used to power the pumping of protons across the inner membrane. At the end of the electron chain, the electrons combine with two hydrogen ions and oxygen to form water. Notice that O_2 is the final electron acceptor, and when it is not available, the transport of electrons comes to a screeching halt! No hydrogen ions are pumped and no ATP is produced.

3. The hydrogen ions flow back down their gradient through a channel in the transmembrane protein known as ATP synthase. **ATP synthase** harnesses the **proton-motive force**—the gradient of hydrogen ions—to phosphorylate ADP, forming ATP. The proton-motive force is in place because the inner membrane of the mitochondria is impermeable to hydrogen ions. Like water behind a dam with its only exit being a spillway, electrons are held behind the inner membrane with their only exit ATP synthase.
4. This process is referred to as chemiosmosis. **Chemiosmosis** is an energy-coupling mechanism that uses energy stored in the form of an H^+ gradient across a membrane to drive cellular work (ATP synthesis in our example). The electron transport chain and chemiosmosis compose **oxidative phosphorylation**. This specific term is used because ADP is phosphorylated and oxygen is necessary to keep the electrons flowing.
5. The ATP yield per molecule of glucose is 30 to 32 ATP. Oxidative phosphorylation produces 26 to 28 of the total. (You may notice this number is less than you might have learned in an earlier text, but more accurately reflects the current biochemical analysis.)

> ***STUDY TIP*** Sketch this process and explain it verbally. This is a fundamental biological process that you should understand.

Concept 9.5 Fermentation and anaerobic respiration enable cells to produce ATP without the use of oxygen

- **Anaerobic respiration** by certain prokaryotes generates ATP without oxyge using an electron transport chain.
- **Fermentation** is an expansion of glycolysis in which ATP is generated b substrate-level phosphorylation.
- Fermentation consists of glycolysis (recall that glycolysis produces 2 net AT molecules) and reactions that regenerate NAD^+. In glycolysis oxygen is no needed to accept electrons; NAD^+ is the electron acceptor. Therefore, th pathways of fermentation must regenerate NAD^+.
- In **alcohol fermentation**, pyruvate is converted to ethanol, releasing CO_2 an oxidizing NADH in the process to create more NAD^+.
- In **lactic acid fermentation**, pyruvate is reduced by NADH (NAD^+ is forme in the process), and lactate is formed as a waste product.
- **Facultative anaerobes** can make ATP by aerobic respiration if oxygen i present, but can switch to fermentation under anaerobic conditions. **Obligat anaerobes** cannot survive in the presence of oxygen.

Concept 9.6 Glycolysis and the citric acid cycle connect to many other metabolic pathways

- In addition to glucose and other sugars, proteins and fats are often used t generate ATP through cellular respiration.
- **Phosphofructokinase** is an allosteric enzyme that acts as a regulator c respiration.

Chapter 10: Photosynthesis

YOU MUST KNOW

- The summary equation of photosynthesis including the source and fate of the reactants and products.
- How leaf and chloroplast anatomy relates to photosynthesis.
- How photosystems convert solar energy to chemical energy.
- How linear electron flow in the light reactions results in the formation of ATP, NADPH, and O_2.
- How chemiosmosis generates ATP in the light reactions.
- How the Calvin cycle uses the energy molecules of the light reactions to produce G3P.

Concept 10.1 Photosynthesis converts light energy to the chemical energy of food

- Before you look at the molecular details of photosynthesis, it is important to think of photosynthesis in an ecological context.
  - Life on Earth is solar powered by autotrophs. **Autotrophs** are "self-feeders"; they sustain themselves without eating anything derived from other organisms. Autotrophs are the ultimate source of organic compounds and are therefore known as *producers.*
  - **Heterotrophs** live on compounds produced by other organisms and are thus known as *consumers*. Animals immediately come to mind as heterotrophs, but also remember that decomposers like fungi and many prokaryotes are heterotrophs. Heterotrophs are dependent on the process of photosynthesis for both food and oxygen.
- **Chloroplasts** are the specific sites of photosynthesis in plant cells.
  - Chloroplasts are organelles that are mostly located in the cells that make up the **mesophyll** tissue found in the interior of the leaf.
  - Use Figure 3.5 to become familiar with the structure of chloroplasts. An envelope of two membranes encloses the **stroma**, which is a dense fluid-filled area. Within the stroma is a vast network of interconnected membranous sacs called **thylakoids**. The thylakoids segregate the stroma from another compartment, the **thylakoid space**.
  - **Chlorophyll** is located in the thylakoid membranes and is the light-absorbing pigment that drives photosynthesis and gives plants their green color.
- The exterior of the lower epidermis of a leaf contains many tiny pores called **stomata**, through which carbon dioxide enters and oxygen and water vapor exit the leaf.

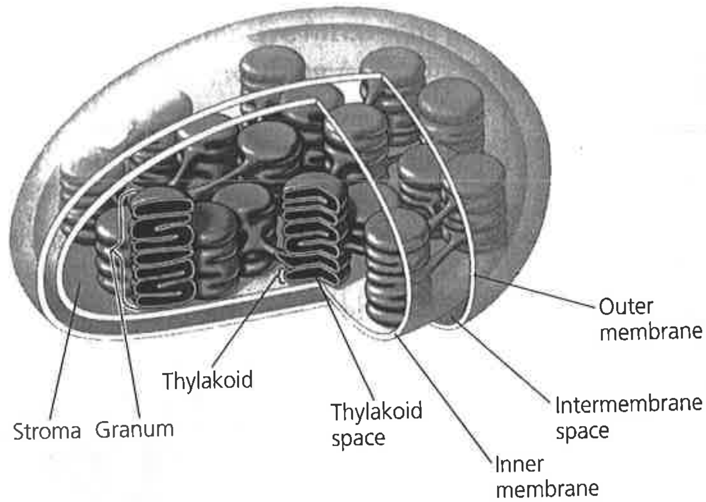


Figure 3.5 Chloroplast structure

> ***STUDY TIP*** Practice drawing a chloroplast in the margin of this page. Label its parts and know what major events occur in each region.

- The overall reaction of photosynthesis looks like this:

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

  - Notice that the overall chemical change during photosynthesis is the reverse of the one that occurs during cellular respiration.
  - All the oxygen you breathe was formed in the process of photosynthesis when a water molecule was split! Water is split for its electrons, which are transferred along with hydrogen ions from water to carbon dioxide, reducing it to sugar. This process requires energy (an endergonic process), which is provided by the sun.

- Photosynthesis is a chemical process that requires two stages to complete.
- The **light reactions** occur in the thylakoid membranes where solar energy is co verted to chemical energy. The net products of the light reactions are **NADF** (which stores electrons), **ATP**, and **oxygen**. Here are the primary events.

  1. Light is absorbed by chlorophyll and drives the transfer of electrons from water to $NADP^+$, forming **NADPH**.
  2. Water is split during these reactions, and O_2 is released.
  3. **ATP** is generated, using chemiosmosis to power the addition of a phosphate group to ADP, a process called **photophosphorylation.**

- The **Calvin cycle** occurs in the stroma, where CO_2 from the air is incorpora into organic molecules in **carbon fixation**. The Calvin cycle uses the fixed carb plus NADPH and ATP from the light reactions in the formation of new sugar

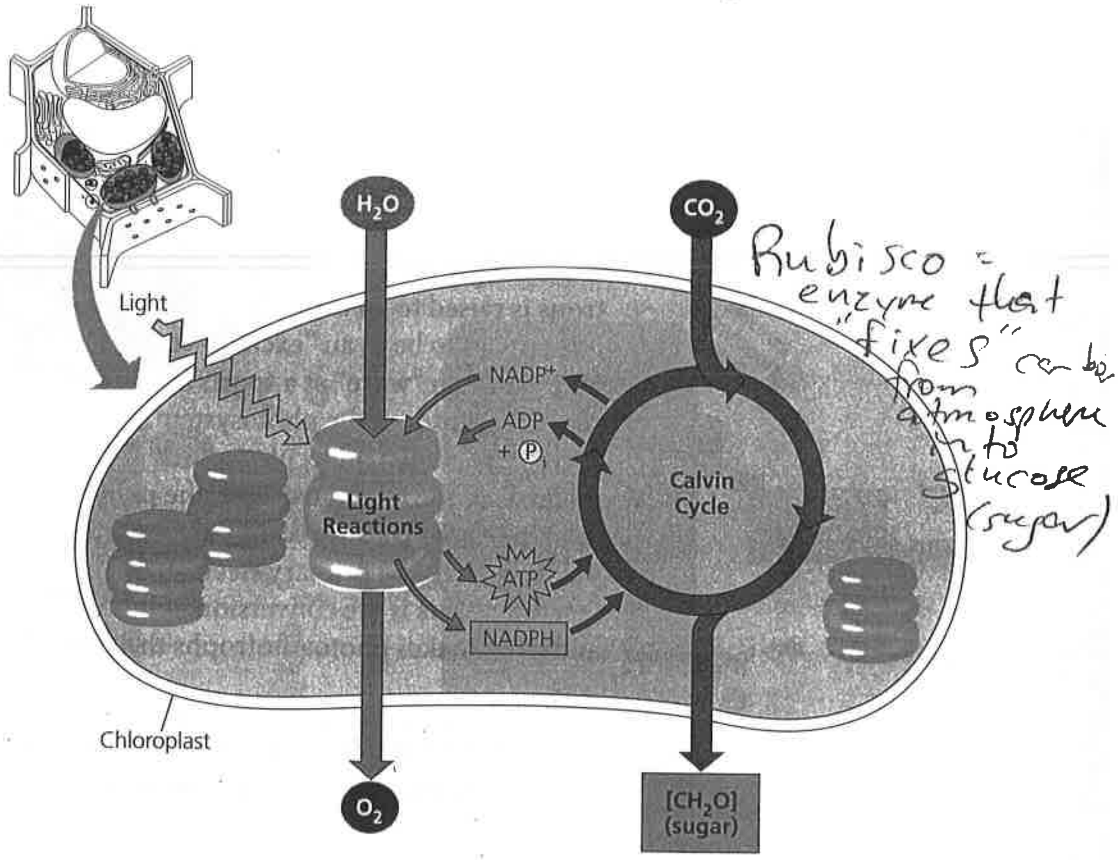


Figure 3.6 Overview of photosynthesis

> ***STUDY TIP*** Use Figure 3.6 above to help in understanding where reactions occur and the overall purpose of the two stages of photosynthesis. If you understand the big picture, the details will be easier to comprehend.

Concept 10.2 The light reactions convert solar energy to the chemical energy of ATP and NADPH

- Not surprisingly, light is an important concept in photosynthesis.
  - Light is electromagnetic energy, and it behaves as though it is made up of discrete particles, called **photons**—each of which has a fixed quantity of energy.
  - Substances that absorb light are called **pigments**, and different pigments absorb light of different wavelengths. Chlorophyll is a pigment that absorbs violet-blue and red light while transmitting and reflecting green light. This is why we see summer leaves as green.
  - A graph plotting a pigment's light absorption versus wavelength is called an **absorption spectrum.** The absorption spectrum of chlorophyll provides clues to the effectiveness of different wavelengths for driving photosynthesis. This is confirmed by an action spectrum.
  - An **action spectrum** for photosynthesis graphs the effectiveness of different wavelengths of light in driving the process of photosynthesis. Note examples of both of these graphs in your text, Figure 10.10.

- Photons of light are absorbed by certain groups of pigment molecules in the thylakoid membrane of chloroplasts. These groups are called **photosystems** and consist of two parts: a light-harvesting complex and a reaction center.
  - The **light-harvesting complex** is made up of many chlorophyll and carotenoid molecules (accessory pigments in the thylakoid membrane); this allows the complex to gather light effectively. When chlorophyll absorbs light energy in the form of photons, one of the molecule's electrons is raised to an orbital of higher potential energy. The chlorophyll is then said to be in an "excited" state.
  - Like a human "wave" at a sports arena, the energy is transferred to the **reaction center** of the photosystem. The reaction center consists of two chlorophyll *a* molecules, which donate the electrons to the second member of the reaction center, the **primary electron acceptor**. The solar-powered transfer of an electron from the reaction-center chlorophyll *a* pair to the primary electron acceptor is the first step of the light reactions. This is the conversion of light energy to chemical energy, and what makes photoautotrophs the producers of the natural world.
- Thylakoid membranes contain two photosystems that are important to photosynthesis—**photosystem I (PS I)** and **photosystem II (PS II)**. PS I is sometimes designated P700 because the chlorophyll *a* in the reaction center of this photosystem absorbs red light of this wavelength the best; PS II is sometimes referred to as P680 for the same reason. Don't let switches in designation be confusing.
- Following are the major steps of the light reactions of photosynthesis. The key to the light reactions is a flow of electrons through the photosystems in the thylakoid membrane, a process called **linear (noncyclic) electron flow**. Find each step in Figure 3.7 as you read the following summary:

  1. Photosystem II absorbs light energy, allowing the P680 reaction center of two chlorophyll *a* molecules to donate an electron to the primary electron acceptor. The reaction-center chlorophyll is oxidized and now requires an electron.
  2. An enzyme splits a water molecule into two hydrogen ions, two electrons, and an oxygen atom. The electrons are supplied to the P680 chlorophyll *a* molecules. The oxygen combines with another oxygen molecule, forming the O_2 that will be released into the atmosphere.
  3. The original excited electron passes from the primary electron acceptor of photosystem II to photosystem I through an electron transport chain (similar to the electron chain in cellular respiration).
  4. The energy from the transfer of electrons down the electron transport chain is used to pump protons, creating a gradient that is used in chemiosmosis to phosphorylate ADP to ATP. ATP will be used as energy in the formation of carbohydrates in the Calvin cycle.
  5. Meanwhile, light energy has also activated PS I, resulting in the donation of an electron to its primary electron acceptor. The electrons just donated by PS I are replaced by the electrons from PS II. (Keep in mind that the ultimate source of electrons is water.)

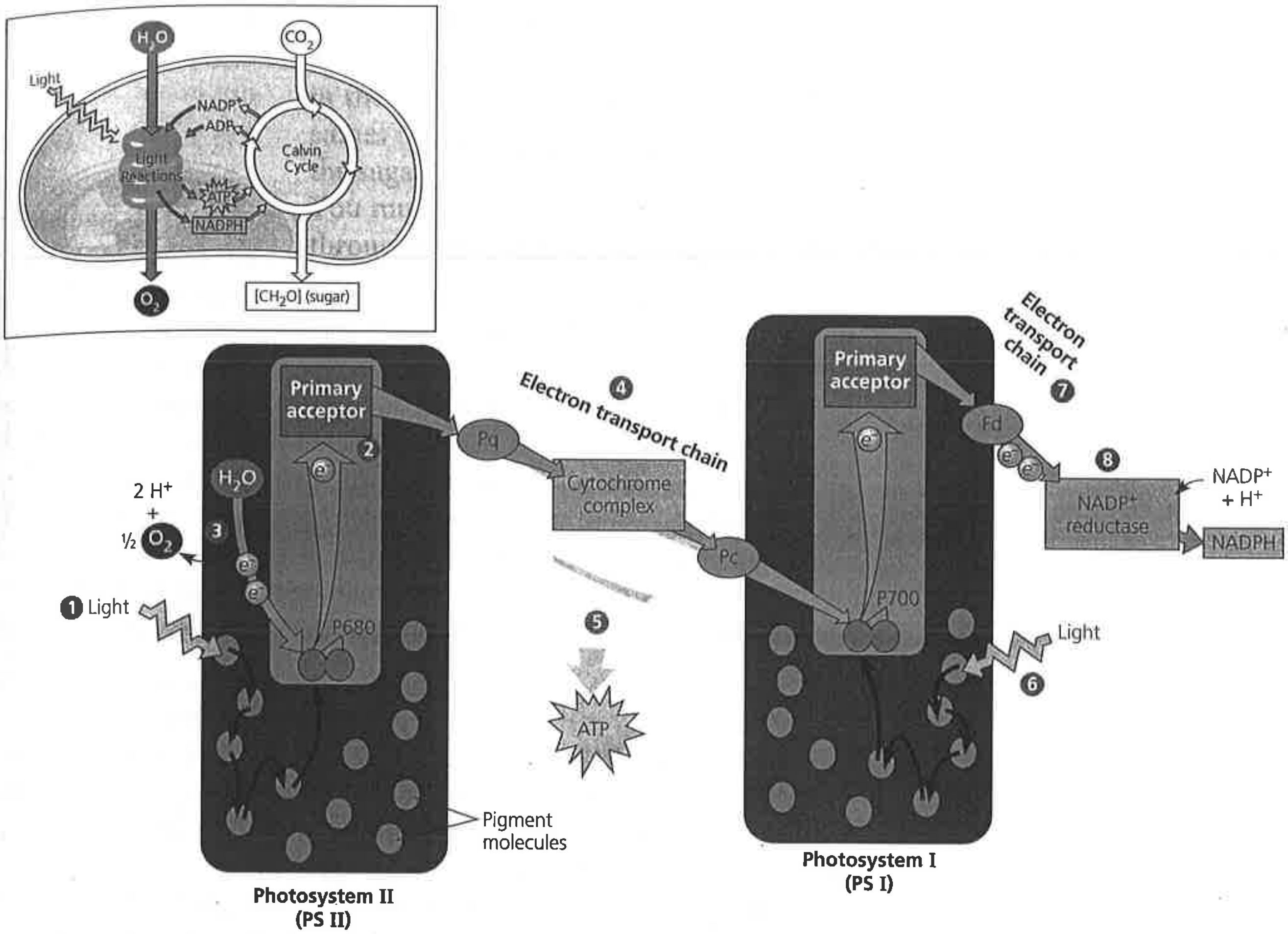


Figure 3.7 Noncyclic electron flow

6. The primary electron acceptor of photosystem I passes the excited electrons along to another electron transport chain, which transmits them to $NADP^+$, which is reduced to NADPH—the second of the two important light-reaction products. The high-energy electrons of NADPH are now available for use in the Calvin cycle.

- An alternative to linear electron flow is **cyclic electron flow**. Cyclic electron flow uses PS I, but not PS II. Cyclic electron flow uses a short circuit of linear electron flow by cycling the excited electrons back to their original starting point in PS I. Cyclic electron flow produces ATP by chemiosmosis, but no NADPH is produced and no oxygen is released.
- Chloroplasts and mitochondria generate ATP by the same basic mechanism: chemiosmosis. Examining Figure 3.8 on the next page will quickly demonstrate the same basic chemiosmotic plan as cellular respiration. Use Figure 3.8 to illustrate the following:
  - An electron transport chain uses the flow of electrons to pump protons across the thylakoid membrane.
  - A proton-motive force is created within the thylakoid space that can be utilized by ATP synthase to phosphorylate ADP to ATP. Notice that the

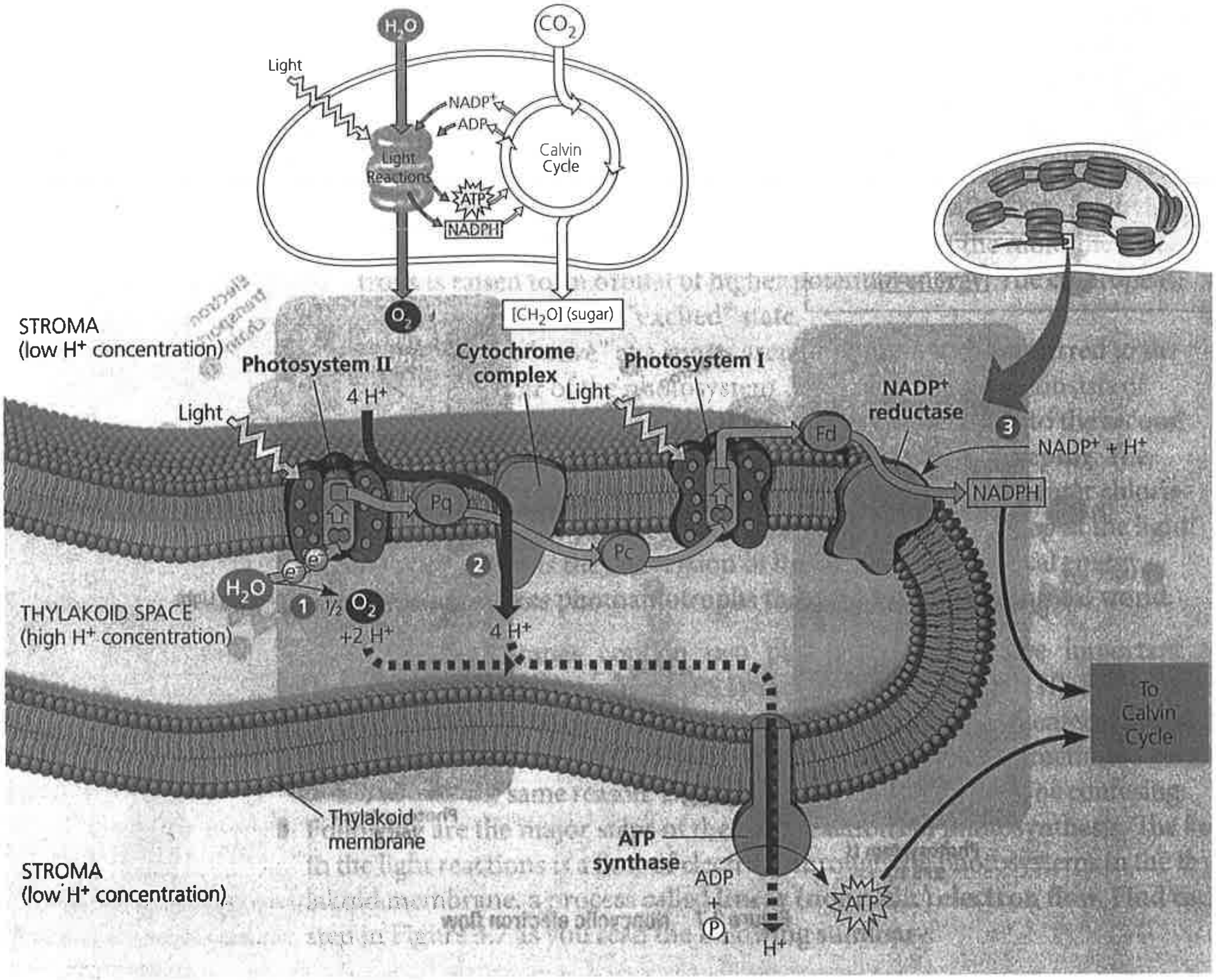


Figure 3.8 Light reactions and chemiosmosis

proton-motive force is generated in three places: (1) hydrogen ions from water; (2) hydrogen ions pumped across the membrane by the cytochrome complex; (3) the removal of a hydrogen ion from the stroma when $NADP^+$ is reduced to NADPH.

- Although similar, chemiosmosis in cellular respiration and photosynthesis are not identical. In addition to some spatial differences, the key conceptual difference is that mitochondria use chemiosmosis to transfer chemical energy from food molecules to ATP, whereas chloroplasts transform light energy into chemical energy in ATP. This is the essence of the difference between a consumer and a producer.

> ***TIP FROM THE READERS***
> Create and use a model of electron transport across either the inner membrane of the mitochondria or a thylakoid membrane to explain the production of ATP. Be able to predict how changes in the model would affect the output of ATP.

Concept 10.3 The Calvin cycle uses the chemical energy of ATP and NADPH to convert CO_2 to sugar

- In the course of the **Calvin cycle**, carbon enters in the form of CO_2 and leaves in the form of a sugar. The cycle spends ATP as an energy source and consumes NADPH as reducing power for adding high-energy electrons to make the sugar. Use Figure 3.9 to chart each step summarized in the outline below. You must note that in order to net one molecule of G3P, the cycle must go through three rotations and fix three molecules of CO_2.

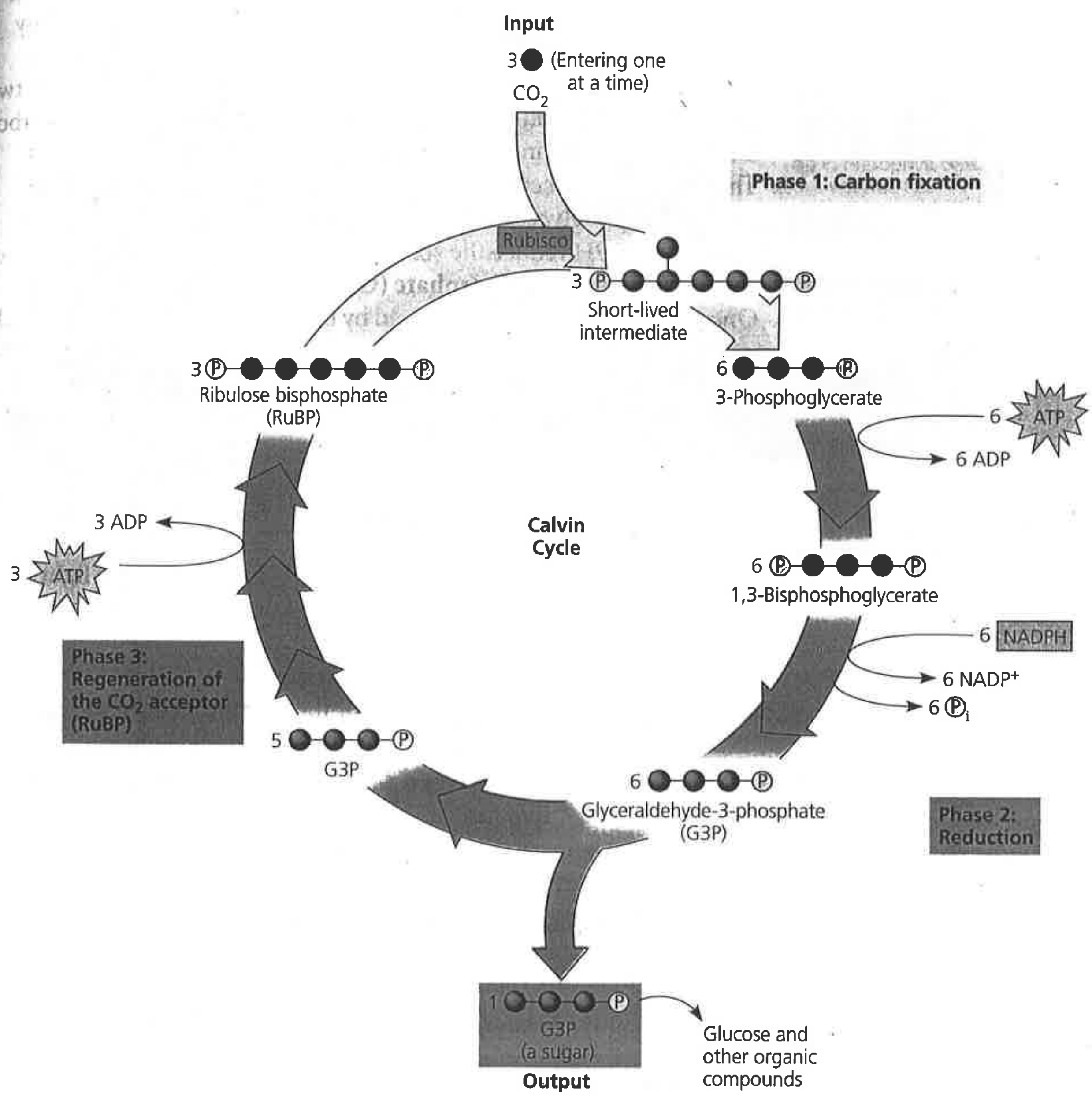


Figure 3.9 Calvin cycle

> ***STUDY TIP*** Try sketching the Calvin cycle as you read these steps. When you are done, you should have a figure much like Figure 3.9. Be able to explain this process!

- These are the major steps of the Calvin cycle. It is not important that you memorize the intermediate organic molecules, but it is important to understand the conceptual scheme of reducing CO_2 to a sugar.
  1. Three CO_2 molecules are attached to three molecules of the five-carbon sugar **ribulose bisphosphate (RuBP)**. These reactions are catalyzed by the enzyme **rubisco** (probably the most common protein in the biosphere) and produce an unstable product that immediately splits into two three-carbon compounds called 3-phosphoglycerate. At this point carbon has been fixed—the incorporation of CO_2 into an organic compound.
  2. The 3-phosphoglycerate molecules are phosphorylated to become 1,3-bisphosphoglycerate.
  3. Next, 6 NADPH reduce the six 1,3-bisphosphoglycerate molecules to six **glyceraldehyde 3-phosphate (G3P)**.
  4. One G3P leaves the cycle to be used by the plant cell. Two G3P molecules can combine to form glucose, which is generally listed as the final product of photosynthesis.
  5. Finally, RuBP is regenerated as the 5 G3P are reworked into three of the starting molecules, with the expenditure of 3 ATP molecules.
- In the Calvin cycle, the formation of one net G3P requires the following energy molecules:
  - *Nine molecules of ATP* are consumed (to be replenished by the light reactions) along with *six molecules of NADPH* (also to be replenished by the light reactions).
  - One of the six G3P molecules produced in the Calvin cycle is a net gain, and will be used for biosynthesis or the energy needs of the cell.

> **WHAT'S IMPORTANT TO KNOW?**
> Concept 10.4 is not required for the AP exam, but your teacher may use the information here as a nice example of adaptations to arid conditions.

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

- The overall problem is that CO_2 enters the leaf through stomata, the same pores through which water exits the leaf in transpiration.
- The specific problem for C_3 plants is as follows:
  - On hot dry days C_3 plants produce less sugar because the declining levels of CO_2 in the leaf starves the Calvin cycle. This occurs because the plant must keep its stomata closed to conserve water—thus, no CO_2 uptake.
  - Additionally, the enzyme rubisco can bind O_2 in place of CO_2. This causes the oxidation or breakdown of RuBP, resulting in a loss of energy and carbon for the plant—a metabolic process called

photorespiration. Photorespiration can drain away as much as 50% of the carbon fixed by the Calvin cycle!

- How can hot, arid regions have any plants? They have metabolic adaptations (as well as structural ones covered in Topic 8) that reduce photorespiration. The two most important of these adaptations are C_4 and CAM plants.
- C_4 plants have two kinds of photosynthetic cells: bundle-sheath cells and mesophyll cells. The **bundle-sheath cells** are grouped around the leaf's veins, and the mesophyll cells are dispersed elsewhere around the leaf.

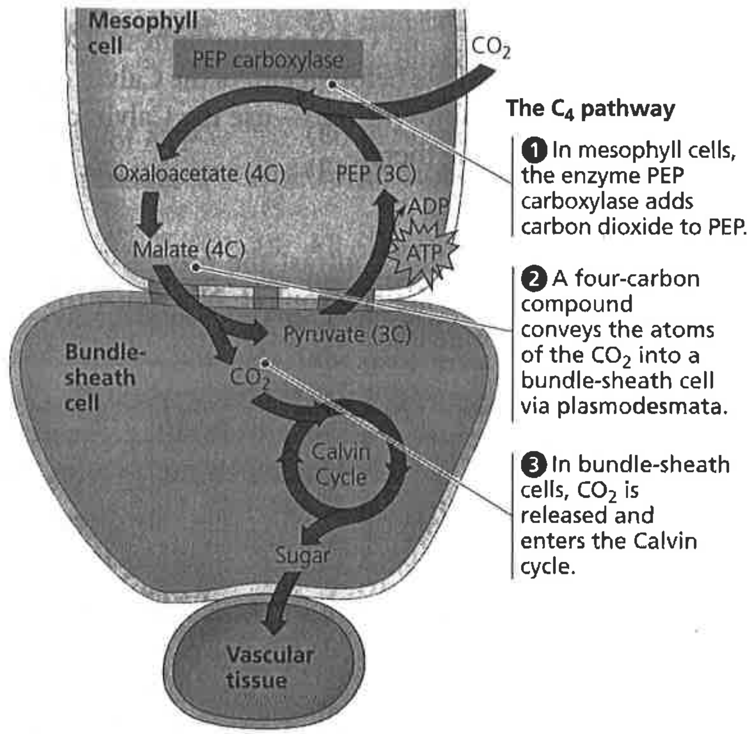


Figure 3.10 C_4 photosynthesis

- Use Figure 3.10 above as a guide for the following steps to C_4 photosynthesis:

1. CO_2 is added to **phosphoenolpyruvate** (PEP) to form the four-carbon compound **oxaloacetate** (hence the designation C_4 plant). This reaction is catalyzed by **PEP carboxylase**, which does not combine with O_2 and does not participate in photorespiration. At this point carbon is fixed.
2. The mesophyll cells export the oxaloacetate to the bundle-sheath cells, which break down the oxaloacetate, releasing CO_2. The C_4 pathway acts as a CO_2 pump.
3. The CO_2 in the bundle-sheath cells is then converted into carbohydrates through the normal Calvin cycle.

   - In C_4 plants, the mesophyll cells pump CO_2 into the bundle-sheath cells, keeping the CO_2 concentration high enough so that rubisco will be more likely to bind to CO_2 rather than O_2. This reduces photorespiration. In C_4 plants the two stages of photosynthesis are separated structurally, providing a process that minimizes photorespiration and enhances sugar production.

- **CAM photosynthesis** is another adaptation to hot, dry climates.
  - These plants keep their stomata closed during the day to prevent excessive water loss. Of course, this also prevents gas exchange. At night, the stomata open and CO_2 is fixed in organic acids and stored in vacuoles. In the morning when the stomata close, the plant cells release the stored CO_2 from the acids and proceed with photosynthesis.
  - In CAM plants the two stages of photosynthesis are separated temporally.
- In both C_4 and CAM photosynthesis, CO_2 is first transformed into an organic intermediate before it enters the Calvin cycle. All of the processes—C_3, C_4, and CAM photosynthesis—use the Calvin cycle; they just have different methods for getting there.

For Additional Review

Compare and contrast the process of chemiosmosis in both the mitochondrion and the chloroplast. Note how the H^+ gradient is established and the orientation of the ATP synthase molecules.

Level 1: Knowledge/Comprehension Questions

1. The purpose of cellular respiration in a eukaryotic cell is to
   (A) synthesize carbohydrates from CO_2.
   (B) synthesize fats and proteins from CO_2.
   (C) break down carbohydrates to provide energy for the cell in the form of ATP.
   (D) break down carbohydrates to provide energy for the cell in the form of ADP.
   (E) provide oxygen to the cell.

$$2\,K + Br_2 \rightarrow 2\,K^+ + 2\,Br^-$$

2. In the course of the above reaction, potassium is
   (A) neutralized.
   (B) oxidized.
   (C) reduced.
   (D) sublimated.
   (E) recycled.

3. The net result of glycolysis is
   (A) 4 ATP and 4 NADH.
   (B) 4 ATP and 2 NADH.
   (C) 2 ATP and 4 NADH.
   (D) 2 ATP and 2 NADH.
   (E) 4 ATP and 8 NADH.

4. One glucose molecule provides enough carbons for two trips through the citric acid cycle. How many molecules of ATP are directly produced in this process?
   (A) 1
   (B) 2
   (C) 3
   (D) 4
   (E) 5

5. The process that produces the greatest amount of ATP during respiration is
   (A) glycolysis.
   (B) fermentation.
   (C) the citric acid cycle.
   (D) oxidative phosphorylation.
   (E) lactic acid formation.

Directions: The group of questions that follow, 6 through 10, consists of five lettered choices followed by a list of numbered phrases or sentences. For each numbered phrase or sentence, select the one choice that is most closely related to it. Each choice may be used once, more than once, or not at all in each group.

Questions 6–10

(A) Chemiosmosis
(B) Electron transport chain
(C) The citric acid cycle
(D) Glycolysis
(E) Fermentation

6. The process by which glucose is split into pyruvate

7. The process by which a hydrogen ion gradient is used to produce ATP

8. A process that makes a small amount of ATP and can produce lactic acid as a by-product

9. A series of membrane-embedded electron carriers that ultimately create the hydrogen ion gradient to drive the synthesis of ATP

10. The process by which the chemical breakdown of glucose is completed and CO_2 is produced

11. Groups of photosynthetic pigment molecules situated in the thylakoid membrane are called
(A) photosystems.
(B) carotenoids.
(C) chlorophyll.
(D) grana.
(E) CAM plants.

12. The main products of the light reactions of photosynthesis are
(A) NADPH and $FADH_2$.
(B) NADPH and ATP.
(C) ATP and $FADH_2$.
(D) ATP and CO_2.
(E) ATP and H_2O.

13. The process in photosynthesis that bears the most resemblance to chemiosmosis and oxidative phosphorylation in cell respiration is called
(A) cyclic electron flow.
(B) linear electron flow.
(C) ATP synthase coupling.
(D) substrate-level phosphorylation.
(E) glycolysis.

14. The major product of the Calvin cycle is
(A) rubisco.
(B) oxaloacetate.
(C) ribulose bisphosphate.
(D) pyruvate.
(E) glyceraldehyde 3-phosphate.

15. All of the following statements are *false* EXCEPT
(A) C_3 plants grow better in hot, arid conditions than do C_4 plants.
(B) C_4 plants grow better in cold, moist conditions than do C_3 plants.
(C) C_3 plants grow better in hot, arid conditions than do CAM plants.
(D) CAM plants grow better in cold, moist conditions than do C_3 plants.
(E) CAM plants and C_4 plants both grow better in hot, arid conditions than do C_3 plants.

16. All of the following statements about photosynthesis are *true* EXCEPT
(A) the light reactions convert solar energy to chemical energy in the form of ATP and NADPH.
(B) the Calvin cycle uses ATP and NADPH to convert CO_2 to sugar.
(C) photosystem I contains P700 chlorophyll *a* molecules at the reaction center; photosystem II contains P680 molecules.
(D) in chemiosmosis, electron transport chains pump protons (H^+) across a membrane from a region of high H^+ concentration to a region of low H^+ concentration.
(E) the steps of the Calvin cycle use ATP and NADPH to convert CO_2 to sugar.

17. Which of the following is mismatched with its location?
    (A) light reactions—grana
    (B) electron transport chain—thylakoid membrane
    (C) Calvin cycle—stroma
    (D) ATP synthesis—double membrane surrounding chloroplast
    (E) splitting of water—thylakoid space

18. The chlorophyll known as P680 has its electron "holes" filled by electrons from
    (A) photosystem I.
    (B) photosystem II.
    (C) water.
    (D) NADPH.
    (E) CO_2.

19. CAM plants avoid photorespiration by
    (A) fixing CO_2 into organic acids during the night; these acids then release CO_2 during the day.
    (B) performing the Calvin cycle at night.
    (C) fixing CO_2 into four-carbon compounds in the mesophyll, which release CO_2 in the bundle-sheath cells.
    (D) using PEP carboxylate to fix CO_2 to ribulose bisphosphate (RuBP).
    (E) keeping their stomata open during the day.

20. How many "turns" of the Calvin cycle are required to produce one molecule of glucose?
    (A) 1
    (B) 2
    (C) 3
    (D) 6
    (E) 12

21. What are the final electron acceptors for the electron transport chains in the light reaction: of photosynthesis and in cellular respiration?
    (A) O_2 in both
    (B) CO_2 in both
    (C) H_2O in the light reactions and O_2 in respiration
    (D) P700 and $NADP^+$ in the light reactions and NAD^+ or FAD in respiration
    (E) $NADP^+$ in the light reactions and O_2 in respiration

Level 2: Application/Analysis/Synthesis Questions

After reading the paragraph, answer the question(s) that follow.

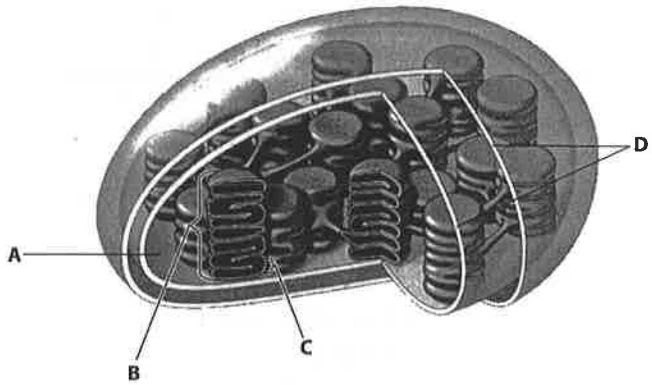
You're conducting an experiment to determine the effect of different wavelengths of light on the absorption of carbon dioxide as an indicator of the rate of photosynthesis in aquatic ecosystems. If the rate of photosynthesis increases, the amount of carbon dioxide in the environment will decrease and vice versa. You've added an indicator to each solution. When the carbon dioxide concentration decreases, the color of the indicator solution also changes.

Small aquatic plants are placed into three con tainers of water mixed with carbon dioxide an indicator solution. Container A is placed un der normal sunlight, B under green light, and (under red light. The containers are observed for 24-hour period.

1. Based on your knowledge of the process of photosynthesis, the plant in the container placed under red light would probably
   (A) absorb no CO_2.
   (B) absorb the same amount of CO_2 as the plants under both the green light and normal sunlight.
   (C) absorb less CO_2 than the plants under the green light.
   (D) absorb more CO_2 than the plants under the green light.

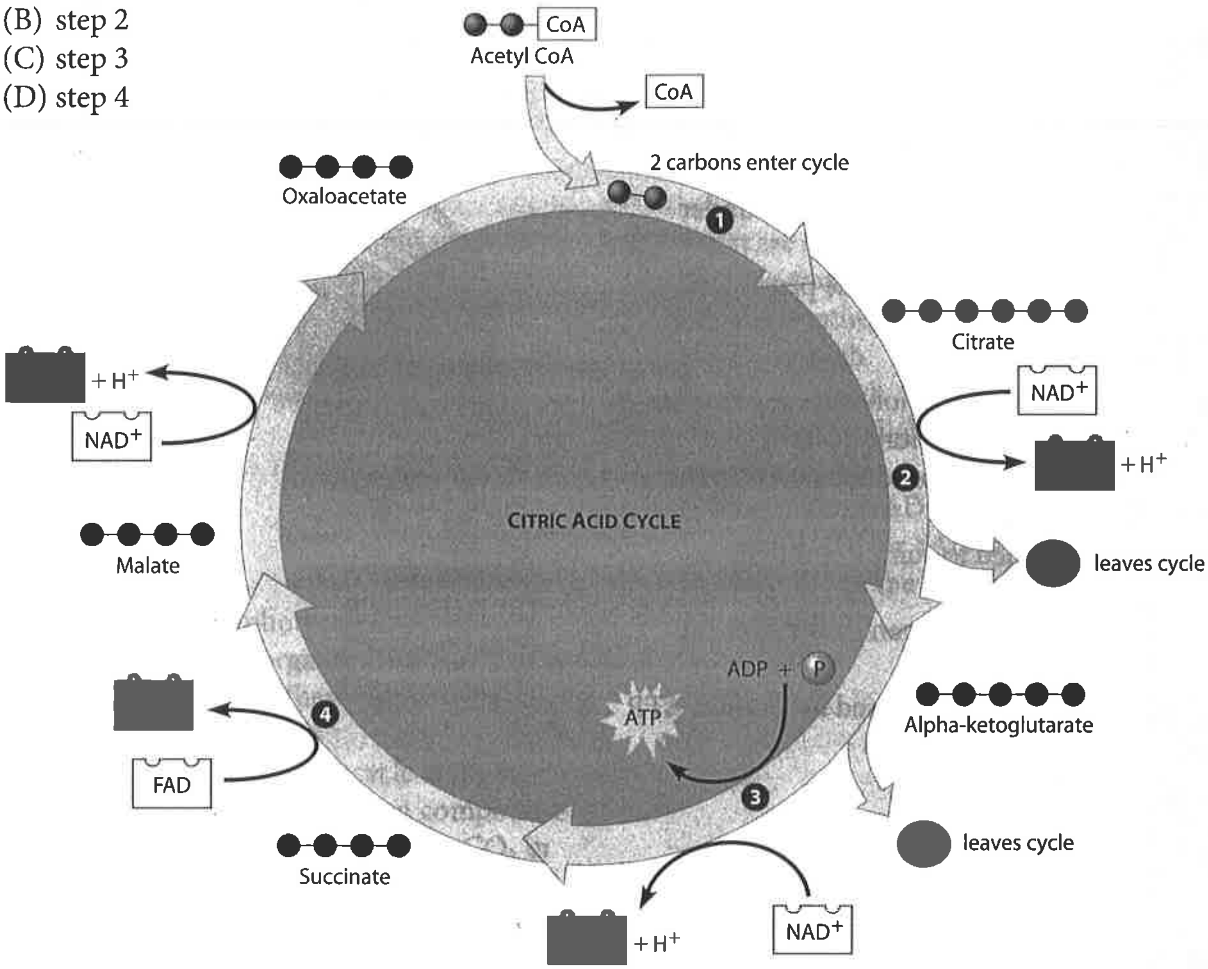
2. Carbon dioxide absorption is an appropriate indicator of photosynthesis because
   (A) CO_2 is needed to produce sugars in the Calvin cycle.
   (B) CO_2 is needed to complete the light reactions.
   (C) plants produce oxygen gas by splitting CO_2.
   (D) the energy in CO_2 is used to produce ATP and NADPH.

3. In this drawing of a chloroplast, which structure represents the location of the Calvin cycle?



   (A) structure A
   (B) structure B
   (C) structure C
   (D) structure D

4. In the figure below, which step of the citric acid cycle requires both NAD^+ and ADP as reactants?
   (A) step 1
   (B) step 2
   (C) step 3
   (D) step 4



After reading the paragraph, answer the question(s) that follow.

As a scientist employed by the FDA, you've been asked to sit on a panel to evaluate a pharmaceutical company's application for approval of a new weight loss drug called Fat Away. The company has submitted a report summarizing the results of their animal and human testing. In the report, it was noted that Fat Away works by affecting the electron transport chain. It decreases the synthesis of ATP by making the mitochondrial membrane permeable to H^+, which allows H^+ to leak from the intermembrane space to the mitochondrial matrix. This effect leads to weight loss.

5. The method of weight loss described for Fat Away shows that the drug is acting as a metabolic
   (A) feedback inhibitor.
   (B) oxygen carrier.
   (C) redox promoter.
   (D) uncoupler.

6. Fat Away prevents ATP from being made by
   (A) destroying the H^+ gradient that allows ATP synthase to work.
   (B) preventing glycolysis from occurring.
   (C) preventing the conversion of NADH to NAD^+.
   (D) slowing down the citric acid cycle.

Free-Response Question

1. *Cellular respiration and photosynthesis are basic cellular processes. Below are key events in cellular respiration and/or photosynthesis.*

   (a) **Explain** how a photosystem converts light energy to chemical energy.
   (b) **Explain** the specific role of glycolysis in cellular respiration.
   (c) **Describe** the function of water in both cellular respiration and photosynthesis.

TOPIC 4

Mendelian Genetics

Chapter 13: Meiosis and Sexual Life Cycles

YOU MUST KNOW

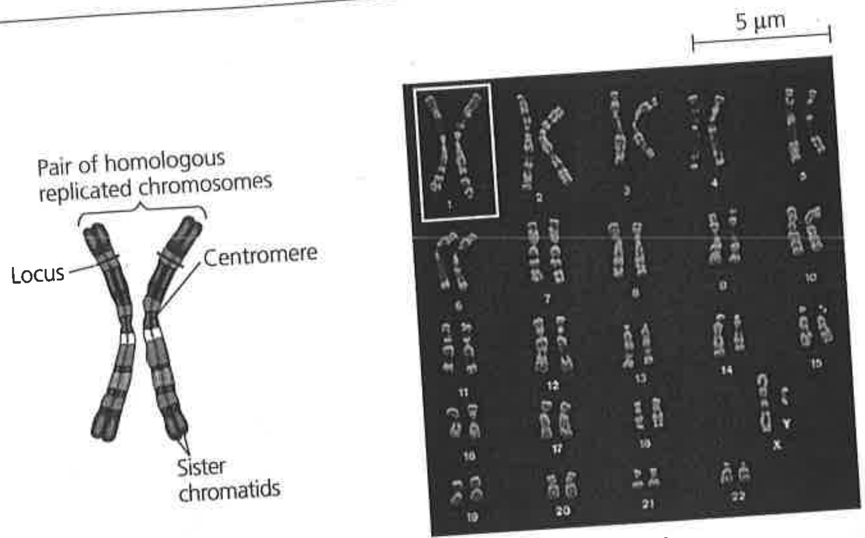
- The differences between asexual and sexual reproduction.
- The role of meiosis and fertilization in sexually reproducing organisms.
- The importance of homologous chromosomes to meiosis.
- How the chromosome number is reduced from diploid to haploid through the stages of meiosis.
- Three important differences between mitosis and meiosis.
- The importance of crossing over, independent assortment, and random fertilization to increasing genetic variability.

Concept 13.1 Offspring acquire genes from parents by inheriting chromosomes

- **Genes** are segments of DNA that code for the basic units of heredity and are transmitted from one generation to the next. In animals and plants, reproductive cells that transmit genes from one generation to the next are called **gametes.**
- A **locus** (plural, *loci*) is the location of a gene on a chromosome. See Figure 4.1a.
  - In **asexual reproduction** a single parent is the sole parent and passes copies of all its genes to its offspring. In asexual reproduction the new offspring arise by mitosis and have virtually exact copies of the parent's genome. An individual that reproduces asexually gives rise to a **clone,** a group of genetically identical individuals.
  - In **sexual reproduction,** two individuals (parents) contribute genes to the offspring. This form of reproduction results in greater genetic variation in the offspring than asexual reproduction.

Concept 13.2 Fertilization and meiosis alternate in sexual life cycles

- A **life cycle** is the generation-to-generation sequence of stages in the reproductive history of an organism, from conception to production of its own offspring.



(a) (b)

Figure 4.1 Metaphase chromosome (a) and human karyotype (b)

- **Somatic cells** are any cells in the body that are not gametes. Each somatic cel in humans has 46 chromosomes. Liver cells and neurons are somatic cells.
- The **karyotype** of an organism refers to a picture of its complete set of chro mosomes, arranged in pairs of homologous chromosomes from the larges pair to the smallest pair. Figure 4.1b is a karyotype made from a human sc matic cell. Notice that the 46 chromosomes are paired into 23 homologou chromosomes.
- In **homologous chromosomes** both chromosomes of each pair carry gen that control the same inherited characteristics. If a gene for eye color is fou at a specific locus on one chromosome, its homologs will have the same gene the same locus.
  - Homologous chromosomes are similar in length and centromere position, and they have the same staining pattern.
  - One homologous chromosome from each pair is inherited from each parent; in other words, half of the set of 46 chromosomes in your somatic cells was inherited from your mother, and the other half was inherited from your father.
- Exceptions to the rule that all chromosomes are part of a homologous may be found with the sex chromosomes—in humans, it is the **X** and **Y**. man females have a homologous pair of chromosomes, XX, but males one X chromosome and one Y chromosome. Nonsex chromosomes are c **autosomes.**
- *What sex did the somatic cell come from that was used to make the karyoty Figure 4.1?* (Check your answer in Part V.)
- **Gametes**—meaning sperm and ova (eggs)—are haploid cells. Haploid contain half the number of chromosomes of somatic cells. In humans, gai contain 22 autosomes plus a single sex chromosome (either X or Y), g them a haploid number of 23. The haploid number of chromosomes is bolized by *n*.

- **Meiosis** and **fertilization** are the key events in sexually reproducing life cycles. The human life cycle in Figure 4.2 is typical of a sexually reproducing animal.

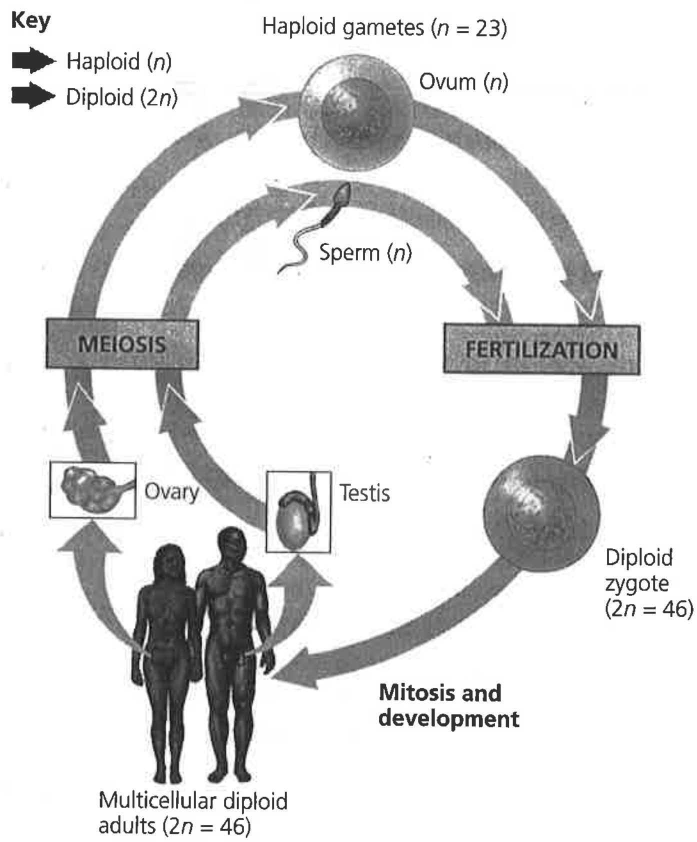


Figure 4.2 Human life cycle

- During **fertilization** (the combination of a sperm cell and an egg cell), one haploid gamete from the father fuses with one haploid gamete from the mother. The result is a fertilized egg called a **zygote**. It is **diploid** (has two sets of chromosomes) and may be symbolized by $2n$.
- **Meiosis** is the type of cell division that reduces the numbers of sets of chromosomes from two to one. Fertilization restores the diploid number as the gametes are combined. Fertilization and meiosis alternate in the life cycles of sexually reproducing organisms.

Concept 13.3 *Meiosis reduces the number of chromosome sets from diploid to haploid*

- Meiosis and mitosis look similar—both are preceded by the replication of the cell's DNA, for instance, but in meiosis this replication is followed by *two* stages of cell division, meiosis I and meiosis II.
- The final result of meiosis is *four* **daughter cells**, each of which has *half* as many chromosomes as the parent cell.

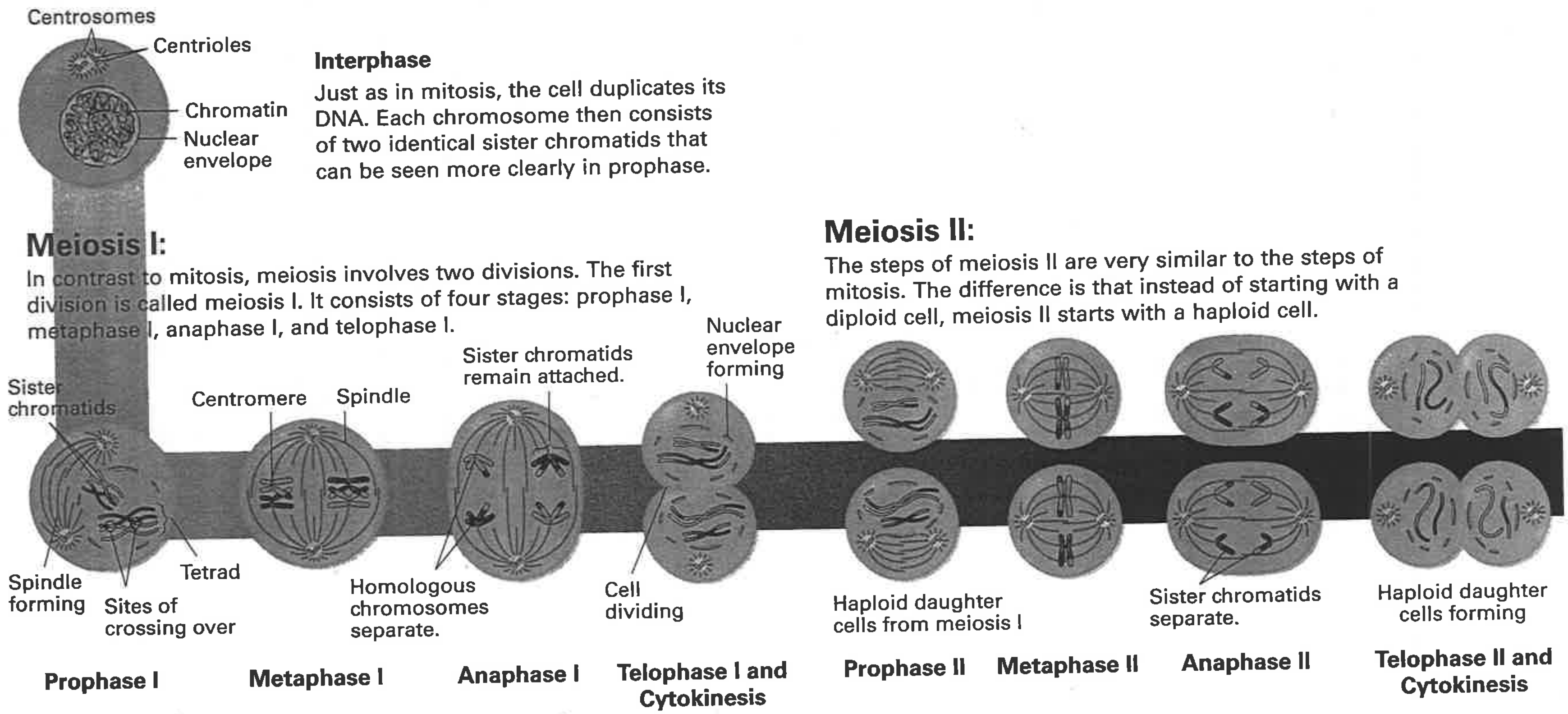


Figure 4.3 Meiosis in an animal cell

Carefully follow the stages in Figure 4.3 as they are explained:

- **Interphase:** Each of the chromosomes makes a copy of itself; that is, each chromosome replicates its DNA, roughly doubling the amount of DNA in the cell. The centrosome also divides during this phase.

> ***STUDY TIP*** Understanding prophase I is critical to understanding meiosis. Study the unique events of prophase I carefully!

- **Meiosis I:** The first cellular division in meiosis is referred to as meiosis I.
  - **Prophase I:** The chromosomes condense, resulting in two sister chromatids attached at their centromeres.
    - **Synapsis** occurs—that is, the joining of homologous chromosomes along their length. This newly formed structure is called a *tetrad* and precisely aligns the homologous chromosomes gene by gene. This perfect alignment is necessary for the next step—crossing over.
    - In **crossing over** the DNA from one homolog is cut and exchanged with an exact portion of DNA from the other homolog. Essentially, a small part of the DNA from one parent is exchanged with the DNA from the other parent. *The result of crossing over is to increase genetic variation.* Where crossing over has occurred (two to three times per homologous pair), crisscrossed regions termed **chiasmata** form, which hold the homologs together until anaphase I.
    - After crossing over, the centrioles move away from each other, the nuclear envelope disintegrates, and spindle microtubules attach to the kinetochores forming on the chromosomes that begin to move to the metaphase plate of the cell.

> ***ORGANIZE YOUR THOUGHTS***
>
> In Prophase I:
>
> 1. Synapsis occurs, forming tetrads.
> 2. Crossing over occurs between *homologous chromosomes* in the tetrads.
> 3. Crossing over increases genetic variation.
> 4. Areas of crossing over form chiasmata.
> 5. The nuclear envelope disintegrates, allowing the spindle to attach to the homologs.

  - **Metaphase I:** The homologous pairs of chromosomes are lined up at the metaphase plate, and microtubules from each pole attach to each member of the homologous pairs in preparation for pulling them to opposite ends of the cell. How many homologous pairs are found in the cell in Figure 4.3? (There are four chromosomes and two homologous pairs.)

- **Anaphase I:** The spindle apparatus helps to move the chromosomes toward opposite ends of the cell; sister chromatids stay connected and move together toward the poles.
- **Telophase I** and **cytokinesis:** The homologous chromosomes move until they reach the opposite poles. Each pole, then, contains a haploid set of chromosomes, with each chromosome still consisting of two sister chromatids.
  - Cytokinesis is the division of the cytoplasm and occurs during telo phase. A **cleavage furrow** occurs in animal cells, and **cell plates** (th forming new cell wall) occur in plant cells. Both result in the formatio of two haploid cells.

- **Meiosis II:** The second cellular division in meiosis is referred to as meiosis II.
  - **Prophase II:** A spindle apparatus forms, and sister chromatids move toward the metaphase plate.
  - **Metaphase II:** The chromosomes are lined up on the metaphase plate, and the kinetochores of each sister chromatid prepare to move to the opposite poles.
  - **Anaphase II:** The centromeres of the sister chromatids separate, and individual chromosomes move to opposite ends of the cell.
  - **Telophase II** and **cytokinesis:** The chromatids have moved all the way to opposite ends of the cell, nuclei reappear, and cytokinesis occurs. Each of the four daughter cells has the haploid number of chromosomes and is genetically different from the other daughter cells and from the parent cell.

STUDY TIP Be prepared to cite the following three examples when asked t explain differences between mitosis and meiosis.

- Three events occur during meiosis I that do not occur during mitosis.
  1. Synapsis and crossing over normally do not occur during mitosis.
  2. At metaphase I, paired homologous chromosomes (tetrads) are posi tioned on the metaphase plate, rather than individual replicated chr mosomes, as in mitosis.
  3. At anaphase I, duplicated chromosomes of each homologous pair se arate but the sister chromatids of each duplicated chromosome stay attached. In mitosis, the chromatids separate.

TIP FROM THE READERS
When is chromosome number reduced? When does the cell go from diplo to haploid? Be sure you know and understand this! Refer again to Figure 4 and you should see that chromosome number is reduced during **meiosis** Each chromosome consists of two sister chromatids but the homologo pairs have separated.

Concept 13.4 Genetic variation produced in sexual life cycles contributes to evolution

STUDY TIP There are three important processes that contribute to variation. They are given below. Be able to list and explain them.

- **Crossing over:** During prophase I the exchange of genetic material on homologous chromosomes between nonsister chromatids occurs. Use Figure 4.3 to help make this unique feature of meiosis clear. Notice that all four chromatids that make up the tetrad are different due to crossing over. In metaphase II when sister chromatids separate, each chromatid is unique, thus increasing variation.
- **Independent assortment of chromosomes:** In metaphase I, when the homologous chromosomes are lined up on the metaphase plate, they can pair up in any combination, with any of the homologous pairs facing either pole. This means that there is a 50% chance that a particular daughter cell will get a maternal chromosome or a paternal chromosome from the homologous pair.
- **Random fertilization:** Because each egg and sperm is different, as a result of independent assortment and crossing over, each combination of egg and sperm is unique.

Chapter 14: Mendel and the Gene Idea

YOU MUST KNOW

- Terms associated with genetics problems: P, F_1, F_2, dominant, recessive, homozygous, heterozygous, phenotype, and genotype.
- How to derive the proper gametes when working a genetics problem.
- The difference between an allele and a gene.
- How to read a pedigree.
- How to use data sets to determine Mendelian patterns of inheritance.

Concept 14.1 Mendel used the scientific approach to identify two laws of inheritance

- True-breeding parents in a genetic cross are called the **P (parental) generation**; their offspring are called the **F_1 (first filial) generation**. If the F_1 population is crossed, their offspring are called the **F_2 (second filial) generation.**
- The following are four related concepts that make up Mendel's model explaining the 3:1 inheritance pattern that he observed among F_2 offspring.

    1. **Alternative versions of genes cause variations in inherited characteristics among offspring.** For example, consider flower color in peas.

The gene for flower color in pea plants comes in two versions: white and purple. These alternative versions of the gene, called **alleles**, are the result of slightly different DNA sequences.

2. **For each character, every organism inherits one allele from each parent.**
3. **If the two alleles are different, then the *dominant allele* will be fully expressed in the offspring, whereas the *recessive allele* will have no noticeable effect on the offspring.**
4. **The two alleles for each character separate during gamete production.** If the parent has two of the same alleles, then the offspring will all get that version of the gene, but if the parent has two different alleles for a gene, each offspring has a 50% chance of getting one of the two alleles. This is Mendel's **law of segregation.**

> *STUDY TIP* Use Figure 4.4 to find each of the four basic concepts of Mendel's model.

- **Law of independent assortment** was Mendel's second law. It states that eac pair of alleles will segregate (separate) independently during gamete formatio

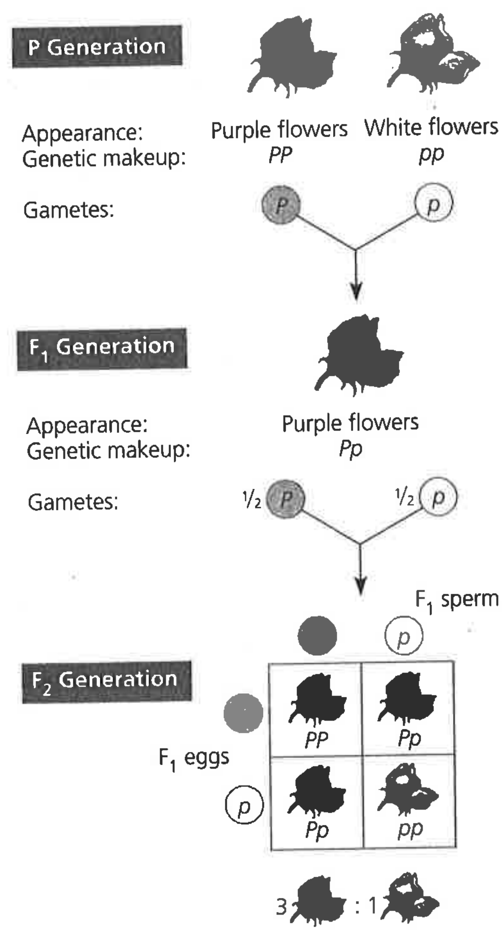
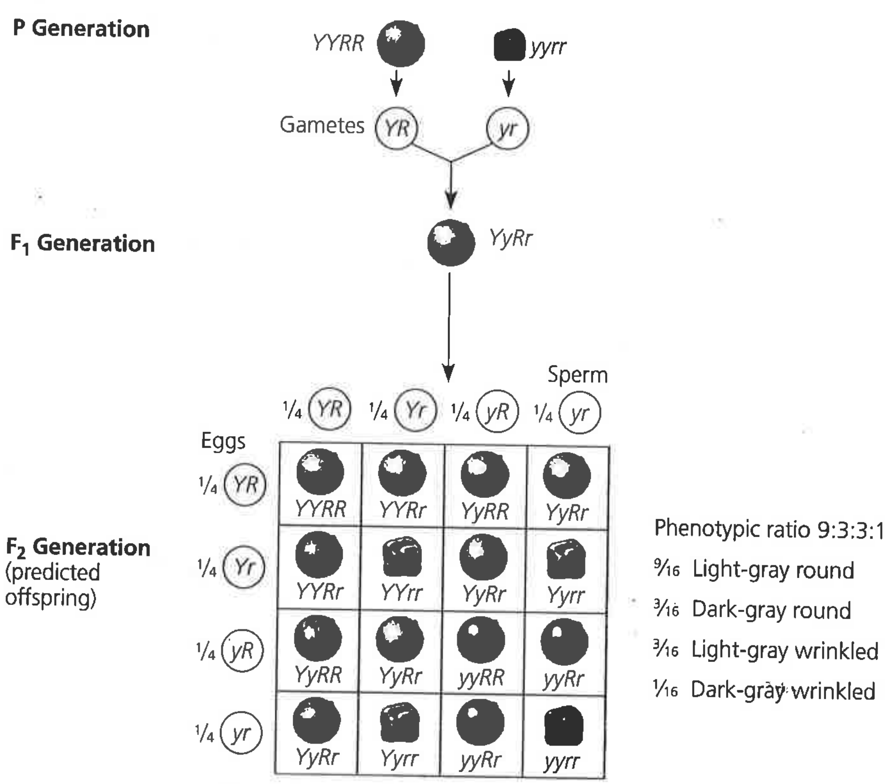


Figure 4.4 Mendel's law of segregation

- **Homozygous** organisms have two of the same alleles for a particular trait. If the dominant allele for a trait is designated as *R* (dominant traits are generally capitalized), and the recessive allele is designated *r* (recessive traits are generally not capitalized), then an individual could be homozygous for the dominant trait (*RR*) or homozygous for the recessive trait (*rr*).
- A **heterozygous** organism has two different alleles for a trait (*Rr*).
- **Phenotype** refers to an organism's expressed physical traits, and **genotype** refers to an organism's genetic makeup. For example, the phenotype of a seed might be round, and its genotype could be *RR* or *Rr*.
- A **testcross** is done to determine if an individual showing a dominant trait is homozygous or heterozygous. A homozygous dominant parent will yield all dominant phenotypes in the offspring ($RR \times rr$), whereas a heterozygous parent will give a ratio of one dominant trait to one recessive trait.
- A **monohybrid cross** is a cross involving the study of only one character (e.g., flower color), whereas a **dihybrid cross** is a cross intended to study two characters (e.g., flower color and seed shape).
- The diagram below shows the results of a dihybrid cross. In this case, in the parental generation two homozygous plants are crossed: one homozygous dominant for light gray and round seeds (*YYRR*) and one homozygous recessive for dark gray and wrinkled seeds (*ppyy*). The only gamete type the first parent can produce is *YR*, and the only gamete the second parent can produce is *yr*. The F_1 generation, therefore, is composed of individuals with genotype *YyRr*. Crossing *YyRr* with a second *YyRr* gives an F_2 generation that completes the cross and looks like Figure 4.5.



Mendel's Law of Independent Assortment

Figure 4.5 Mendel's law of independent assortment

> ***STUDY TIP*** When working genetics problems, be sure your have written the genotypes of the parents correctly and derived the gametes correctly. Study Figure 4.5, paying special attention to how the gametes were obtained for the F_2 generation.

Concept 14.2 The laws of probability govern Mendelian inheritance

- Understanding how to predict genetic crosses involves familiarity with the basic laws of probability. There are two laws that you will use directly in solving genetics problems:
  - **The rule of multiplication:** When calculating the probability that two or more independent events will occur together in a specific combination, multiply the probabilities of each of the two events. Thus, the probability of a coin landing face up two times in two flips is $^1/_2 \times {}^1/_2 = {}^1/_4$. If you cross two organisms with the genotypes *AABbCc* and *AaBbCc*, the probability of an offspring having the genotype *AaBbcc* is $^1/_2 \times {}^1/_2 \times {}^1/_4 = {}^1/_{16}$.
  - **The rule of addition:** When calculating the probability that any of two or more mutually exclusive events will occur, you need to add together their individual probabilities. For example, if you are tossing a die, what is the probability that it will land on either the side with 4 spots or the side with 5 spots? ($^1/_6 + {}^1/_6 = {}^1/_3$)

> ***STUDY TIP*** What are the chances of event 1 ***and*** event 2? Multiply them. What are the chances of event 1 ***or*** event 2? Add them.

Concept 14.3 Inheritance patterns are often more complex than predicted by simple Mendelian genetics

- **Complete dominance** is dominance in which the heterozygote and the homo zygote for the dominant allele are indistinguishable. A *Yy* yellow seed is just a yellow as a *YY* yellow seed.
- **Codominance** occurs when two alleles are dominant and affect the phenotyp in two different but equal ways. The traditional example for this type of domi nance is human blood types. Notice in the chart below that in type AB bloo both alleles are completely expressed and so are codominant.

Phenotype	Genotype	Antibody Expressed
A	I^AI^A or I^Ai	Anti-B
B	I^BI^B or I^Bi	Anti-A
AB	I^AI^B	None
O	*ii*	Anti-A, Anti-B

- **Incomplete dominance** is a type of dominance in which the F_1 hybrids have an appearance that is in between that of the two parents. For example, if two plants, one with white flowers and one with red flowers, were crossed and all of the offspring had pink flowers, you could conclude that the trait for flower color exhibits incomplete dominance. Breeding two of the hybrids with incomplete dominance gives a flower ratio of 1 red: 2 pink: 1 white.
- **Multiple alleles** occur when a gene has more than two alleles. Again, a good example of this is seen in human blood types. The chart shows the three alleles in human blood types: I^A, I^B, and i. Notice how the three alleles combine to form different blood types.
- **Pleiotropy** is the property of a gene that causes it to have multiple phenotypic effects. For example, sickle-cell disease has multiple symptoms all due to a single defective gene.
- In **epistasis**, a gene at one locus alters the effects of a gene at another locus. For example, an individual may have genes for heavy skin pigmentation, but if a separate gene that produces the pigment is defective, the genes for pigment deposition will not be expressed. This would lead to a condition known as albinism.
- In **polygenic inheritance**, two or more genes have an additive effect on a single character in the phenotype (such as height or skin color in humans). When several genes are involved, the phenotype usually is described by a bell-shaped curve, with fewer individuals at each extreme and most individuals clustered in the middle.

Concept 14.4 Many human traits follow Mendelian patterns of inheritance

- A **pedigree** is a diagram that shows the relationship between parents and offspring across two or more generations. (See Figure 4.6.) In a typical pedigree, circles represent females, and squares represent males. White open circles or squares indicate that the individual did not or does not express a particular trait, whereas the shaded ones indicate that the individual expresses or expressed that trait. Through the patterns they reveal, pedigrees can help determine the genome of individuals that comprise them; pedigrees can also help predict the genome of future offspring.

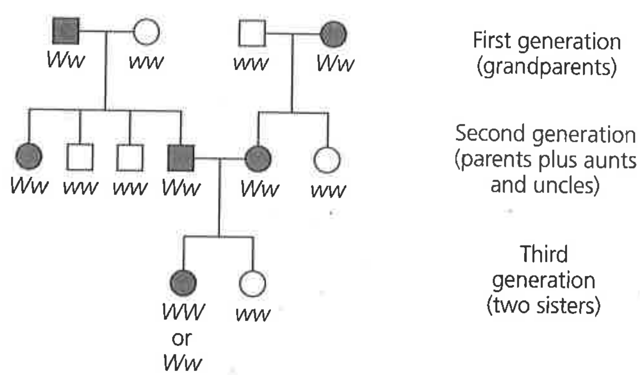


Figure 4.6 Human pedigree analysis

- **Recessively inherited disorders** require two copies of the defective gene for the disorder to be expressed. Examples include the following:
  - **Cystic fibrosis** is caused by a mutation in an allele that codes for a cell membrane protein that functions in the transport of chloride ions into and out of cells. The resulting high extracellular levels of chloride cause mucus to be thicker and stickier, leading to organ malfunction and recurrent bacterial infections.
  - **Tay-Sachs** disease is caused by an allele that codes for a dysfunctional enzyme, which is unable to break down certain lipids in the brain. As these lipids accumulate in the brain cells, the child suffers from blindness, seizures, and degeneration of brain function, leading to death.
  - **Sickle-cell disease** is caused by an allele that codes for a mutant hemoglobin molecule that forms long rods when the oxygen levels in the blood are low. These long rods cause the red blood cell to sickle, clogging small blood vessels and leading to pain, organ damage, and even paralysis.
- **Lethal dominant alleles** require only one copy of the allele in order for the disorder to be expressed. Usually, only late-acting lethal alleles are passed on.
- **Huntington's disease** is caused by a lethal dominant allele. It is a degenerative disease of the nervous system, which usually doesn't affect the individual until he or she is over 40 years old.
- Genetic testing may be used on a fetus to detect certain genetic disorders. Two common tests are amniocentesis and chorionic villus sampling (CVS).
  - **Amniocentesis** occurs when the physician removes amniotic fluid from around the fetus. The amniotic fluid can be utilized to detect some genetic disorders, and the cells in the fluid can be cultured for a karyotype.
  - **Chorionic villus sampling** involves using a narrow tube inserted through the cervix to suction out a tiny sample of the placenta that contains only fetal cells. A karyotype can immediately be developed from these cells.

Chapter 15: The Chromosomal Basis of Inheritance

YOU MUST KNOW

- How the chromosome theory of inheritance connects the physical movement of chromosomes in meiosis to Mendel's laws of inheritance.
- The unique pattern of inheritance in sex-linked genes.
- How alteration of chromosome number or structurally altered chromosomes (deletions, duplications, etc.) can cause genetic disorders.
- How genomic imprinting and inheritance of mitochondrial DNA are exceptions to standard Mendelian inheritance.

Concept 15.1 Mendelian inheritance has its physical basis in the behavior of chromosomes

- The **chromosome theory of inheritance** states that genes have specific locations (called *loci*) on chromosomes and that it is chromosomes that segregate and assort independently. It is important to connect this physical movement of chromosomes in meiosis to Mendel's laws of inheritance.
    - A **sex-linked gene** is one located on a sex chromosome (X or Y in humans). After the chromosome theory of inheritance was formed, *Thomas Hunt Morgan* discovered the existence of sex-linked genes.

Concept 15.2 Sex-linked genes exhibit unique patterns of inheritance

- In humans, there are two types of sex chromosomes, X and Y. Normal females have two X chromosomes, whereas normal males have one X and one Y chromosome.
- Sex-linked genes may be either X-linked or Y-linked. Figure 4.7 shows the unique pattern of inheritance in X-linked genes. In addition to tracking the gene from one generation to the next, it is also necessary to track the sex of the offspring. Figure 4.7 is based on work with *Drosophila* (fruit flies) performed by Thomas Hunt Morgan, but the pattern is the same in humans.

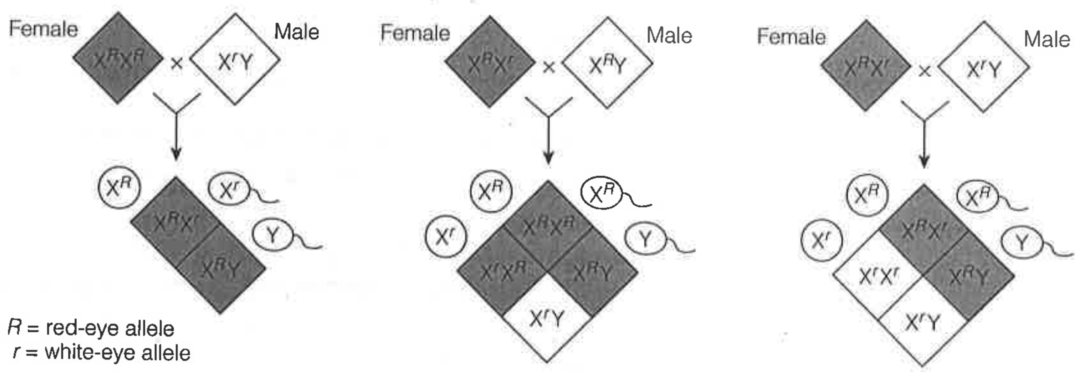


Figure 4.7 Patterns of inheritance with sex-linked traits

- Each egg or ovum contains an X chromosome; there are two types of sperm: those with an X chromosome and those with a Y chromosome. In fertilization, there is a 50% chance that a sperm carrying an X or Y will reach and penetrate the egg first. Thus, gender is determined by chance and by the male sperm cell in humans.
- Fathers pass X-linked genes on to their daughters but not to their sons; fathers pass the Y chromosome to their sons.
- Females will express an X-linked trait exactly like any other trait, but males, with only one X chromosome, will express the allele on the X chromosome they inherited from their mother. The terms *homozygous* and *heterozygous* do not apply to a male pattern of sex-linked genes.
- The vast majority of genes on the X chromosome are not related to sex.

- Several X-linked disorders have medical significance:
  - **Duchenne muscular dystrophy** is an X-linked disorder characterized by a progressive weakening of the muscles and loss of coordination. Affected individuals rarely live past their early 20s.
  - **Hemophilia** is an X-linked disorder characterized by having blood with an inability to clot normally, caused by the absence of proteins required for blood clotting.
- **X-inactivation** regulates gene dosage in females. Although female mammals inherit two X chromosomes, one of the X chromosomes (randomly chosen) in each cell of the body becomes inactivated during embryonic development by **methylation**. As a result, males and females have the same effective dose of genes with loci on the X chromosome.
- The inactive chromosome condenses into a **Barr body**, which lies along the inside of the nuclear envelope. Still, females are not affected as heterozygote carriers of problematic alleles, because half of their sex chromosomes are normal and produce the necessary proteins.

Concept 15.3 Linked genes tend to be inherited together because they are located near each other on the same chromosome

- **Linked genes** are located on the same chromosome and therefore tend to be inherited together during cell division.
- **Genetic recombination** is the production of offspring with a new combination of genes inherited from the parents. Many genetic crosses yield some offspring with the same phenotype as one of the parents (these offspring are referred to as **parental types**) and some offspring with phenotypes different from either parent (these offspring are referred to as **recombinants**).
- **Crossing over** can explain why some linked genes get separated during meiosis. During meiosis, unlinked genes follow independent assortment because they are located on different chromosomes. Linked genes are located on the same chromosome and would not be predicted to follow independent assortment. However, sometimes genetic crosses give results that seem to indicate some independent assortment has occurred, even when genes are on the same chromosome. These results are not due to independent assortment but can be explained by crossing over. Research further indicates that the farther apart two genes are on a chromosome, the higher the probability that crossing over will occur between them. The likelihood of crossing over between different genes on the same chromosome is expressed as a percent.
- A **linkage map** is a genetic map that is based on the percentage of crossover events.
- A **map unit** is equal to a 1% recombination frequency. Map units are used to express relative distances along the chromosome.

Concept 15.4 Alterations of chromosome number or structure cause some genetic disorders

- **Nondisjunction** occurs when the members of a pair of homologous chromosomes do not separate properly during meiosis I, or sister chromatids don't separate properly during meiosis II.
- As a result of nondisjunction, one gamete receives two copies of the chromosome, while the other gamete receives none. In the next step, if the faulty gametes engage in fertilization, the offspring will have an incorrect chromosome number. This is known as **aneuploidy**.
- Fertilized eggs that have received three copies of the chromosome in question are said to be **trisomic**; those that have received just one copy of a chromosome are said to be **monosomic** for the chromosome.
- **Polyploidy** is the condition of having more than two complete sets of chromosomes, forming a $3n$ or $4n$ individual. Rare in animals, this condition is fairly frequent in plants.
- Portions of a chromosome may also be lost or rearranged, resulting in the following mutations:
    - A **deletion** occurs when a chromosomal fragment is lost, resulting in a chromosome with missing genes.
    - A **duplication** occurs when a chromosomal segment is repeated.
    - An **inversion** occurs when a chromosomal fragment breaks off and reattaches to its original position—but backward, so that the part of the fragment that was originally at the attachment point is now at the end of the chromosome.
    - A **translocation** occurs when the deleted chromosome fragment joins a *nonhomologous* chromosome.
- Human disorders caused by chromosomal alterations include the following:
    - **Down syndrome:** An aneuploid condition that is the result of having an extra chromosome 21 (trisomy 21). Down syndrome includes characteristic facial features, short stature, heart defects, and developmental delays.
    - **Klinefelter syndrome:** An aneuploid condition in which a male possesses the sex chromosomes XXY (an extra X). Klinefelter males have male sex organs but are sterile.
    - **Turner syndrome:** A monosomic condition in which the female has just one sex chromosome, an X. Turner syndrome females are sterile because the reproductive organs do not mature. Turner syndrome is the only known viable monosomy in humans.

Concept 15.5 Some inheritance patterns are exceptions to standard Mendelian inheritance

- In mammals, the phenotypic effect of a gene may depend on which allele is inherited from each parent, a phenomenon called **genomic imprinting**.
- Genes that are present in mitochondria and plastids are inherited only from the mother because the zygote's cytoplasm comes from the egg.

Level 1: Knowledge/Comprehension Questions

1. A couple has six children, all daughters. If the woman has a seventh child, what is the probability that the seventh child will be a daughter?
   (A) $^6/_7$
   (B) $^1/_7$
   (C) $^1/_{36}$
   (D) $^1/_{49}$
   (E) $^1/_2$

2. If alleles *R* and *S* are on two different chromosomes, and the probability of gamete *R* segregating into a gamete is $^1/_4$, while the probability of allele *S* segregating into a gamete is $^1/_2$, what is the probability that both will segregate into the same gamete?
   (A) $^1/_4 \times ^1/_2$
   (B) $^1/_4 \div ^1/_2$
   (C) $^1/_4 + ^1/_2$
   (D) $^1/_4 + ^1/_4$
   (E) $^1/_2$

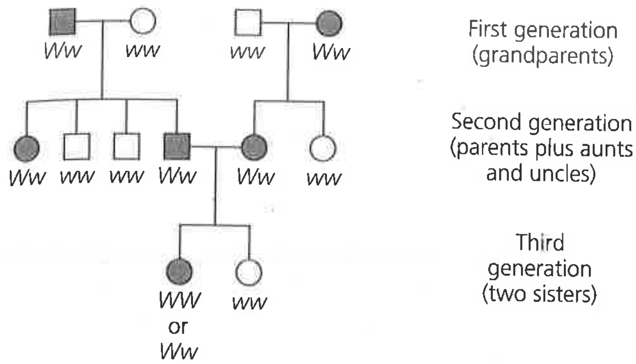
3. In llamas, coat color is controlled by a gene that exists in two allelic forms. If a homozygous yellow llama is crossed with a homozygous brown llama, the offspring have gray coats. If two of the gray-coated offspring were crossed, what percentage of their offspring would have brown coats?
   (A) 100%
   (B) 75%
   (C) 50%
   (D) 25%
   (E) 0%

4. Which of the following is NOT true of meiosis?
   (A) During metaphase, spindle microtubules first come into contact with chromosomes.
   (B) The chromosome number in the newly formed cells is half that of the parent cell.
   (C) The homologous chromosomes line up along the metaphase plate, or equator of the cell.
   (D) The cytoplasm of the cell and all its organelles are divided approximately in half.
   (E) In anaphase II, the sister chromatids travel to opposite ends of the cell.

5. In rabbits, the trait for short hair (*S*) is dominant, and the trait for long hair (*s*) is recessive. The trait for green eyes (*G*) is dominant, and the trait for blue eyes (*g*) is recessive. A cross between two rabbits produces a litter of six short-haired rabbits with green eyes, and two short-haired rabbits with blue eyes. What is the most likely genotype of the parent rabbits in this cross?
   (A) *ssgg* × *ssgg*
   (B) *SSGG* × *SSGG*
   (C) *SsGg* × *SsGg*
   (D) *SsGg* × *SSGg*
   (E) *ssGG* × *ssGG*

6. In humans, hemophilia is an X-linked recessive trait. If a man and a woman have a son who is affected with hemophilia, which of the following is definitely *true*?
   (A) The mother carries an allele for hemophilia.
   (B) The father carries an allele for hemophilia.
   (C) The father is afflicted with hemophilia.
   (D) Both parents carry an allele for hemophilia.
   (E) The boy's paternal grandfather has hemophilia.

7. Which of the following explains a significantly low rate of crossing over between two genes?
   (A) They are located far apart on the same chromosome.
   (B) They are located on separate but homologous chromosomes.
   (C) The genes code for proteins that have similar functions.
   (D) The genes code for proteins that have very different functions.
   (E) The genes are located very close together on the same chromosome.



8. In the pedigree above, circles represent females and squares represent males; those who express a particular trait are shaded, whereas those who do not are not shaded. Which pattern of inheritance best describes the pedigree for this trait?
(A) X-linked recessive
(B) X-linked dominant
(C) autosomal recessive
(D) autosomal dominant
(E) codominant

Questions 9–10 refer to an individual with type O blood, whose mother has type A blood.

9. The father must have which of the following blood types?
(A) A, B, or O
(B) AB or A
(C) AB or B
(D) AB only
(E) O only

10. If the type O individual were to mate with a person with type AB blood, which of the following is the best calculation of the ratio of the offspring?
(A) 3 I^Ai:1 I^Bi
(B) 2 I^Ai:1 I^Bi
(C) I^Ai:I^Bi
(D) 1 I^Ai:2 I^AI^B:1 I^Bi
(E) 9 I^AI^B:3 I^Ai:3 I^Bi:1 O

11. Two yellow mice with the genotype *Yy* are mated. After many offspring, $^2/_3$ are yellow and $^1/_3$ are not yellow (a 2:1 ratio). Mendelian genetics dictates that this cross should produce offspring that were $^1/_4$ *YY* (yellow), $^1/_2$ *Yy* (yellow), and $^1/_4$ *yy* (not yellow). What is the most likely conclusion from this experiment?
(A) The mice did not bear enough offspring for the ratio calculation to be specific.
(B) *Y* is lethal in the homozygous form and caused death early in development.
(C) Nondisjunction occurred.
(D) A mutation masked the effects of the *Y* allele.
(E) A mutation masked the effects of the *y* allele.

12. All of the following contribute to genetic recombination EXCEPT
(A) random fertilization.
(B) independent assortment.
(C) crossing over.
(D) gene linkage.
(E) random gene mutation.

13. In cucumbers, warty (*W*) is dominant over dull (*w*), and green (*G*) is dominant over orange (*g*). A cucumber plant that is homozygous for warty and green is crossed with one that is homozygous for dull and orange. The F_1 generation is then crossed. If a total of 144 offspring is produced in the F_2 generation, which of the following is the closest to the number of dull green cucumbers expected?
(A) 3
(B) 10
(C) 28
(D) 80
(E) 111

14. The restoration of the diploid chromosome number after halving in meiosis is due to
(A) synapsis.
(B) fertilization.
(C) mitosis.
(D) DNA replication.
(E) chiasmata.