LECTURE PRESENTATIONS
For CAMPBELL BIOLOGY, NINTH EDITION
Jane B. Reece, Lisa A. Urry, Michael L. Cain, Steven A. Wasserman, Peter V. Minorsky, Robert B. Jackson

Chapter 1

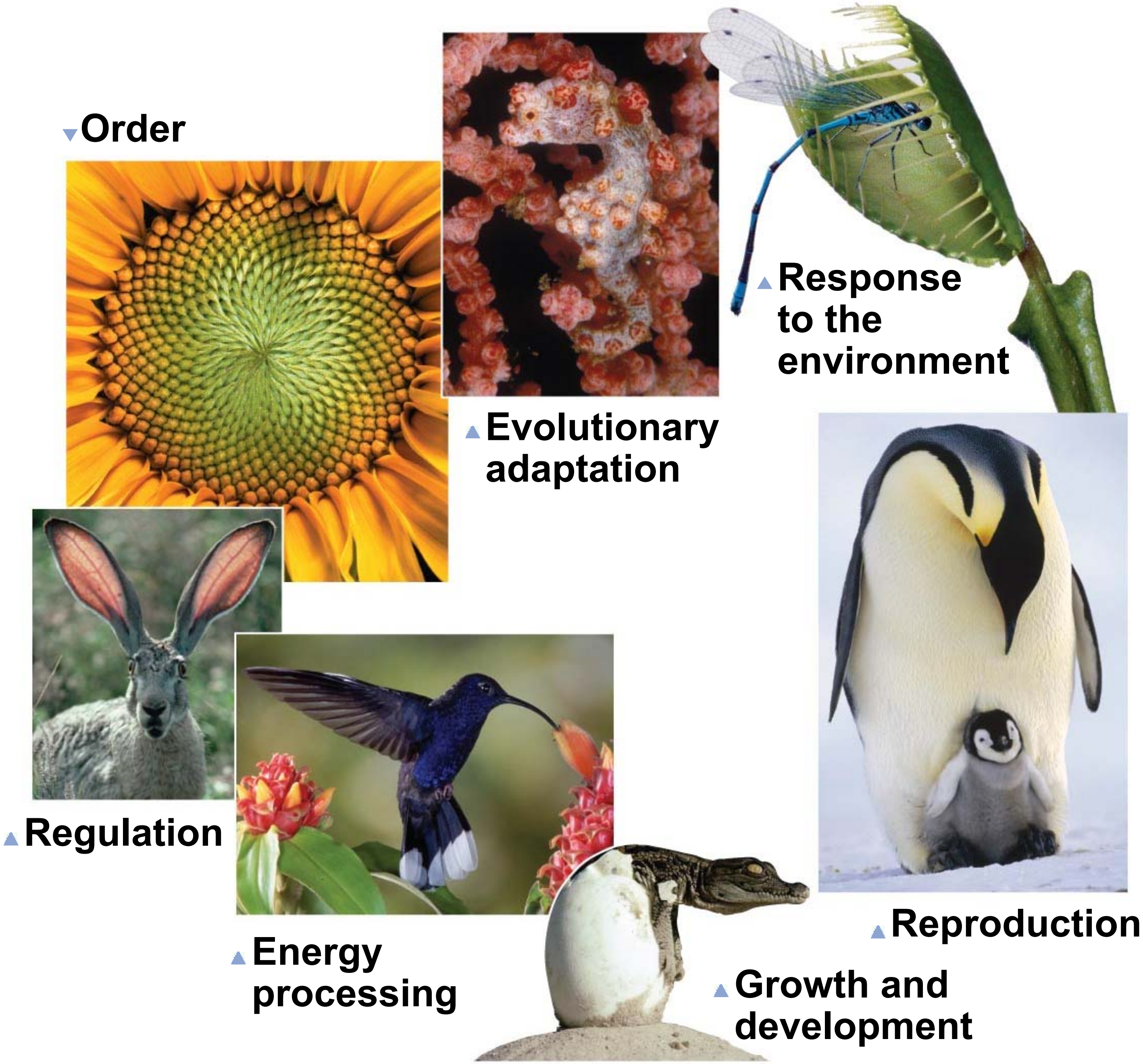
Introduction: Themes in the Study of Life

Lectures by
Erin Barley
Kathleen Fitzpatrick

Overview: Inquiring About Life

- An organism's **adaptations** to its environment are the result of evolution
  - For example, the **ghost plant** is adapted to conserving water; this helps it to survive in the crevices of rock walls
- **Evolution** *is the process of change that has transformed life on Earth*

- **Biology** *is the scientific study of life*
- Biologists ask questions such as
  - How does a single cell develop into an organism?
  - How does the human mind work?
  - How do living things interact in communities?
- *Life defies a simple, one-sentence definition*
- Life is recognized by what living things do


Order
Evolutionary adaptation
Response to the environment
Regulation
Energy processing
Growth and development
Reproduction

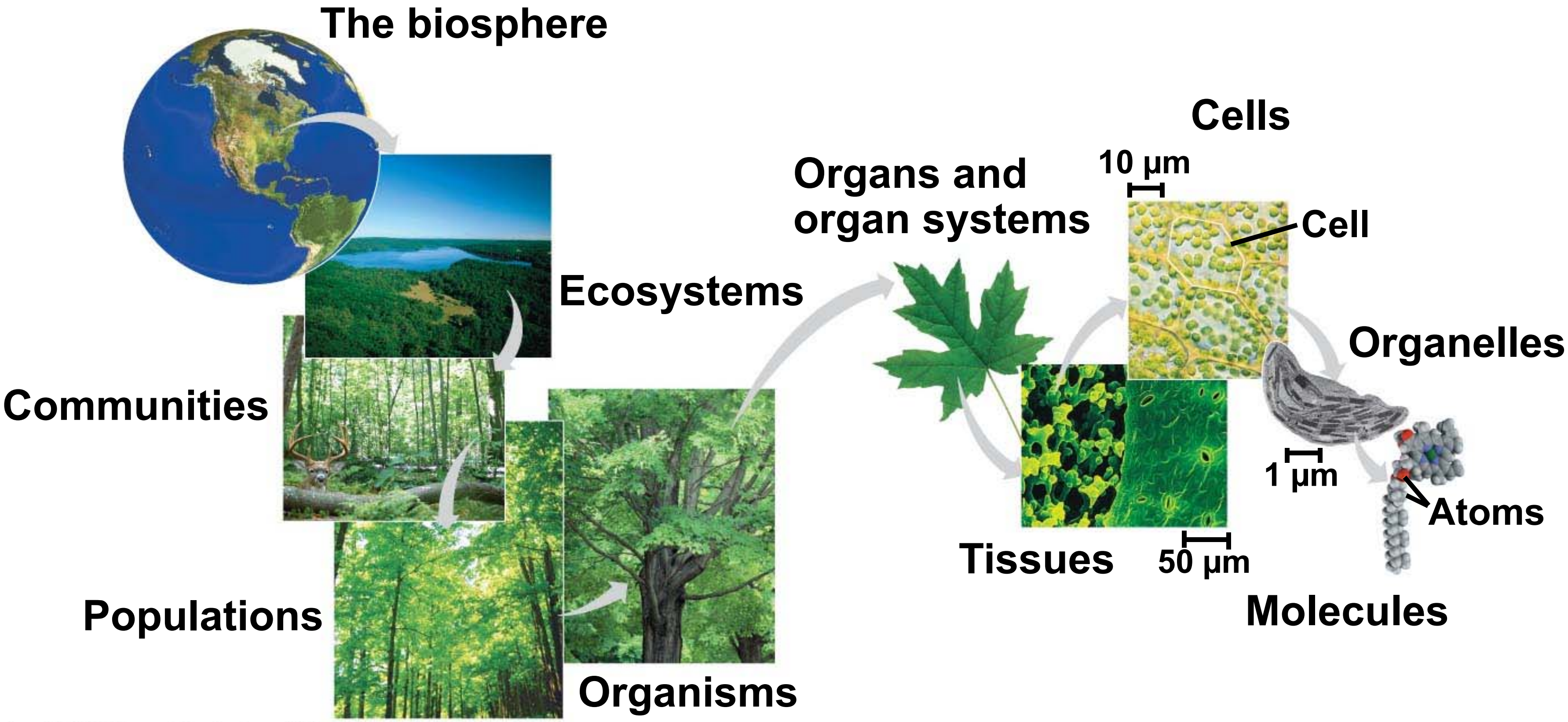
Concept 1.1: The themes of this book make connections across different areas of biology

- Biology consists of more than memorizing factual details
- Themes help to organize biological information

Theme: New Properties Emerge at Each Level in the Biological Hierarchy

- Life can be studied at different levels, from molecules to the entire living planet
- The study of life can be divided into different levels of biological organization

Fig. 1-4



The biosphere
Ecosystems
Communities
Populations
Organisms
Organs and organ systems
Cells
10 µm
Cell
Organelles
1 µm
Atoms
Tissues
50 µm
Molecules

Emergent Properties

- **Emergent properties** result from the arrangement and interaction of parts within a system
- Emergent properties characterize nonbiological entities as well
  - For example, a functioning bicycle emerges only when all of the necessary parts connect in the correct way

The Power and Limitations of Reductionism

- **Reductionism** is the reduction of complex systems to simpler components that are more manageable to study
  - For example, studying the molecular structure of DNA helps us to understand the chemical basis of inheritance

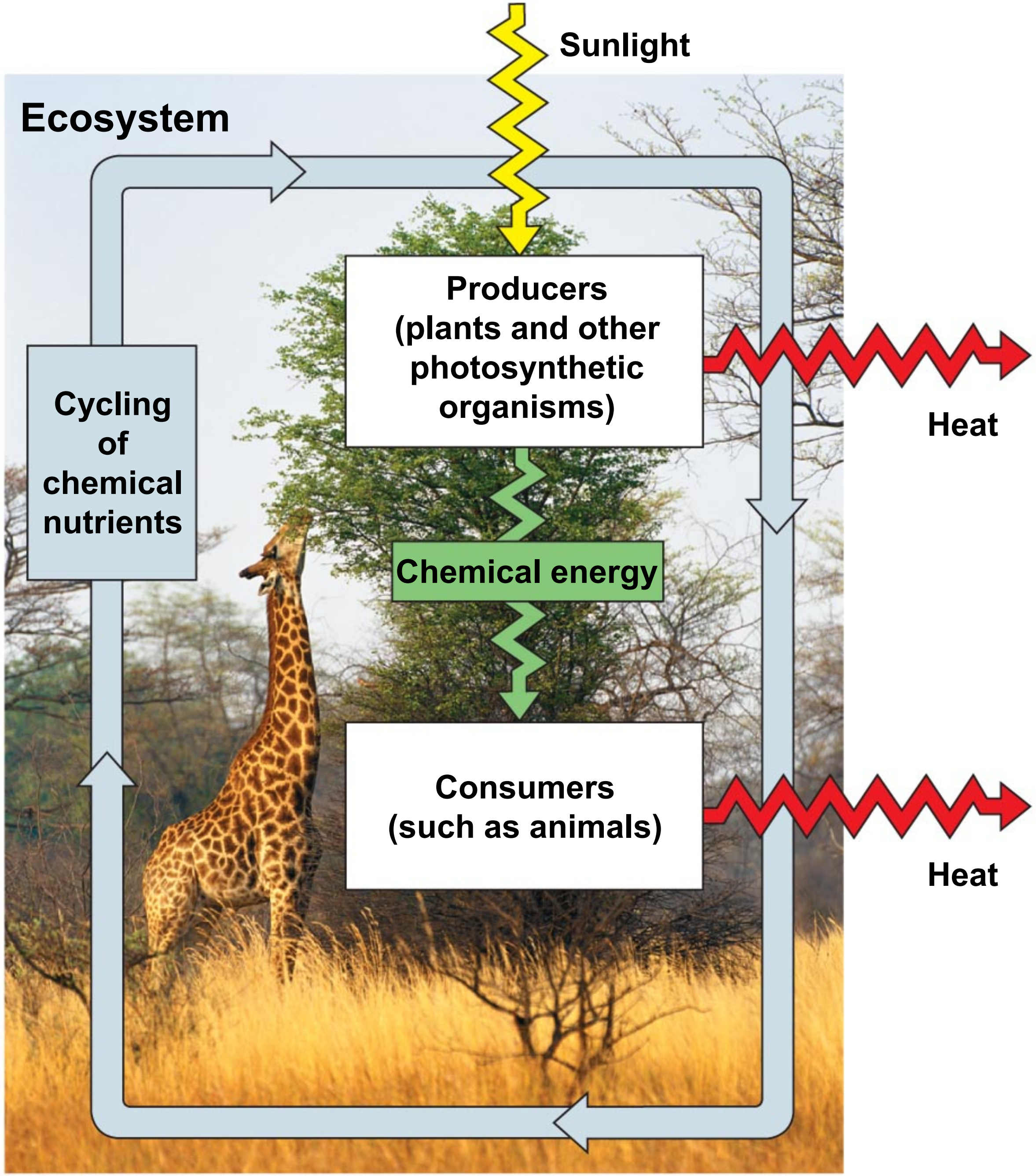
Systems Biology

- **A system** *is a combination of components that function together*
- **Systems biology** constructs models for the dynamic behavior of whole biological systems
- The systems approach **poses questions** such as
  - How does a drug for blood pressure affect other organs?
  - How does increasing CO_2 alter the biosphere?

Theme: Organisms Interact with Other Organisms and the Physical Environment

- Every organism **interacts with its environment**, including **nonliving factors** and other **organisms**
- Both organisms and their environments are **affected by the interactions** between them
  - For example, a **tree** takes up water and minerals from the soil and carbon dioxide from the air; the tree releases oxygen to the air and roots help form soil

Fig. 1-5


Sunlight
Ecosystem
Producers
(plants and other
photosynthetic
organisms)
Heat
Cycling
of
chemical
nutrients
Chemical energy
Consumers
(such as animals)
Heat

- **Humans have modified our environment**
  - For example, half the human-generated CO_2 stays in the atmosphere and contributes to **global warming**
- Global warming is a major aspect of **global climate change**
- It is important to understand the effects of global climate change on the Earth and its populations

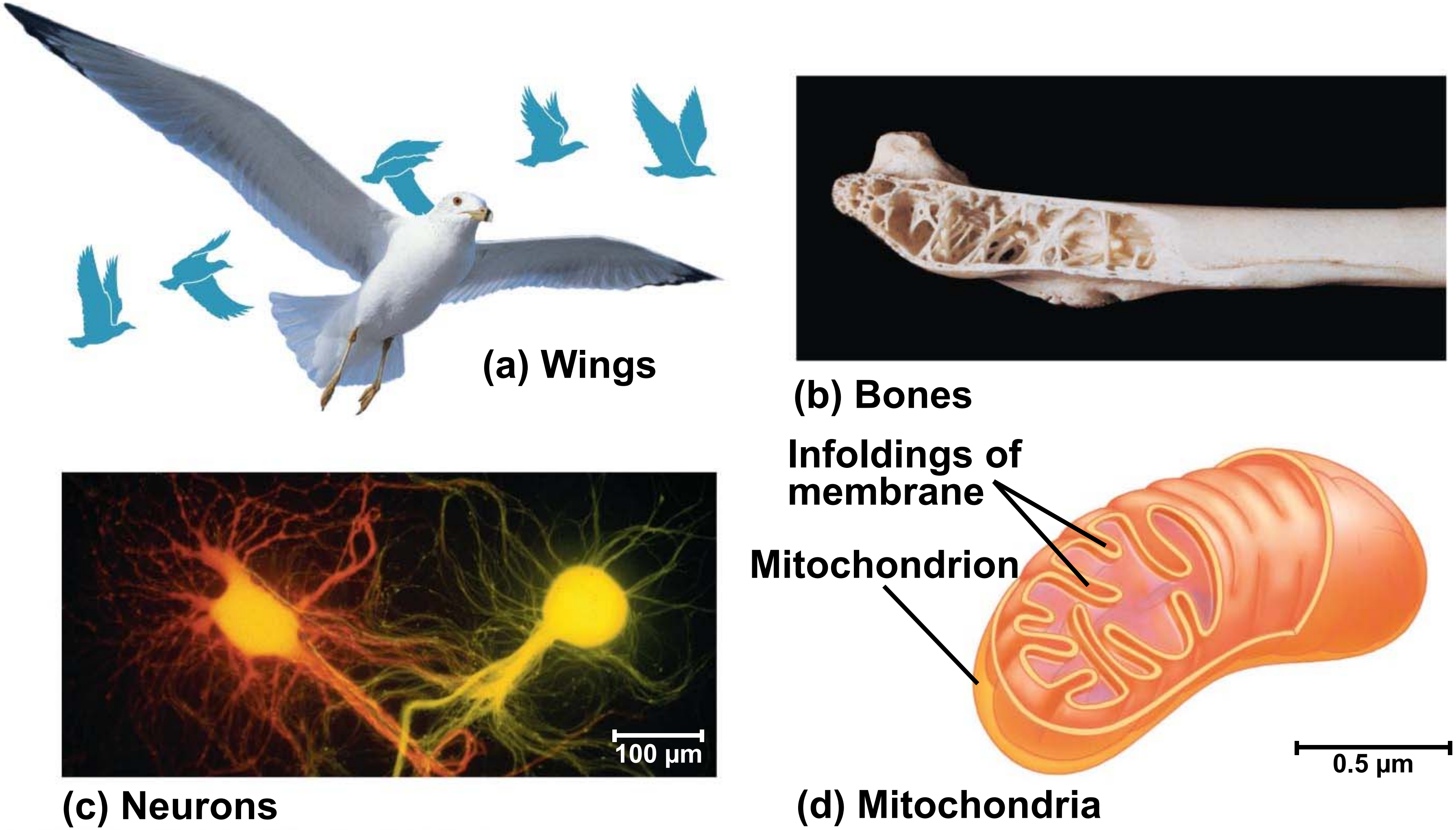
Theme: Life Requires Energy Transfer and Transformation

- A fundamental characteristic of living organisms is their use of energy to carry out life's activities
- **Work**, including moving, growing, and reproducing, requires a **source of energy**
- Living organisms transform energy from one form to another
  - For example, **light energy** is converted to **chemical energy**, then **kinetic energy**
- Energy flows through an ecosystem, usually **entering as light** and **exiting as heat**

Theme: Structure and Function are Correlated at All Levels of Biological Organization

- Structure and function of living organisms are closely related
  - For example, a **leaf is thin and flat**, *maximizing the capture of light by chloroplasts*
  - For example, **the structure of a bird's wing** is adapted to flight

Fig. 1-6

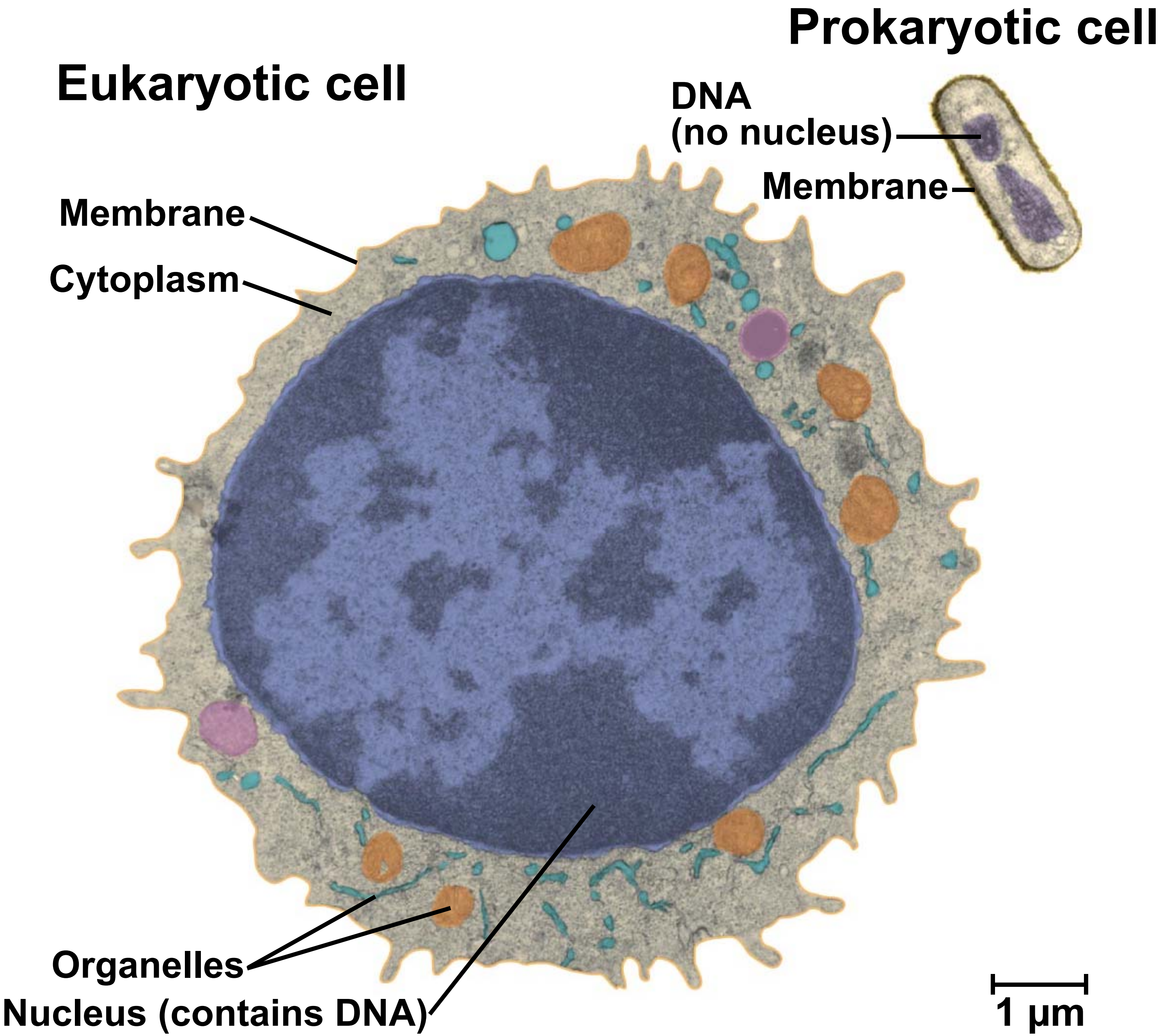

(a) Wings
(b) Bones
Infoldings of membrane
Mitochondrion
100 µm
0.5 µm
(c) Neurons
(d) Mitochondria

Theme: The Cell Is an Organism's *Basic Unit of Structure and Function*

- *The cell is the lowest level of organization that can perform all activities required for life*
- **All cells:**
  - *Are enclosed by a membrane*
  - *Use DNA as their genetic information*

- A **eukaryotic cell** *has membrane-enclosed organelles, the largest of which is usually the nucleus*
- By comparison, a **prokaryotic cell** is simpler and usually smaller, and does not contain a nucleus or other membrane-enclosed organelles

Fig. 1-8

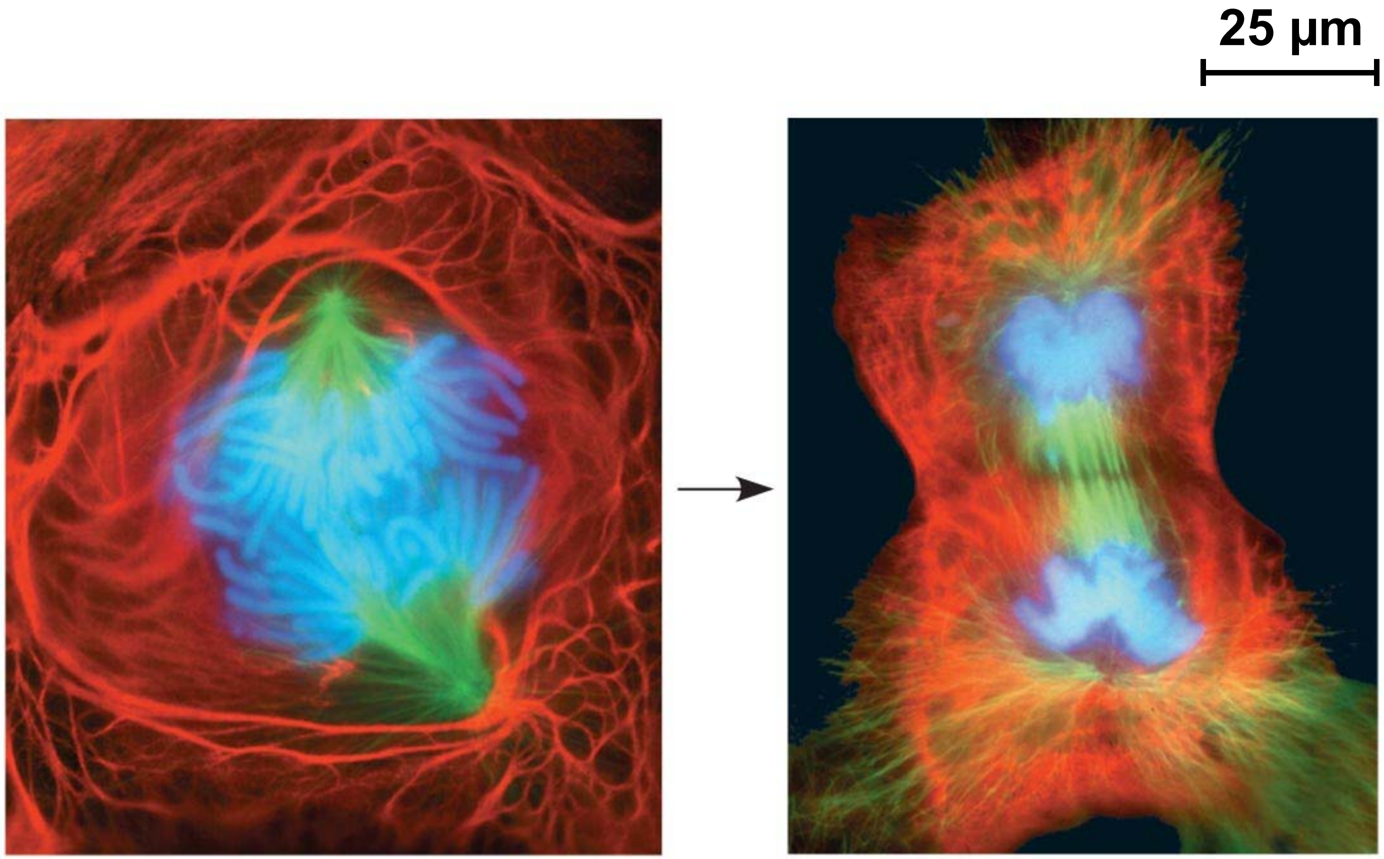


Eukaryotic cell
Prokaryotic cell
DNA
(no nucleus)
Membrane
Membrane
Cytoplasm
Organelles
Nucleus (contains DNA)
1 µm

Theme: The Continuity of Life Is Based on Heritable Information in the Form of DNA

- Chromosomes contain most of a cell's genetic material in the form of **DNA** (deoxyribonucleic acid)
- DNA is the substance of genes
- **Genes** are the units of inheritance that transmit information from parents to offspring
- The **ability of cells to divide** is the **basis of all reproduction, growth, and repair** of multicellular organisms.

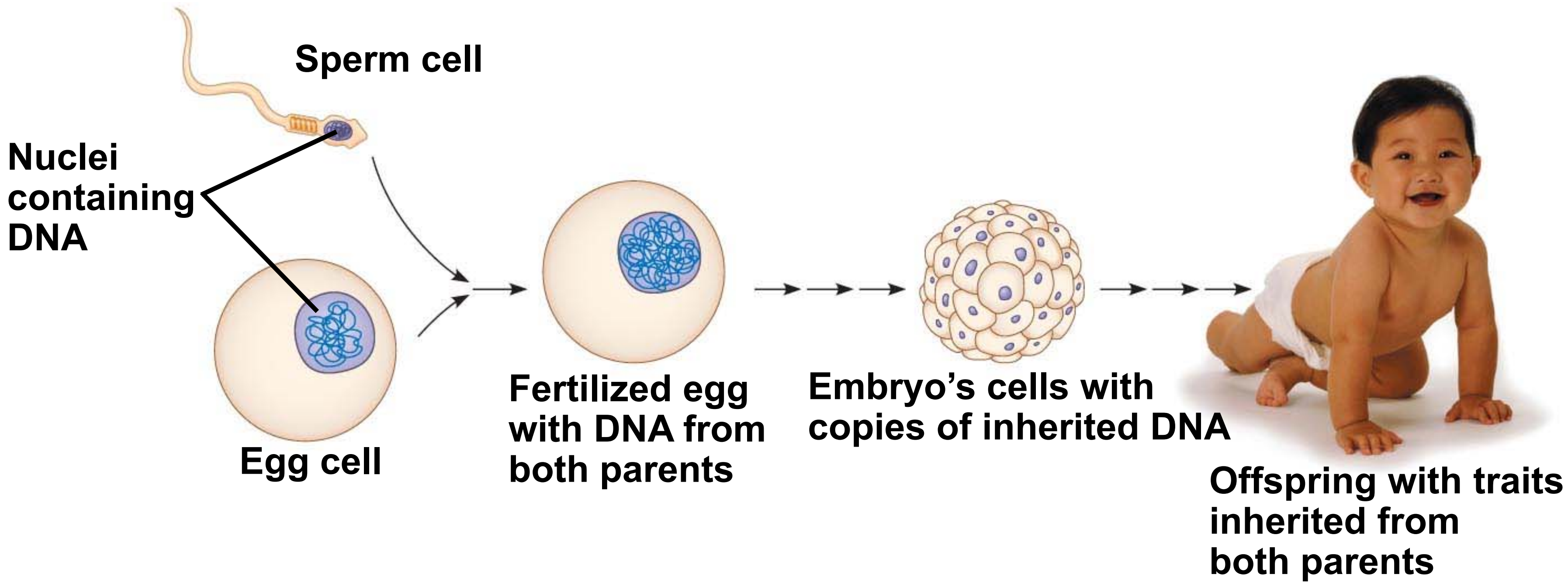
Fig. 1-7



DNA Structure and Function

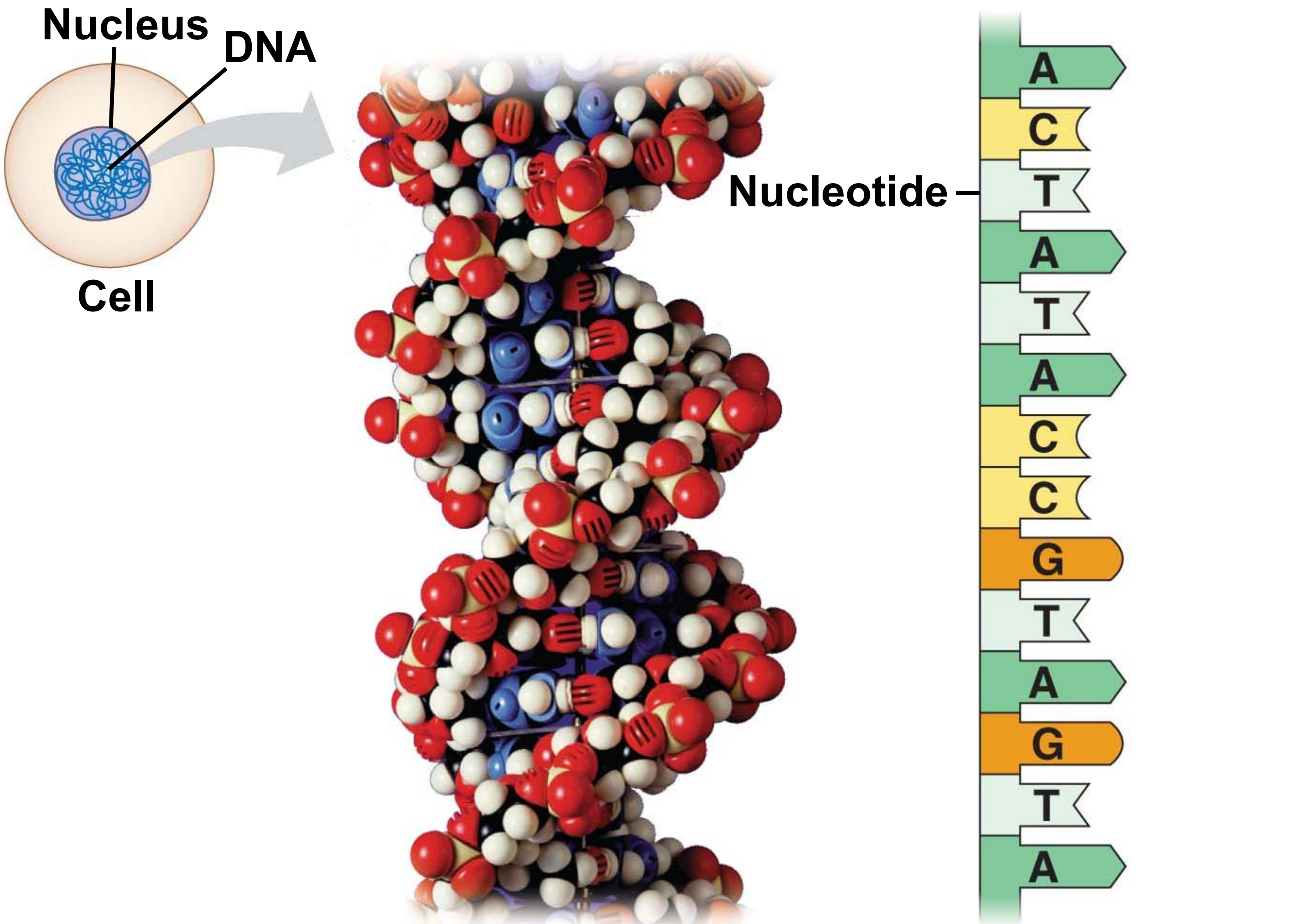
- Each **chromosome** has one long DNA molecule with hundreds or thousands of genes
- Genes encode information for building proteins
- DNA is inherited by offspring from their parents
- DNA controls the development and maintenance of organisms

Fig. 1-9


Sperm cell
Nuclei containing DNA
Egg cell
Fertilized egg with DNA from both parents
Embryo's cells with copies of inherited DNA
Offspring with traits inherited from both parents

- Each **DNA molecule** is made up of **two long chains arranged in a double helix**
- **Each link** of a chain is one of **four kinds** of chemical building blocks called **nucleotides** and nicknamed **A, G, C, and T**

Fig. 1-10



(a) DNA double helix (b) Single strand of DNA

- **Genes control protein** production indirectly
- **DNA is transcribed** into **RNA** then **translated into a protein**
- Gene expression *is the process of converting information from gene to cellular product*

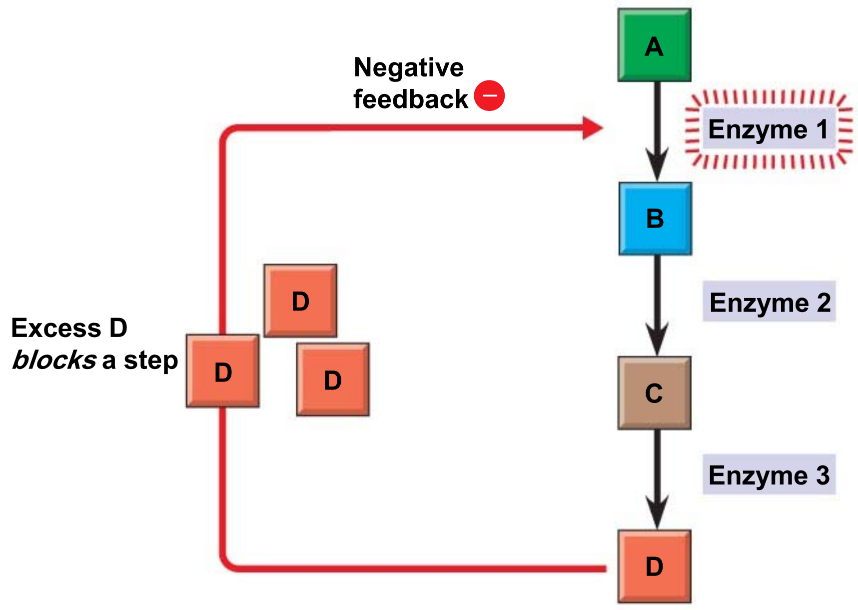
Genomics: *Large-Scale Analysis of DNA Sequences*

- An organism's **genome** is *its entire set of genetic instructions*
- The human genome and those of many other organisms have been sequenced using **DNA-sequencing machines**
- **Genomics** *is the study of sets of genes within and between species*
- **Bioinformatics**, *which is the use of computational tools to process a large volume of data*

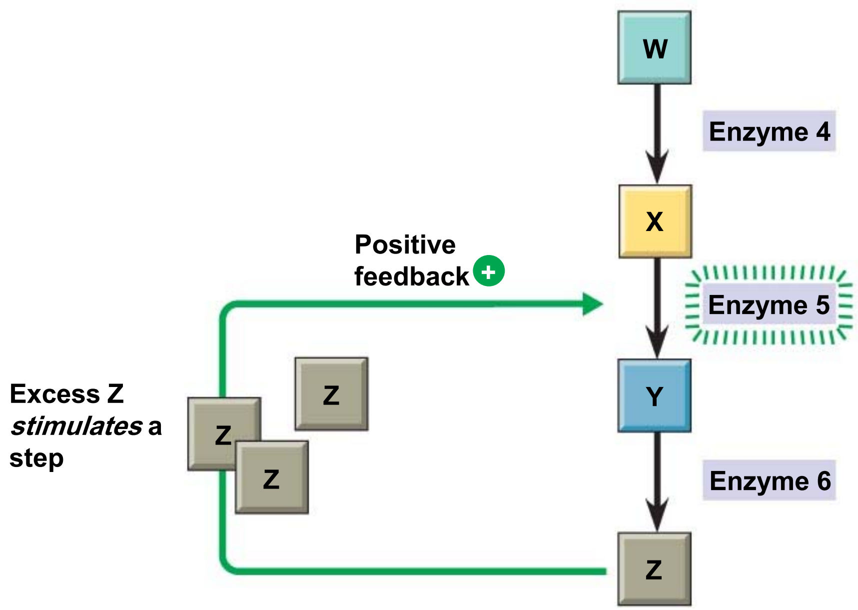
Theme: Feedback Mechanisms Regulate Biological Systems

- **Feedback mechanisms** allow biological processes to **self-regulate**
- **Negative feedback** means that as more of a product accumulates, the process that creates it slows and less of the product is produced
- **Positive feedback** means that as more of a product accumulates, the process that creates it speeds up and more of the product is produced

Fig. 1-13



(a) Negative feedback



(b) Positive feedback

Evolution, the Overarching Theme of Biology

- Evolution makes sense of everything we know about biology
- **Organisms are modified descendants of common ancestors**

- **Evolution** explains patterns of **unity** and **diversity** in living organisms
- *Similar traits* among organisms are explained by *descent from common ancestors*
- **Differences** among organisms are explained by the **accumulation of heritable changes**

Concept 1.2: The Core Theme: Evolution accounts for the unity and diversity of life

- "**Nothing in biology makes sense except in the light of evolution**"
- **Evolution unifies biology** at different scales of size throughout the history of life on Earth

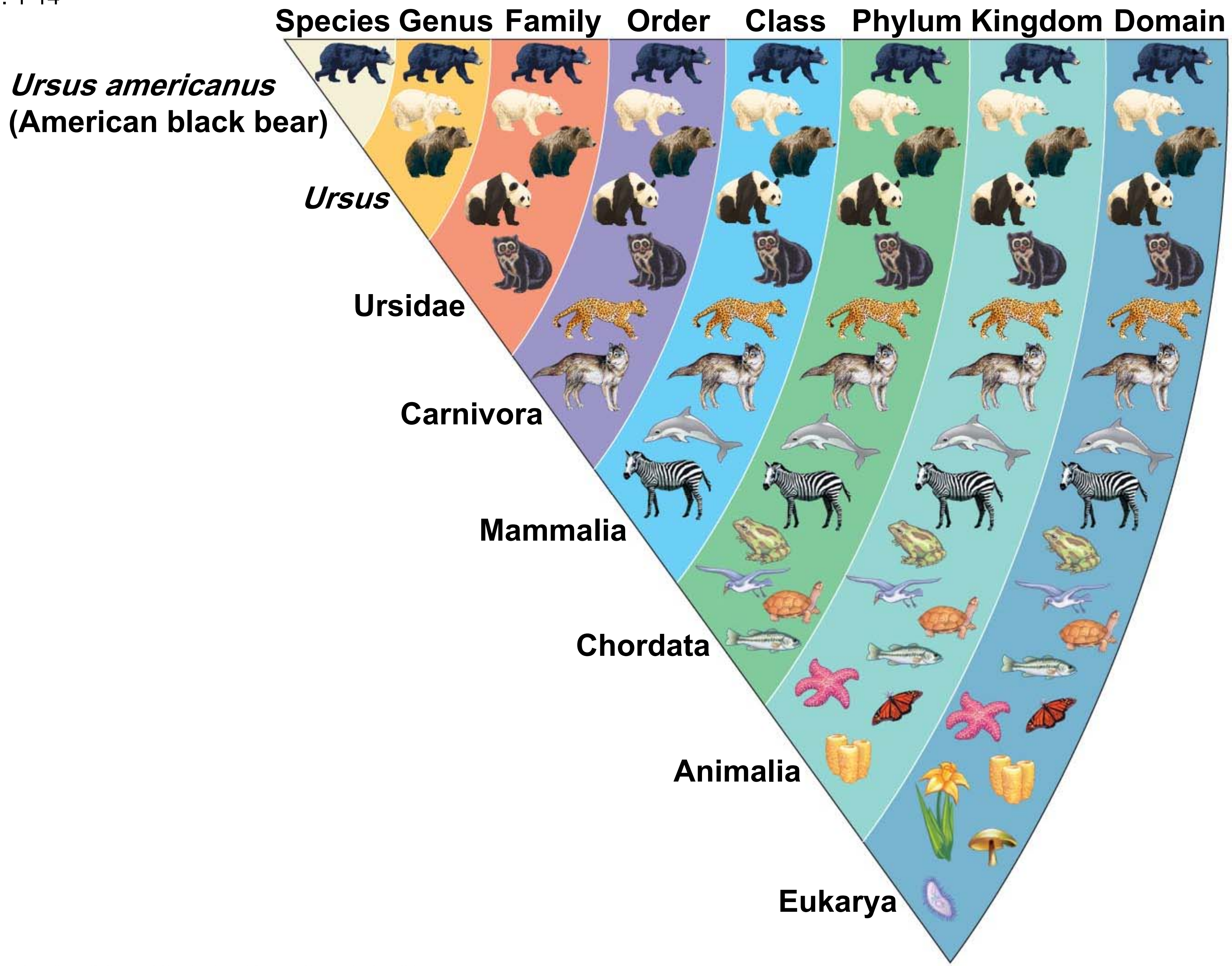
Classifying the Diversity of Life

- **Approximately 1.8 million species** have been identified and named to date, and thousands more are identified each year
- Estimates of the total number of species that actually exist range from **10 million to over 100 million**

Grouping Species: The Basic Idea

- **Taxonomy** *is the branch of biology that names and classifies species into groups of increasing breadth*
- **Domains**, followed by **kingdoms**, are the broadest units of classification

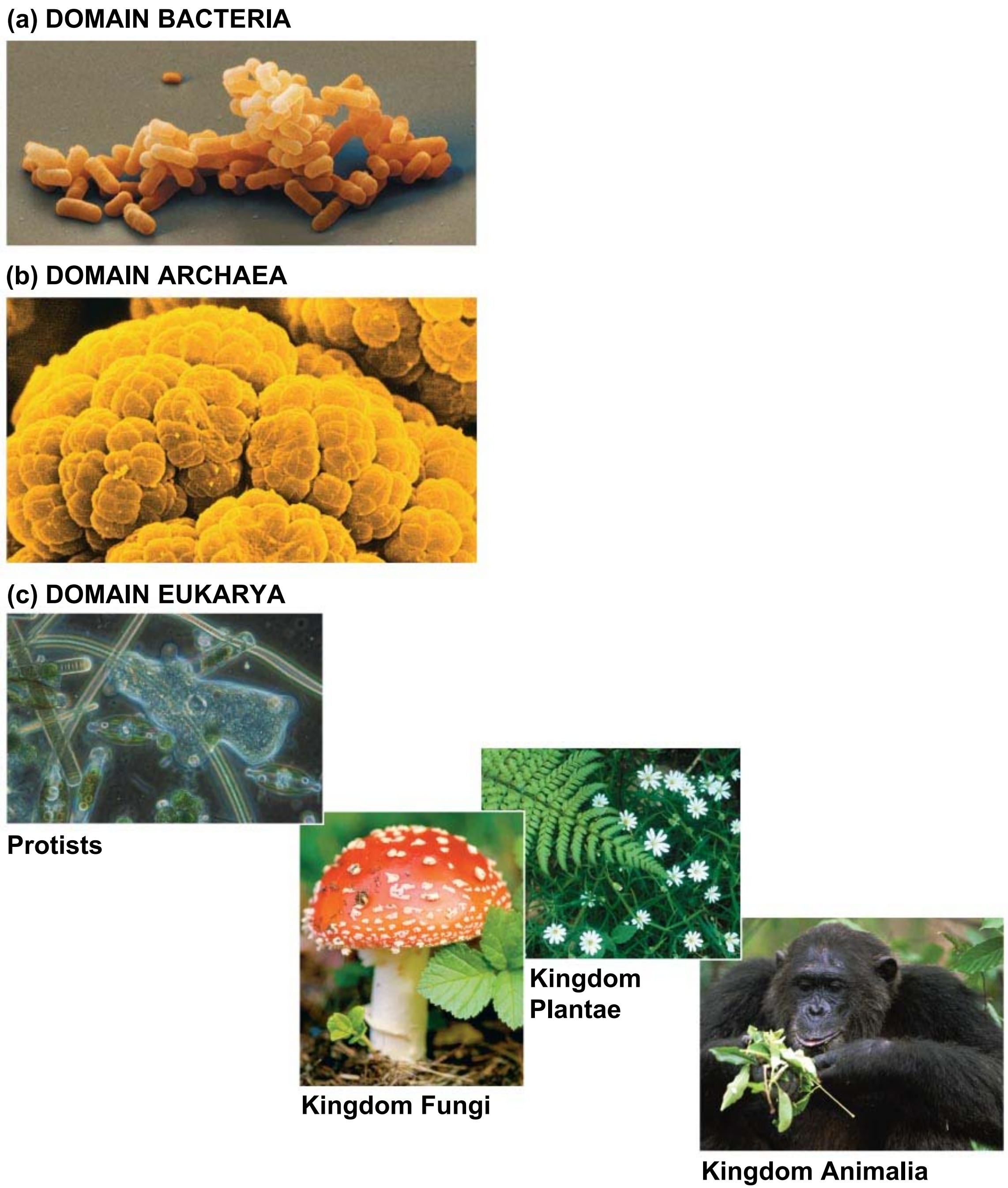
Fig. 1-14


Species
Genus
Family
Order
Class
Phylum
Kingdom
Domain
Ursus americanus
(American black bear)
Ursus
Ursidae
Carnivora
Mammalia
Chordata
Animalia
Eukarya

The Three Domains of Life

- Organisms are divided into **three domains**
- Domain **1)** **Bacteria** and domain **2)** **Archaea** compose the **prokaryotes**
- Most prokaryotes are single-celled and microscopic

Fig. 1-15


(a) DOMAIN BACTERIA
(b) DOMAIN ARCHAEA
(c) DOMAIN EUKARYA
Protists
Kingdom Fungi
Kingdom Plantae
Kingdom Animalia

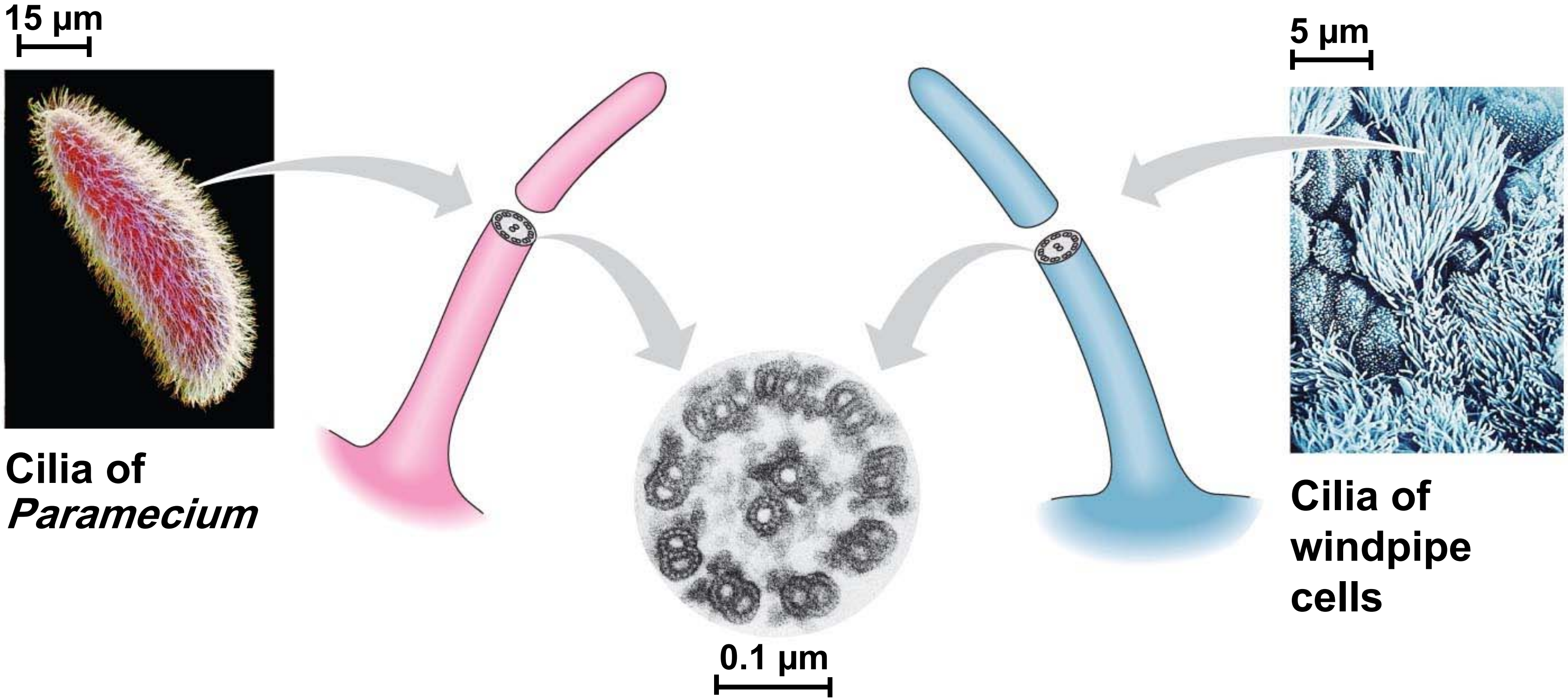
- Domain 3) **Eukarya** includes all eukaryotic organisms
- Domain Eukarya includes **three multicellular kingdoms**
  - **Plants**, which produce their own food by photosynthesis
  - **Fungi**, which absorb nutrients
  - **Animals**, which ingest their food

- Other eukaryotic organisms were formerly grouped into the **Protist kingdom**, though these are now often grouped into many separate groups

Unity in the Diversity of Life

- **A striking unity underlies the diversity of life; for example**
  - *DNA is the universal genetic language common to all organisms*
  - *Unity is evident in many features of cell structure*

Fig. 1-16

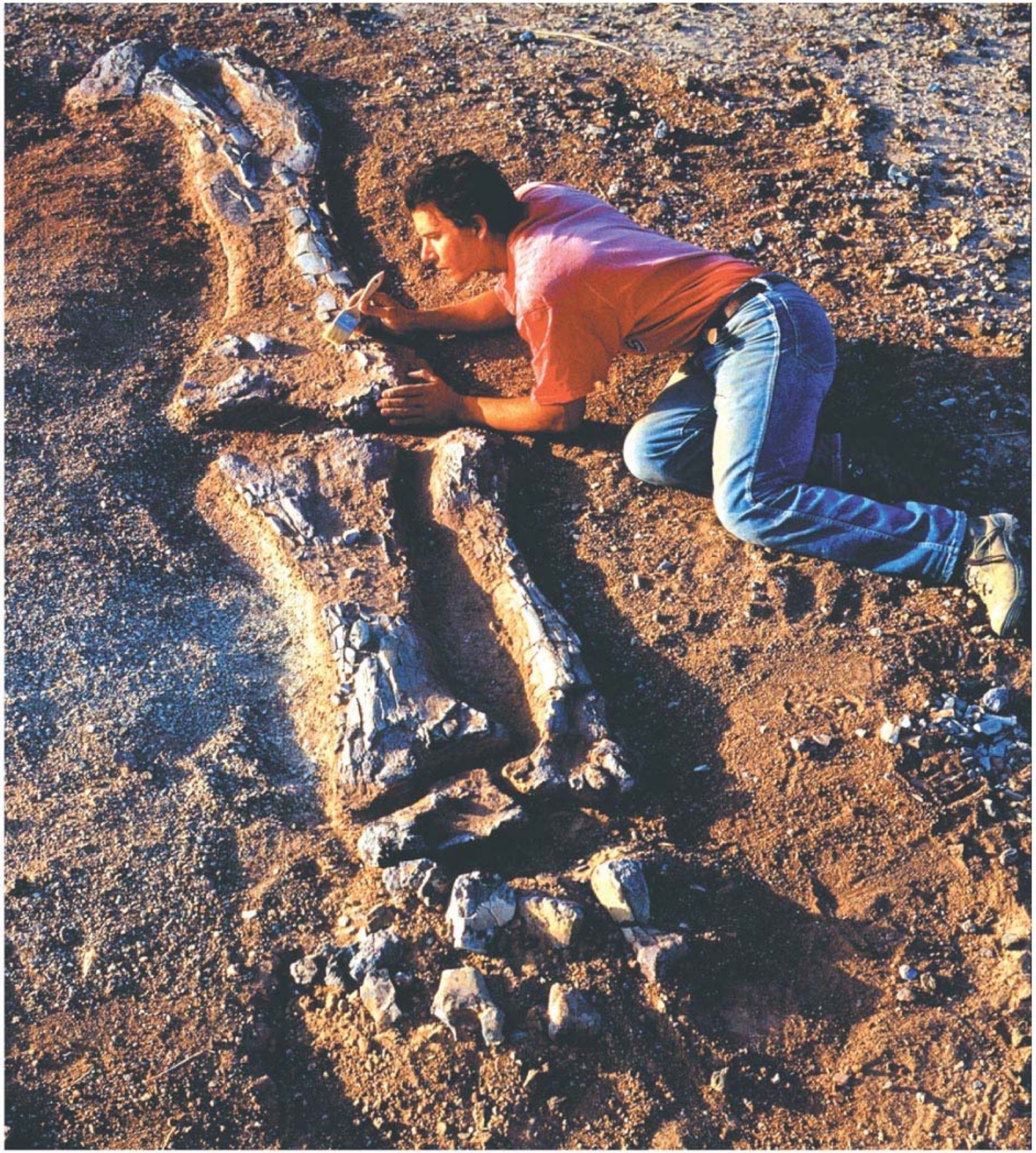


Cross section of a cilium, as viewed with an electron microscope

Charles Darwin and the Theory of Natural Selection

- Fossils and other evidence document the evolution of life on Earth over **billions of years**

Fig. 1-17



- Charles Darwin published ***On the Origin of Species by Means of Natural Selection*** in 1859
- Darwin made two main points
  - *Species showed evidence of "descent with modification" from common ancestors*
  - *Natural selection is the mechanism behind "descent with modification"*
- Darwin's theory explained the **duality of unity and diversity**

Fig. 1-18

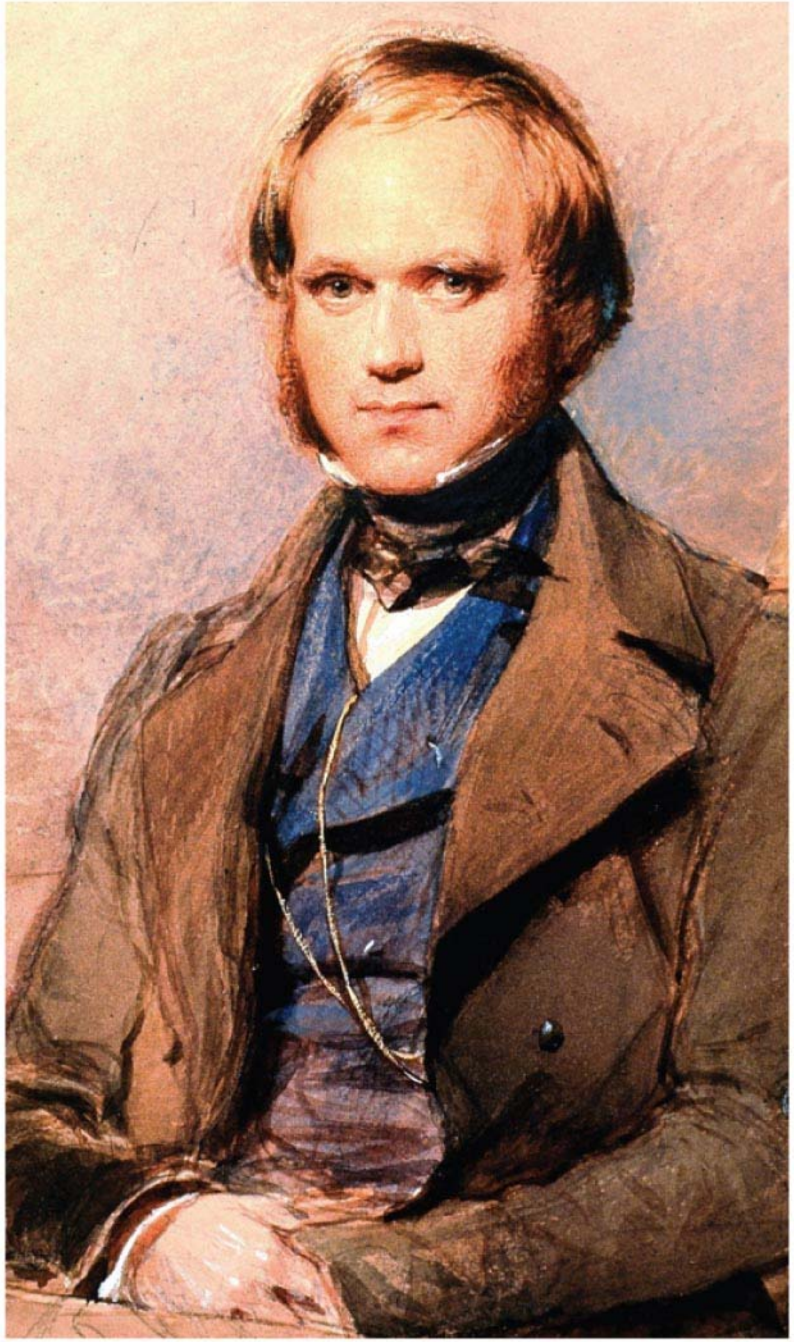
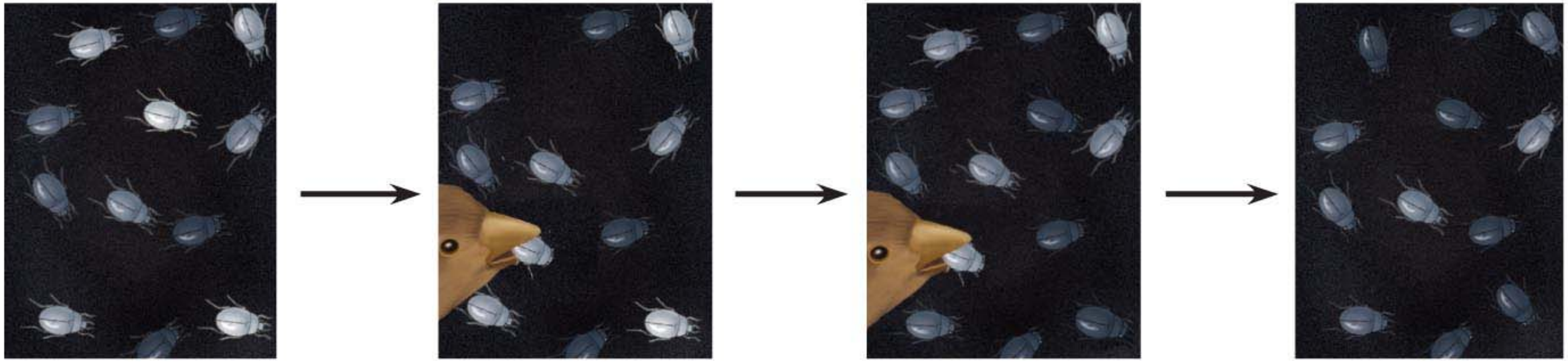


Fig. 1-19

- **The environment** "**selects**" for the propagation of beneficial traits
- Darwin called this process **natural selection**

Fig. 1-20



1 **Population with varied inherited traits.**

2 **Elimination of individuals with certain traits.**

3 **Reproduction of survivors.**

4 **Increasing frequency of traits that enhance survival and reproductive success.**

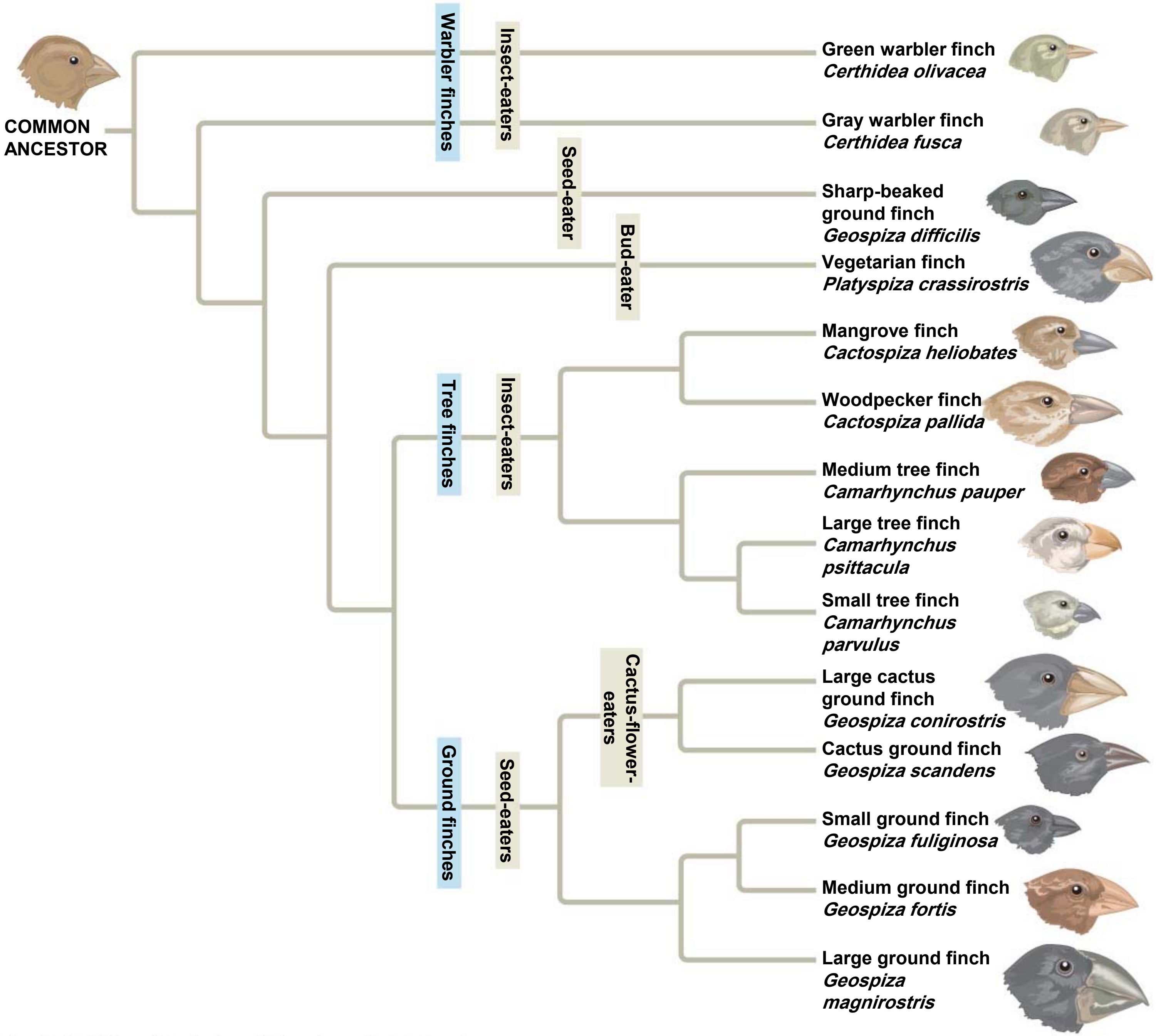
- **Natural selection** results in **the adaptation** of organisms to their environment
  - For example, bat wings are an example of adaptation

The Tree of Life

- "**Unity in diversity**" arises from "**descent with modification**"
  - For example, the forelimb of the bat, human, and horse and the whale flipper all share a common skeletal architecture
- Fossils provide additional evidence of anatomical unity from descent with modification

- **Darwin proposed that natural selection could cause an ancestral species to give rise to two or more descendent species**
  - For example, the finch species of the Galápagos Islands are descended from a common ancestor
- **Evolutionary relationships** are often illustrated with **treelike diagrams** that show ancestors and their descendents

Fig. 1-22


COMMON ANCESTOR
Warbler finches
Insect-eaters
Seed-eater
Bud-eater
Tree finches
Insect-eaters
Ground finches
Seed-eaters
Cactus-flower-eaters
Green warbler finch
Certhidea olivacea
Gray warbler finch
Certhidea fusca
Sharp-beaked ground finch
Geospiza difficilis
Vegetarian finch
Platyspiza crassirostris
Mangrove finch
Cactospiza heliobates
Woodpecker finch
Cactospiza pallida
Medium tree finch
Camarhynchus pauper
Large tree finch
Camarhynchus psittacula
Small tree finch
Camarhynchus parvulus
Large cactus ground finch
Geospiza conirostris
Cactus ground finch
Geospiza scandens
Small ground finch
Geospiza fuliginosa
Medium ground finch
Geospiza fortis
Large ground finch
Geospiza magnirostris

Water

I believe that as the methods of structural chemistry are further applied to physiological problems, it will be found that the significance of the hydrogen bond for physiology is greater than that of any other single structural feature.

—*Linus Pauling,* The Nature of the Chemical Bond, *1939*

Water is the most abundant substance in living systems, making up 70% or more of the weight of most organisms. The first living organisms on Earth doubtless arose in an aqueous environment, and the course of evolution has been shaped by the properties of the aqueous medium in which life began.

2.1 Weak Interactions in Aqueous Systems

Hydrogen bonds between water molecules provide the cohesive forces that make water a liquid at room temperature and favor the extreme ordering of molecules that is typical of crystalline water (ice). Polar biomolecules dissolve readily in water because they can replace water-water interactions with more energetically favorable water-solute interactions. In contrast, nonpolar biomolecules interfere with water-water interactions but are unable to form water-solute interactions—consequently, nonpolar molecules are poorly soluble in water. In aqueous solutions, nonpolar molecules tend to cluster together. Hydrogen bonds and ionic, hydrophobic (Greek, "water-fearing"), and van der Waals interactions are individually weak, but collectively they have a very significant influence on the three-dimensional structures of proteins, nucleic acids, polysaccharides, and membrane lipids.

Hydrogen Bonding Gives Water Its Unusual Properties

Water has a higher melting point, boiling point, and heat of vaporization than most other common solvents (Table 2–1). These unusual properties are a consequence of attractions between adjacent water molecules that give liquid water great internal cohesion. A look at the electron structure of the H_2O molecule reveals the cause of these intermolecular attractions.

Each hydrogen atom of a water molecule shares an electron pair with the central oxygen atom. The geometry of the molecule is dictated by the shapes of the outer electron orbitals of the oxygen atom, which are similar to the sp^3 bonding orbitals of carbon (see Fig. 1–14). These orbitals describe a rough tetrahedron, with a hydrogen atom at each of two corners and unshared electron pairs at the other two corners (Fig. 2–1a). The H—O—H bond angle is 104.5°, slightly less than the 109.5° of a perfect tetrahedron because of crowding by the nonbonding orbitals of the oxygen atom.

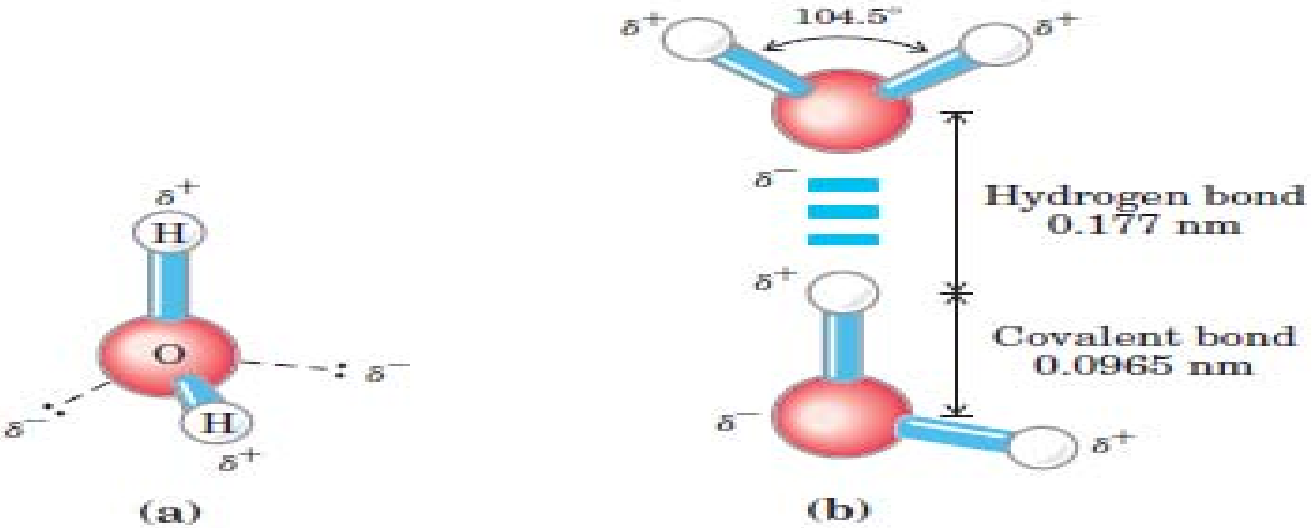


FIGURE 2–1 Structure of the water molecule. (a) The dipolar nature of the H_2O molecule is shown in a ball-and-stick model; the dashed lines represent the nonbonding orbitals. There is a nearly tetrahedral arrangement of the outer-shell electron pairs around the oxygen atom; the two hydrogen atoms have localized partial positive charges (δ^+) and the oxygen atom has a partial negative charge (δ^-). **(b)** Two H_2O molecules joined by a hydrogen bond (designated here, and throughout this book, by three blue lines) between the oxygen atom of the upper molecule and a hydrogen atom of the lower one. Hydrogen bonds are longer and weaker than covalent O—H bonds.

TABLE 2–1 Melting Point, Boiling Point, and Heat of Vaporization of Some Common Solvents

	Melting point (°C)	Boiling point (°C)	Heat of vaporization (J/g)*
Water	0	100	2,260
Methanol (CH_3OH)	−98	65	1,100
Ethanol (CH_3CH_2OH)	−117	78	854
Propanol ($CH_3CH_2CH_2OH$)	−127	97	687
Butanol ($CH_3(CH_2)_2CH_2OH$)	−90	117	590
Acetone (CH_3COCH_3)	−95	56	523
Hexane ($CH_3(CH_2)_4CH_3$)	−98	69	423
Benzene (C_6H_6)	6	80	394
Butane ($CH_3(CH_2)_2CH_3$)	−135	−0.5	381
Chloroform ($CHCl_3$)	−63	61	247

*The heat energy required to convert 1.0 g of a liquid at its boiling point and at atmospheric pressure into its gaseous state at the same temperature. It is a direct measure of the energy required to overcome attractive forces between molecules in the liquid phase.

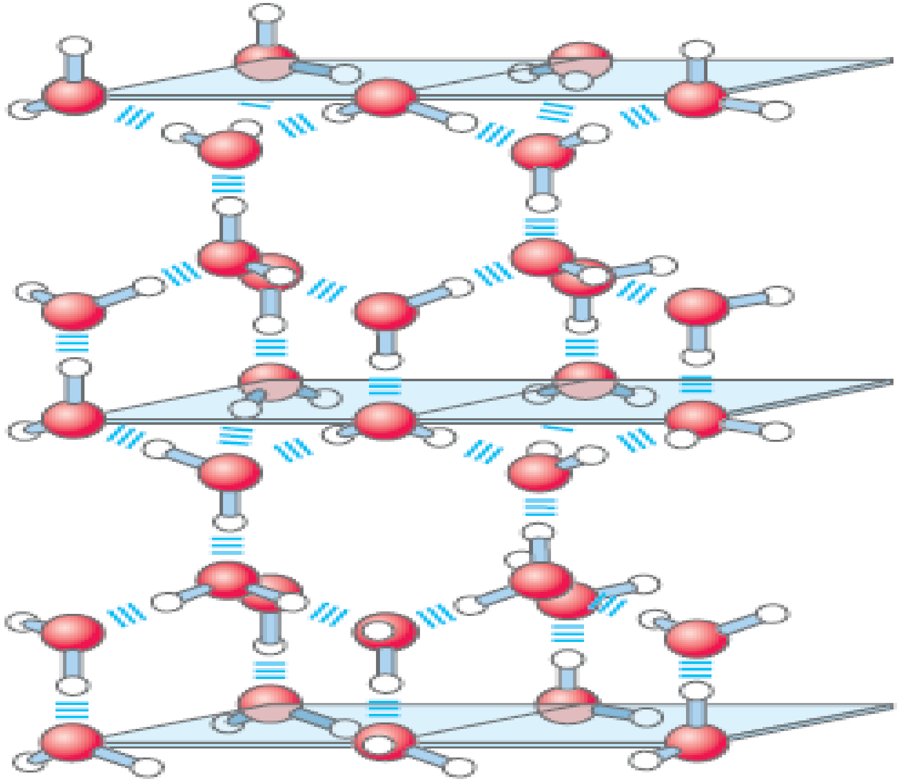


FIGURE 2–2 Hydrogen bonding in ice. In ice, each water molecule forms four hydrogen bonds, the maximum possible for a water molecule, creating a regular crystal lattice. By contrast, in liquid water at room temperature and atmospheric pressure, each water molecule hydrogen-bonds with an average of 3.4 other water molecules. This crystal lattice structure makes ice less dense than liquid water, and thus ice floats on liquid water.

$$H_2O\ (\text{solid}) \rightarrow H_2O\ (\text{liquid}) \qquad \Delta H = +5.9\ \text{kJ/mol}$$

$$H_2O\ (\text{liquid}) \rightarrow H_2O\ (\text{gas}) \qquad \Delta H = +44.0\ \text{kJ/mol}$$

During melting or evaporation, the entropy of the aqueous system increases as more highly ordered arrays of water molecules relax into the less orderly hydrogen-bonded arrays in liquid water or into the wholly disordered gaseous state. At room temperature, both the melting of ice and the evaporation of water occur spontaneously; the tendency of the water molecules to associate through hydrogen bonds is outweighed by the energetic push toward randomness. Recall that the free-energy change (ΔG) must have a negative value for a process to occur spontaneously: $\Delta G = \Delta H - T\ \Delta S$, where ΔG represents the driving force, ΔH the enthalpy change from making and breaking bonds, and ΔS the change in randomness. Because ΔH is positive for melting and evaporation, it is clearly the increase in entropy (ΔS) that makes ΔG negative and drives these changes.

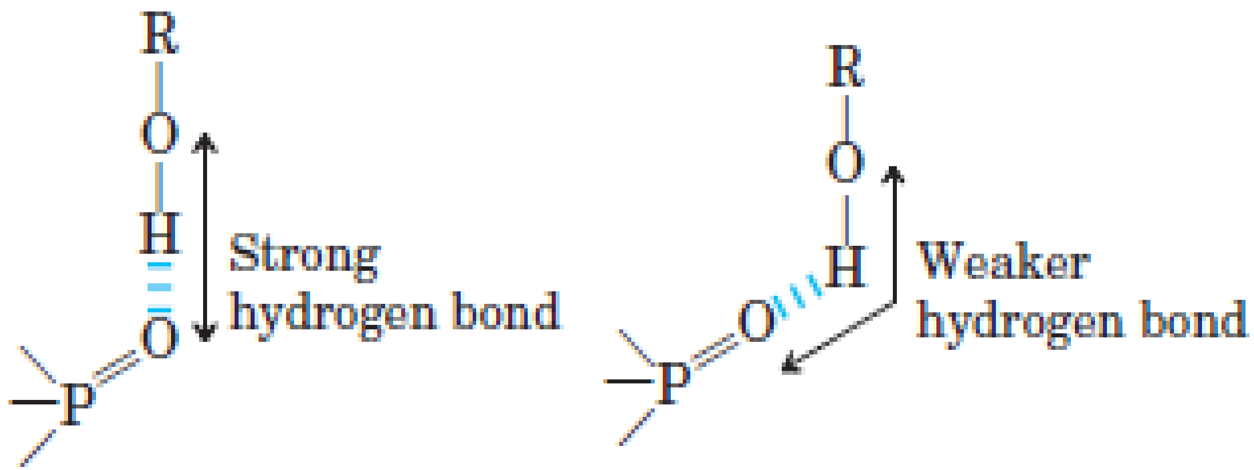
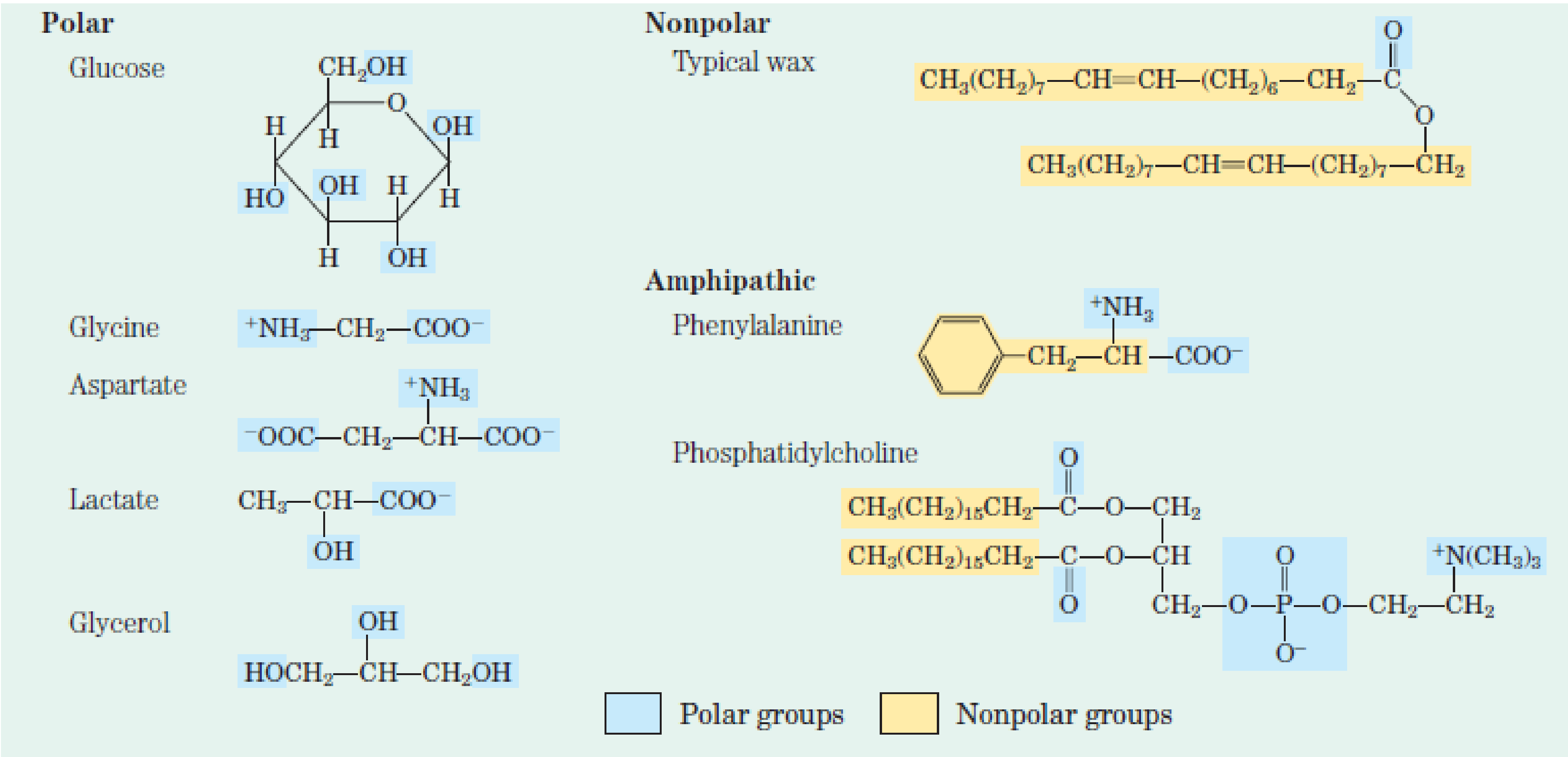


FIGURE 2–5 Directionality of the hydrogen bond. The attraction between the partial electric charges (see Fig. 2–1) is greatest when the three atoms involved in the bond (in this case O, H, and O) lie in a straight line. When the hydrogen-bonded moieties are structurally constrained (when they are parts of a single protein molecule, for example), this ideal geometry may not be possible and the resulting hydrogen bond is weaker.

TABLE 2–2 Some Examples of Polar, Nonpolar, and Amphipathic Biomolecules (Shown as Ionic Forms at pH 7)



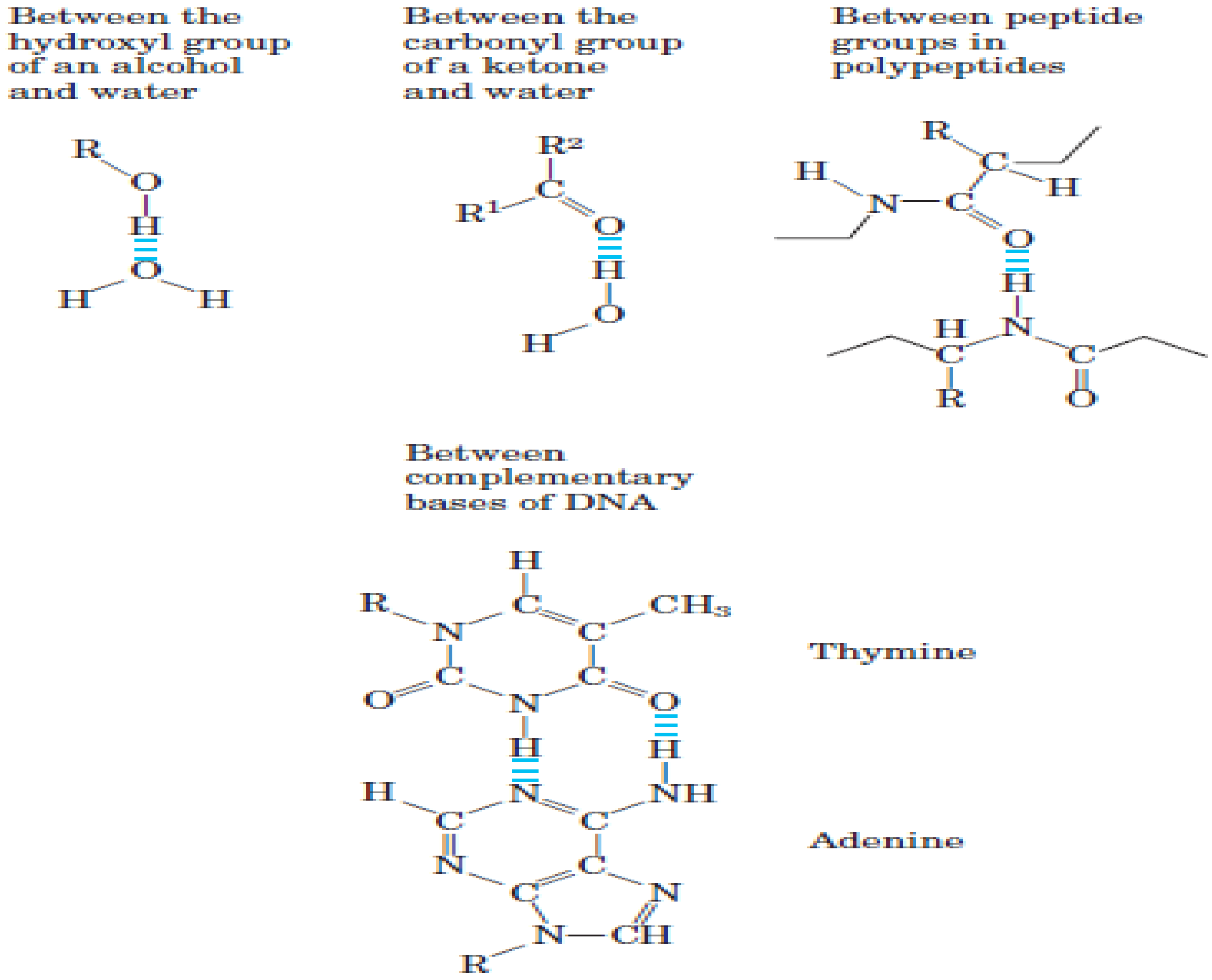


FIGURE 2—4 Some biologically important hydrogen bonds.

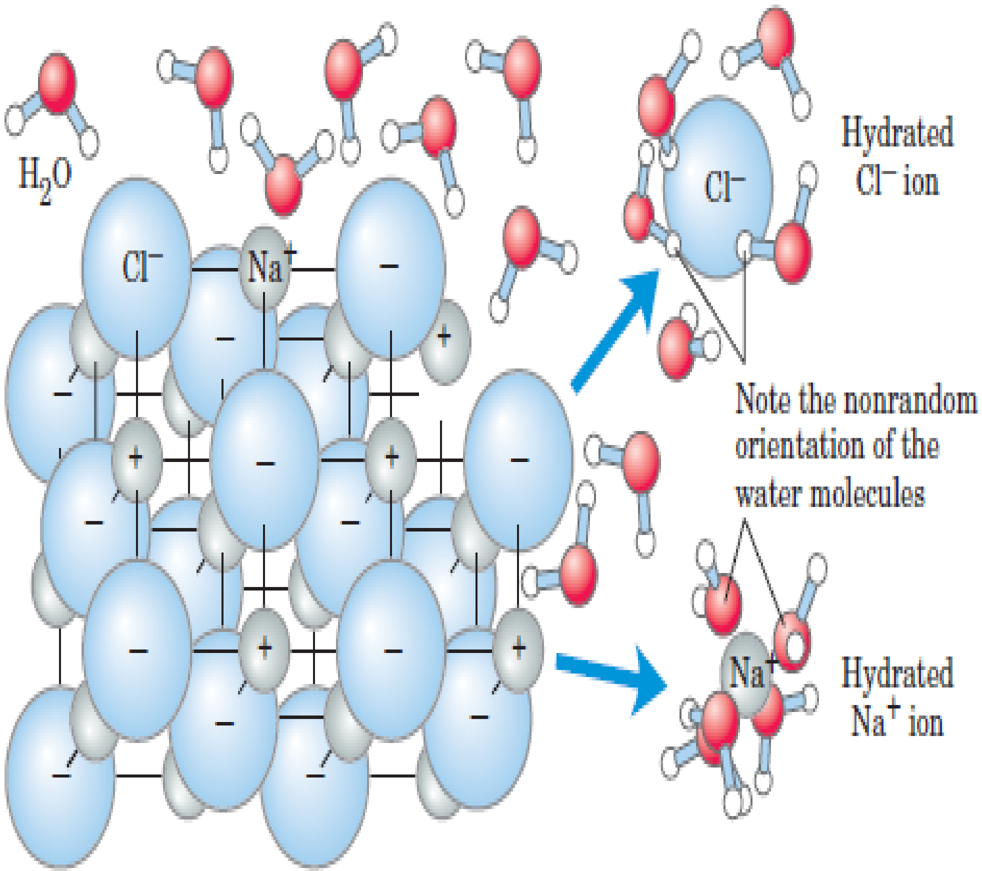


FIGURE 2–6 Water as solvent. Water dissolves many crystalline salts by hydrating their component ions. The NaCl crystal lattice is disrupted as water molecules cluster about the Cl^- and Na^+ ions. The ionic charges are partially neutralized, and the electrostatic attractions necessary for lattice formation are weakened.

Amphipathic compounds contain regions that are polar (or charged) and regions that are nonpolar (Table 2–2). When an amphipathic compound is mixed with water, the polar, hydrophilic region interacts favorably with the solvent and tends to dissolve, but the nonpolar, hydrophobic region tends to avoid contact with the water (**Fig. 2–7a**). The nonpolar regions of the molecules cluster together to present the smallest hydrophobic area to the aqueous solvent, and the polar regions are arranged to maximize their interaction with the solvent (Fig. 2–7b). These stable structures of amphipathic compounds in water, called **micelles**, may contain hundreds or thousands of molecules. The forces

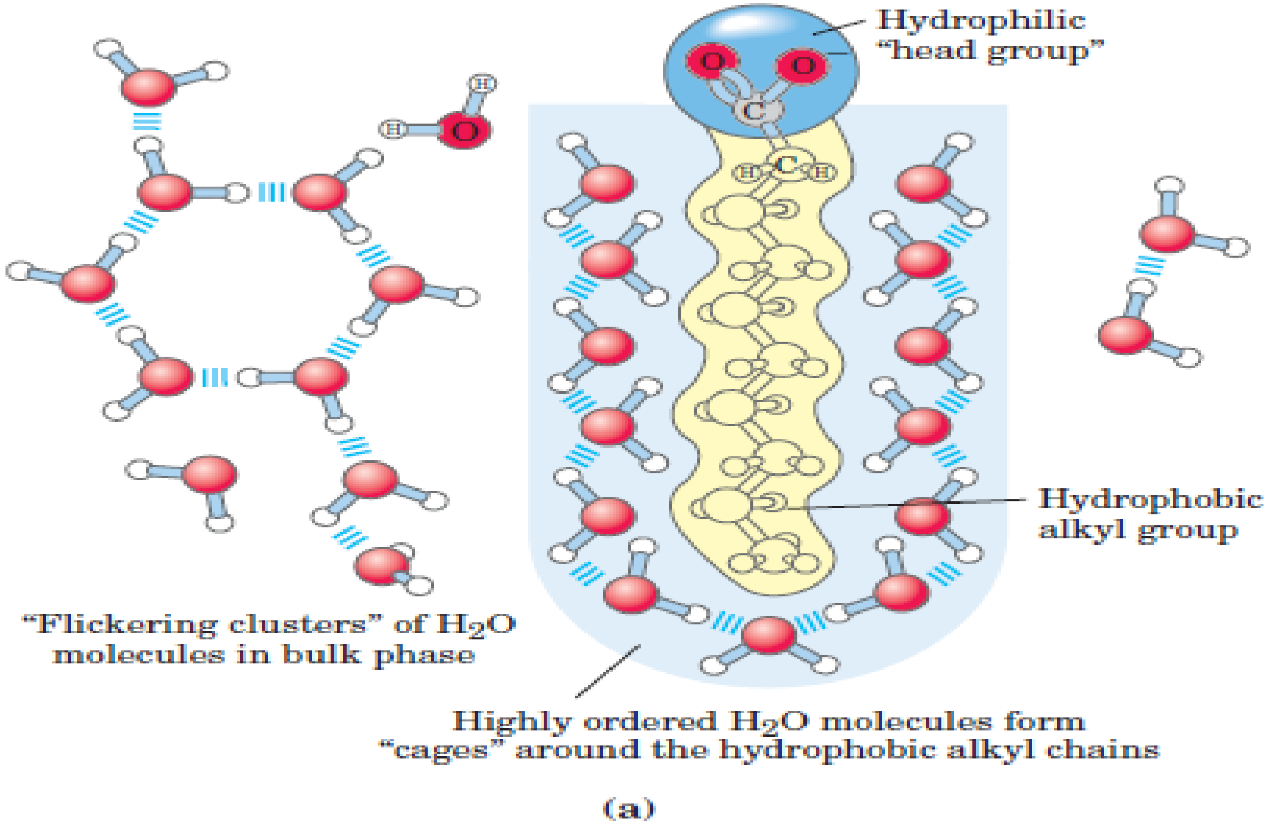
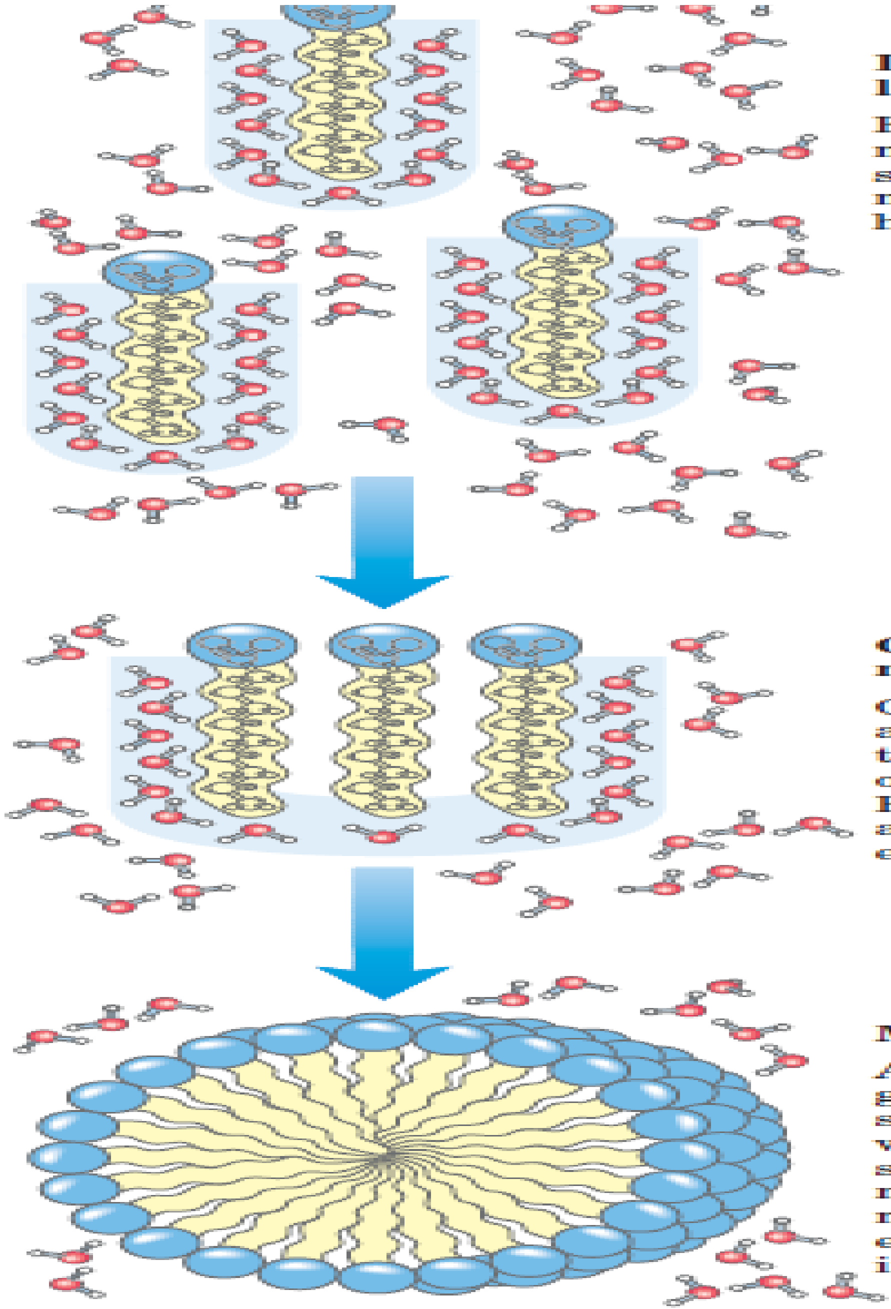
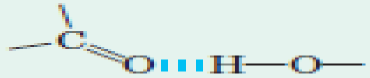
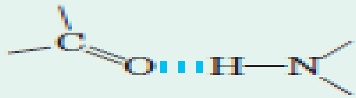
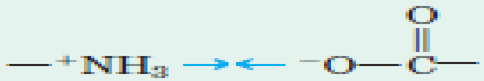
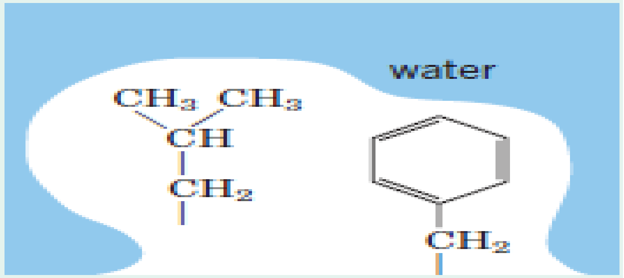


FIGURE 2–7 Amphipathic compounds in aqueous solution. (a) Long-chain fatty acids have very hydrophobic alkyl chains, each of which is surrounded by a layer of highly ordered water molecules. **(b)** By clustering together in micelles, the fatty acid molecules expose the smallest possible hydrophobic surface area to the water, and fewer water molecules are required in the shell of ordered water. The energy gained by freeing immobilized water molecules stabilizes the micelle.



Dispersion of lipids in H_2O
Each lipid molecule forces surrounding H_2O molecules to become highly ordered.
Clusters of lipid molecules
Only lipid portions at the edge of the cluster force the ordering of water. Fewer H_2O molecules are ordered, and entropy is increased.
Micelles
All hydrophobic groups are sequestered from water; ordered shell of H_2O molecules is minimized, and entropy is further increased.

(b)

TABLE 2–5	Four Types of Noncovalent ("Weak") Interactions among Biomolecules in Aqueous Solvent
Hydrogen bonds	
Between neutral groups	
Between peptide bonds	
Ionic interactions	
Attraction	
Repulsion	$—^{+}NH_3 \longleftrightarrow H_3N^{+}—$
Hydrophobic interactions	
van der Waals interactions	Any two atoms in close proximity

2.1 **Water and Polarity:**

A- **Electronegativity**:

Water is a polar molecule, with a partial negative charge on the oxygen atom and partial positive charges on the hydrogen atoms.

B- Polar bonds vs. polar molecules — dipoles.

There are forces of attraction between the unlike partial charges (+ AND -).

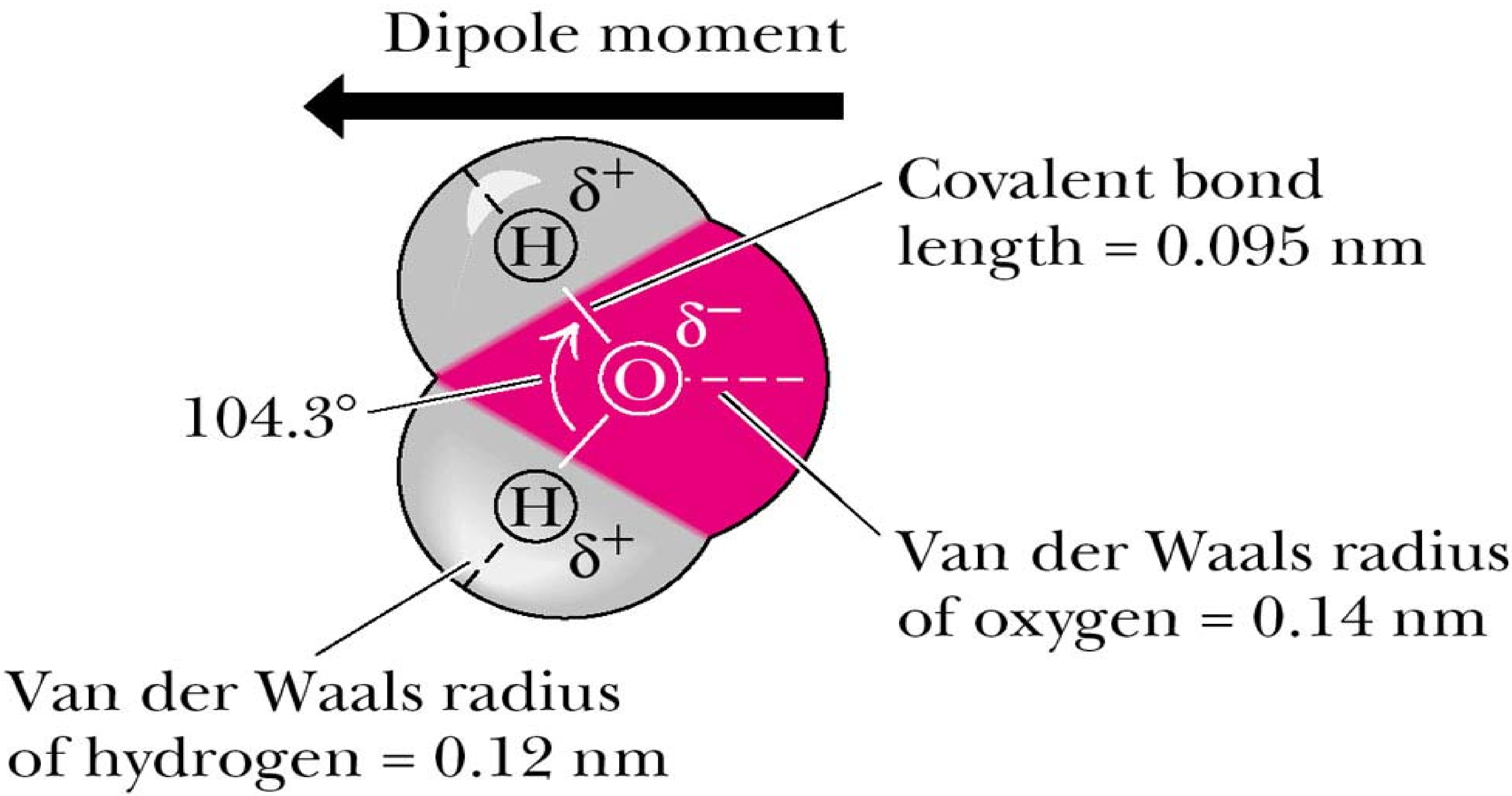
Polar substances tend to dissolve in water, but nonpolar substances do not.

Table 2.1

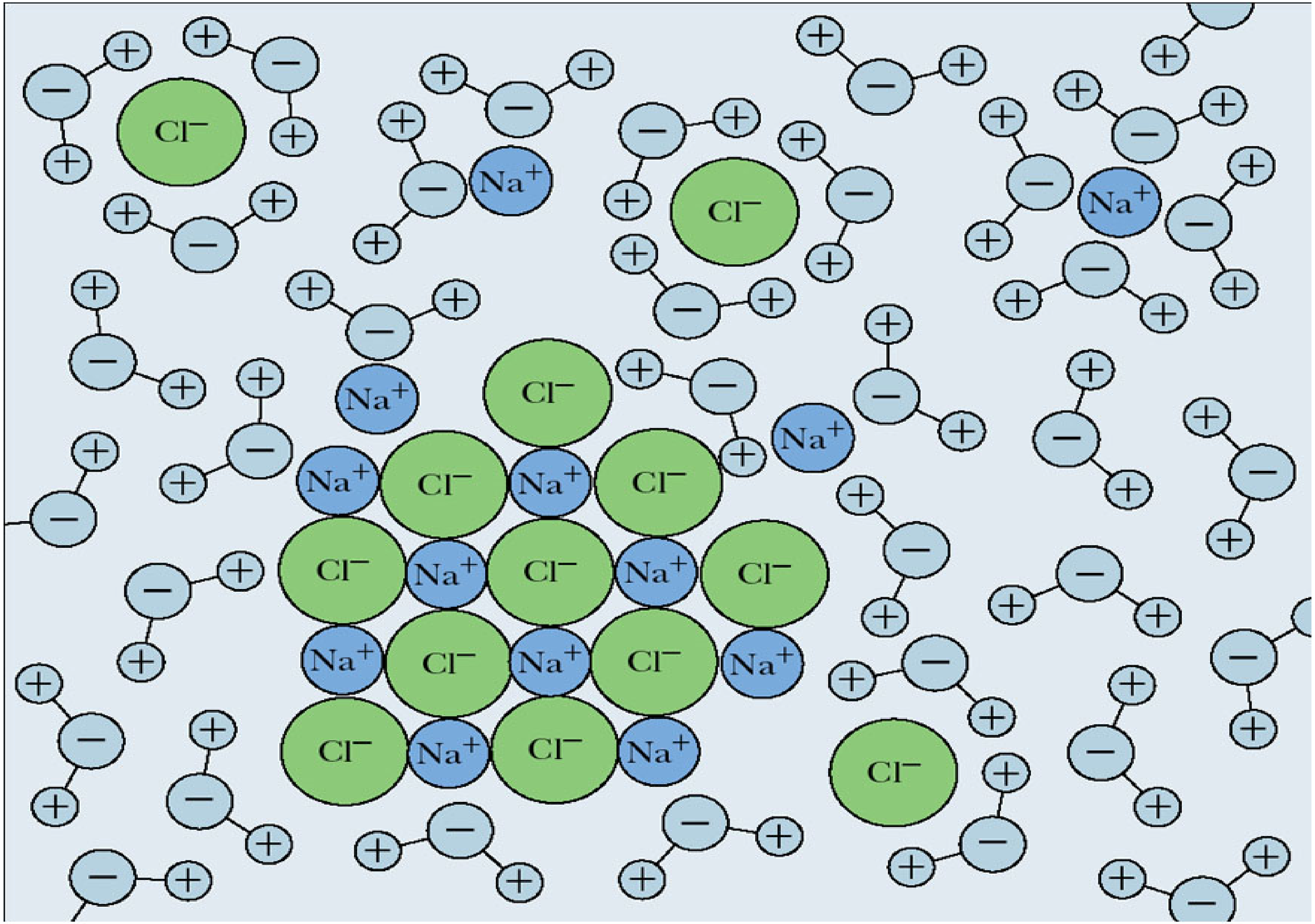
Electronegativities of Selected Elements

Element	Electronegativity*
Oxygen	3.5
Nitrogen	3.0
Sulfur	2.6
Carbon	2.5
Phosphorus	2.2
Hydrogen	2.1

The structure of water:

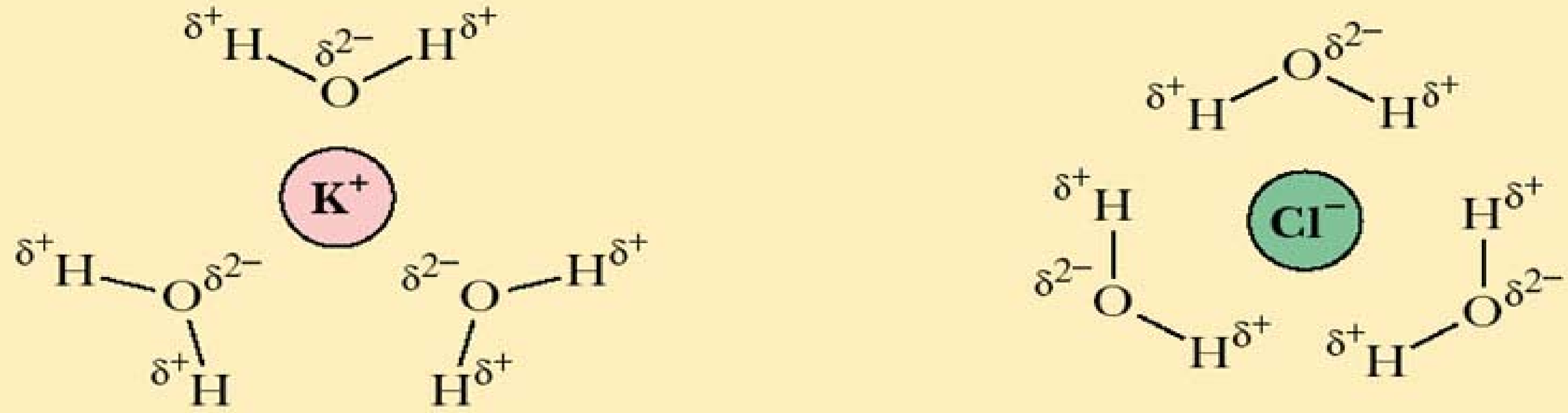


Hydration shells surrounding ions in solution:

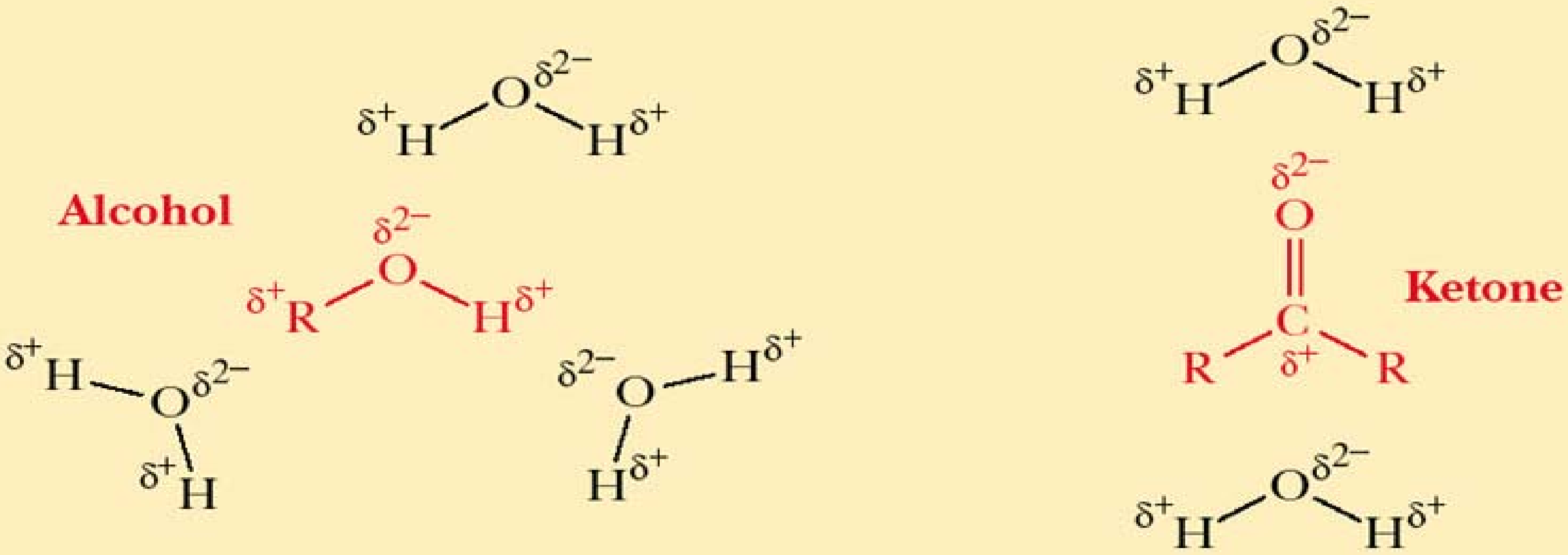


Dissolve in water:

(a) **Ion dipole interaction with water**



(b) **dipole-dipole interaction of polar compounds with water**



C - Solvent properties of water:

Hydrophilic molecules: dissolve in water (ionic and polar substances)

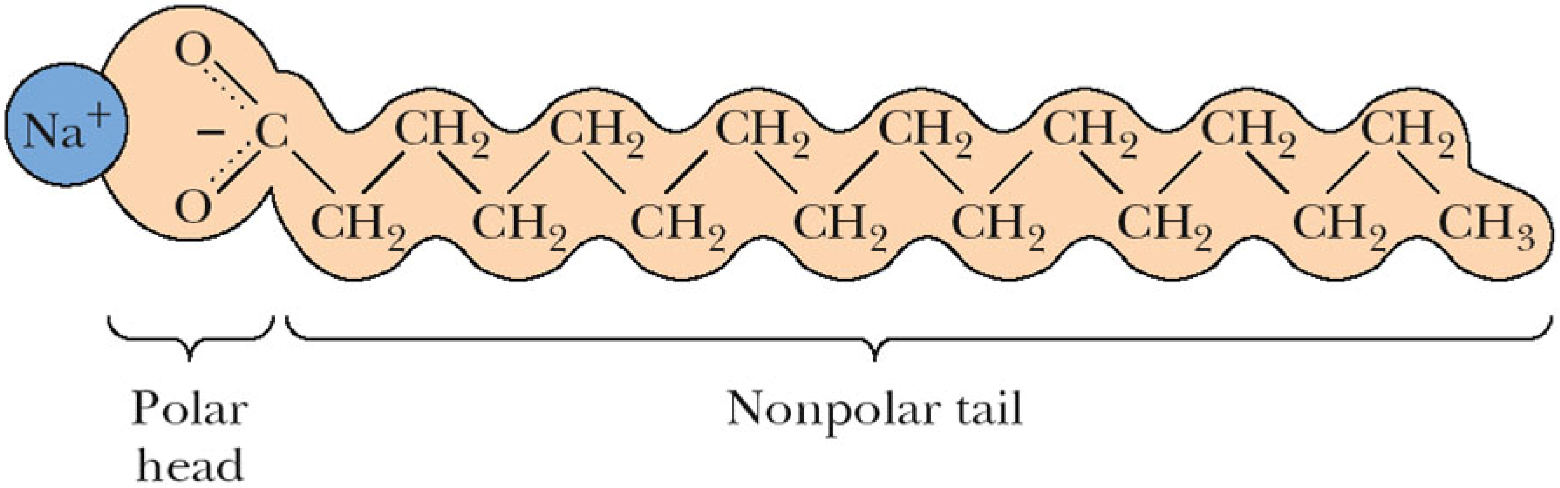
Hydrophobic molecules: don't dissolve in water (non polar substances)

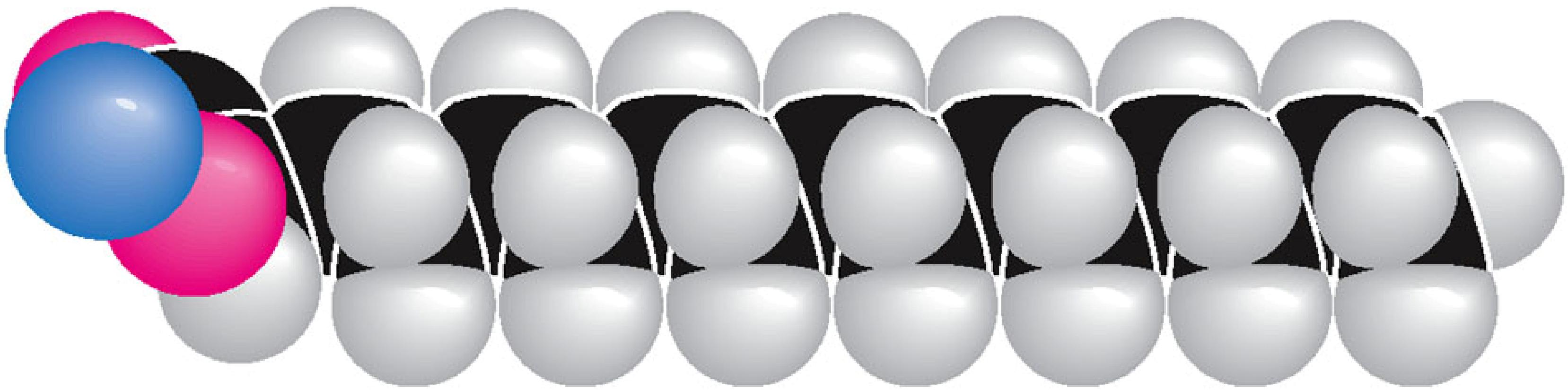
Table 2.2

Examples of Hydrophobic and Hydrophilic Substances

Hydrophilic	Hydrophobic
Polar covalent compounds [e.g., alcohols such as C_2H_5OH (ethanol) and ketones such as $(CH_3)_2C{=}O$ (acetone)]	Nonpolar covalent compounds [e.g., hydrocarbons such as C_6H_{14} (hexane)]
Sugars	Fatty acids, cholesterol
Ionic compounds (e.g., KCl)	
Amino acids, phosphate esters	

Amphipathic molecules, micelles: a molecules that have both hydrophilic and hydrophobic portion (e.g: sodium palmitate = sodium salt of plamitic acid)





Micelle formation by amphipathic molecules in aqueous solution:

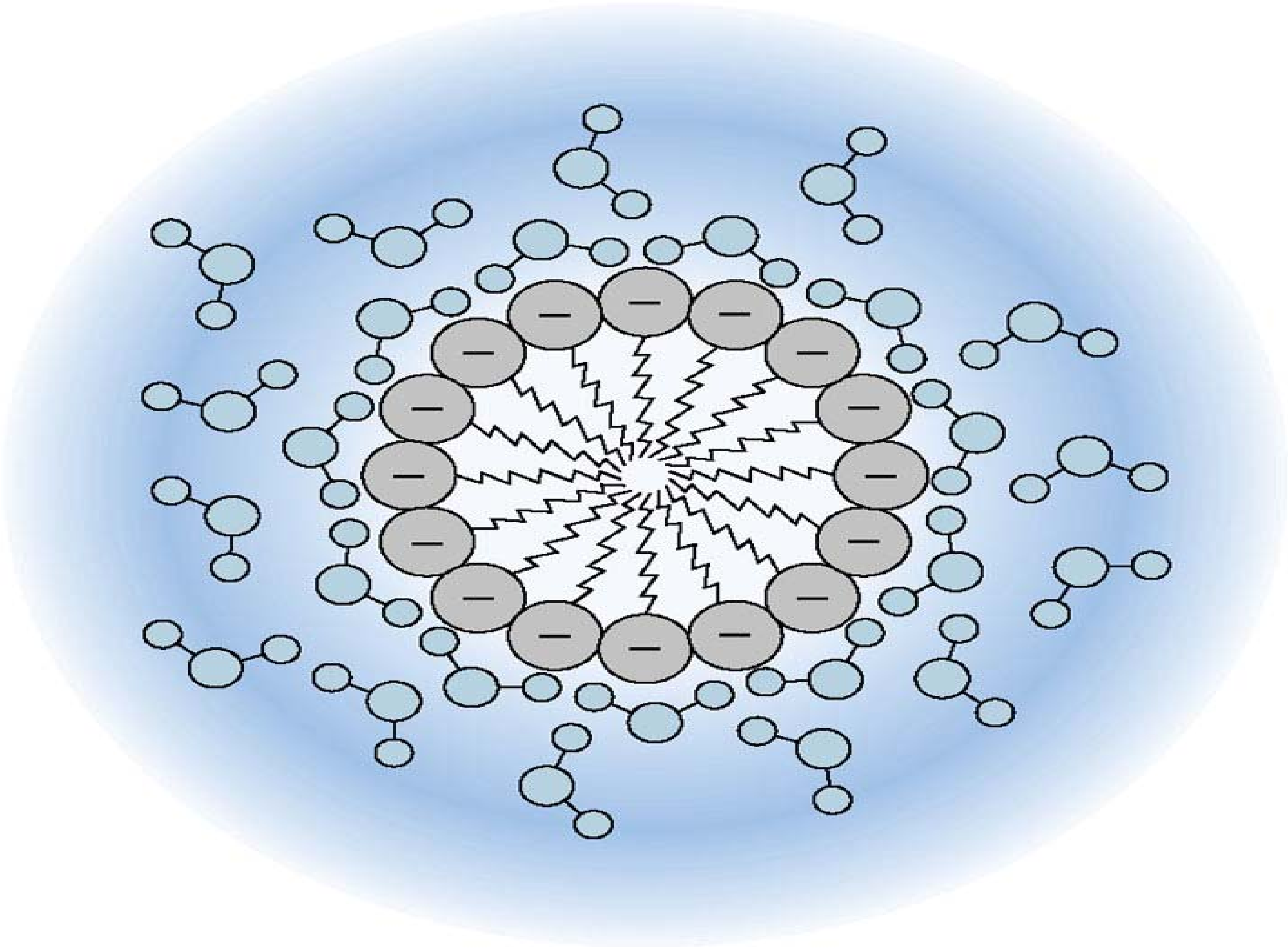


Fig. 2-5, p.37

2.2 Hydrogen Bonds:

- A hydrogen bond is a special case of dipole–dipole interactions.
- In both the liquid state and the solid state, water molecules are extensively **hydrogen-bonded** to one another.
- Hydrogen bonding between water and polar solutes takes place in aqueous solutions.
- The three-dimensional structures of many important biomolecules, including proteins and nucleic acids, are stabilized by hydrogen bonds.

Hyrogen bonding sites: HF molecule has one hydrogen-bond donor and three hydrogen-bond acceptors. **H2O** molecule has two donors and two acceptors. **NH3** molecule has three donors and one acceptor.

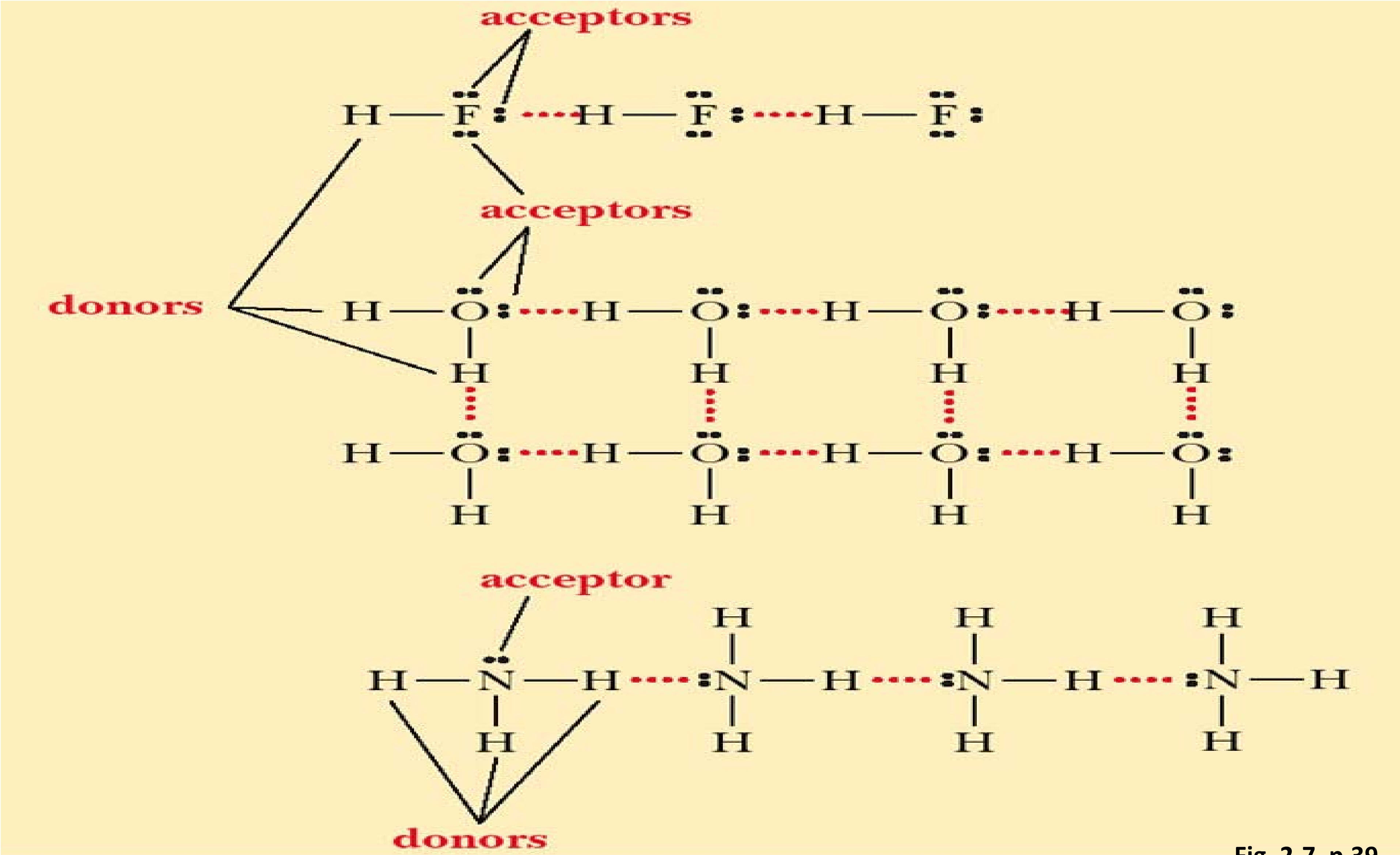
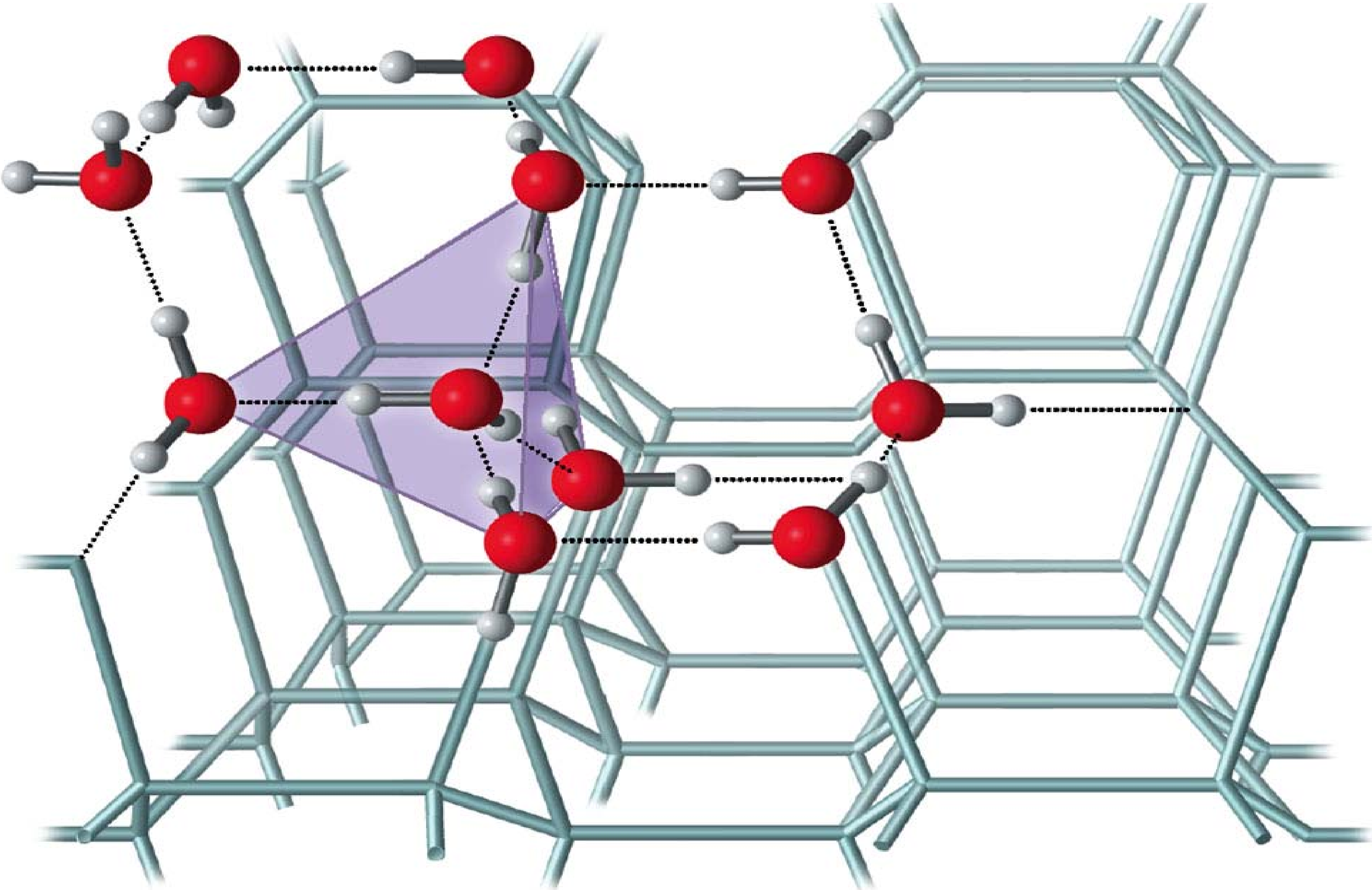


Fig. 2-7, p.39

linear and nonlinear hydrogen bonds:
Nonlinear bonds are weaker than bonds in which all three atoms lie in a straight line.

Fig. 2-6, p.38

Tetrahedral hydrogen bonding in H2O: an array of H2O molecules in an ice crystal. Each H2O molecule is hydrogen-bonded to four others.



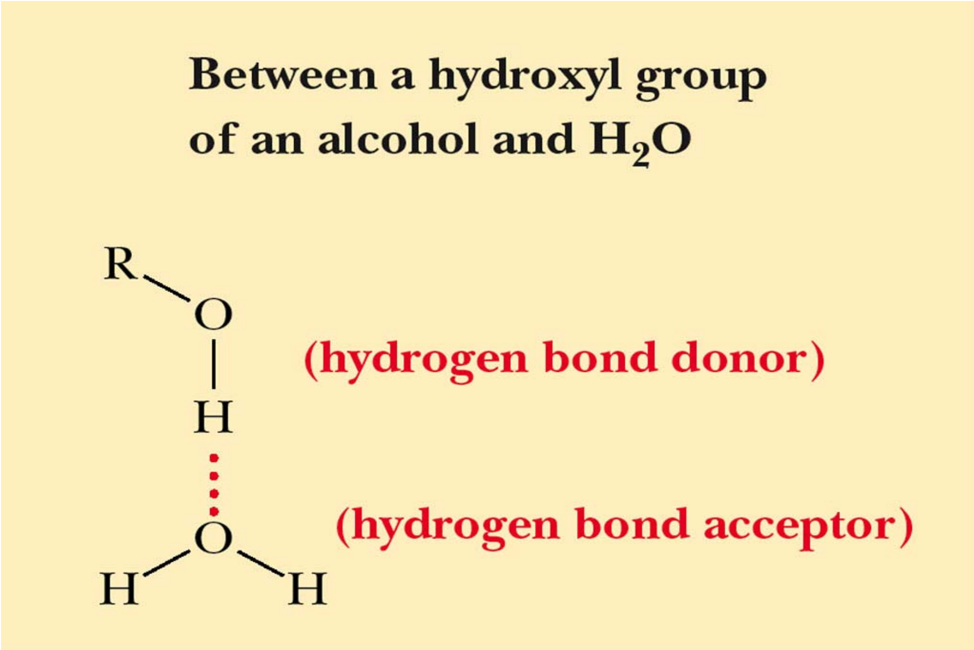
- The ability to form strong hydrogen bonds is responsible for many unique characteristic of water such as very high melting point and boiling point.

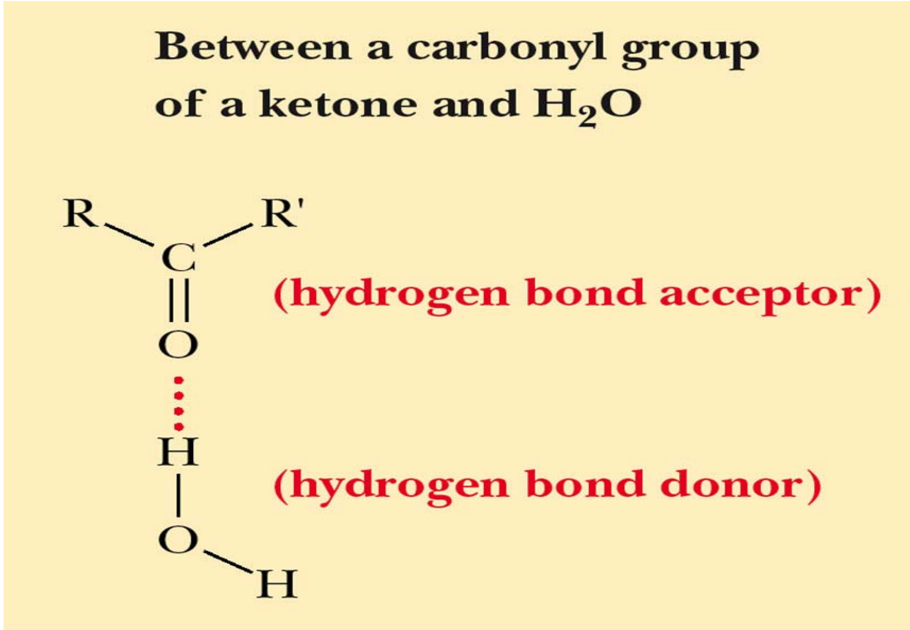
Table 2.4

Comparison of Properties of Water, Ammonia, and Methane

Substance	Molecular Weight	Melting Point (°C)	Boiling Point (°C)
Water (H_2O)	18.02	0.0	100.0
Ammonia (NH_3)	17.03	−77.7	−33.4
Methane (CH_4)	16.04	−182.5	−161.5

Examples of hydrogen bonding between polar groups and water:





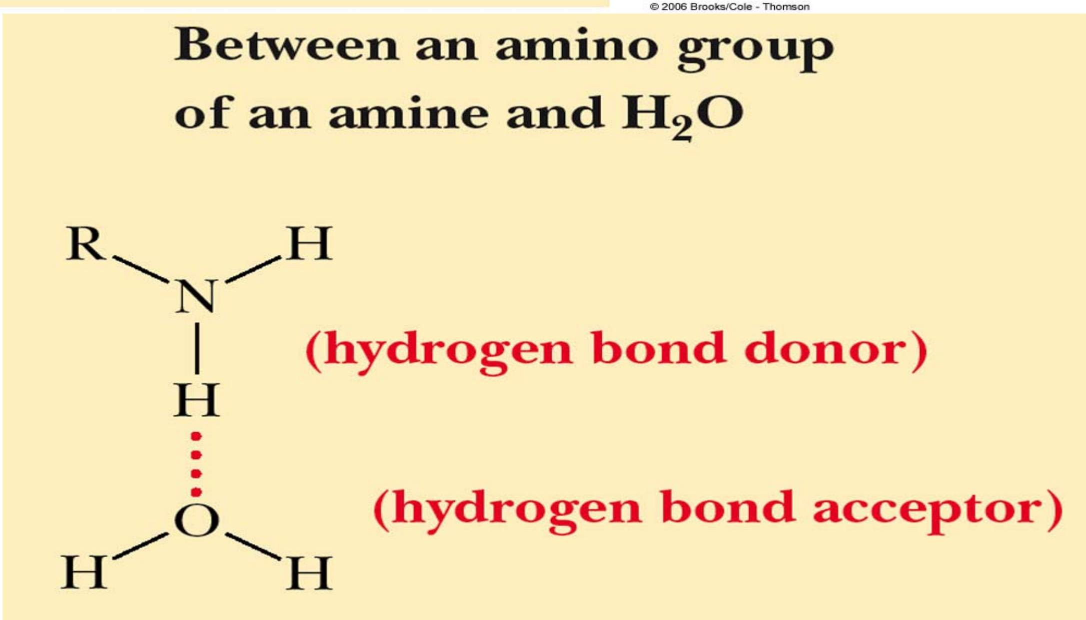
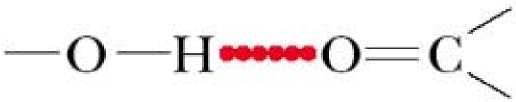
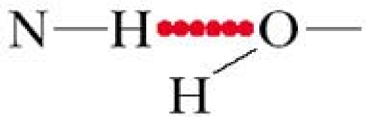
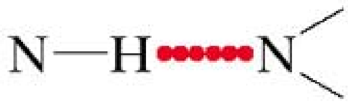
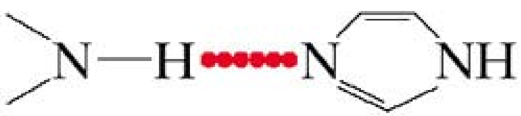
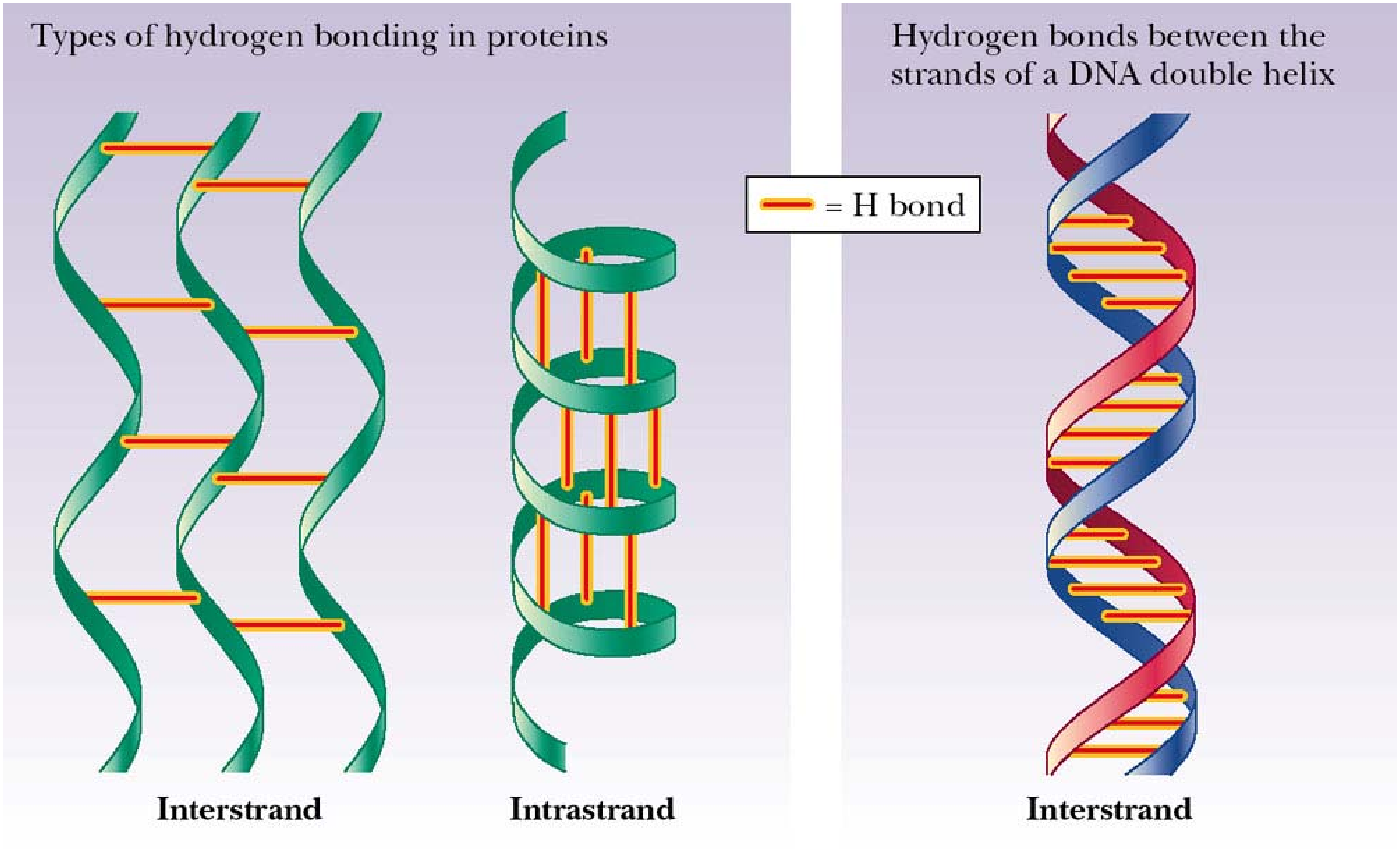


Table 2.5

Examples of Major Types of Hydrogen Bonds Found in Biologically Important Molecules

Bonding Arrangement	Molecules Where the Bond Occurs
	H bond formed in H_2O
	Bonding of water to other molecules
	Important in protein and nucleic acid structures
	
	
	



Types of hydrogen bonding in proteins
Hydrogen bonds between the strands of a DNA double helix
= H bond
Interstrand
Intrastrand
Interstrand

2.3 Acids, Bases and PH:

- Acids are proton donors, and bases are proton acceptors.
- Acid–base reactions involve proton transfer.
- Water can accept and donate protons.
- The degree of dissociation of acids in water can be characterized by an acid dissociation constant, *K*a, which gives a numerical indication of the strength of the acid.

$$HA \rightleftharpoons H^+ + A^-$$

Acid **Conjugate base**

$$Ka = \frac{[H^+][A^-]}{[HA]}$$

- **pH:**
- The self-dissociation of water can be characterized by a similar constant, called ion product constant of water.

$$K_w = [H^+] [OH^-] = 10^{-14}$$

- Since the hydrogen ion concentration of aqueous solutions can vary by many orders of magnitude, it is desirable to define a quantity, pH, that expresses the concentration of hydrogen ions conveniently.
- A similar quantity, p*K*a, can be used as an alternative expression for the strength of any acid.
- The pH of a solution of a weak acid and its conjugate base can be related to the p*K*a of that acid by the Henderson–Hasselbalch equation.

The pH of an aqueous solution reflects, on a logarithmic scale, the concentration of hydrogen ions:

$$\mathbf{pH = \log \frac{1}{[H^+]} = -\log\,[H^+]}$$

The pK_a expresses, on a logarithmic scale, the relative strength of a weak acid or base:

$$pK_a = \log \frac{1}{K_a} = -\log K_a.$$

Henderson-Hasselbalch equation:

$$pH = pK_a + \log \frac{[A^-]}{[HA]}$$

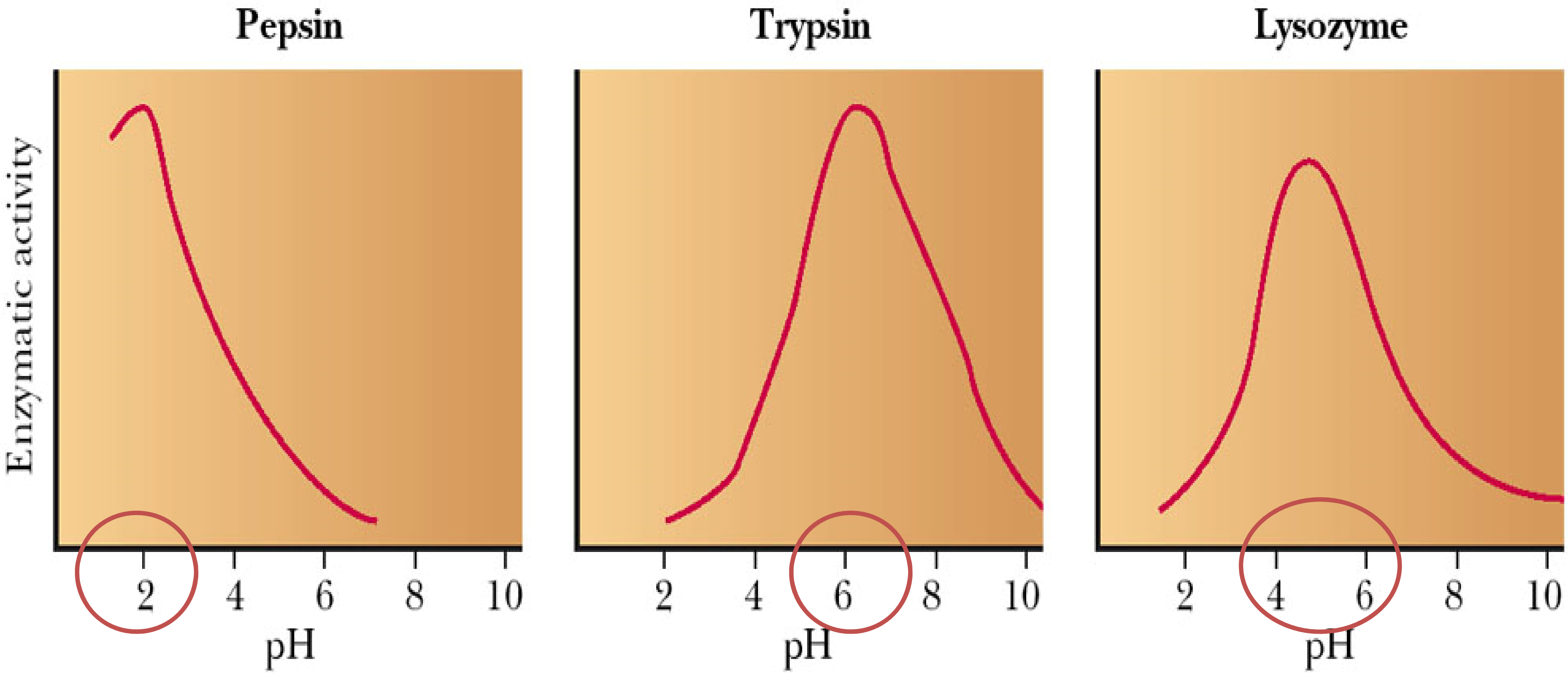
The pKa is the numerical measure of acid strength: The smaller the pKa value, the stronger the acid.

Table 2.6

Dissociation Constants of Some Acids

Acid	HA	A^-	K_a	pK_a
Pyruvic acid	$CH_3COCOOH$	CH_3COCOO^-	3.16×10^{-3}	2.50
Formic acid	$HCOOH$	$HCOO^-$	1.78×10^{-4}	3.75
Lactic acid	$CH_3CHOHCOOH$	$CH_3CHOHCOO^-$	1.38×10^{-4}	3.86
Benzoic acid	C_6H_5COOH	$C_6H_5COO^-$	6.46×10^{-5}	4.19
Acetic acid	CH_3COOH	CH_3COO^-	1.76×10^{-5}	4.76
Ammonium ion	NH_4^+	NH_3	5.6×10^{-10}	9.25
Oxalic acid (1)	HOOC—COOH	HOOC—COO^-	5.9×10^{-2}	1.23
Oxalic acid (2)	HOOC—COO^-	$^-$OOC—COO^-	6.4×10^{-5}	4.19
Malonic acid (1)	HOOC—CH_2—COOH	HOOC—CH_2—COO^-	1.49×10^{-3}	2.83
Malonic acid (2)	HOOC—CH_2—COO^-	$^-$OOC—CH_2—COO^-	2.03×10^{-6}	5.69
Malic acid (1)	HOOC—CH_2—CHOH—COOH	HOOC—CH_2—CHOH—COO^-	3.98×10^{-4}	3.40
Malic acid (2)	HOOC—CH_2—CHOH—COO^-	$^-$OOC—CH_2—CHOH—COO^-	5.5×10^{-6}	5.26
Succinic acid (1)	HOOC—CH_2—CH_2—COOH	HOOC—CH_2—CH_2—COO^-	6.17×10^{-5}	4.21
Succinic acid (2)	HOOC—CH_2—CH_2—COO^-	$^-$OOC—CH_2—CH_2—COO^-	2.3×10^{-6}	5.63
Carbonic acid (1)	H_2CO_3	HCO_3^-	4.3×10^{-7}	6.37
Carbonic acid (2)	HCO_3^-	CO_3^{2-}	5.6×10^{-11}	10.20
Citric acid (1)	HOOC—CH_2—C(OH) (COOH) —CH_2—COOH	HOOC—CH_2—C(OH) (COOH) —CH_2—COO^-	8.14×10^{-4}	3.09
Citric acid (2)	HOOC—CH_2—C(OH) (COOH) —CH_2—COO^-	$^-$OOC—CH_2—C(OH)(COOH) —CH_2—COO^-	1.78×10^{-5}	4.75
Citric acid (3)	$^-$OOC—CH_2—C(OH) (COOH) —CH_2—COO^-	$^-$OOC—CH_2—C(OH) (COO^-)—CH_2—COO^-	3.9×10^{-6}	5.41
Phosphoric acid (1)	H_3PO_4	$H_2PO^-_4$	7.25×10^{-3}	2.14
Phosphoric acid (2)	$H_2PO_4^-$	HPO_4^{2-}	6.31×10^{-8}	7.20
Phosphoric acid (3)	HPO_4^{2-}	PO_4^{3-}	3.98×10^{-13}	12.40

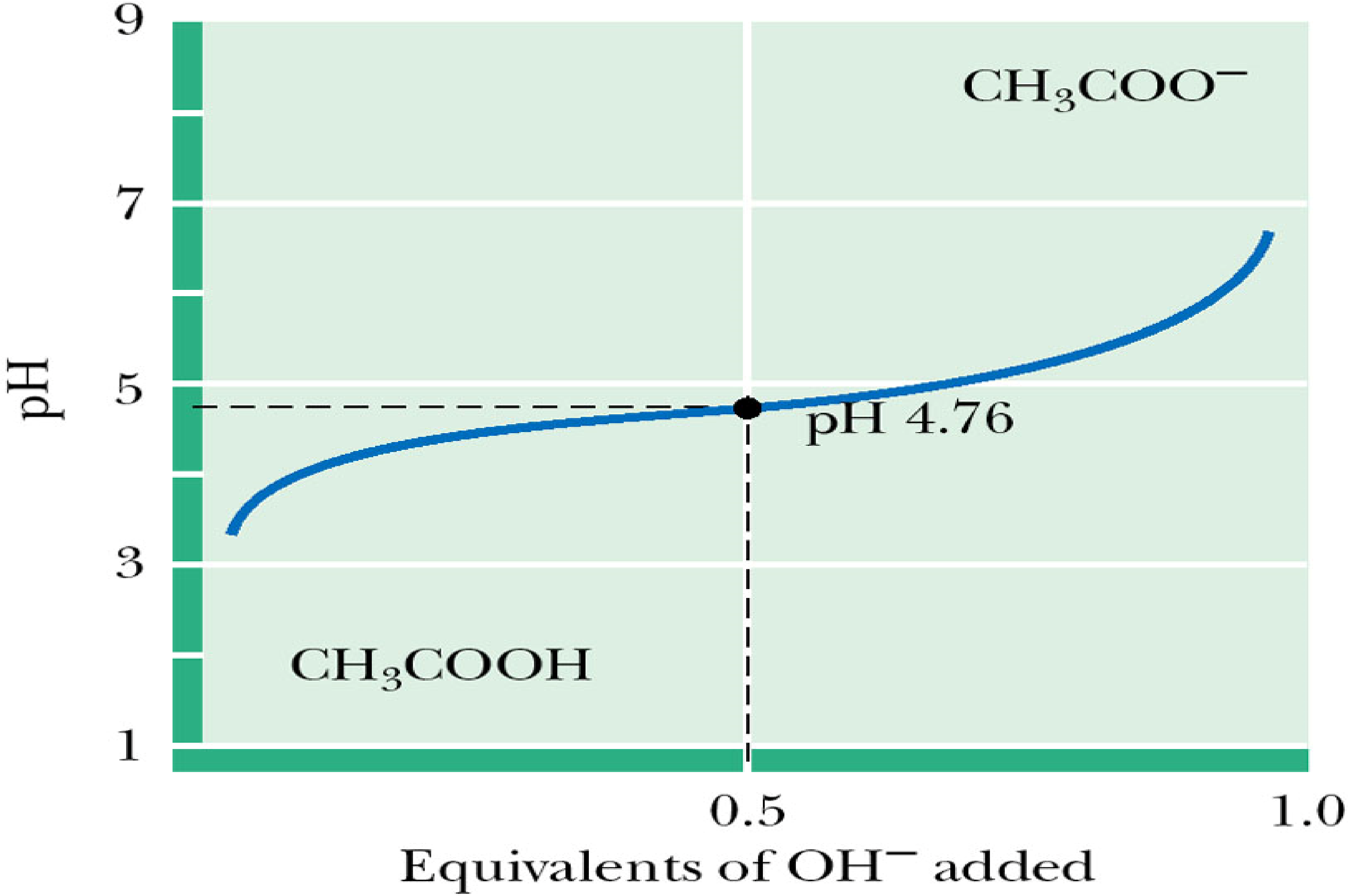
pH versus enzymatic activity



2.4 Titration Curves:

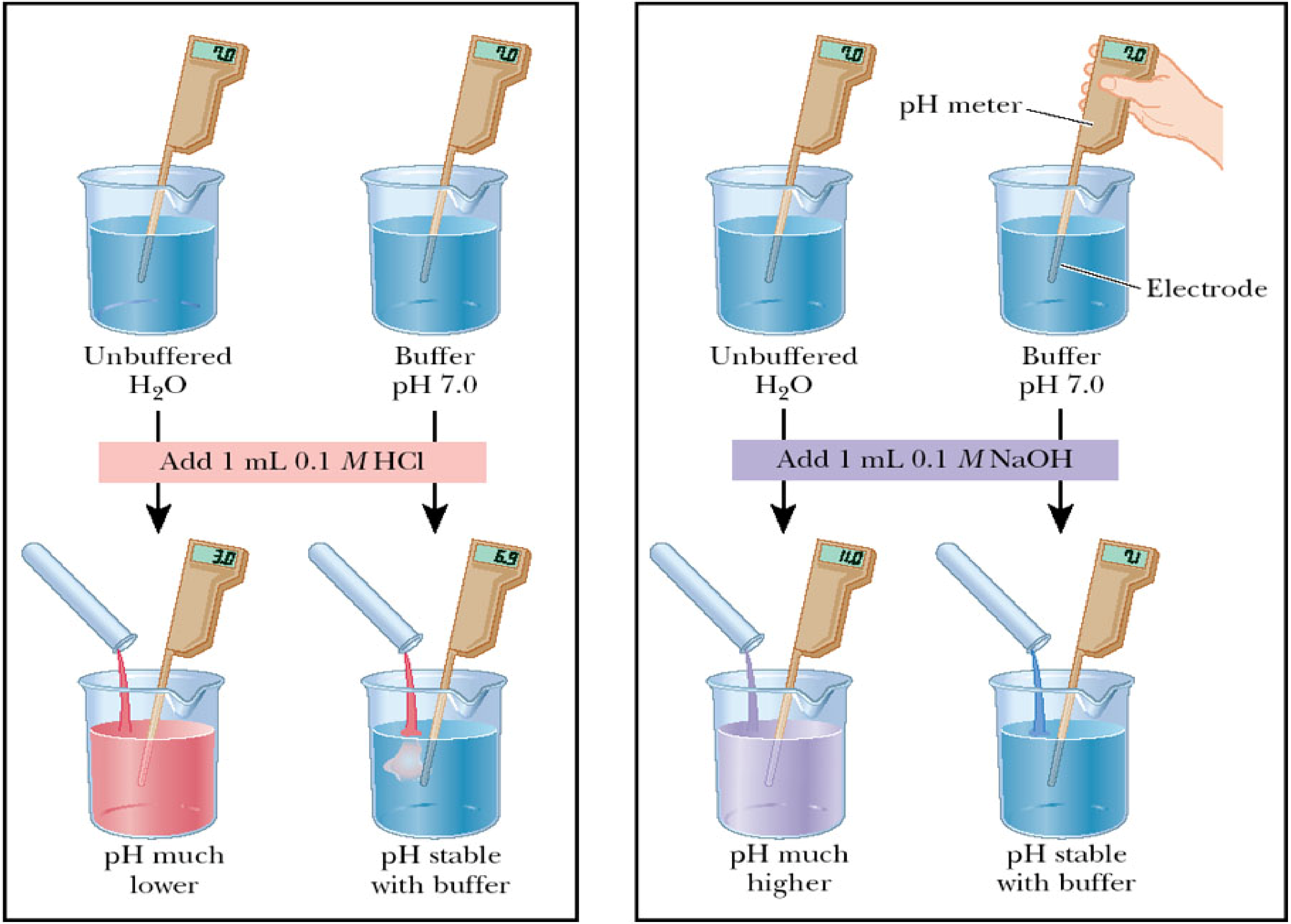
- In an aqueous solution, the relative concentrations of a weak acid and its conjugate base can be related to the titration curve of that acid.
- In the region of the titration curve in which the pH changes very little upon addition of acid or base, the acid/base concentration ratio varies within a fairly narrow range (10:1 at one extreme and 1:10 at the other).
- Equivalence point: the point in the titration at which the acid is exactly neutralized.

Titration curve for acetic acid. The pKa = 4.76



2.5 Buffers:

- Buffer solutions is characterized by their tendency to resist a change in pH on the addition of relatively small amounts of acid or base
- The control of pH by buffers depends on the fact that their compositions reflect the acid/base concentration ratio in the region of the titration curve in which there is little change in pH.
- Buffers required for experimental system to maintain stable pH value.
- Physiological buffers such as bicarbonate blood buffer or phosphate buffer, help maintain physiological pH.


7.0
7.0
Unbuffered
H_2O
Buffer
pH 7.0
Add 1 mL 0.1 *M* HCl
3.0
6.9
pH much
lower
pH stable
with buffer
7.0
7.0
pH meter
Electrode
Unbuffered
H_2O
Buffer
pH 7.0
Add 1 mL 0.1 *M* NaOH
11.0
7.1
pH much
higher
pH stable
with buffer

The relationship between the titration curve and buffering action in H2PO4 -.
a)The titration curve of H2PO4 -, showing the buffer region for the H2PO4 -/HPO4 2- pair.

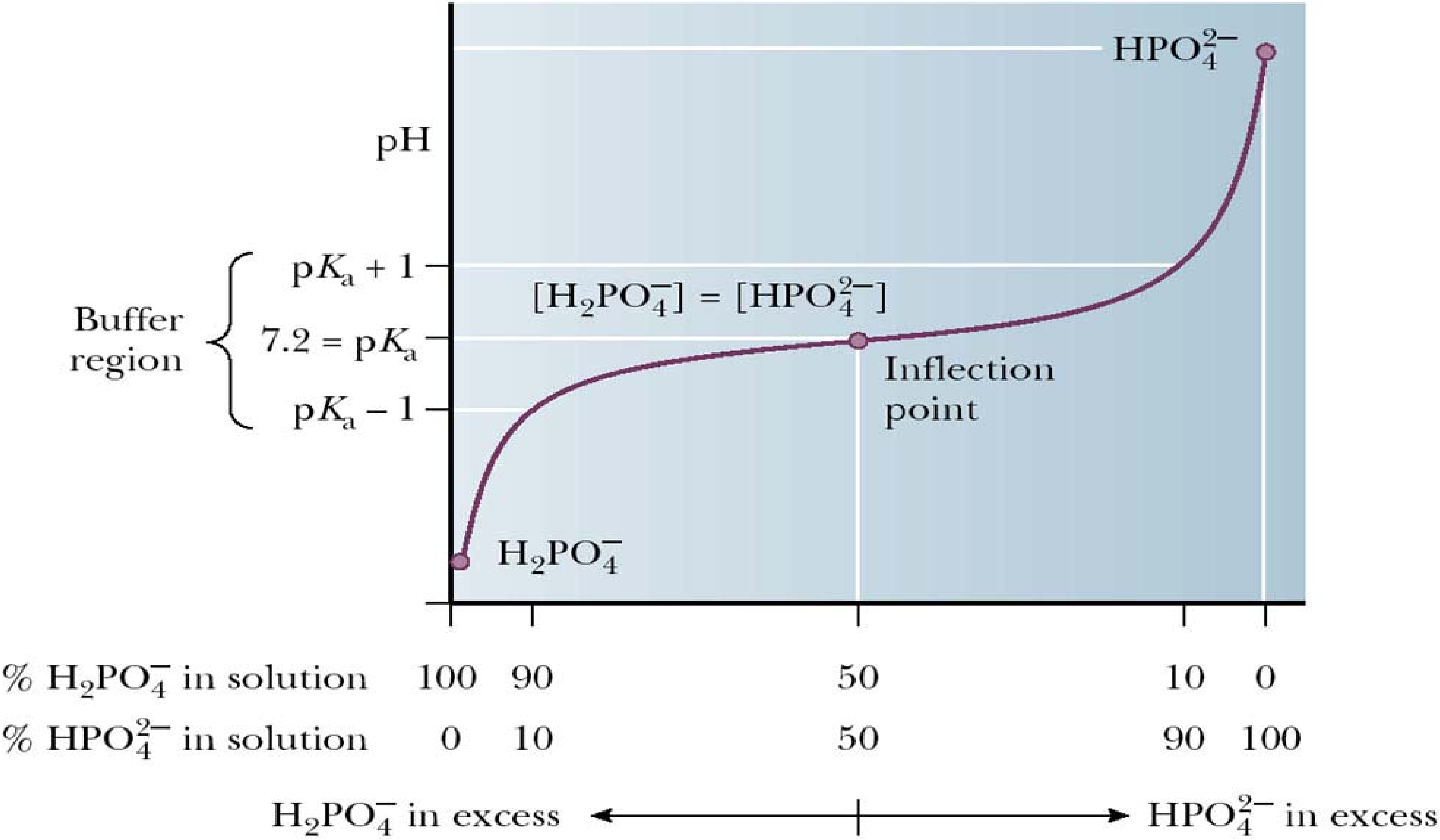
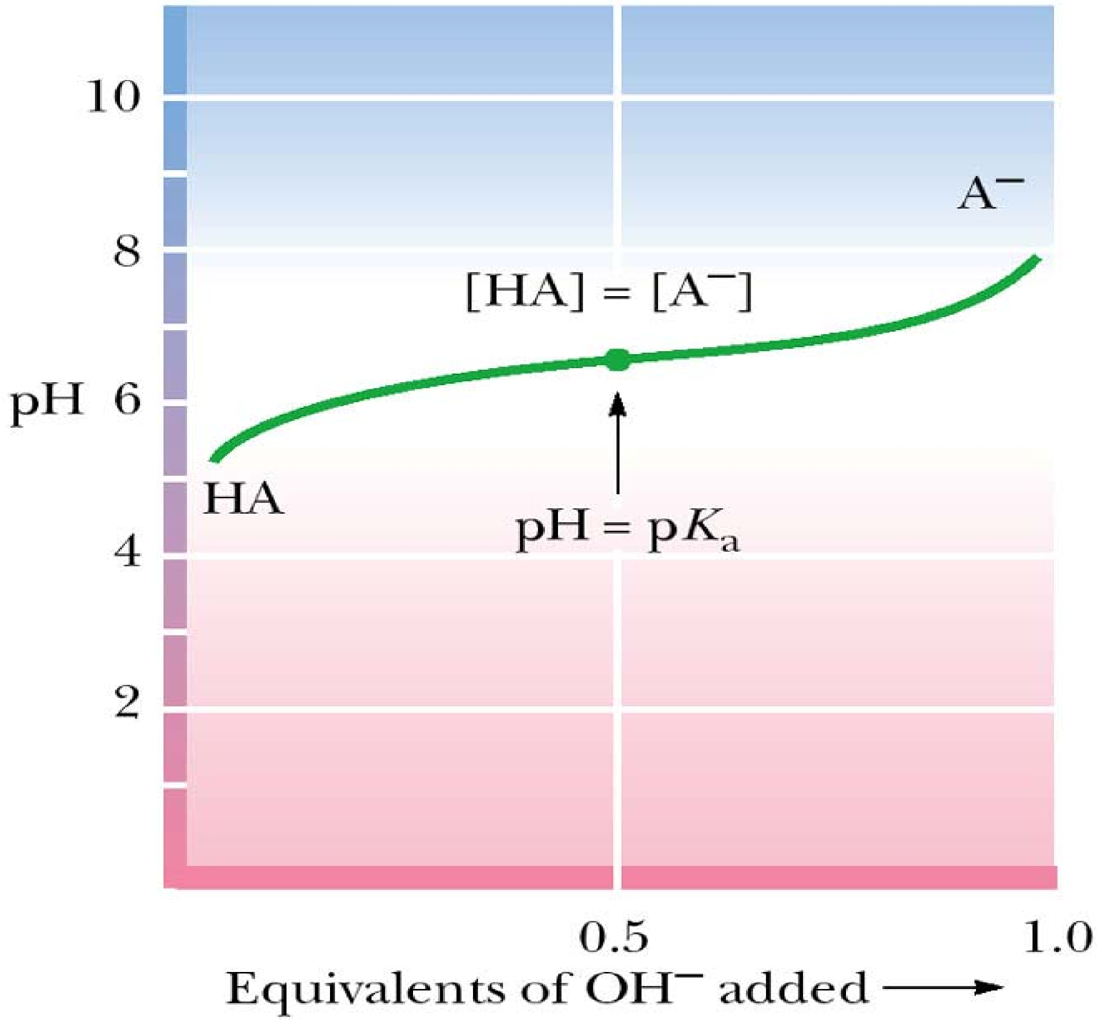


Table 2.7

pH Values and Base/Acid Ratios for Buffers

If the pH equals	The ratio of base form/acid form equals
$pK_a - 3$	1/1000
$pK_a - 2$	1/100
$pK_a - 1$	1/10
pK_a	1/1
$pK_a + 1$	10/1
$pK_a + 2$	100/1
$pK_a + 3$	1000/1



Buffer action:

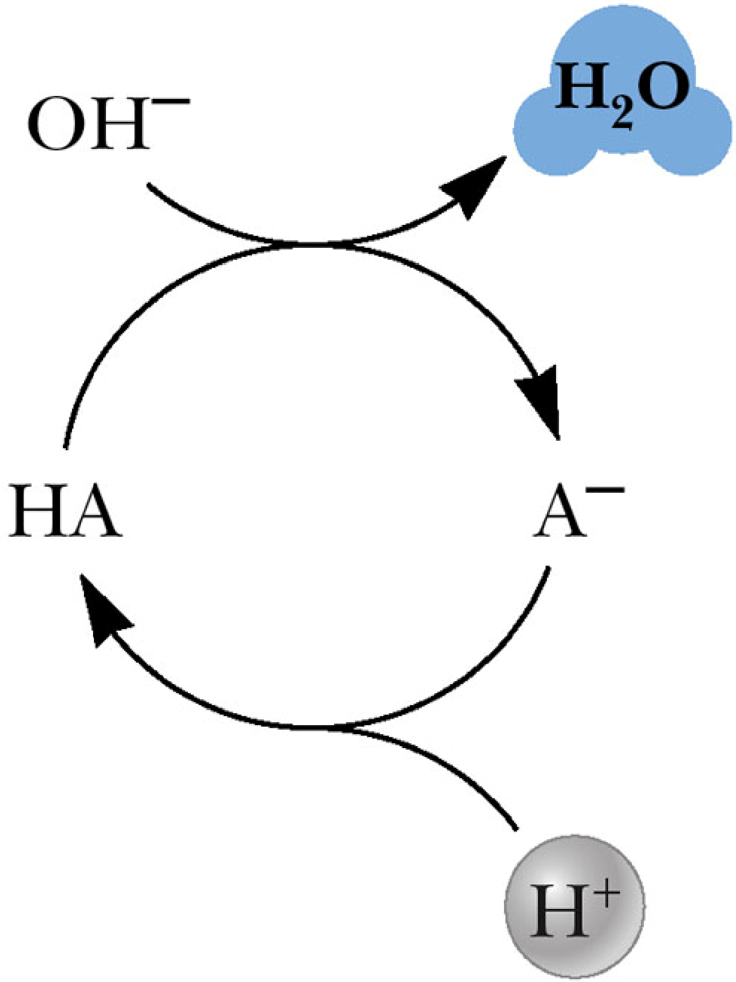
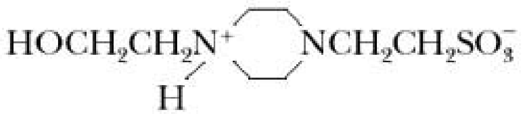
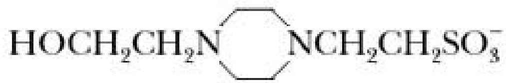
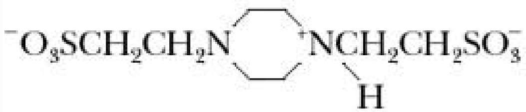
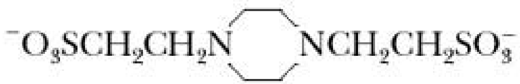


Table 2.8

Acid and Base Forms of Some Useful Biochemical Buffers

Acid Form		Base Form	pK_a
TRIS—H^+ (protonated form) $(HOCH_2)_3CNH_3^+$	N—*tris*[hydroxymethyl]aminomethane (TRIS) $\rightleftharpoons$	TRIS (free amine) $(HOCH_2)_3CNH_2$	8.3
$^-$TES—H^+ (zwitterionic form) $(HOCH_2)_3C\overset{+}{N}H_2CH_2CH_2SO_3^-$	N—*tris*[hydroxymethyl]methyl-2-aminoethane sulfonate (TES) $\rightleftharpoons$	$^-$TES (anionic form) $(HOCH_2)_3CNHCH_2CH_2SO_3^-$	7.55
$^-$HEPES—H^+ (zwitterionic form) 	N—2—hydroxyethylpiperazine-N′-2-ethane sulfonate (HEPES) $\rightleftharpoons$	$^-$HEPES (anionic form) 	7.55
$^-$MOPS—H^+ (zwitterionic form) 	3—[N—morpholino]propane-sulfonic acid (MOPS) $\rightleftharpoons$	$^-$MOPS (anionic form) 	7.2
$^{2-}$PIPES—H^+ (protonated dianion) 	Piperazine—N,N′-*bis*[2-ethanesulfonic acid] (PIPES) $\rightleftharpoons$	$^{2-}$PIPES (dianion) 	6.8

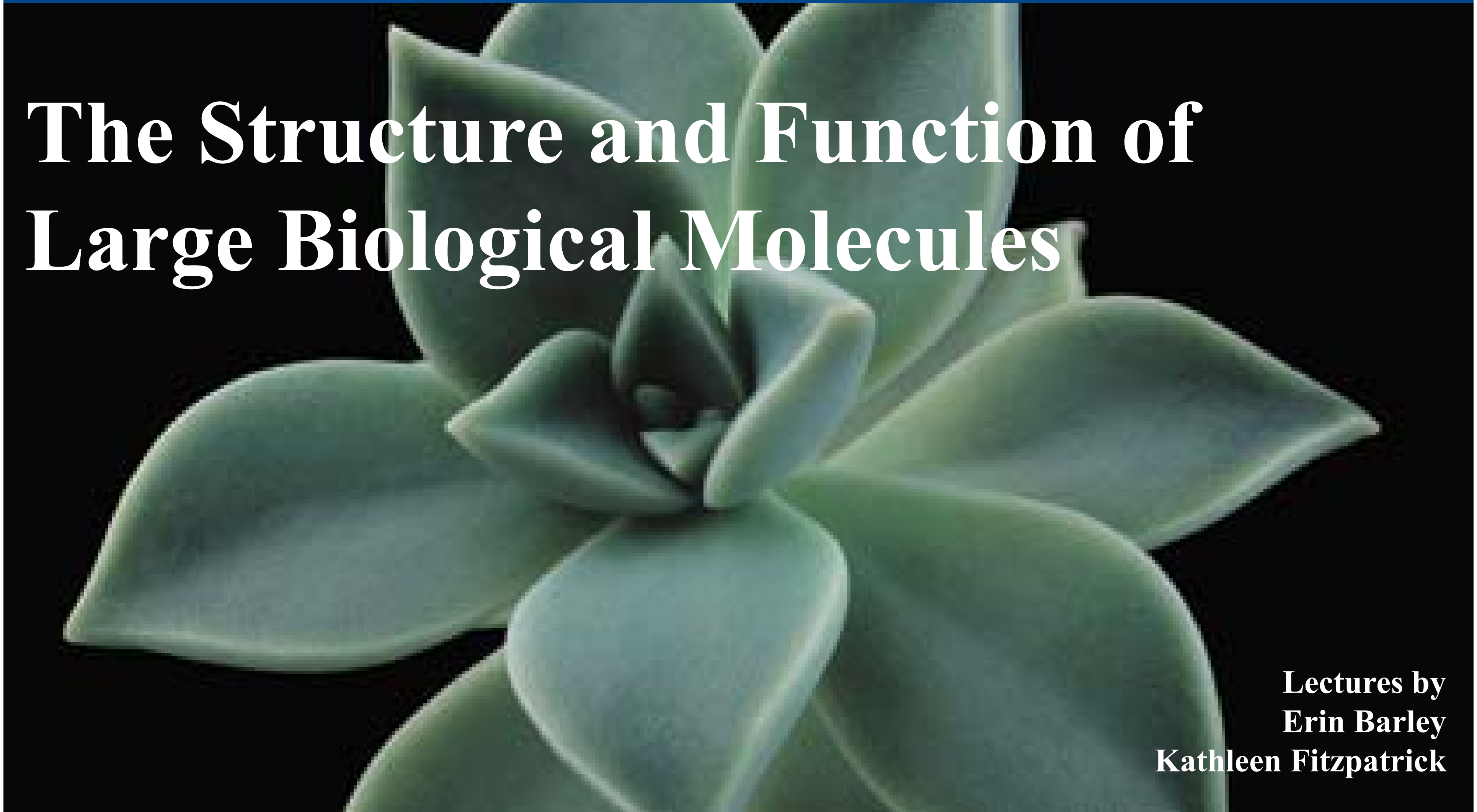
LECTURE PRESENTATIONS

For CAMPBELL BIOLOGY, NINTH EDITION

Jane B. Reece, Lisa A. Urry, Michael L. Cain, Steven A. Wasserman, Peter V. Minorsky, Robert B. Jackson

Chapter 5

The Structure and Function of Large Biological Molecules



Lectures by
Erin Barley
Kathleen Fitzpatrick

Overview: The Molecules of Life

- All living things are made up of four classes of large biological molecules: carbohydrates, lipids, proteins, and nucleic acids
- **Macromolecules** are large molecules composed of thousands of covalently connected atoms
- Molecular structure and function are inseparable

Concept 5.1: Macromolecules are polymers, built from monomers

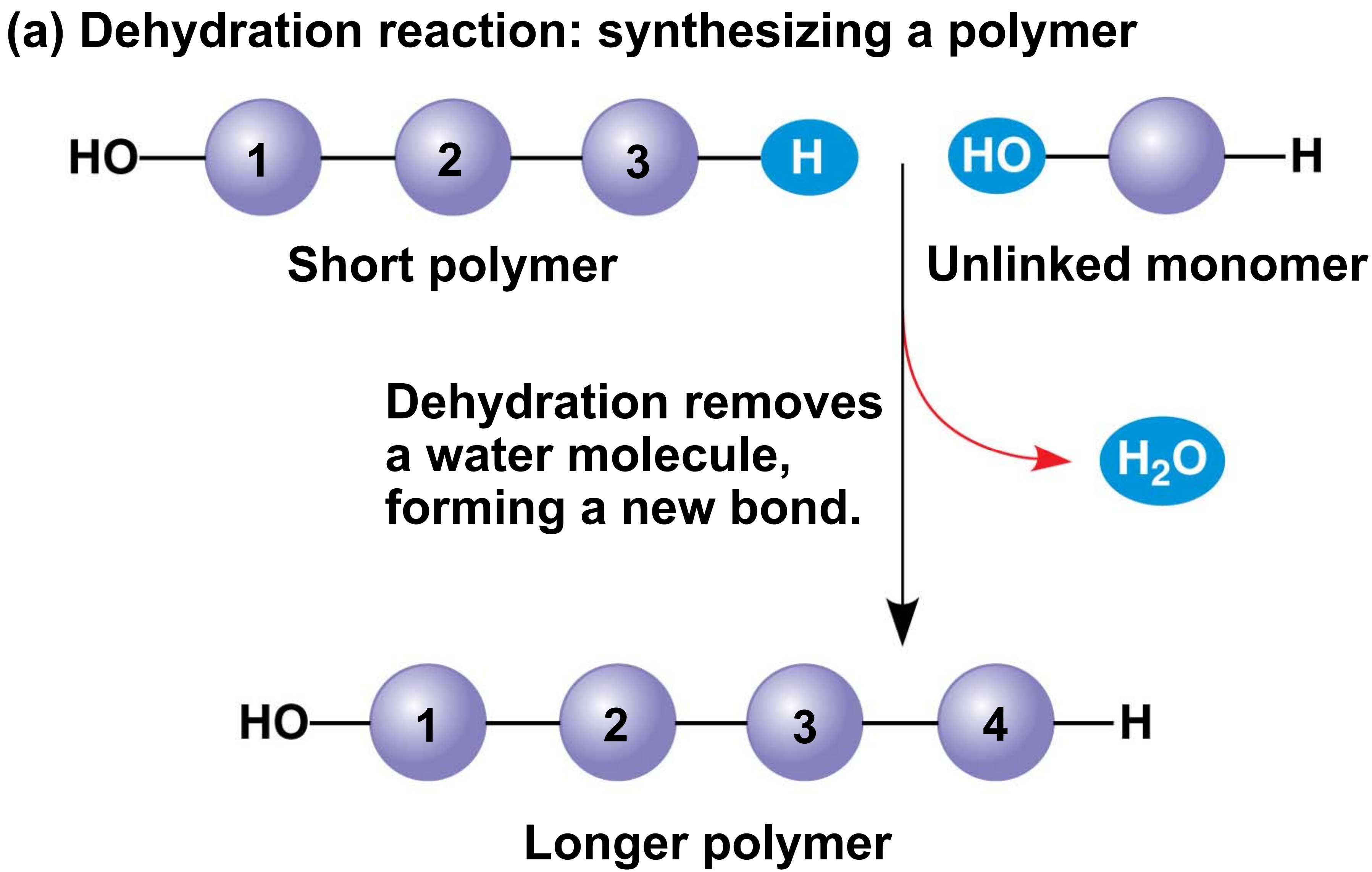
- A **polymer** is a long molecule consisting of many similar building blocks
- These small building-block molecules are called **monomers**
- Three of the four classes of life's organic molecules are polymers
  - Carbohydrates
  - Proteins
  - Nucleic acids

The Synthesis and Breakdown of Polymers

- A **dehydration reaction** occurs when two monomers bond together through the loss of a water molecule
- Polymers are disassembled to monomers by **hydrolysis**, a reaction that is essentially the reverse of the dehydration reaction

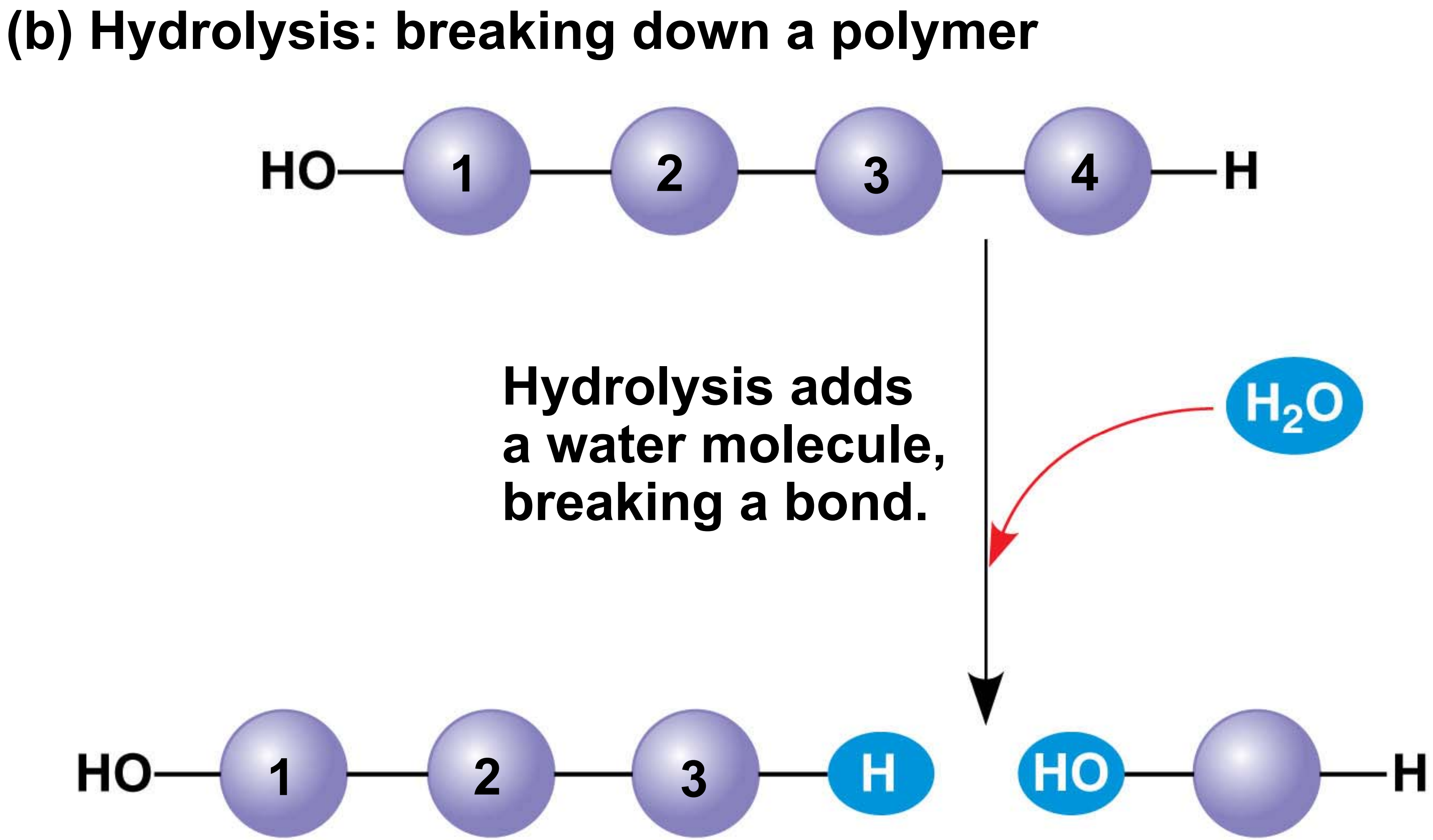
PLAY Animation: Polymers

Figure 5.2a



(a) Dehydration reaction: synthesizing a polymer
HO
1
2
3
H
Short polymer
HO
H
Unlinked monomer
Dehydration removes a water molecule, forming a new bond.
H_2O
HO
1
2
3
4
H
Longer polymer

Figure 5.2b



(b) Hydrolysis: breaking down a polymer
HO
1
2
3
4
H
Hydrolysis adds
a water molecule,
breaking a bond.
H_2O
HO
1
2
3
H
HO
H

The Diversity of Polymers

- Each cell has thousands of different macromolecules
- Macromolecules vary among cells of an organism, vary more within a species, and vary even more between species
- An immense variety of polymers can be built from a small set of monomers

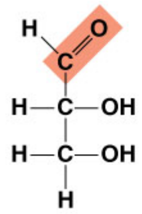
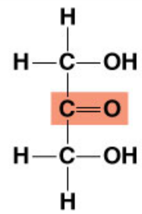
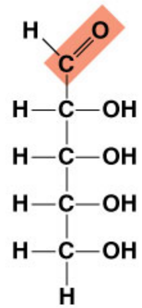
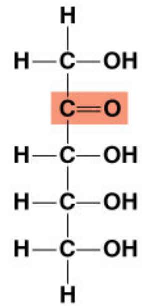
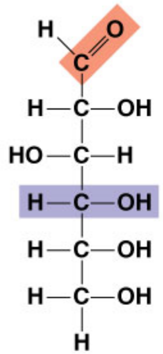
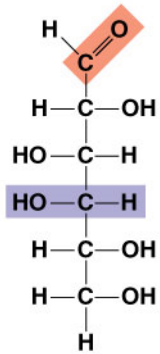
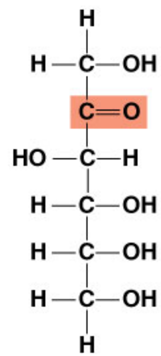
Concept 5.2: Carbohydrates serve as fuel and building material

- **Carbohydrates** include sugars and the polymers of sugars
- The simplest carbohydrates are monosaccharides, or single sugars
- Carbohydrate macromolecules are polysaccharides, polymers composed of many sugar building blocks

Sugars

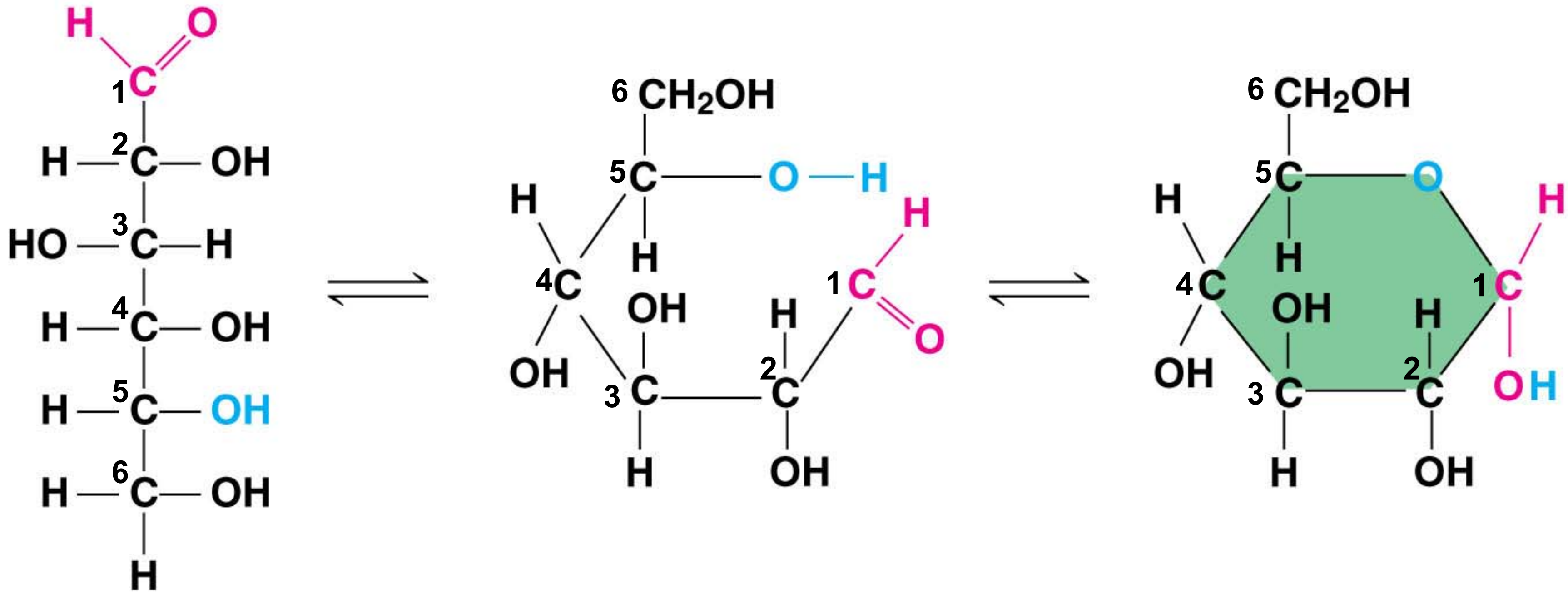
- **Monosaccharides** have molecular formulas that are usually multiples of CH_2O
- Glucose ($C_6H_{12}O_6$) is the most common monosaccharide
- Monosaccharides are classified by
  - The location of the carbonyl group (as aldose or ketose)
  - The number of carbons in the carbon skeleton

Figure 5.3

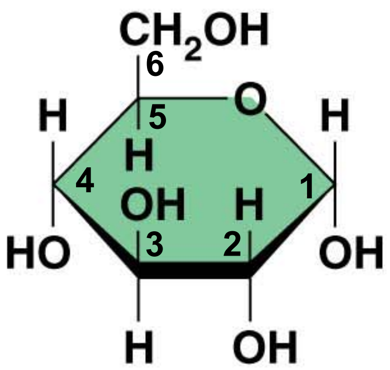
Aldoses (Aldehyde Sugars)	Ketoses (Ketone Sugars)
Trioses: 3-carbon sugars ($C_3H_6O_3$)	
 Glyceraldehyde	 Dihydroxyacetone
Pentoses: 5-carbon sugars ($C_5H_{10}O_5$)	
 Ribose	 Ribulose
Hexoses: 6-carbon sugars ($C_6H_{12}O_6$)	
 Glucose  Galactose	 Fructose

- Though often drawn as linear skeletons, in aqueous solutions many sugars form rings
- Monosaccharides serve as a major fuel for cells and as raw material for building molecules

Figure 5.4



(a) Linear and ring forms

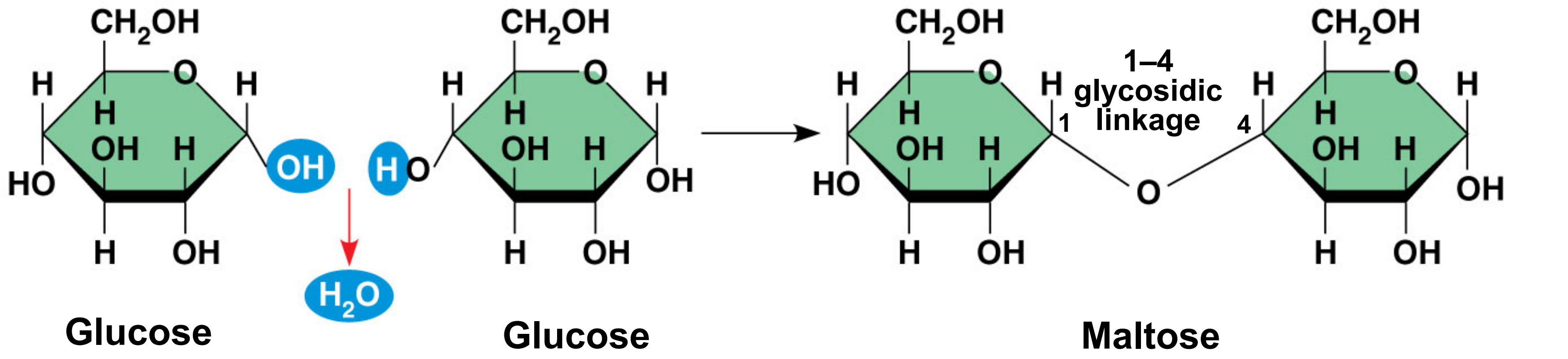


(b) Abbreviated ring structure

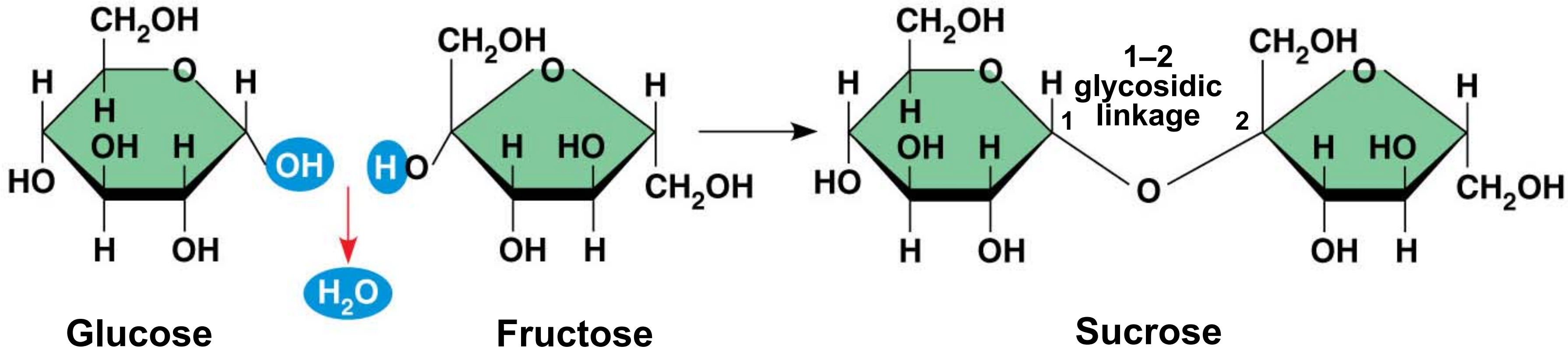
- A **disaccharide** is formed when a dehydration reaction joins two monosaccharides
- This covalent bond is called a **glycosidic linkage**

PLAY Animation: Disaccharide

Figure 5.5



(a) Dehydration reaction in the synthesis of maltose



(b) Dehydration reaction in the synthesis of sucrose

Polysaccharides

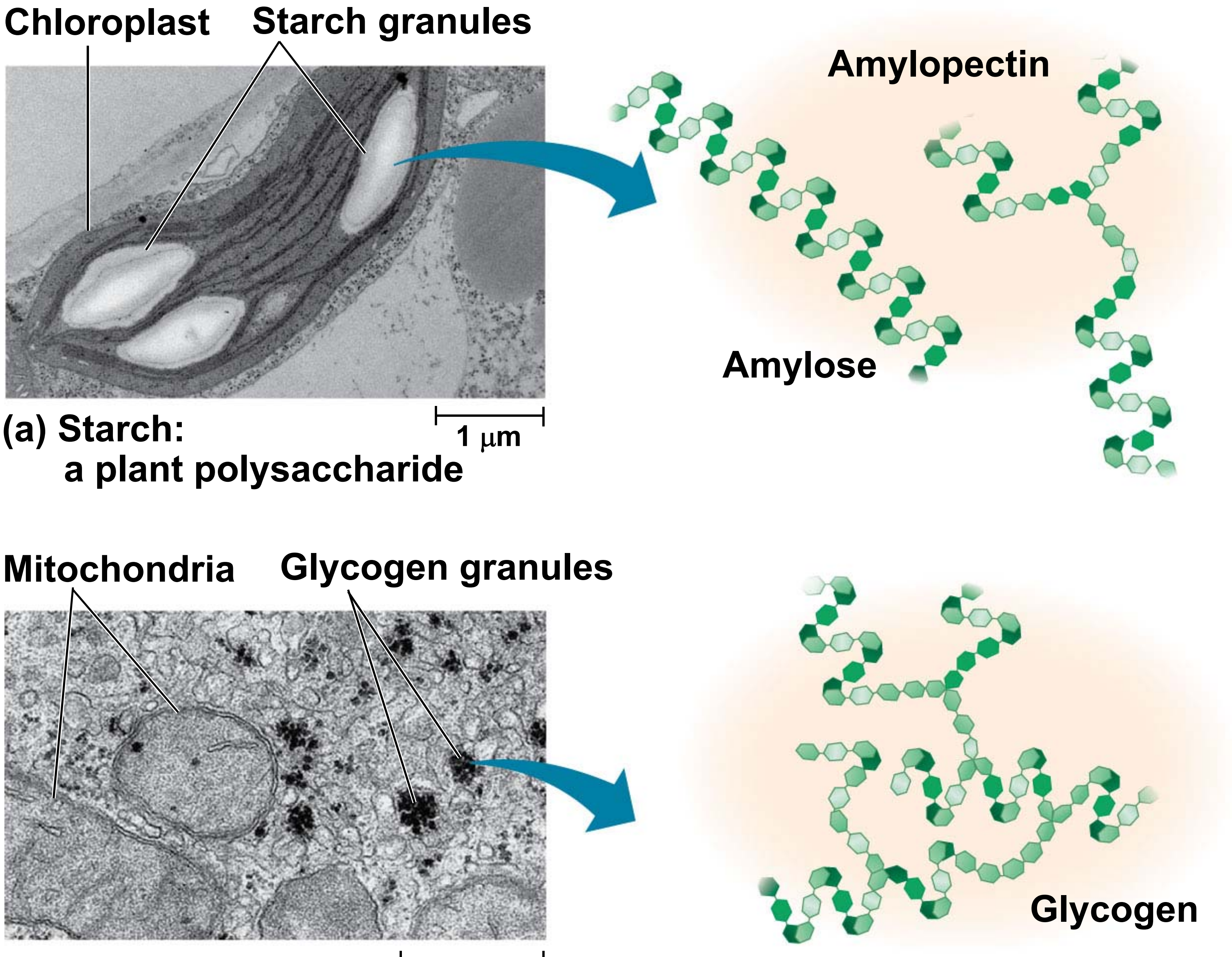
- **Polysaccharides**, the polymers of sugars, have storage and structural roles
- The structure and function of a polysaccharide are determined by its sugar monomers and the positions of glycosidic linkages

Storage Polysaccharides

- **Starch**, a storage polysaccharide of plants, consists entirely of glucose monomers
- Plants store surplus starch as granules within chloroplasts and other plastids
- The simplest form of starch is amylose

- **Glycogen** is a storage polysaccharide in animals
- Humans and other vertebrates store glycogen mainly in liver and muscle cells

Figure 5.6



(a) Starch: a plant polysaccharide

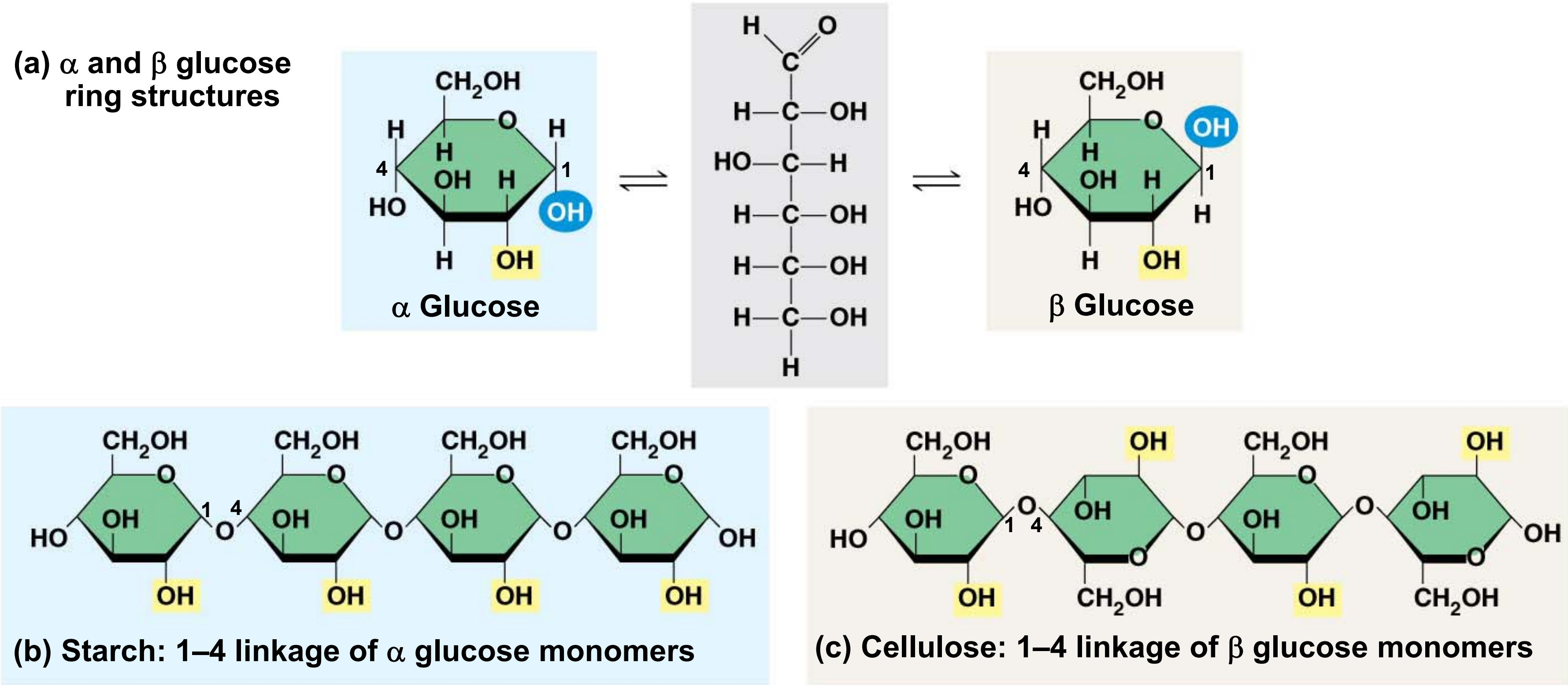
(b) Glycogen: an animal polysaccharide

Structural Polysaccharides

- The polysaccharide **cellulose** is a major component of the tough wall of plant cells
- Like starch, cellulose is a polymer of glucose, but the glycosidic linkages differ
- The difference is based on two ring forms for glucose: alpha (α) and beta (β)

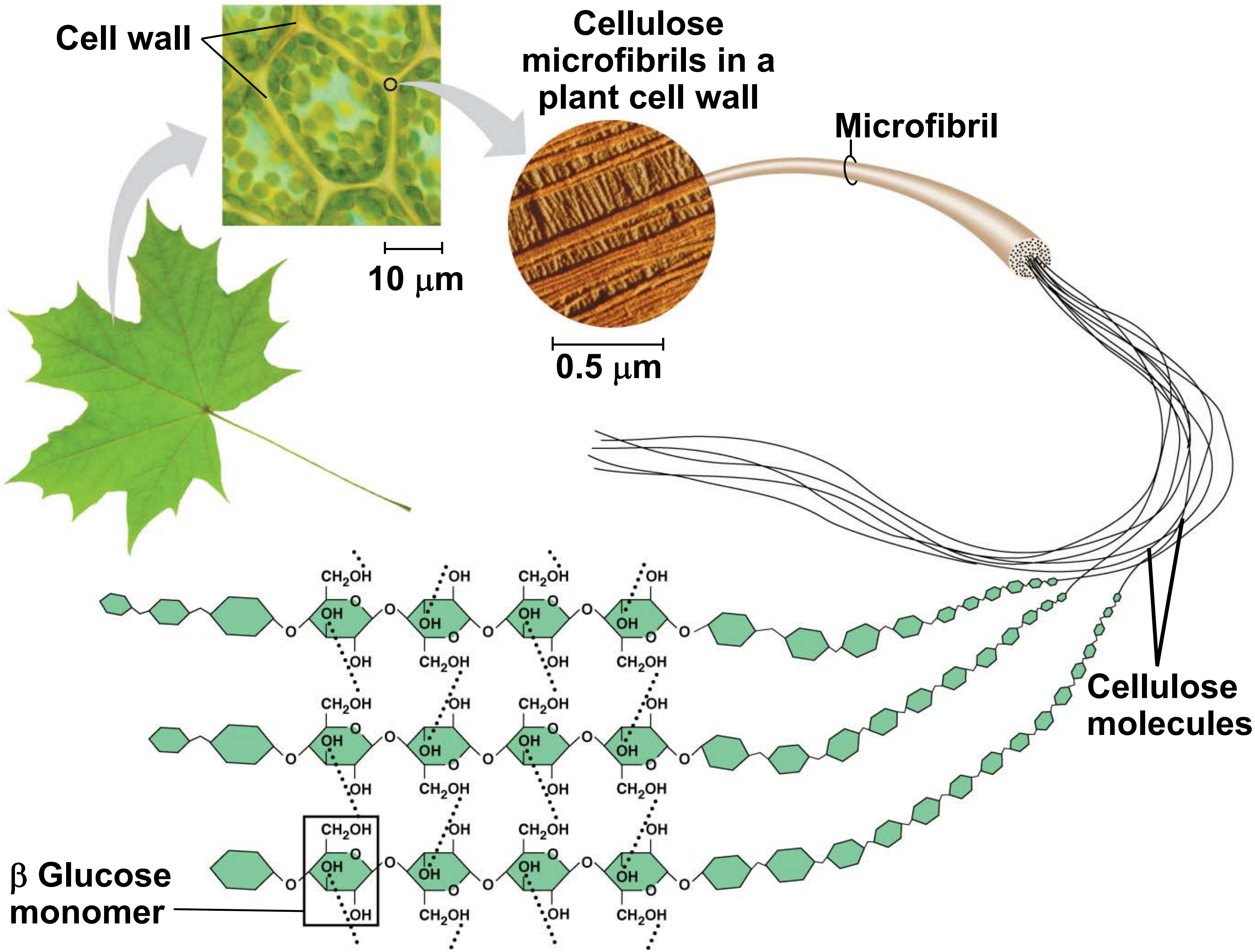
PLAY Animation: Polysaccharides

Figure 5.7


(a) α and β glucose ring structures
α Glucose
β Glucose
(b) Starch: 1–4 linkage of α glucose monomers
(c) Cellulose: 1–4 linkage of β glucose monomers

- Polymers with α glucose are helical
- Polymers with β glucose are straight
- In straight structures, H atoms on one strand can bond with OH groups on other strands
- Parallel cellulose molecules held together this way are grouped into microfibrils, which form strong building materials for plants

Figure 5.8

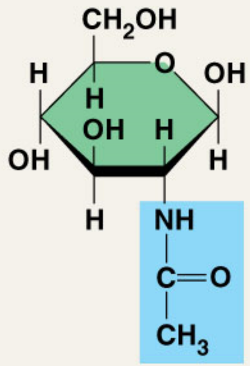


Cell wall
10 μm
Cellulose microfibrils in a plant cell wall
0.5 μm
Microfibril
Cellulose molecules
β Glucose monomer
CH2OH
OH
O

- Enzymes that digest starch by hydrolyzing α linkages can't hydrolyze β linkages in cellulose
- Cellulose in human food passes through the digestive tract as insoluble fiber
- Some microbes use enzymes to digest cellulose
- Many herbivores, from cows to termites, have symbiotic relationships with these microbes

- **Chitin**, another structural polysaccharide, is found in the exoskeleton of arthropods
- Chitin also provides structural support for the cell walls of many fungi

Figure 5.9



The structure of the chitin monomer

Chitin forms the exoskeleton of arthropods.

Chitin is used to make a strong and flexible surgical thread that decomposes after the wound or incision heals.

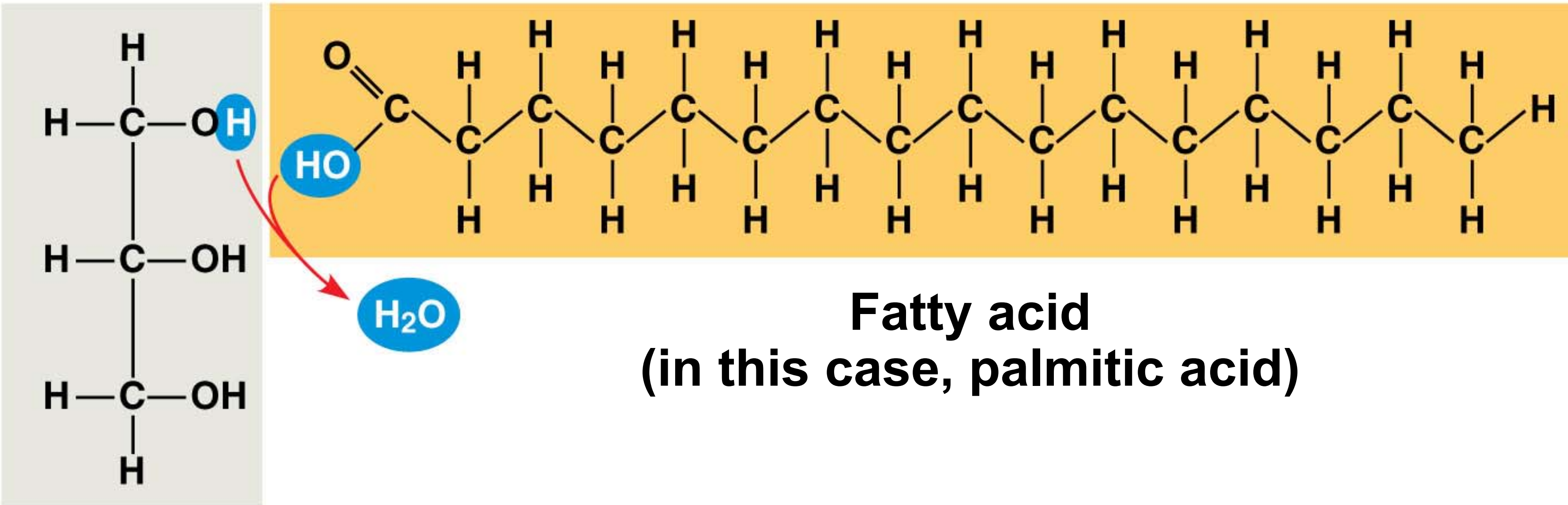
Concept 5.3: Lipids are a diverse group of hydrophobic molecules

- **Lipids** are the one class of large biological molecules that **do not form polymers**
- The unifying feature of lipids is having little or no affinity for water
- Lipids are hydrophobic because they consist mostly of hydrocarbons, which form nonpolar covalent bonds
- The most biologically important lipids are fats, phospholipids, and steroids

Fats

- **Fats** are constructed from two types of smaller molecules: glycerol and fatty acids
- Glycerol is a three-carbon alcohol with a hydroxyl group attached to each carbon
- A **fatty acid** consists of a carboxyl group attached to a long carbon skeleton

Figure 5.10a



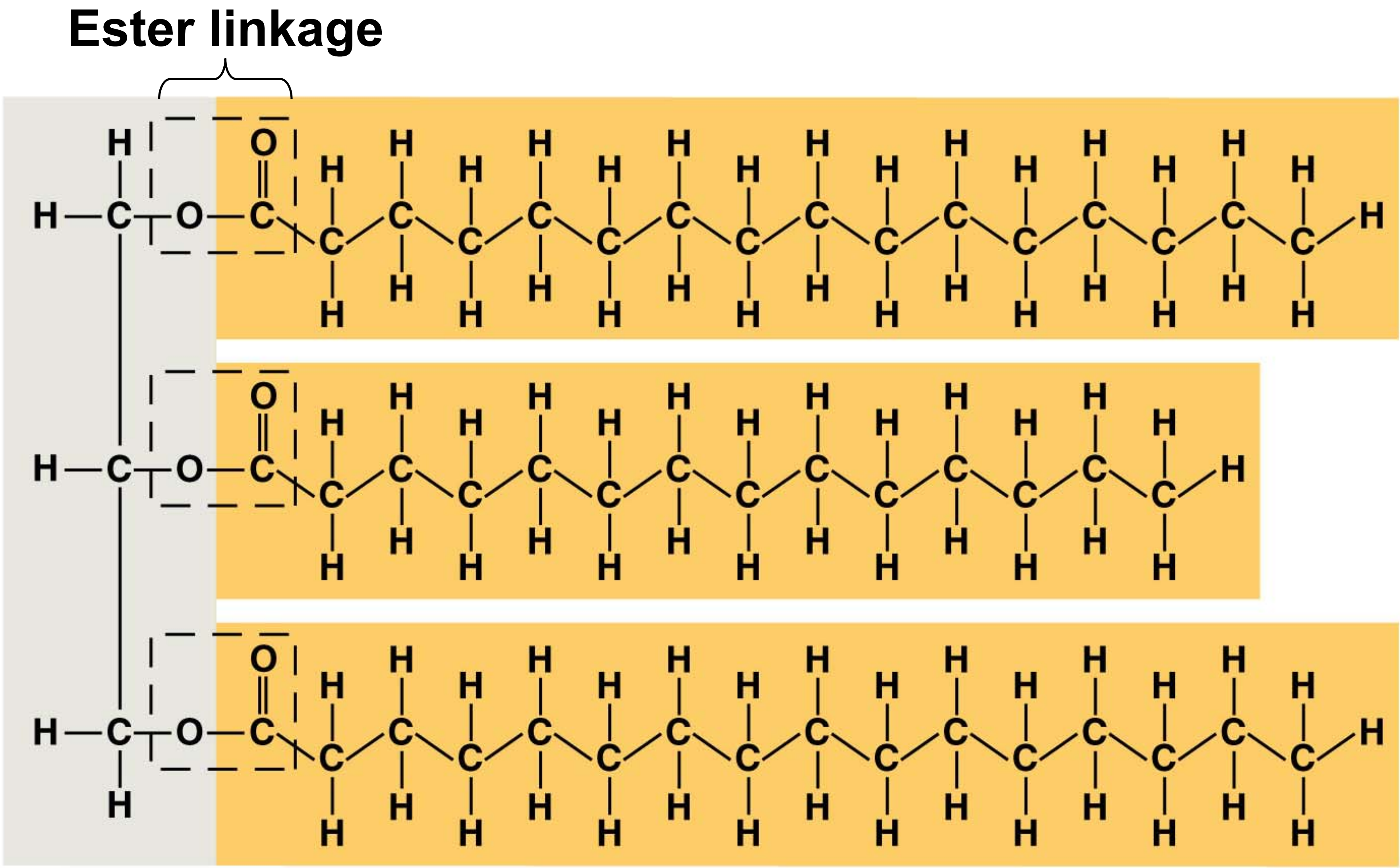
Fatty acid
(in this case, palmitic acid)

Glycerol

(a) One of three dehydration reactions in the synthesis of a fat

- Fats separate from water because water molecules form hydrogen bonds with each other and exclude the fats
- In a fat, three fatty acids are joined to glycerol by an ester linkage, creating a **triacylglycerol**, or triglyceride

Figure 5.10b

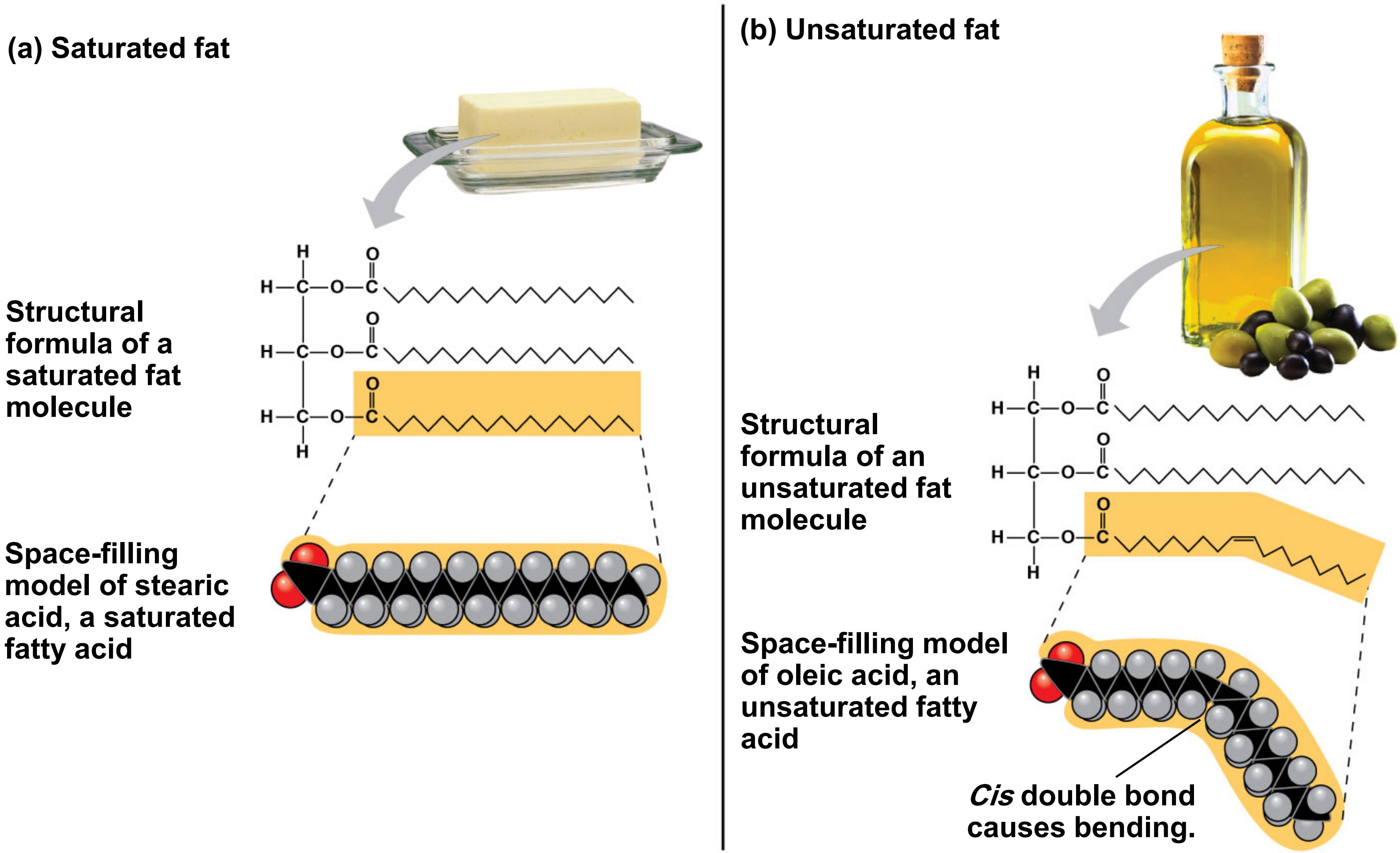


(b) Fat molecule (triacylglycerol)

- Fatty acids vary in length (number of carbons) and in the number and locations of double bonds
- **Saturated fatty acids** have the maximum number of hydrogen atoms possible and no double bonds
- **Unsaturated fatty acids** have one or more double bonds

PLAY Animation: Fats

Figure 5.11


(a) Saturated fat
Structural formula of a saturated fat molecule
Space-filling model of stearic acid, a saturated fatty acid
(b) Unsaturated fat
Structural formula of an unsaturated fat molecule
Space-filling model of oleic acid, an unsaturated fatty acid
Cis double bond causes bending.

- Fats made from saturated fatty acids are called saturated fats, and are solid at room temperature
- Most animal fats are saturated
- Fats made from unsaturated fatty acids are called unsaturated fats or oils, and are liquid at room temperature
- Plant fats and fish fats are usually unsaturated

- A diet rich in saturated fats may contribute to cardiovascular disease through plaque deposits
- Hydrogenation is the process of converting unsaturated fats to saturated fats by adding hydrogen
- Hydrogenating vegetable oils also creates unsaturated fats with *trans* double bonds
- These ***trans* fats** may contribute more than saturated fats to cardiovascular disease

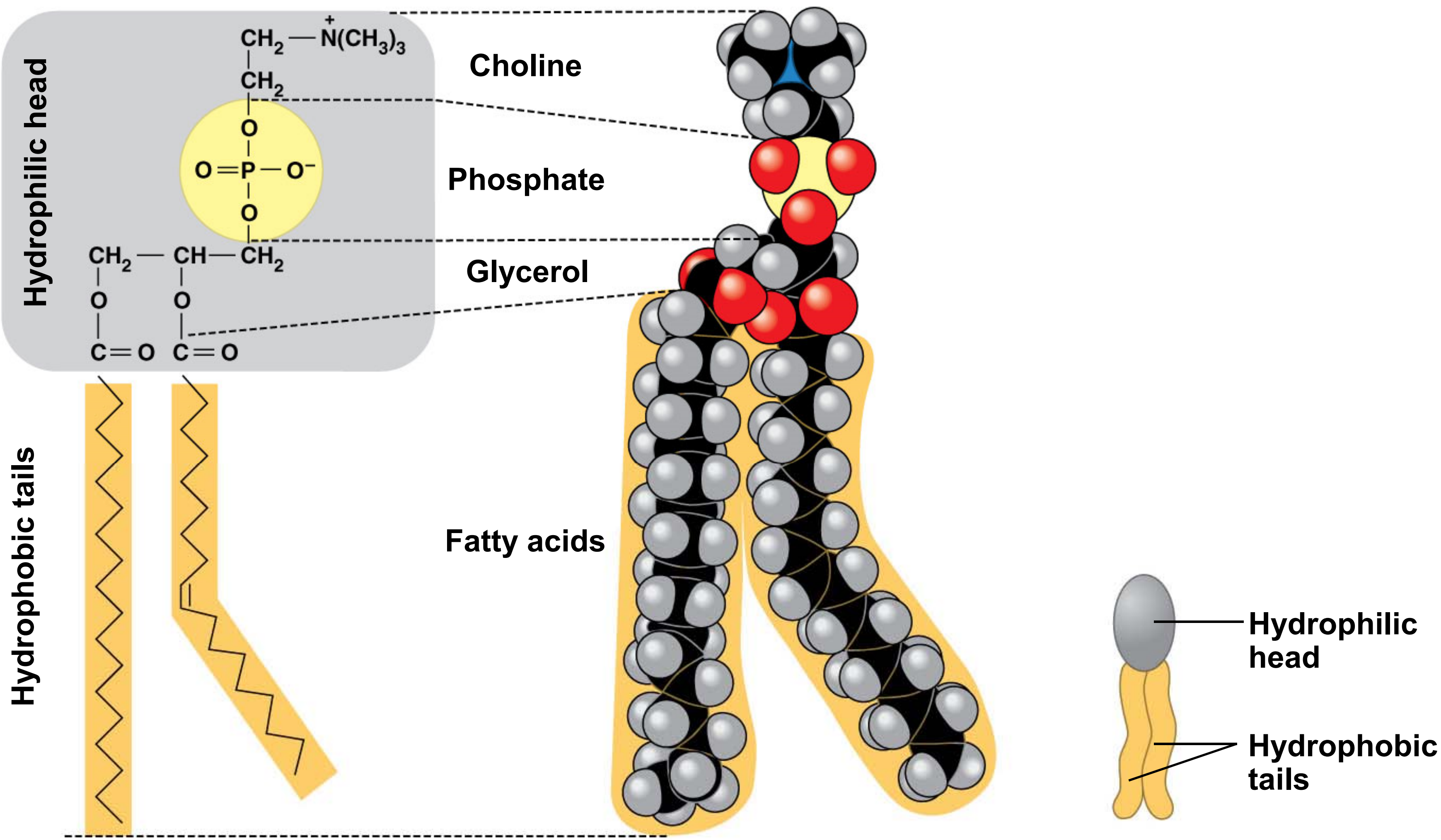
- Certain unsaturated fatty acids are not synthesized in the human body
- These must be supplied in the diet
- These essential fatty acids include the omega-3 fatty acids, required for normal growth, and thought to provide protection against cardiovascular disease

- The major function of fats is energy storage
- Humans and other mammals store their fat in adipose cells
- Adipose tissue also cushions vital organs and insulates the body

Phospholipids

- In a **phospholipid**, two fatty acids and a phosphate group are attached to glycerol
- The two fatty acid tails are hydrophobic, but the phosphate group and its attachments form a hydrophilic head

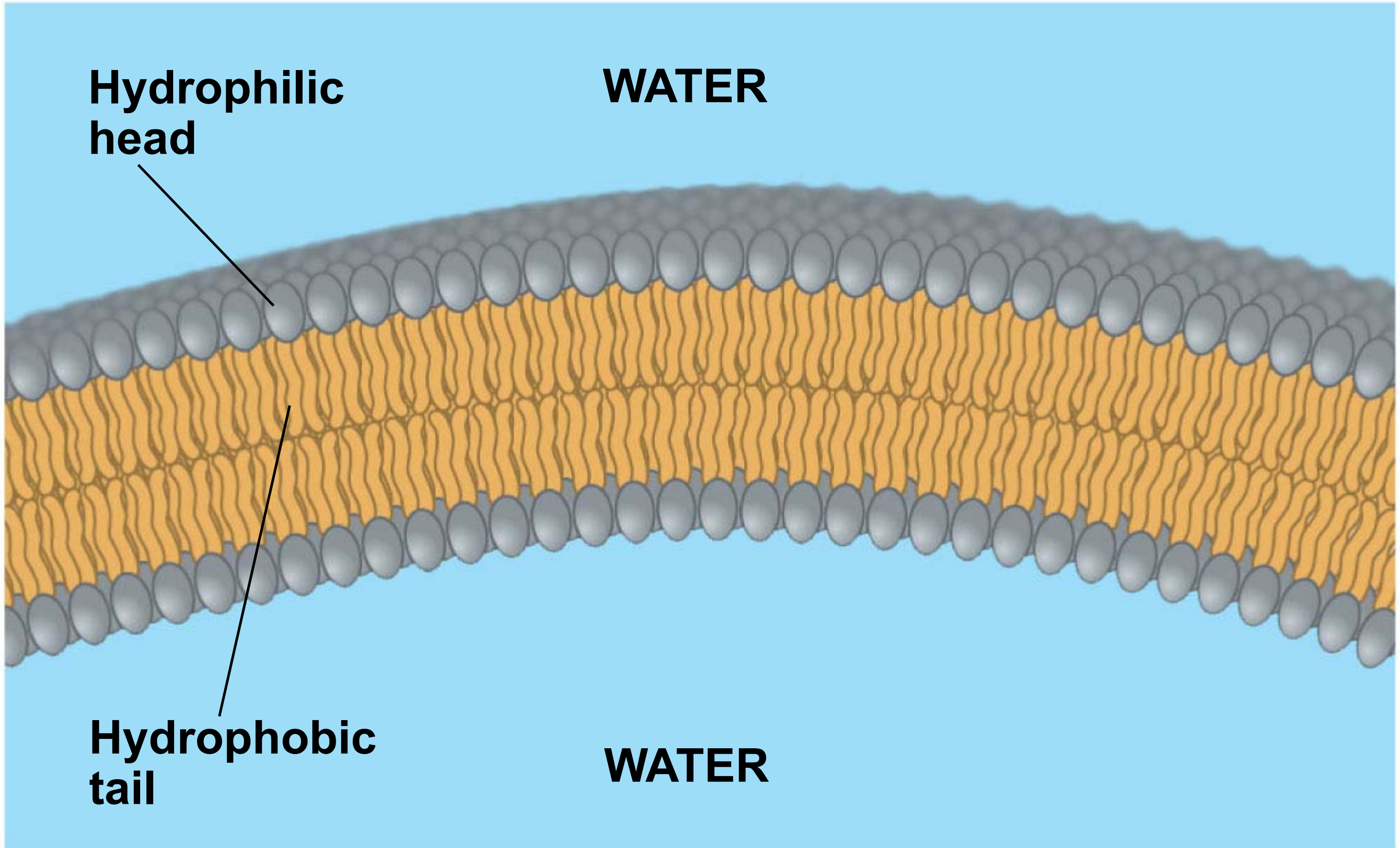
Figure 5.12



(a) Structural formula (b) Space-filling model (c) Phospholipid symbol

- When phospholipids are added to water, they self-assemble into a bilayer, with the hydrophobic tails pointing toward the interior
- The structure of phospholipids results in a bilayer arrangement found in cell membranes
- Phospholipids are the major component of all cell membranes

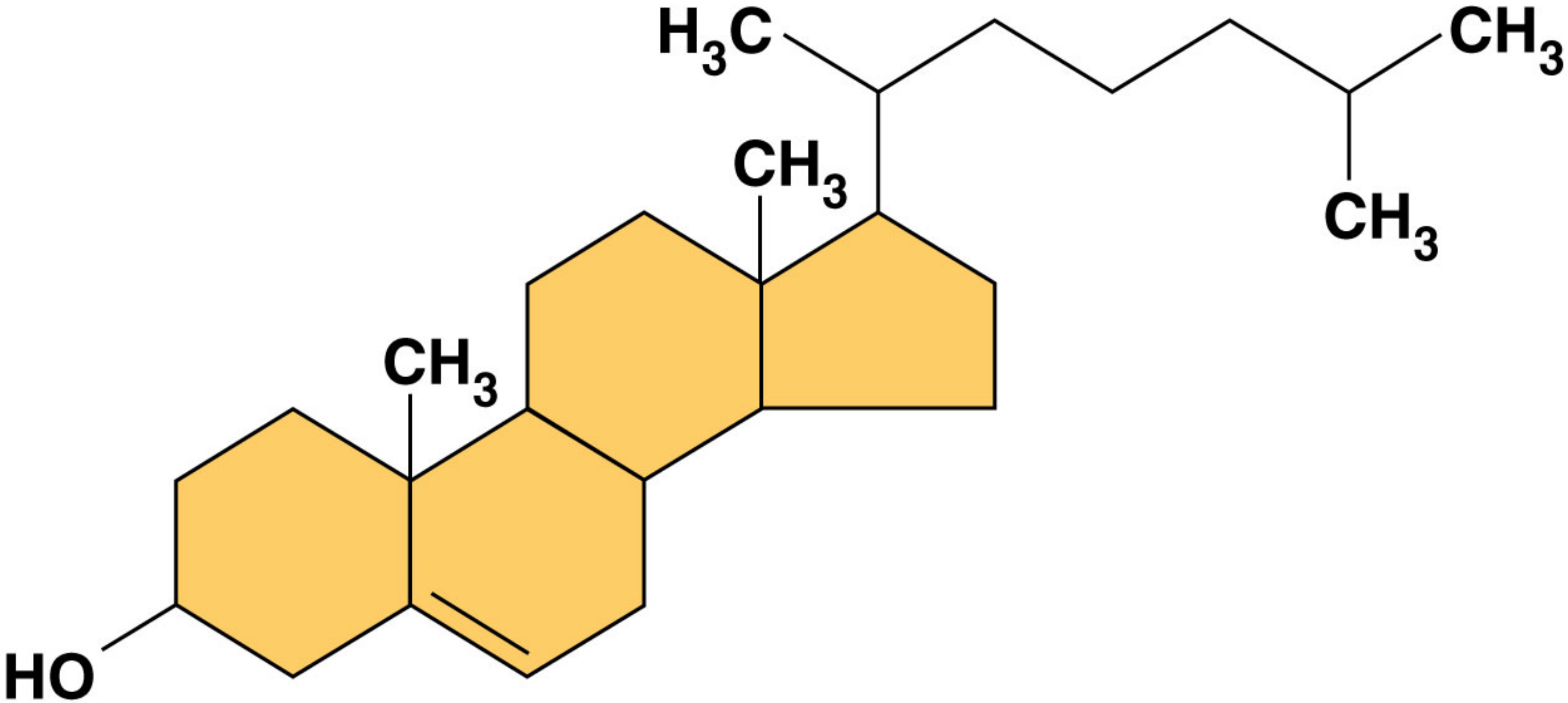
Figure 5.13



Steroids

- **Steroids** are lipids characterized by a carbon skeleton consisting of four fused rings
- **Cholesterol**, an important steroid, is a component in animal cell membranes
- Although cholesterol is essential in animals, high levels in the blood may contribute to cardiovascular disease

Figure 5.14



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

- Proteins account for more than 50% of the dry mass of most cells
- Protein functions include:
  - catalysis of cellular reactions
  - structural support,
  - storage,
  - transport,
  - cellular communications,
  - movement, and
  - defense against foreign substances

Figure 5.15a

Enzymatic proteins

Function: Selective acceleration of chemical reactions

Example: Digestive enzymes catalyze the hydrolysis of bonds in food molecules.

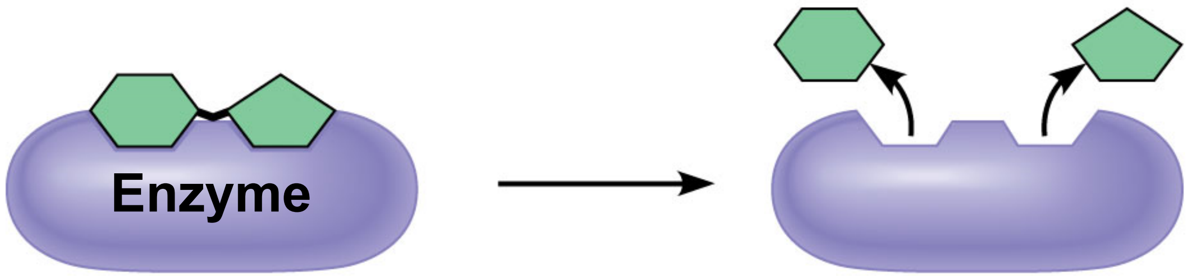
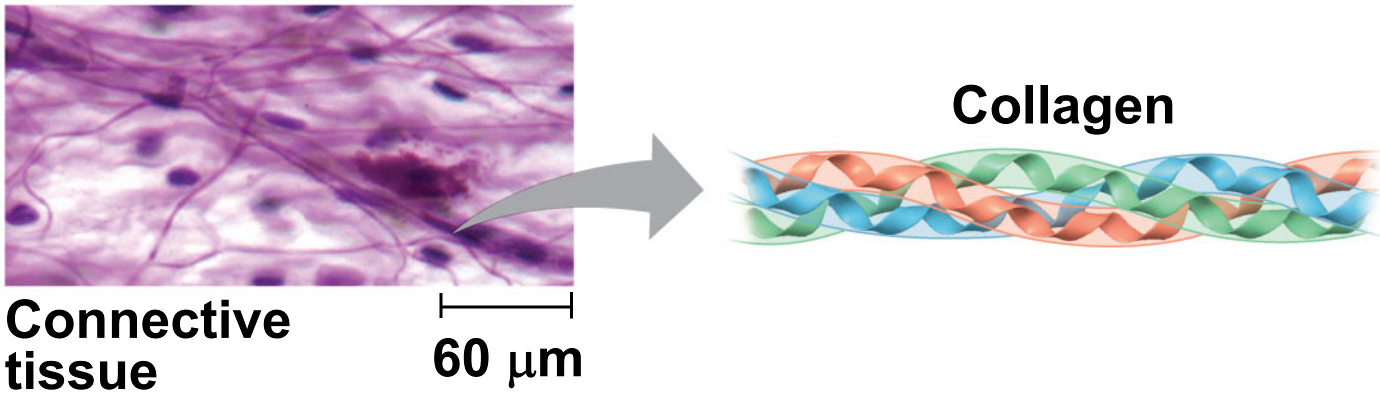


Figure 5.15h

Structural proteins

Function: Support

Examples: Keratin is the protein of hair, horns, feathers, and other skin appendages. Insects and spiders use silk fibers to make their cocoons and webs, respectively. Collagen and elastin proteins provide a fibrous framework in animal connective tissues.



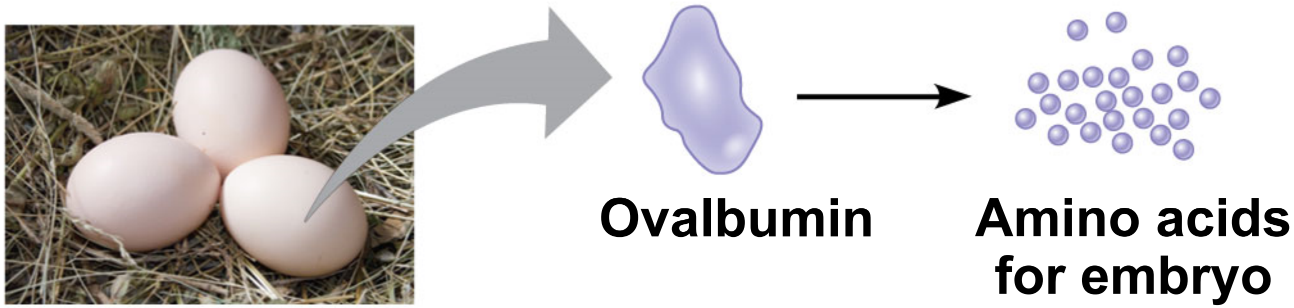
PLAY Animation: Structural Proteins

Figure 5.15b

Storage proteins

Function: Storage of amino acids

Examples: Casein, the protein of milk, is the major source of amino acids for baby mammals. Plants have storage proteins in their seeds. Ovalbumin is the protein of egg white, used as an amino acid source for the developing embryo.



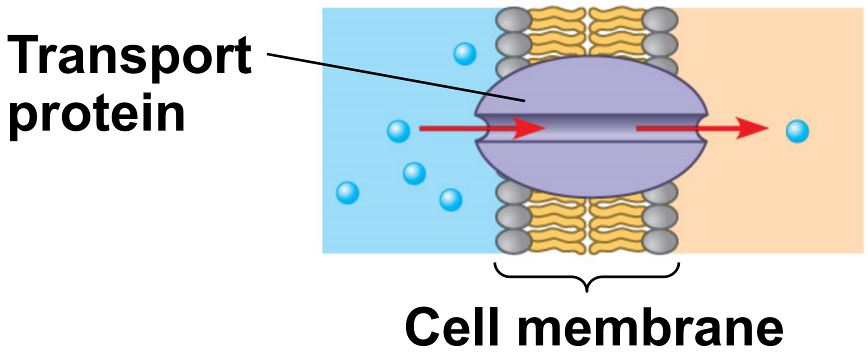
PLAY Animation: Storage Proteins

Figure 5.15f

Transport proteins

Function: Transport of substances

Examples: Hemoglobin, the iron-containing protein of vertebrate blood, transports oxygen from the lungs to other parts of the body. Other proteins transport molecules across cell membranes.



PLAY Animation: Transport Proteins

Figure 5.15c

Hormonal proteins

Function: Coordination of an organism's activities

Example: Insulin, a hormone secreted by the pancreas, causes other tissues to take up glucose, thus regulating blood sugar concentration

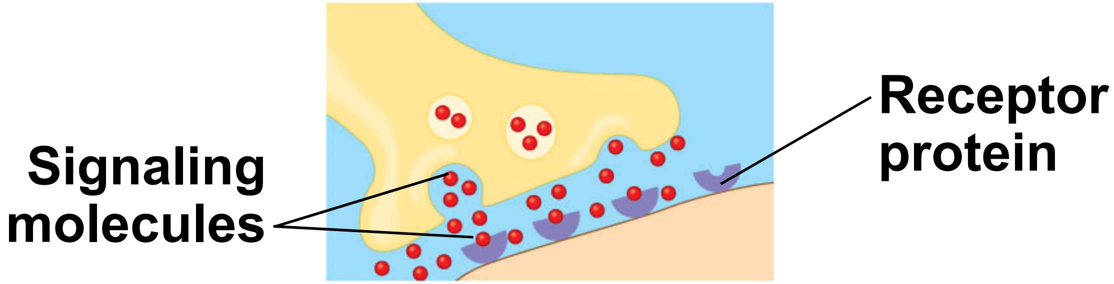
PLAY Animation: Hormonal Proteins

Figure 5.15g

Receptor proteins

Function: Response of cell to chemical stimuli

Example: Receptors built into the membrane of a nerve cell detect signaling molecules released by other nerve cells.



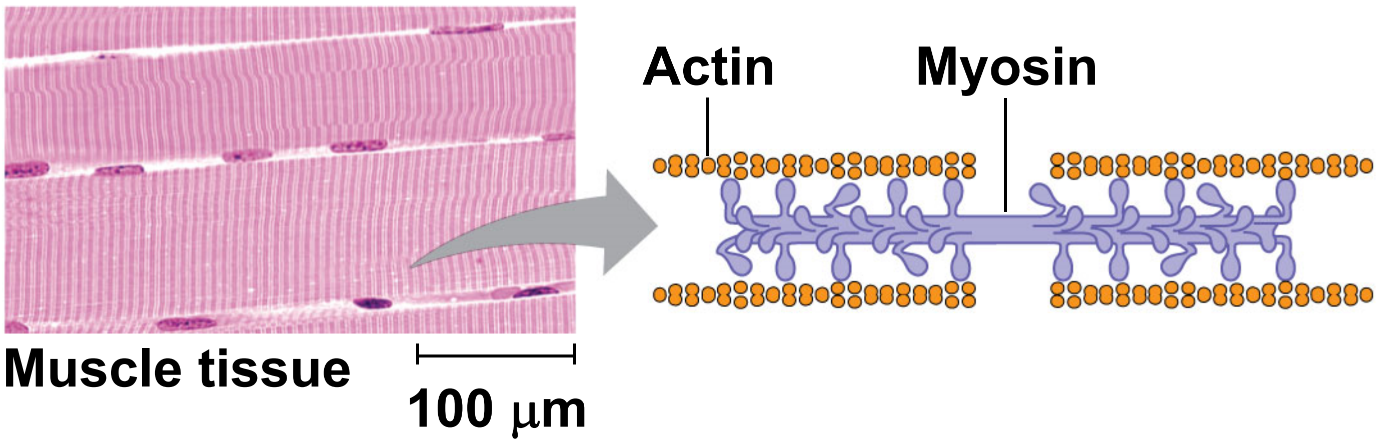
PLAY Animation: Receptor Proteins

Figure 5.15d

Contractile and motor proteins

Function: Movement

Examples: Motor proteins are responsible for the undulations of cilia and flagella. Actin and myosin proteins are responsible for the contraction of muscles.



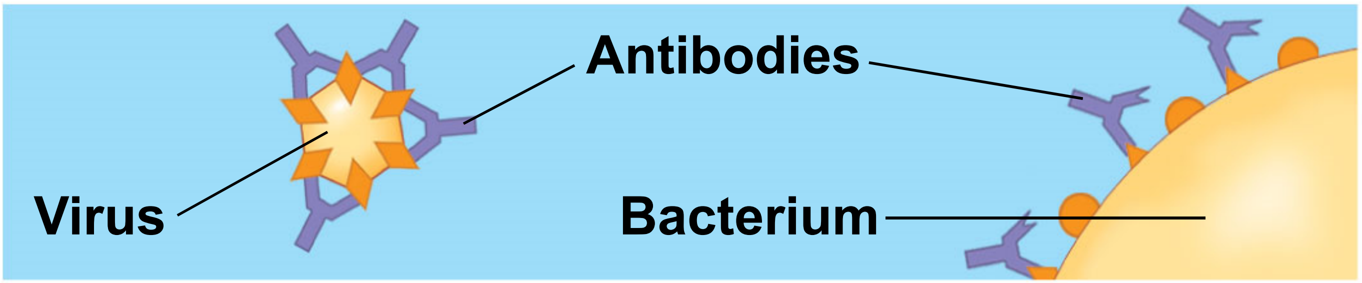
PLAY Animation: Contractile Proteins

Figure 5.15e

Defensive proteins

Function: Protection against disease

Example: Antibodies inactivate and help destroy viruses and bacteria.



PLAY Animation: Defensive Proteins

- **Enzymes** are a type of protein that acts as a **catalyst** to speed up chemical reactions
- Enzymes can perform their functions repeatedly, functioning as workhorses that carry out the processes of life

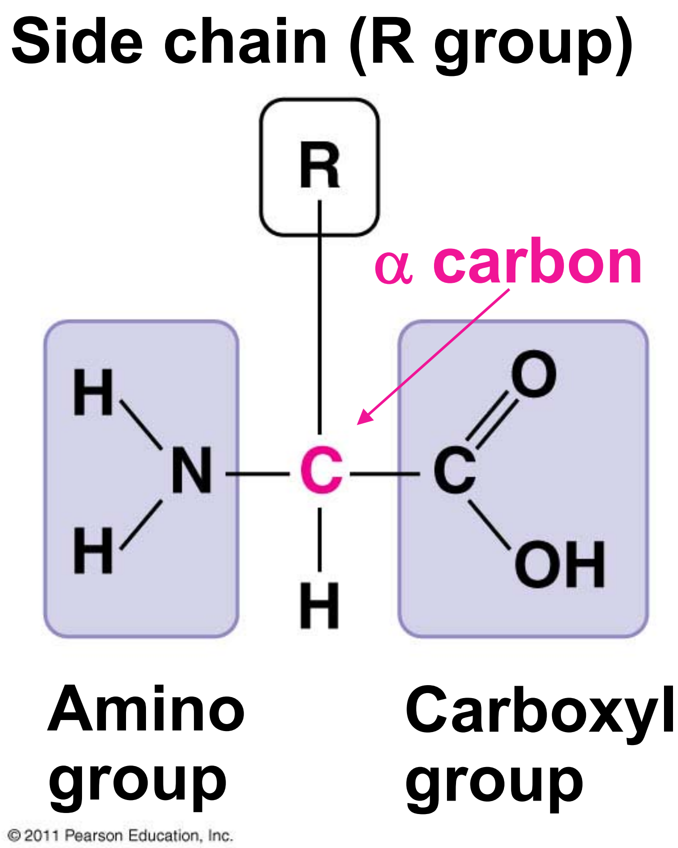
PLAY Animation: Enzymes

Polypeptides

- **Polypeptides** are unbranched polymers built from the same set of 20 amino acids
- A **protein** is a biologically functional molecule that consists of one or more polypeptides

Amino Acid Monomers

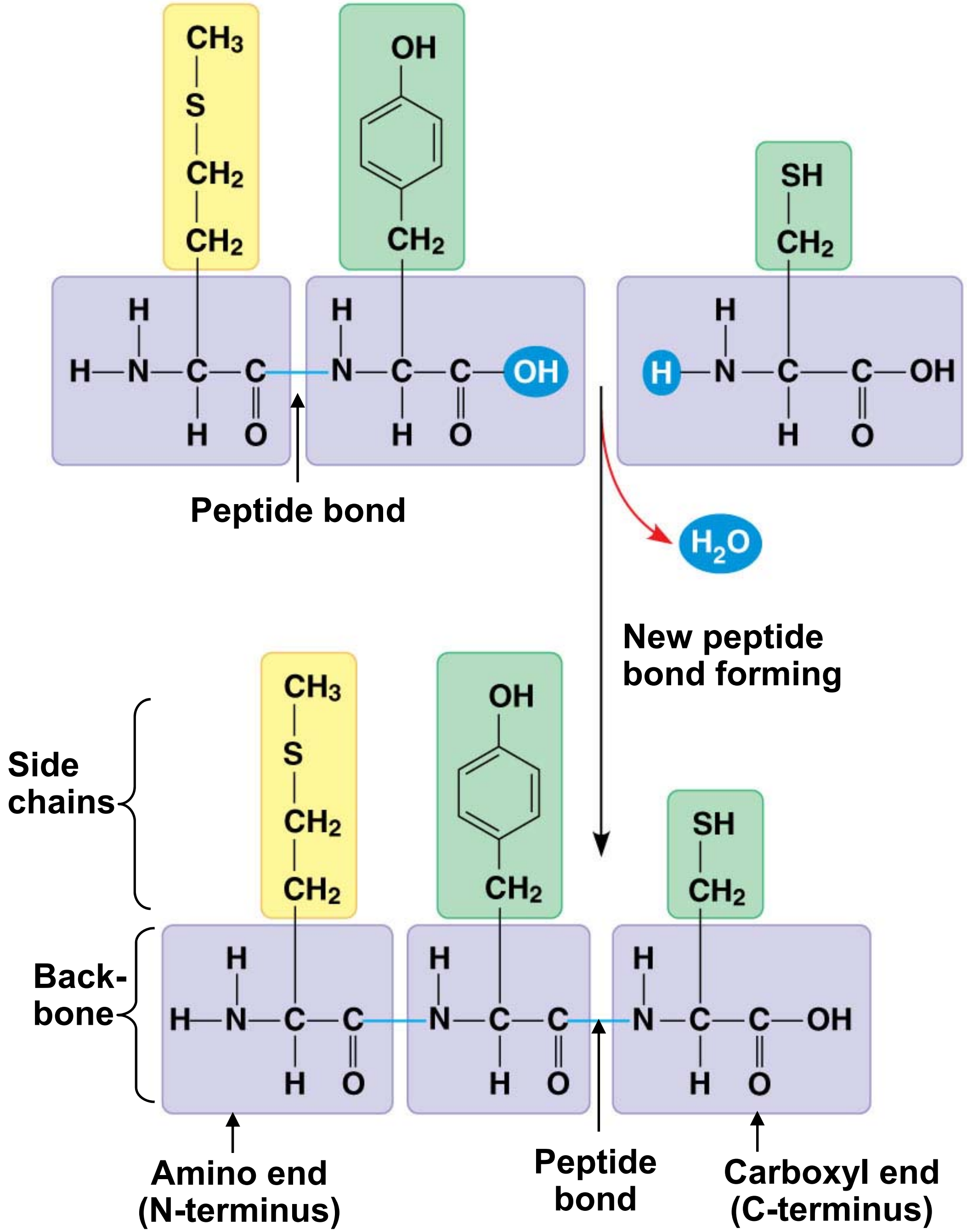
- **Amino acids** are organic molecules with carboxyl and amino groups
- Amino acids differ in their properties due to differing side chains, called R groups



Amino Acid Polymers

- Amino acids are linked by **peptide bonds**
- A polypeptide is a polymer of amino acids
- Polypeptides range in length from a few to more than a thousand monomers
- Each polypeptide has a unique linear sequence of amino acids, with a carboxyl end (C-terminus) and an amino end (N-terminus)

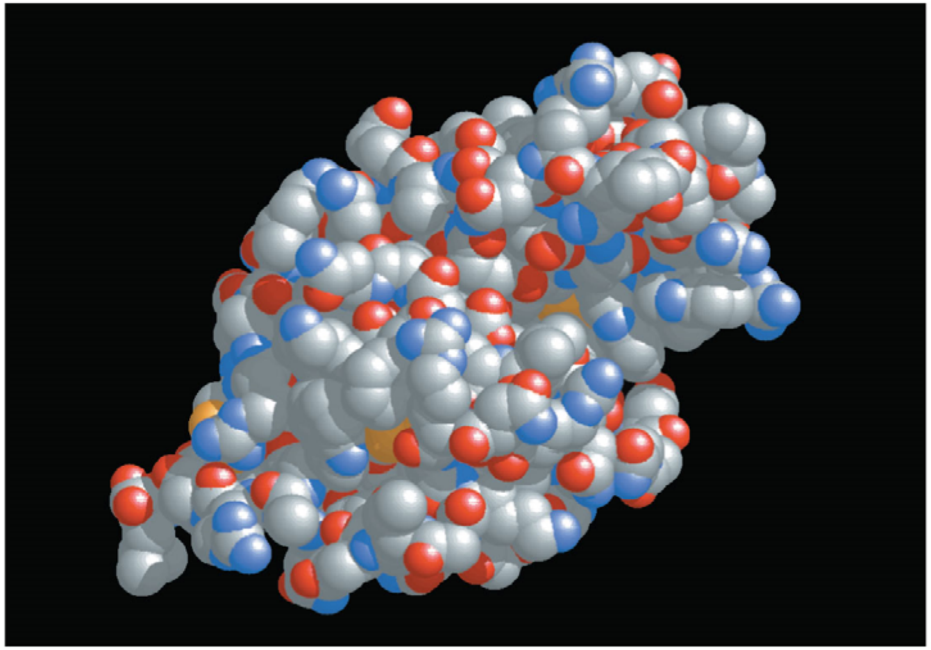
Figure 5.17



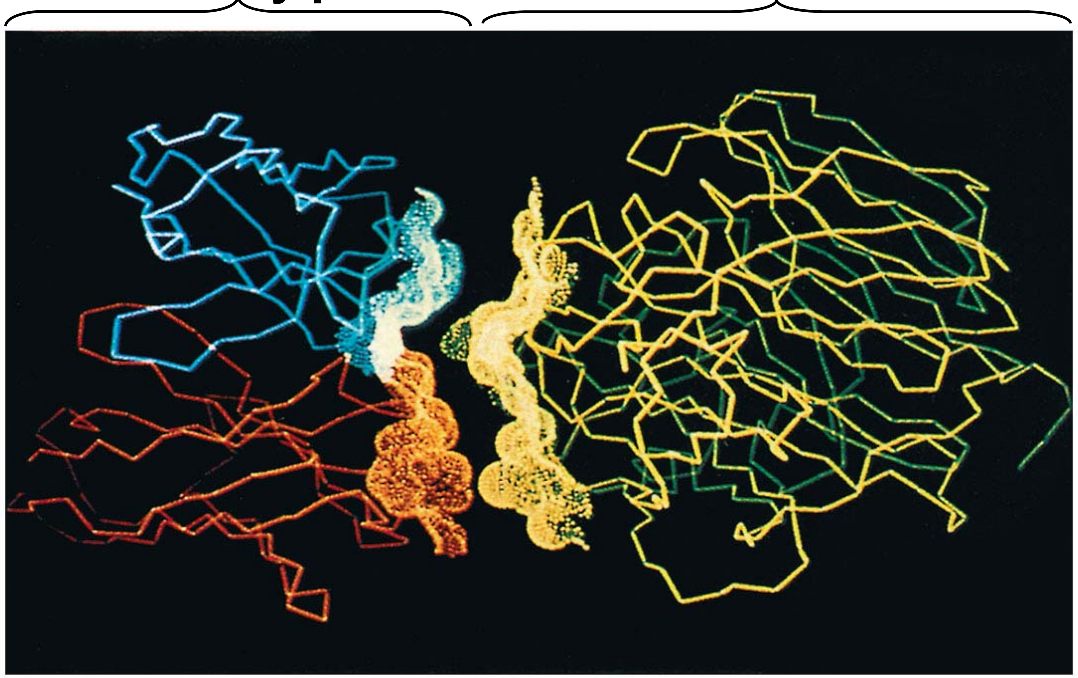
CH3
S
CH2
CH2
OH
CH2
SH
CH2
H
H—N—C—C
H O
H
N—C—C—OH
H O
H
H—N—C—C—OH
H O
Peptide bond
H2O
New peptide
bond forming
Side
chains
Back-
bone
CH3
S
CH2
CH2
OH
CH2
SH
CH2
H
H—N—C—C
H O
H
N—C—C
H O
H
N—C—C—OH
H O
Amino end
(N-terminus)
Peptide
bond
Carboxyl end
(C-terminus)

Protein Structure and Function

- A functional protein consists of one or more polypeptides precisely twisted, folded, and coiled into a unique shape



- The sequence of amino acids determines a protein's three-dimensional structure
- A protein's structure determines its function



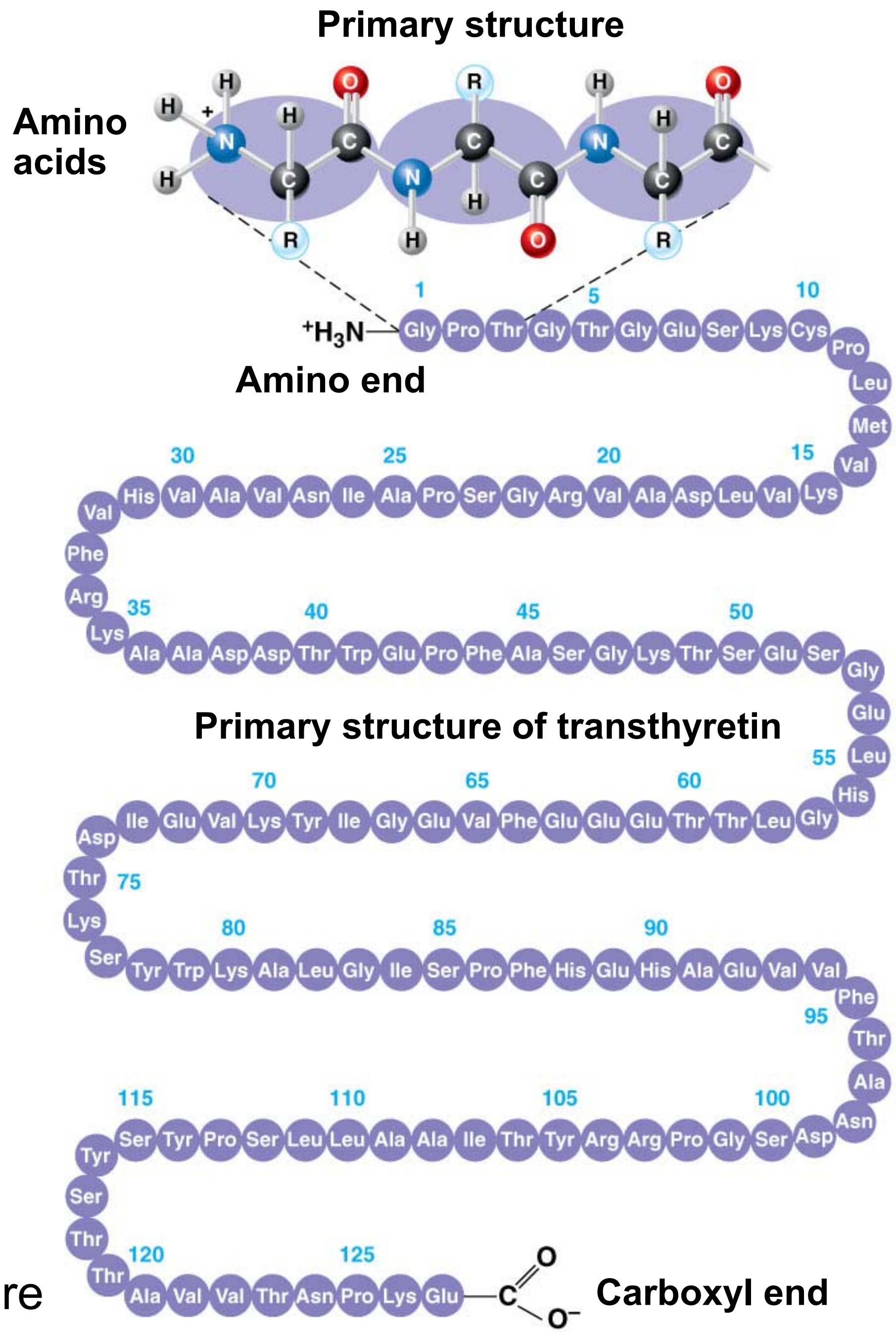
Four Levels of Protein Structure

- The **<u>primary structure</u>** of a protein is its unique sequence of amino acids
- **<u>Secondary structure</u>**, found in most proteins, consists of coils and folds in the polypeptide chain
- **<u>Tertiary structure</u>** is determined by interactions among various side chains (R groups)
- **<u>Quaternary structure</u>** results when a protein consists of multiple polypeptide chains

PLAY Animation: Protein Structure Introduction

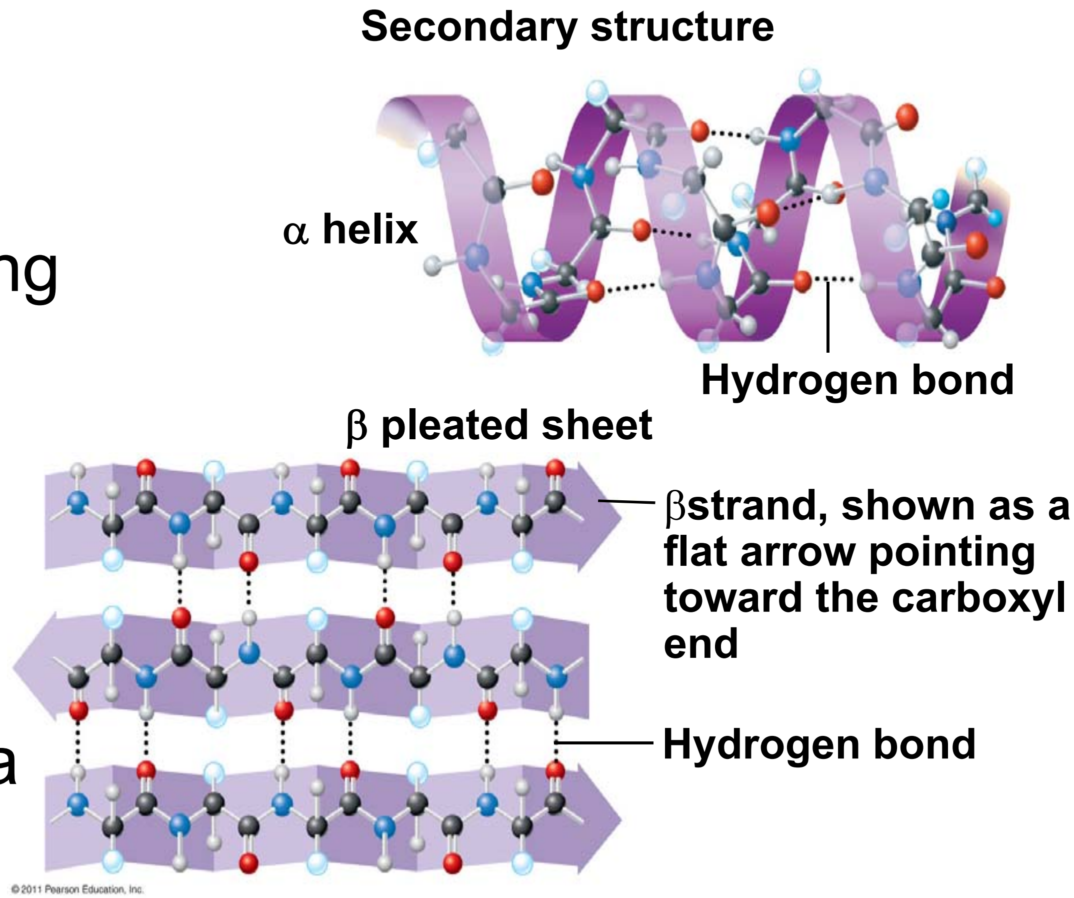
Figure 5.20a

- **Primary structure**, the sequence of amino acids in a protein, is like the order of letters in a long word
- Primary structure is determined by inherited genetic information



PLAY Animation: Primary Protein Structure

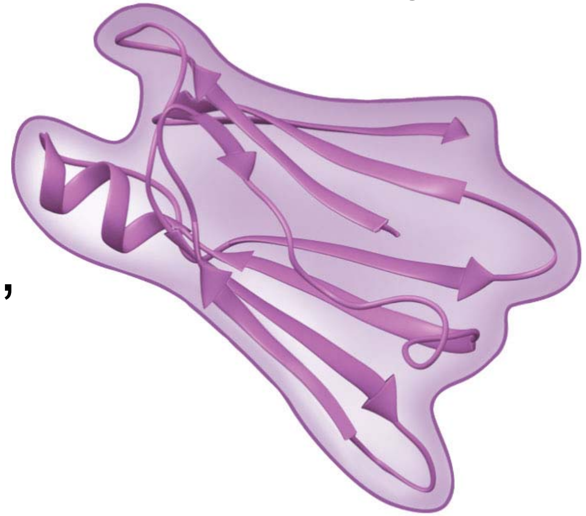
- The coils and folds of **secondary structure** result from hydrogen bonds between repeating constituents of the polypeptide backbone
- Typical secondary structures are a coil called an α **helix** and a folded structure called a **β pleated sheet**



PLAY Animation: Secondary Protein Structure

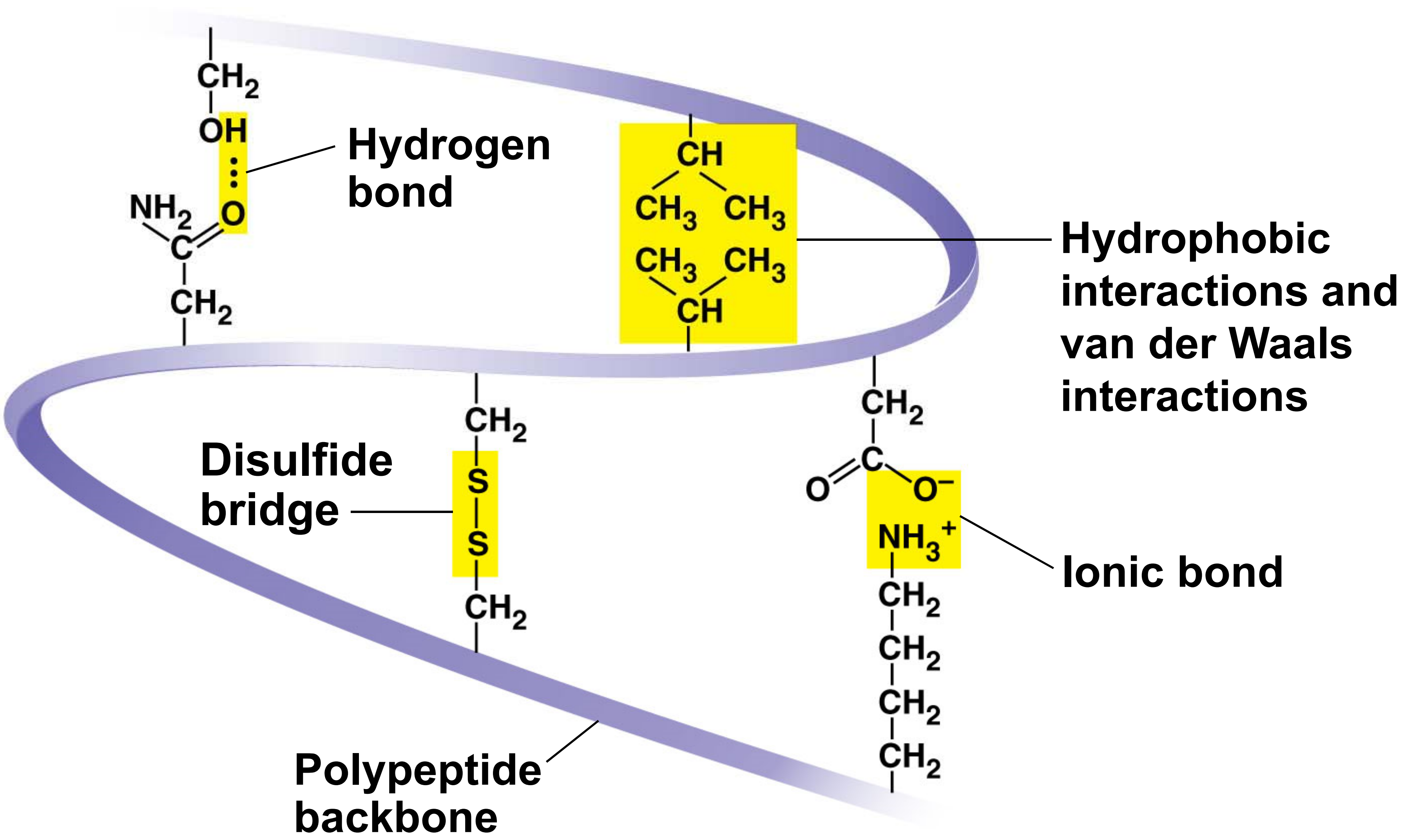
Figure 5.20d

- **Tertiary structure** is determined by interactions between R groups, rather than interactions between backbone constituents
- These interactions between R groups include hydrogen bonds, ionic bonds, **hydrophobic interactions**, and van der Waals interactions
- Strong covalent bonds called **disulfide bridges** may reinforce the protein's structure



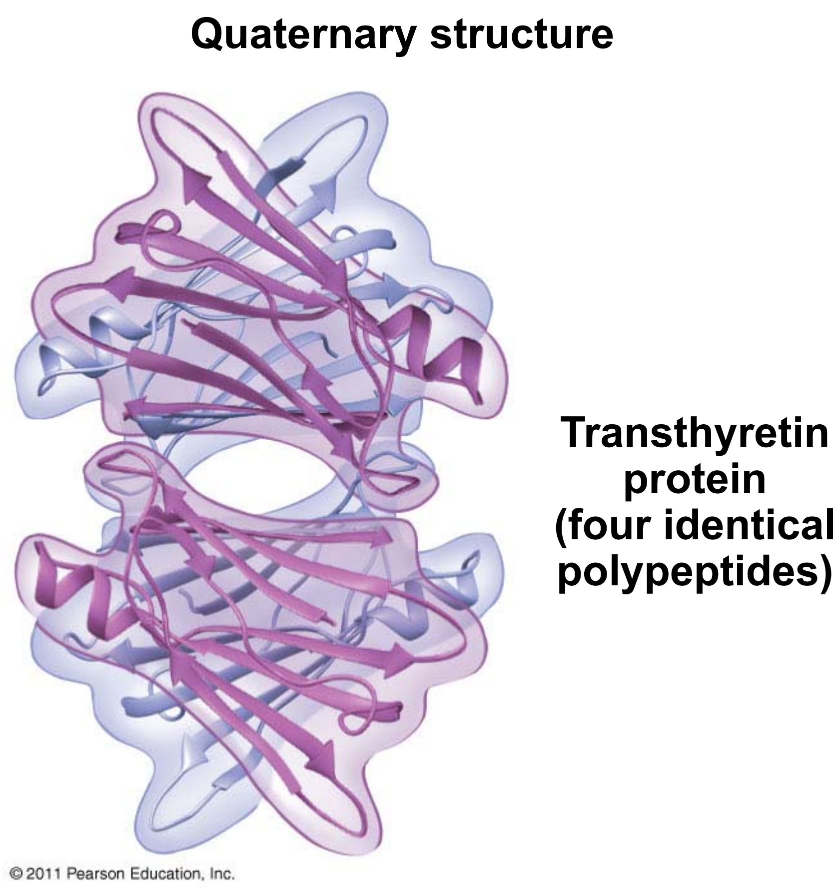
PLAY Animation: Tertiary Protein Structure

Figure 5.20f



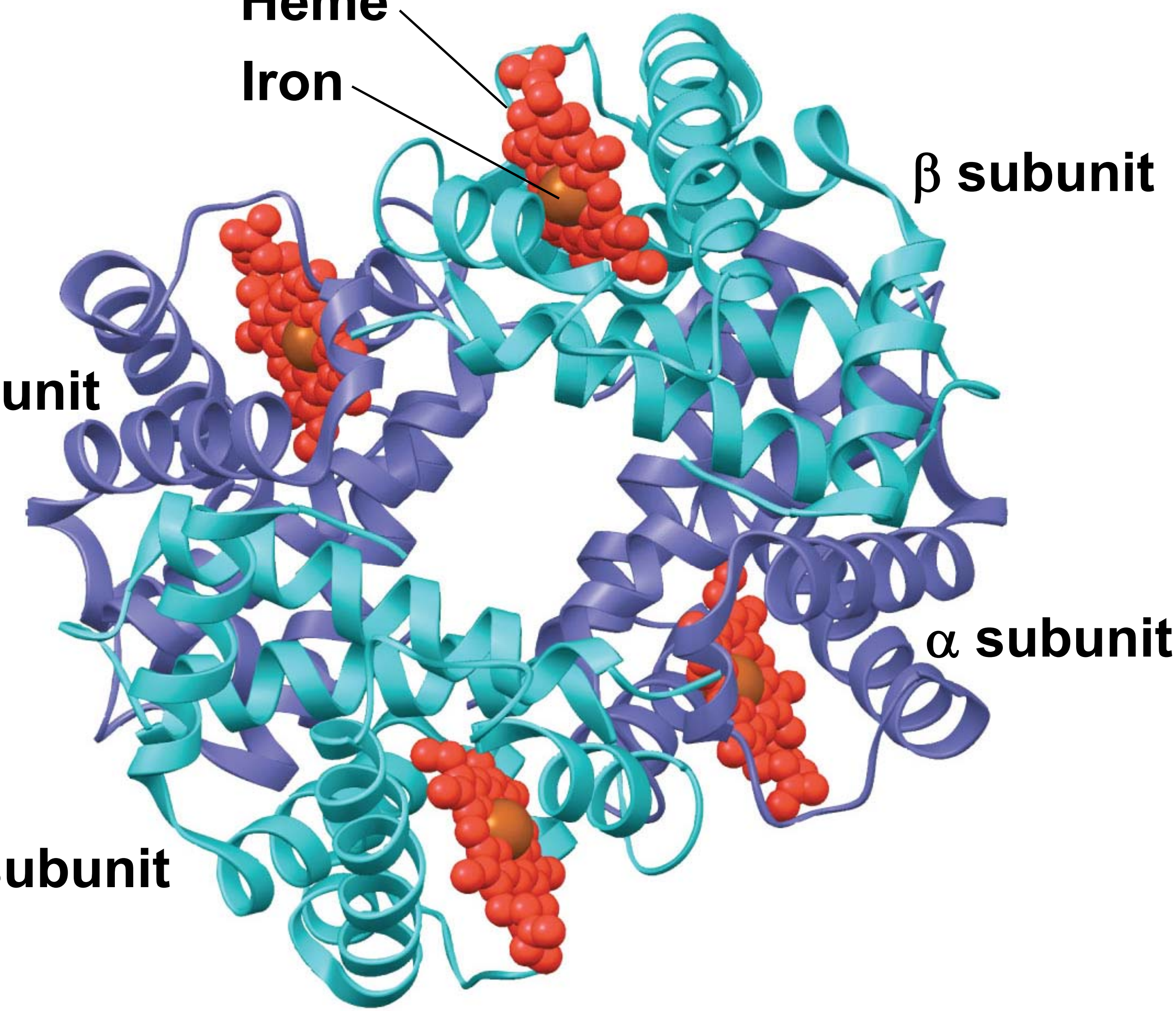
CH2
OH
O
NH2
C
CH2
Hydrogen bond
CH
CH3 CH3
CH3 CH3
CH
Hydrophobic interactions and van der Waals interactions
CH2
S
S
CH2
Disulfide bridge
CH2
C
O
O−
NH3+
CH2
CH2
CH2
CH2
Ionic bond
Polypeptide backbone

- **Quaternary structure** results when two or more polypeptide chains form one macromolecule
- Collagen is a fibrous protein consisting of three polypeptides coiled like a rope
- Hemoglobin is a globular protein consisting of four polypeptides: two alpha and two beta chains



PLAY Animation: Quaternary Protein Structure

Figure 5.20i

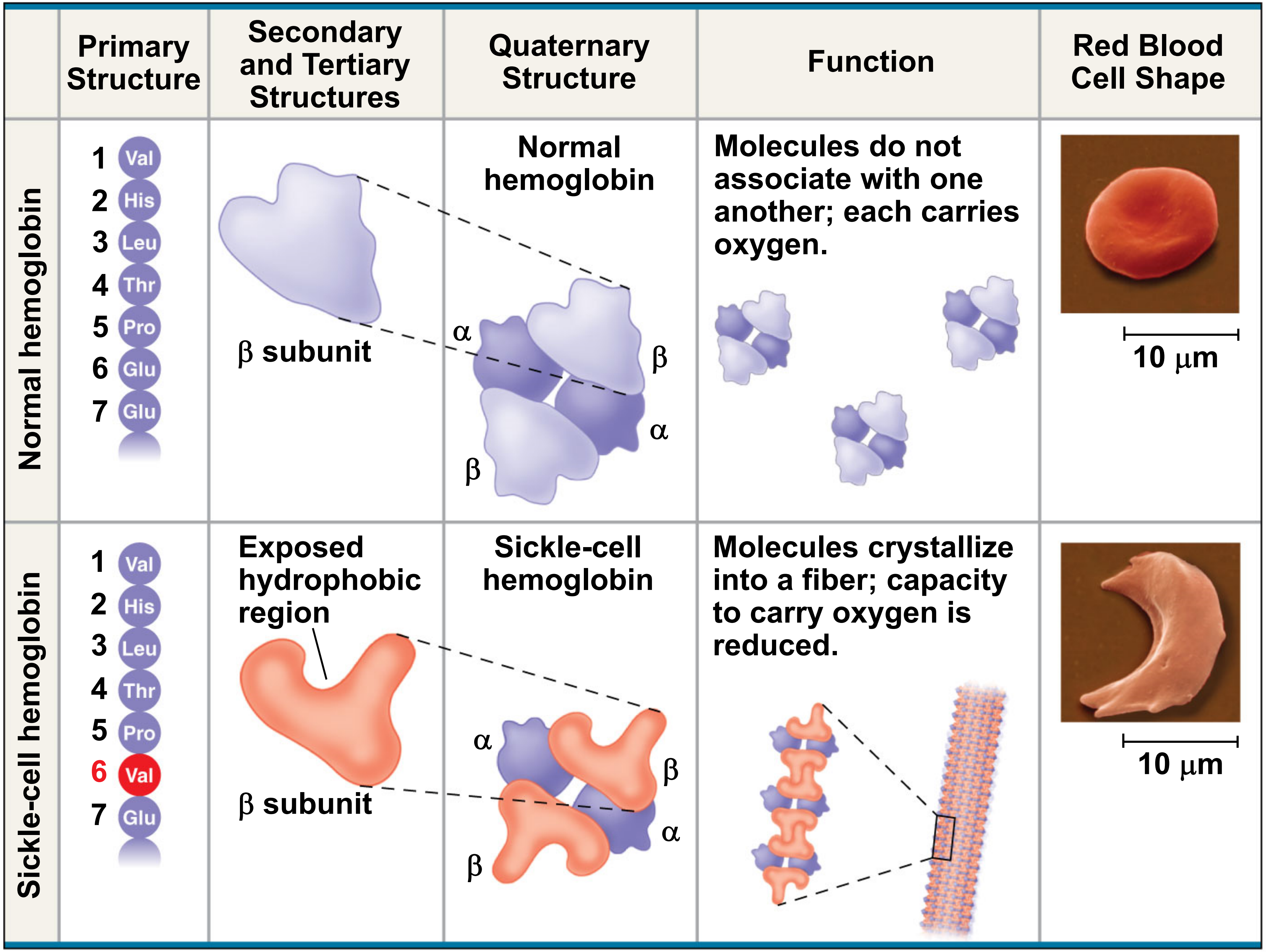


Hemoglobin

Sickle-Cell Disease: A Change in Primary Structure Leads to a Change in Properties

- A slight change in primary structure can affect a protein’s structure and ability to function
- **Sickle-cell disease**, an inherited blood disorder, results from a single amino acid substitution in the protein hemoglobin

Figure 5.21

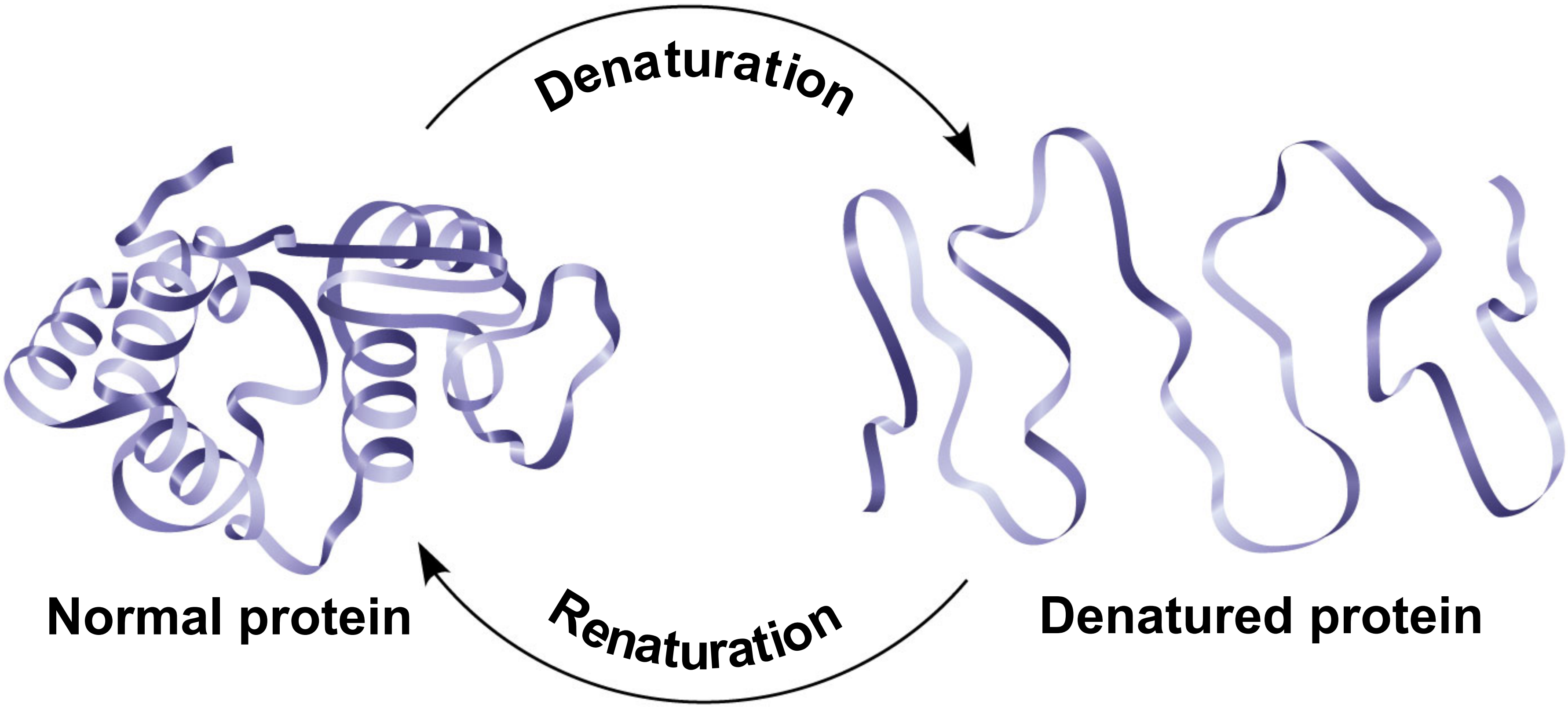


Primary Structure
Secondary and Tertiary Structures
Quaternary Structure
Function
Red Blood Cell Shape
Normal hemoglobin
1 Val
2 His
3 Leu
4 Thr
5 Pro
6 Glu
7 Glu
β subunit
Normal hemoglobin
α
β
α
β
Molecules do not associate with one another; each carries oxygen.
10 µm
Sickle-cell hemoglobin
1 Val
2 His
3 Leu
4 Thr
5 Pro
6 Val
7 Glu
Exposed hydrophobic region
β subunit
Sickle-cell hemoglobin
α
β
α
β
Molecules crystallize into a fiber; capacity to carry oxygen is reduced.
10 µm

What Determines Protein Structure?

- In addition to primary structure, physical and chemical conditions can affect structure
- Alterations in pH, salt concentration, temperature, or other environmental factors can cause a protein to unravel
- This loss of a protein's native structure is called **denaturation**
- A denatured protein is biologically inactive

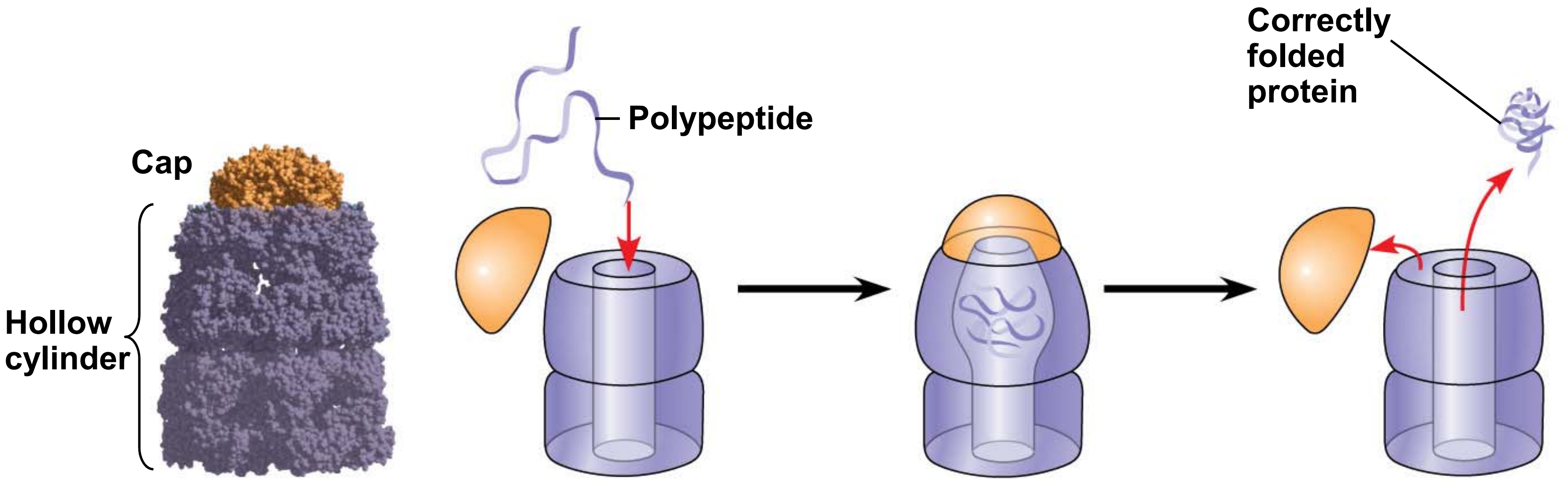
Figure 5.22


Denaturation
Normal protein
Renaturation
Denatured protein

Protein Folding in the Cell

- It is hard to predict a protein's structure from its primary structure
- Most proteins probably go through several stages on their way to a stable structure
- **Chaperonins** are protein molecules that assist the proper folding of other proteins
- Diseases such as Alzheimer's, Parkinson's, and mad cow disease are associated with misfolded proteins

Figure 5.23



Steps of Chaperonin Action:

1. An unfolded polypeptide enters the cylinder from one end.
2. The cap attaches, causing the cylinder to change shape in such a way that it creates a hydrophilic environment for the folding of the polypeptide.
3. The cap comes off, and the properly folded protein is released.

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

- The amino acid sequence of a polypeptide is programmed by a unit of inheritance called a **gene**
- Genes are made of DNA, a **nucleic acid** made of monomers called nucleotides

The Roles of Nucleic Acids

- There are two types of nucleic acids
  - **Deoxyribonucleic acid (DNA)**
  - **Ribonucleic acid (RNA)**
- DNA provides directions for its own replication
- DNA directs synthesis of messenger RNA (mRNA) and, through mRNA, controls protein synthesis
- Protein synthesis occurs in ribosomes

Figure 5.25-1

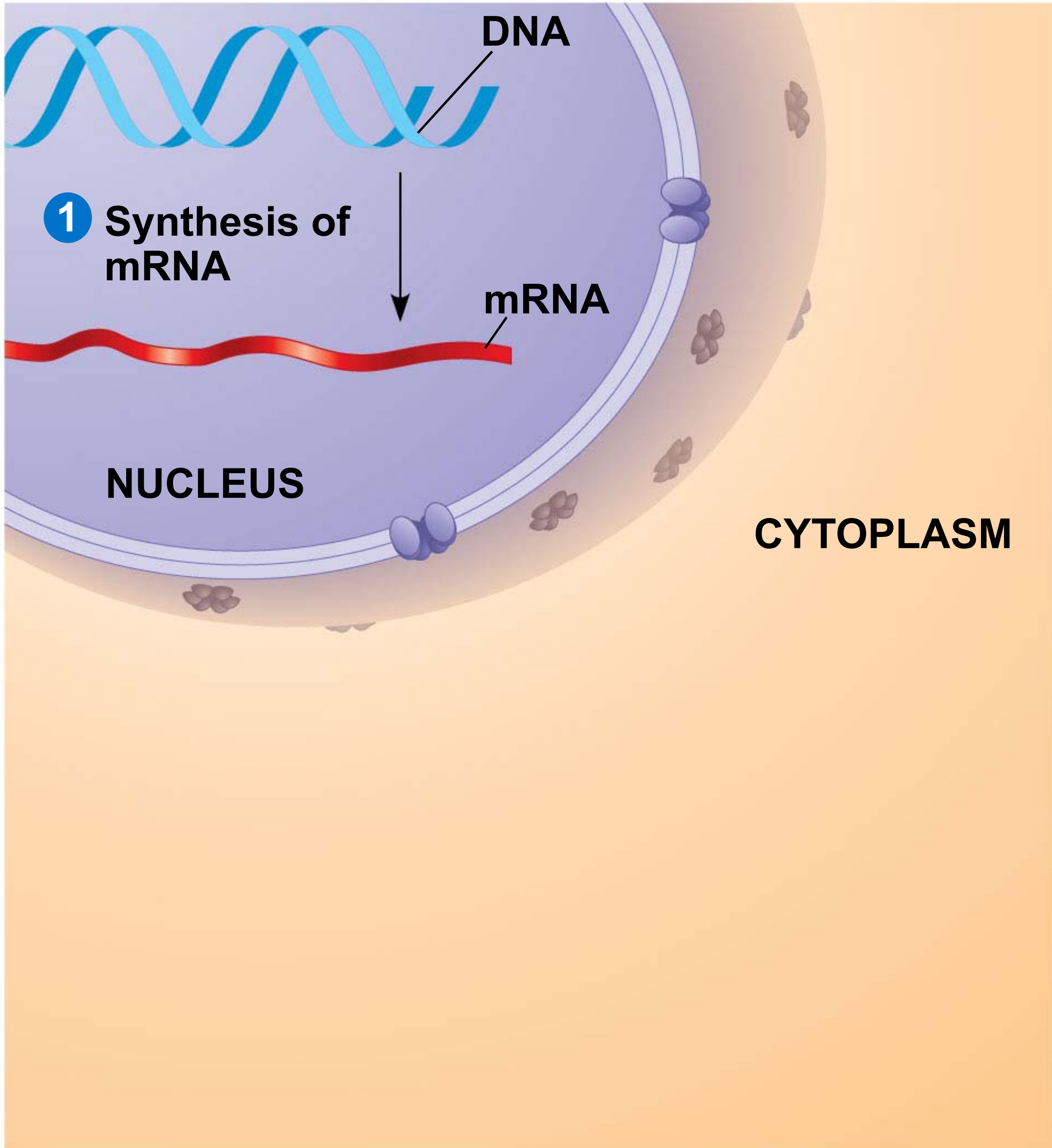
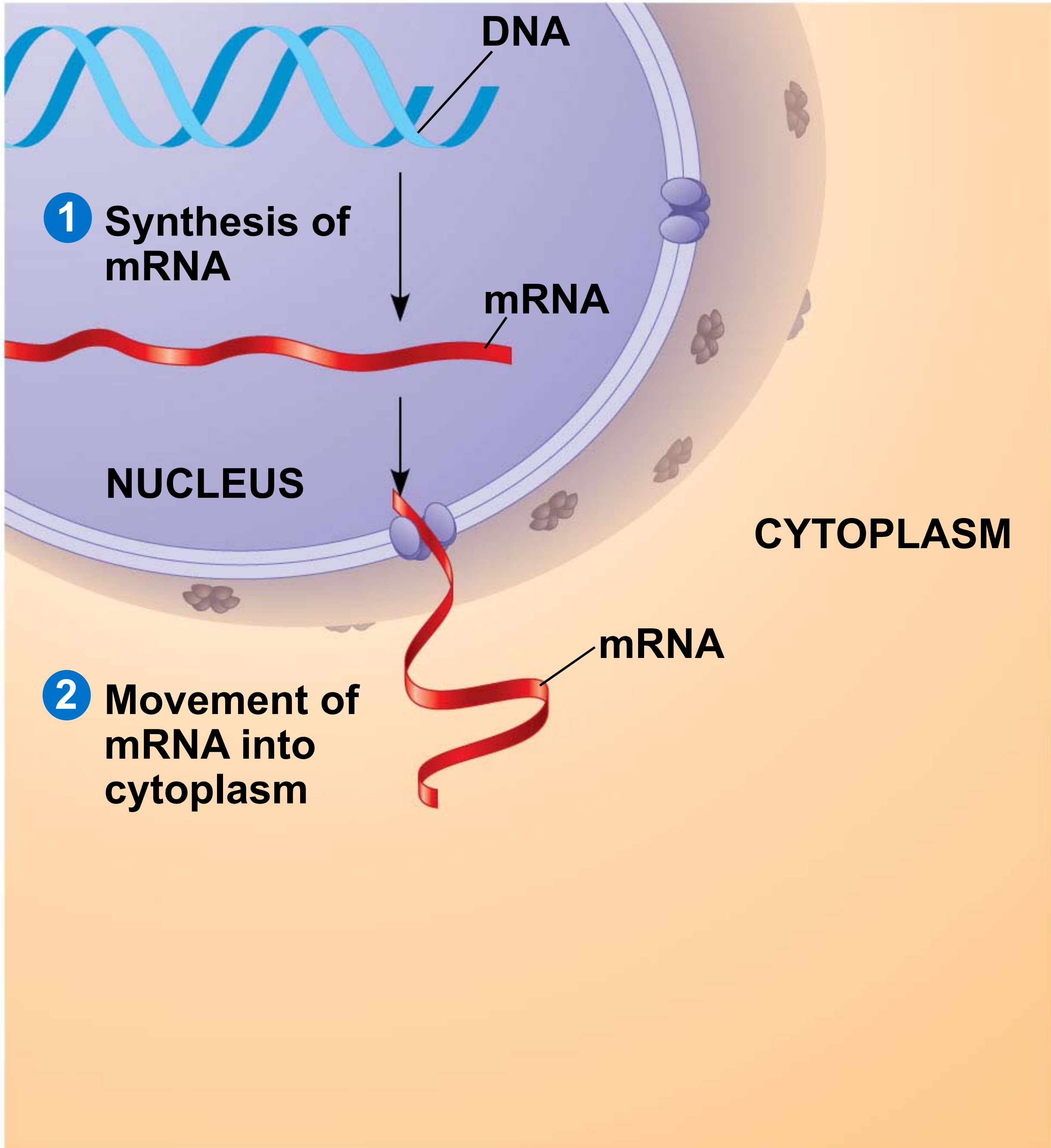
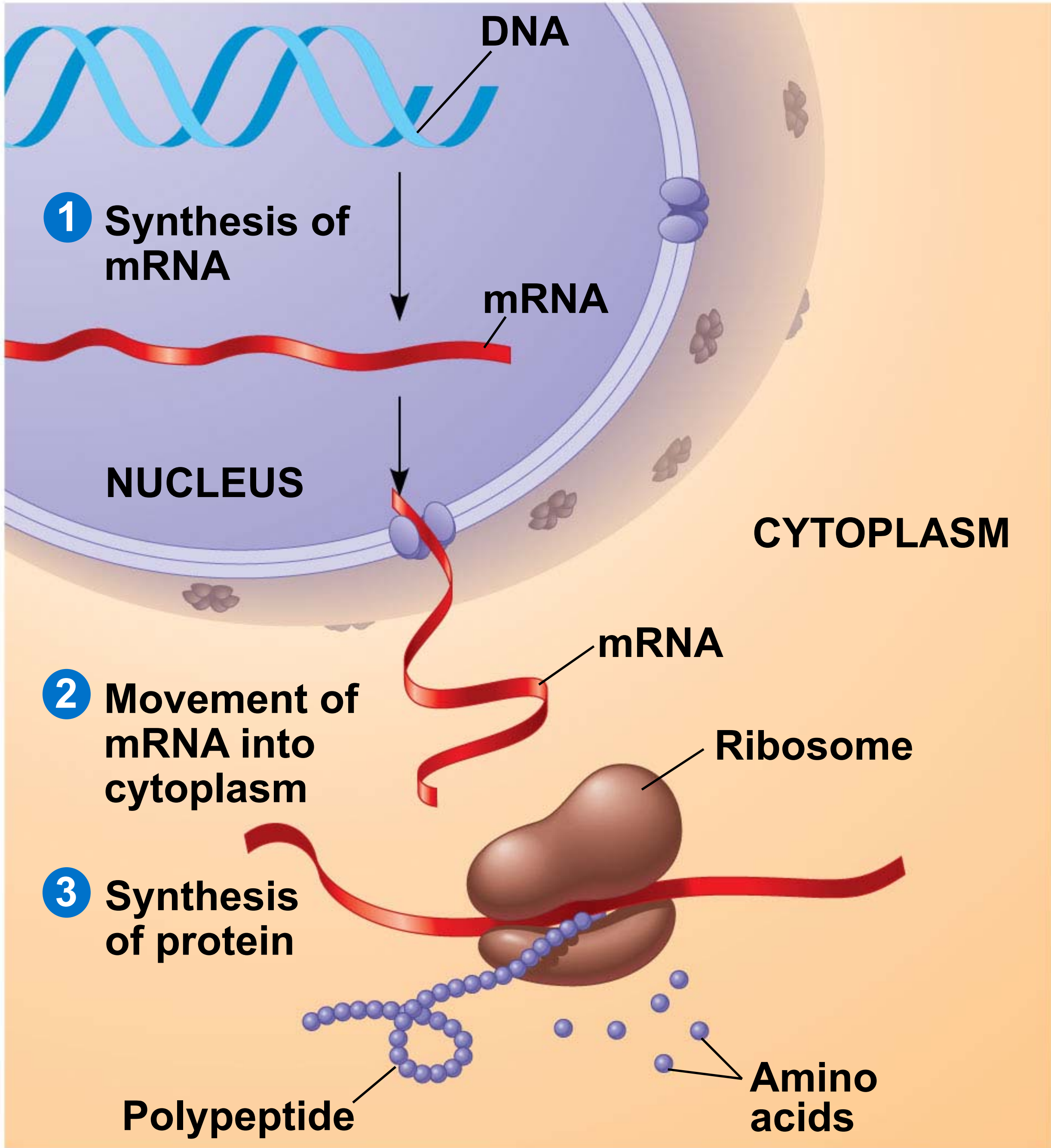


Figure 5.25-2



DNA
1 Synthesis of mRNA
mRNA
NUCLEUS
CYTOPLASM
mRNA
2 Movement of mRNA into cytoplasm

Figure 5.25-3

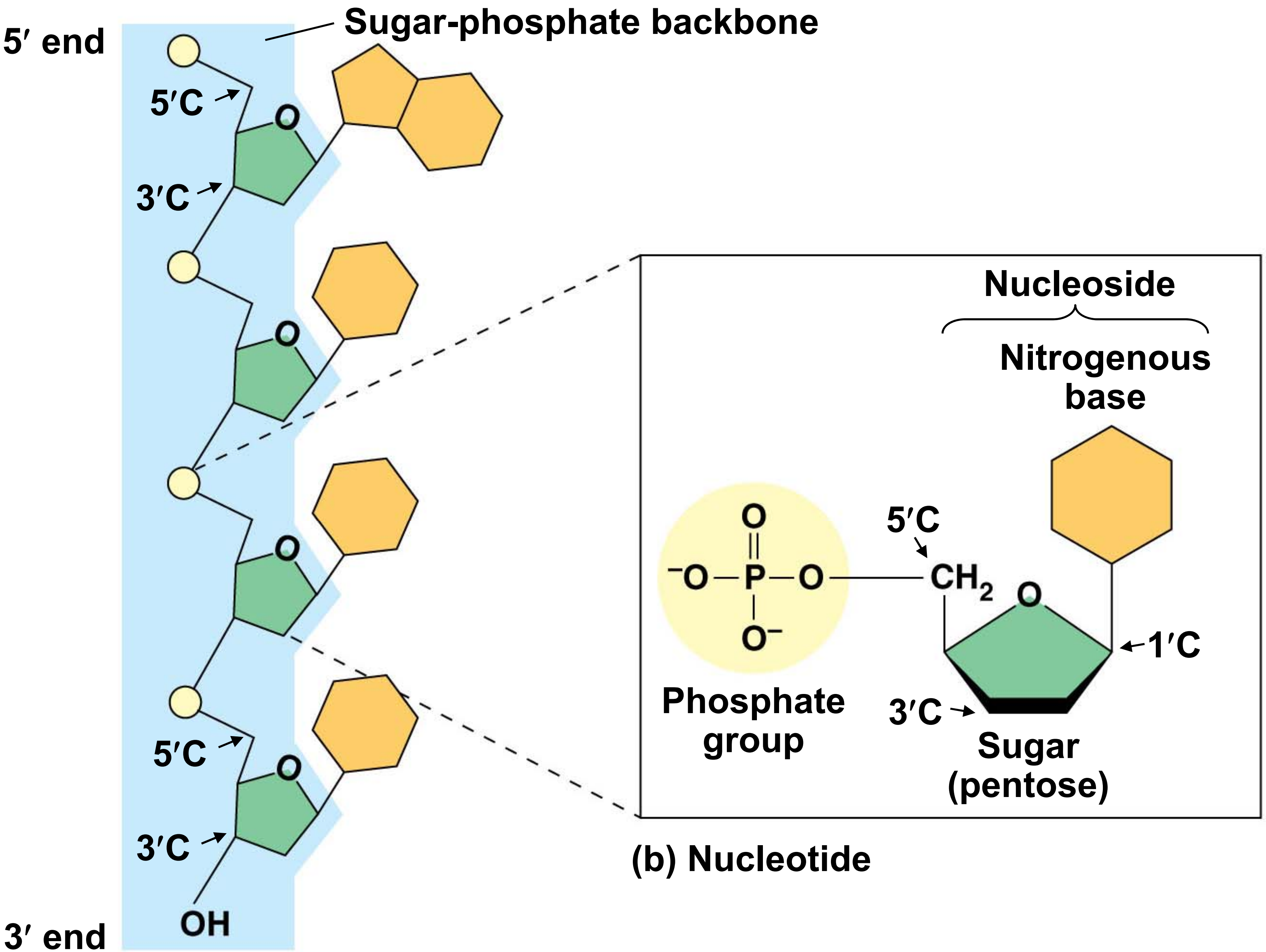


DNA
1 Synthesis of mRNA
mRNA
NUCLEUS
CYTOPLASM
mRNA
2 Movement of mRNA into cytoplasm
Ribosome
3 Synthesis of protein
Polypeptide
Amino acids

The Components of Nucleic Acids

- Nucleic acids are polymers called **polynucleotides**
- Each polynucleotide is made of monomers called **nucleotides**
- Each nucleotide consists of a nitrogenous base, a pentose sugar, and one or more phosphate groups
- The portion of a nucleotide without the phosphate group is called a nucleoside

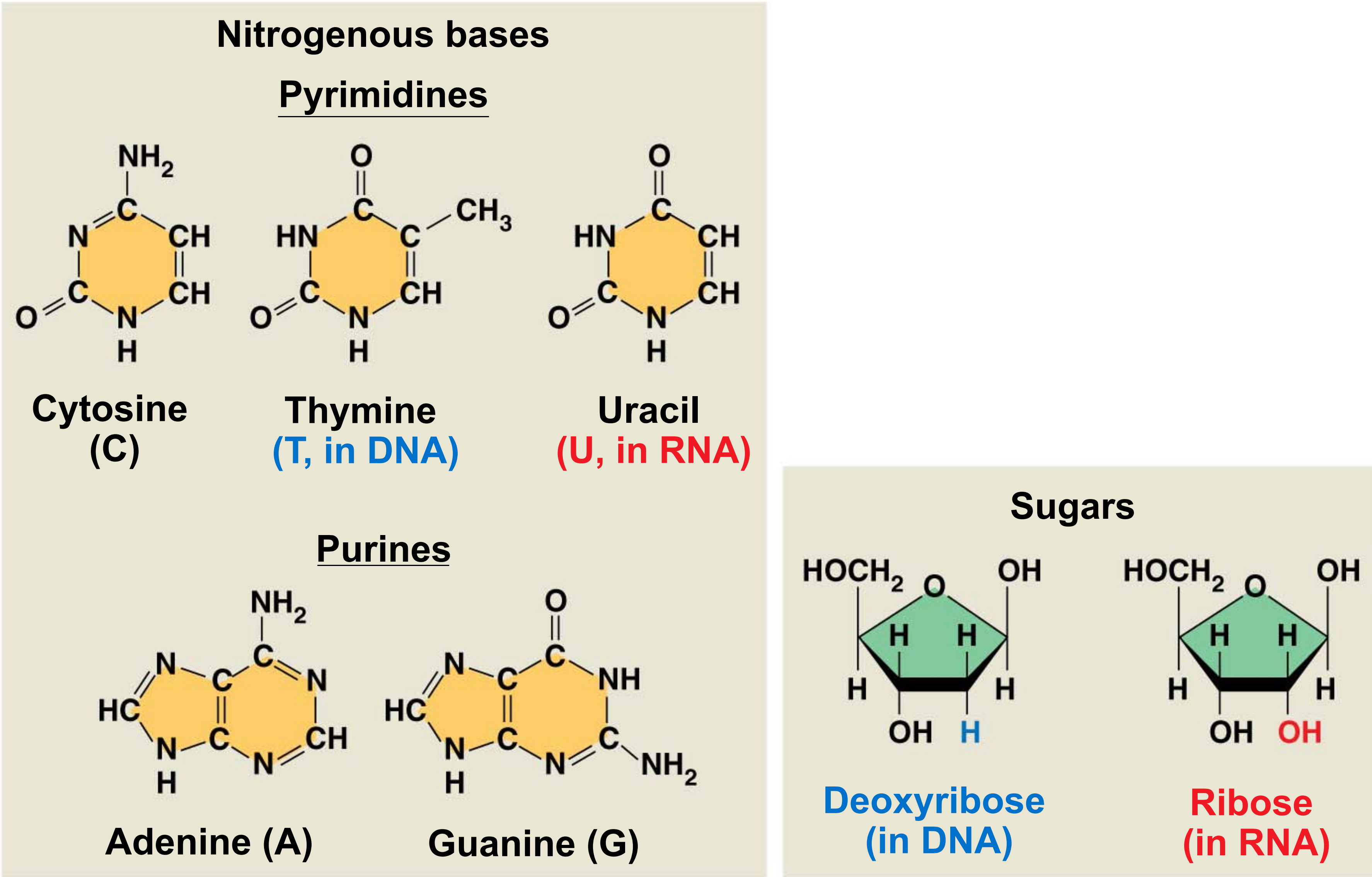
Figure 5.26ab



(a) Polynucleotide, or nucleic acid

(b) Nucleotide

Figure 5.26c



(c) Nucleoside components

- Nucleoside = nitrogenous base + sugar
- There are two families of nitrogenous bases
  - **Pyrimidines** (cytosine, thymine, and uracil) have a single six-membered ring
  - **Purines** (adenine and guanine) have a six-membered ring fused to a five-membered ring
- In DNA, the sugar is **deoxyribose**; in RNA, the sugar is **ribose**
- Nucleotide = nucleoside + phosphate group

Nucleotide Polymers

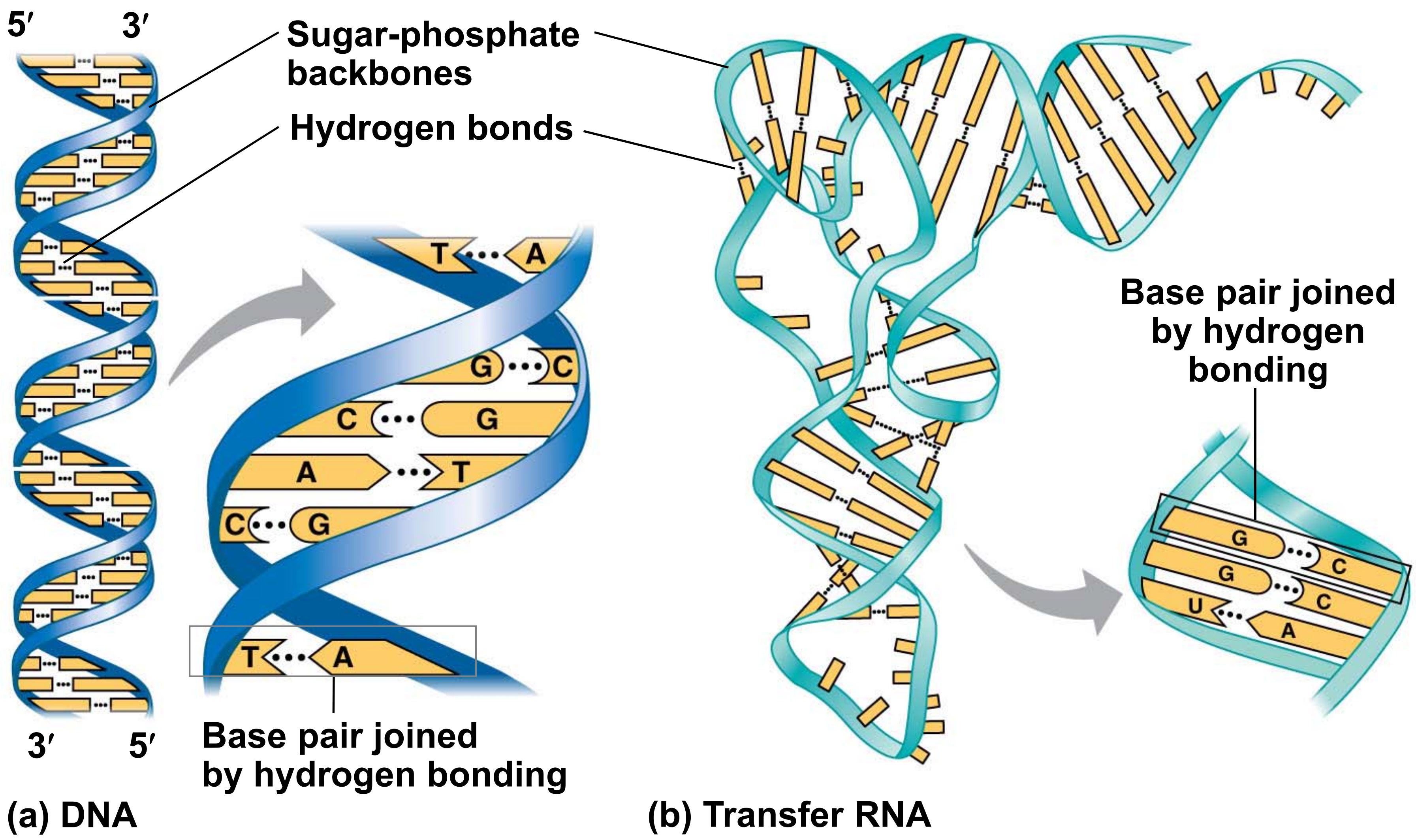
- Nucleotide polymers are linked together to build a polynucleotide
- Adjacent nucleotides are joined by covalent bonds that form between the –OH group on the 3′ carbon of one nucleotide and the phosphate on the 5′ carbon on the next
- These links create a backbone of sugar-phosphate units with nitrogenous bases as appendages
- The sequence of bases along a DNA or mRNA polymer is unique for each gene

The Structures of DNA and RNA Molecules

- RNA molecules usually exist as single polypeptide chains
- DNA molecules have two polynucleotides spiraling around an imaginary axis, forming a **double helix**
- In the DNA double helix, the two backbones run in opposite $5' \rightarrow 3'$ directions from each other, an arrangement referred to as **antiparallel**
- One DNA molecule includes many genes

- The nitrogenous bases in DNA pair up and form hydrogen bonds: adenine (A) always with thymine (T), and guanine (G) always with cytosine (C)
- Called complementary base pairing
- Complementary pairing can also occur between two RNA molecules or between parts of the same molecule
- In RNA, thymine is replaced by uracil (U) so A and U pair

Figure 5.27



5′
3′
Sugar-phosphate backbones
Hydrogen bonds
T A
G C
C G
A T
C G
T A
3′
5′
Base pair joined by hydrogen bonding
(a) DNA
Base pair joined by hydrogen bonding
G C
G C
U A
(b) Transfer RNA

DNA and Proteins as Tape Measures of Evolution

- The linear sequences of nucleotides in DNA molecules are passed from parents to offspring
- Two closely related species are more similar in DNA than are more distantly related species
- Molecular biology can be used to assess evolutionary kinship

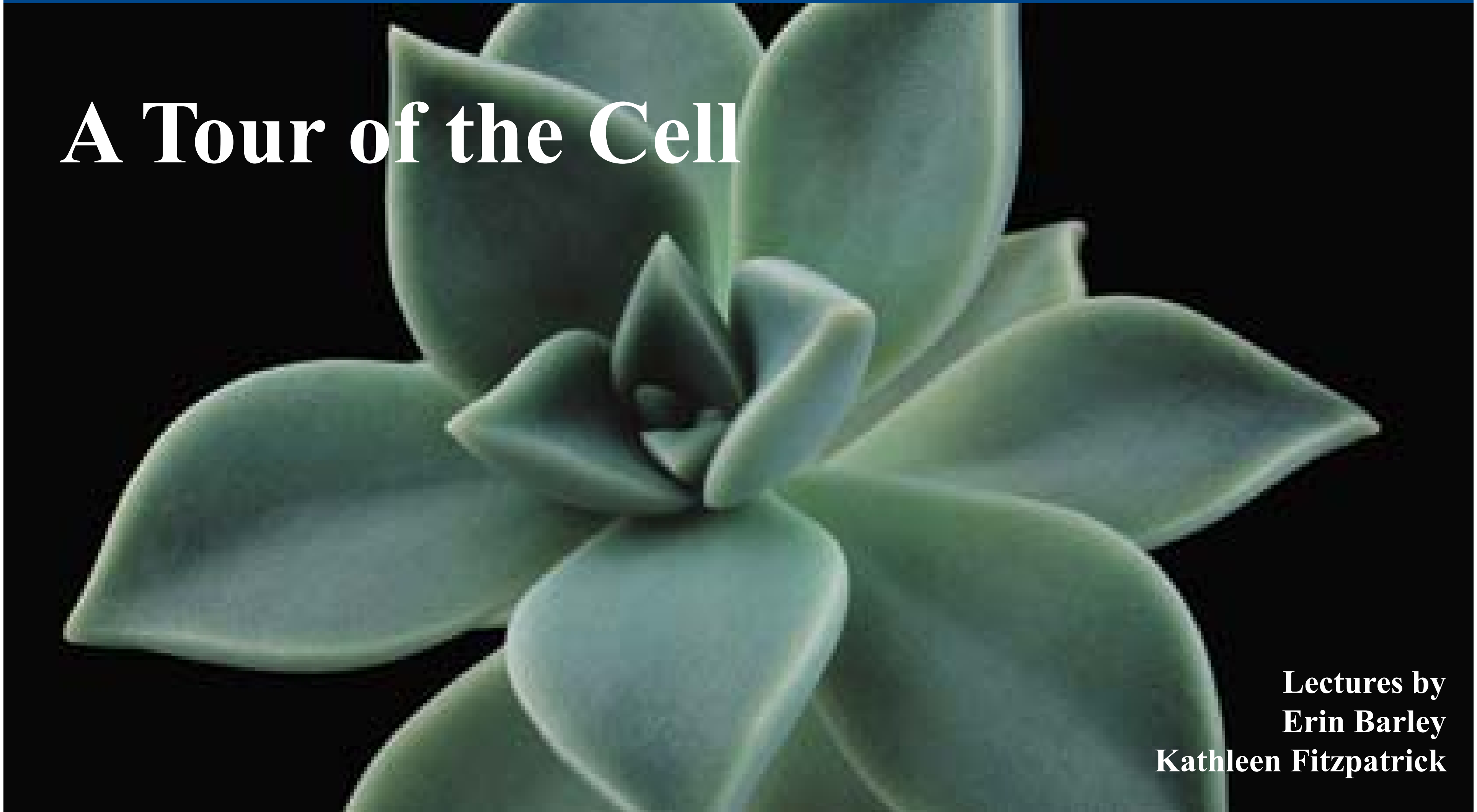
The Theme of Emergent Properties in the Chemistry of Life: *A Review*

- Higher levels of organization result in the emergence of new properties
- Organization is the key to the chemistry of life

LECTURE PRESENTATIONS
For CAMPBELL BIOLOGY, NINTH EDITION
Jane B. Reece, Lisa A. Urry, Michael L. Cain, Steven A. Wasserman, Peter V. Minorsky, Robert B. Jackson

Chapter 6

A Tour of the Cell



Lectures by
Erin Barley
Kathleen Fitzpatrick

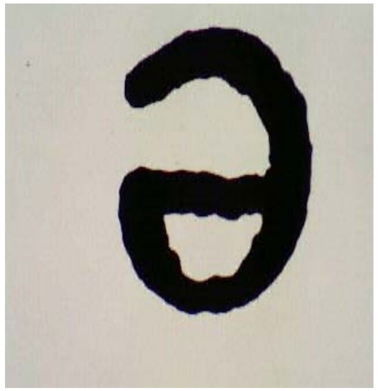
Overview: The Fundamental Units of Life

- All organisms are made of cells
- The cell is the simplest collection of matter that can live
- Cell **structure** is correlated to cellular **function**
- All cells are related by their descent from earlier cells

Concept 6.1: To study cells, biologists use microscopes and the tools of biochemistry

- Though usually too small to be seen by the unaided eye, cells can be complex
- **Microscopy:**
- Scientists use microscopes to visualize cells too small to see with the naked eye
- In a **light microscope (LM)**, visible light passes through a specimen and then through glass lenses, which magnify the image

- The **quality of an image** depends on
  - ***Magnification***, *the ratio of an object's image size to its real size*
  - ***Resolution***, *the measure of the clarity of the image, or the minimum distance of two distinguishable points*
  - ***Contrast***, *visible differences in parts of the sample*



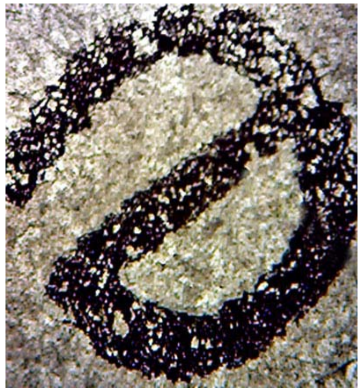


Figure 6.2

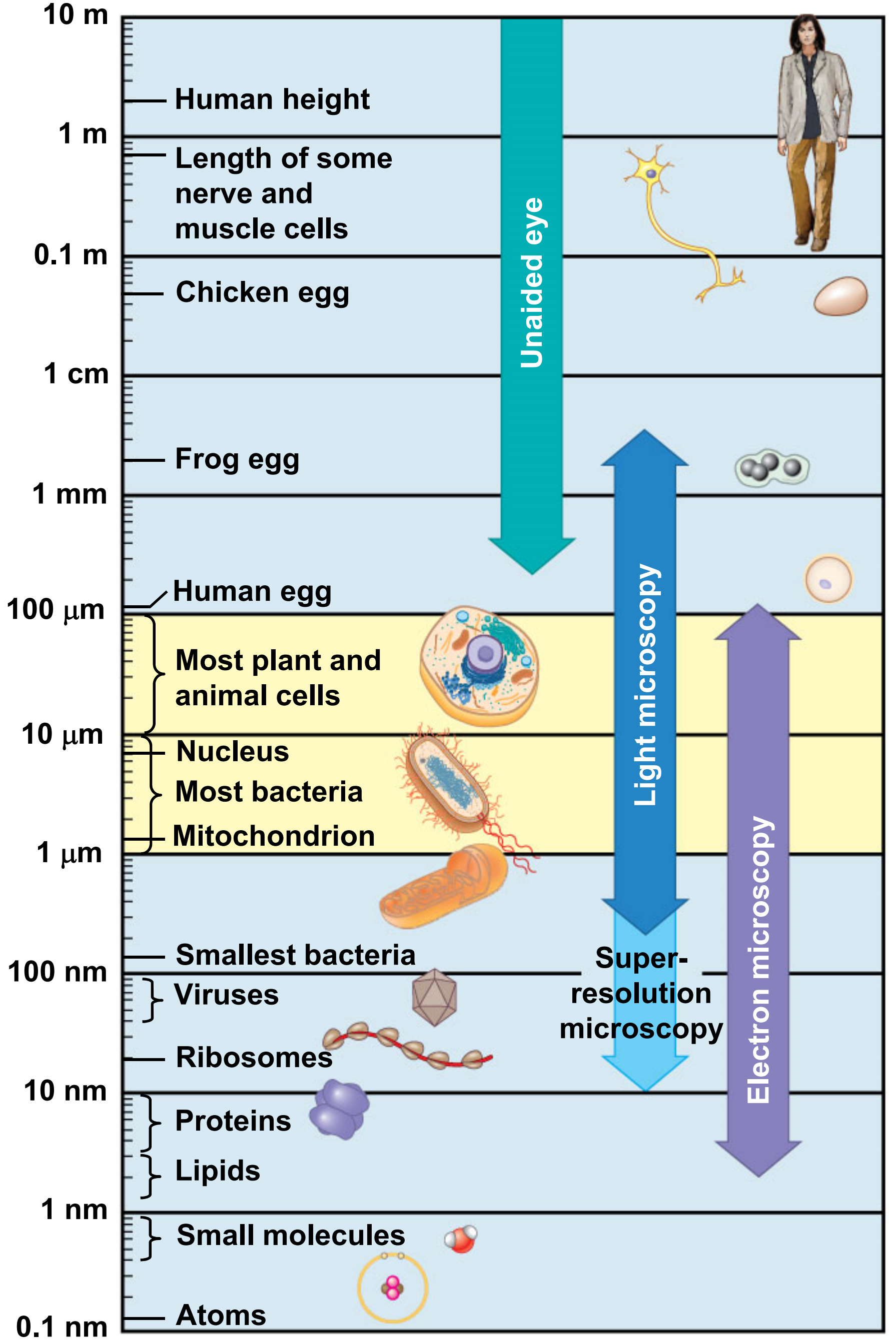
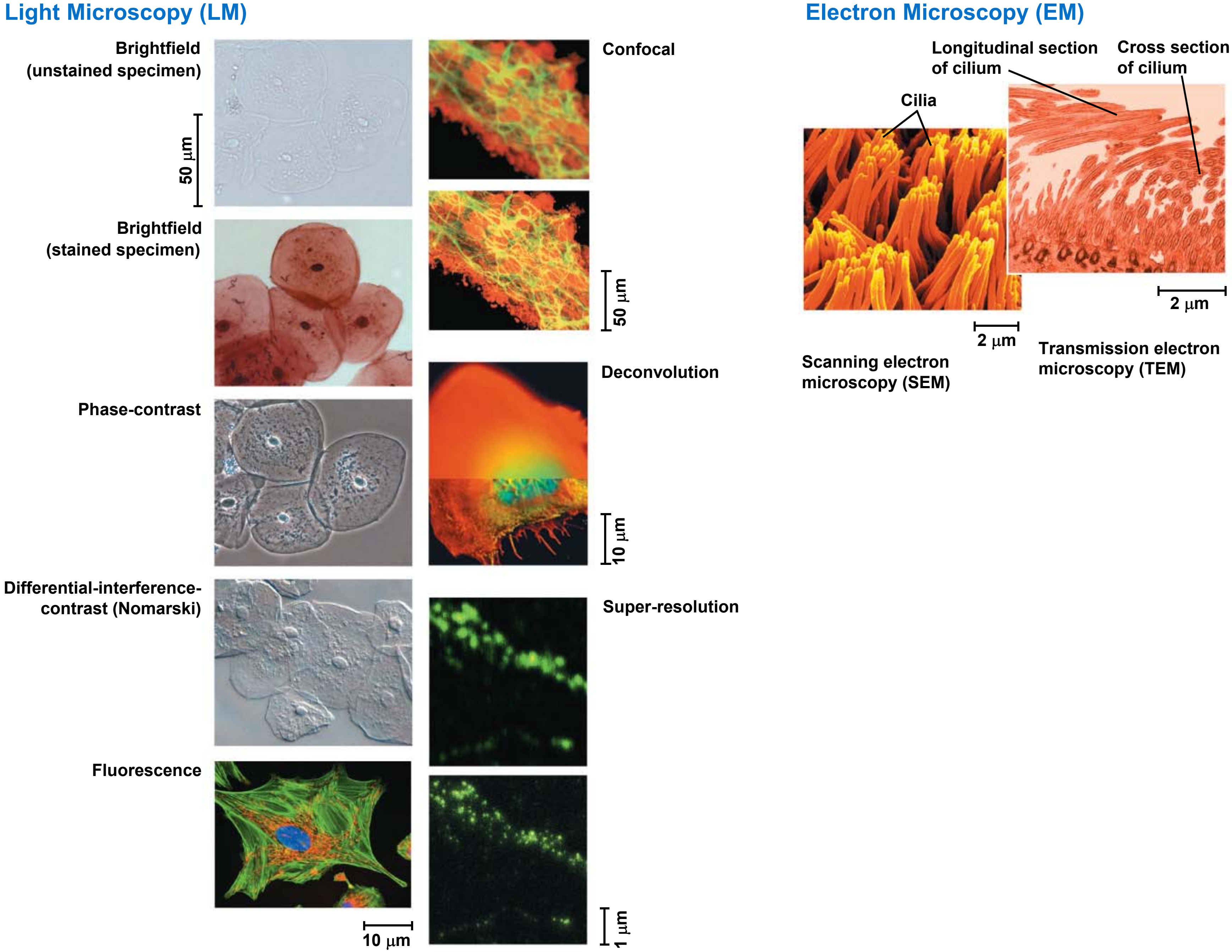

10 m
1 m
0.1 m
1 cm
1 mm
100 µm
10 µm
1 µm
100 nm
10 nm
1 nm
0.1 nm
Human height
Length of some nerve and muscle cells
Chicken egg
Frog egg
Human egg
Most plant and animal cells
Nucleus
Most bacteria
Mitochondrion
Smallest bacteria
Viruses
Ribosomes
Proteins
Lipids
Small molecules
Atoms
Unaided eye
Light microscopy
Super-resolution microscopy
Electron microscopy

Figure 6.3

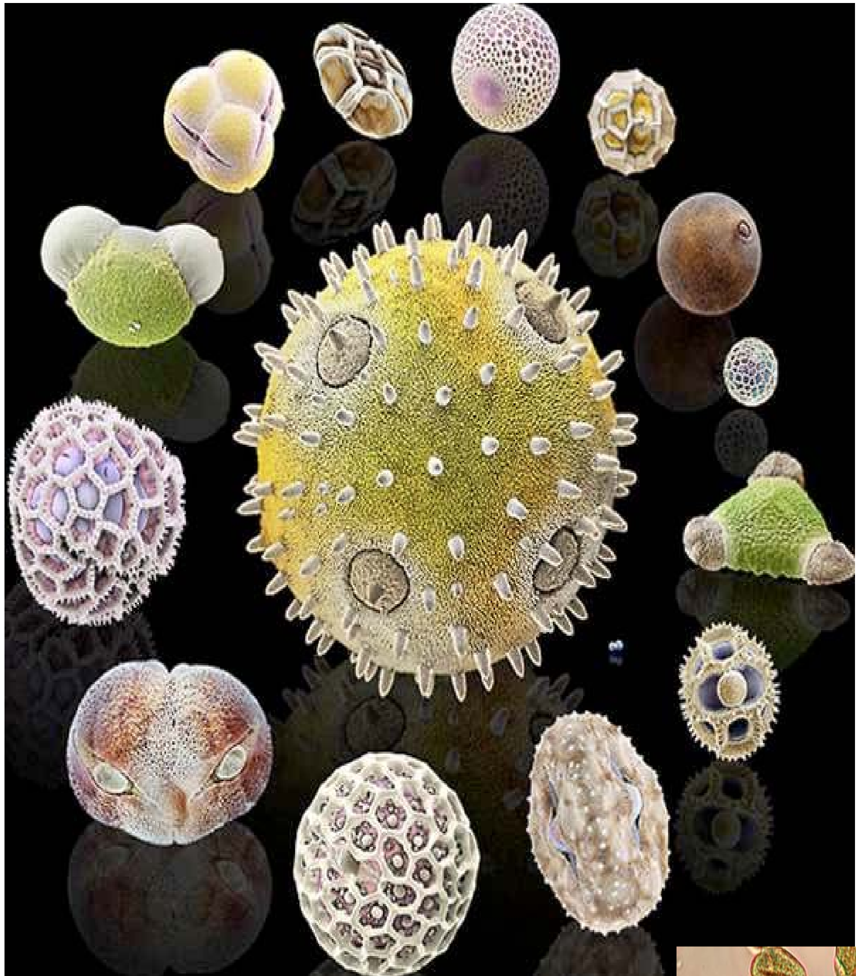


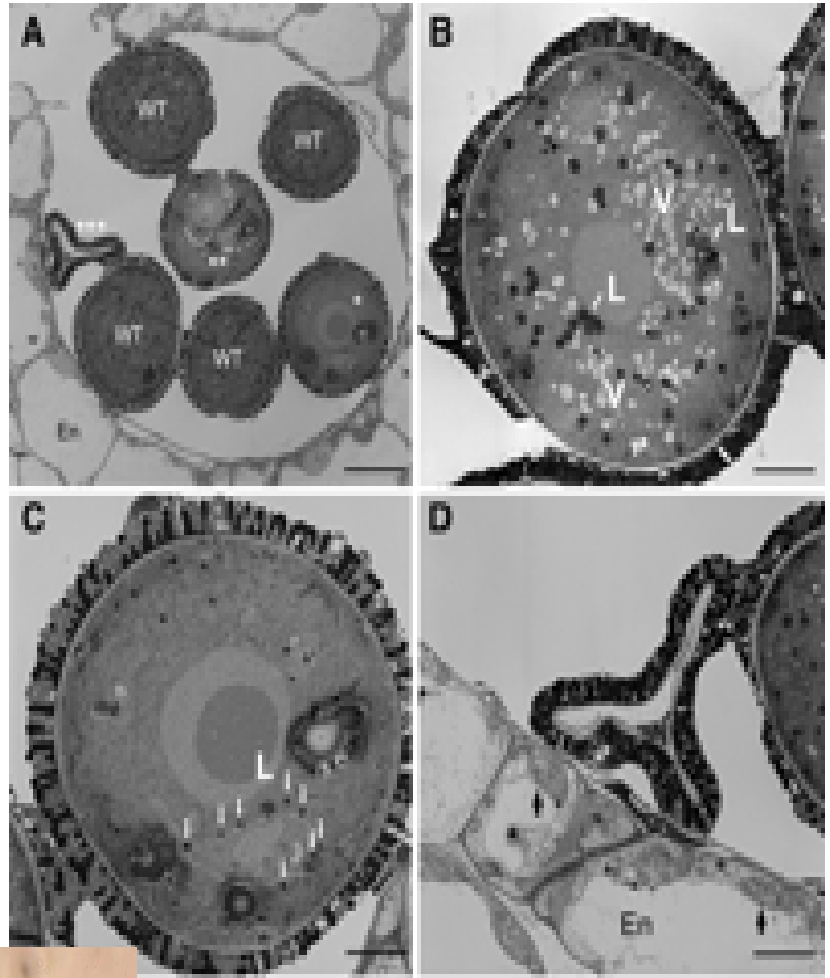
Light Microscopy (LM)
Brightfield (unstained specimen)
50 µm
Brightfield (stained specimen)
Phase-contrast
Differential-interference-contrast (Nomarski)
Fluorescence
10 µm
Confocal
50 µm
Deconvolution
10 µm
Super-resolution
1 µm
Electron Microscopy (EM)
Longitudinal section of cilium
Cross section of cilium
Cilia
2 µm
2 µm
Scanning electron microscopy (SEM)
Transmission electron microscopy (TEM)

- **LMs can magnify** effectively to about **1,000 times** the size of the actual specimen
- Various techniques enhance contrast and enable cell components to be stained or labeled
- Most subcellular structures, including **organelles** (membrane-enclosed compartments), are **too small to be resolved by an LM**

Electron microscopes

- Two basic types of **electron microscopes (EMs)** are used to study subcellular structures
- **Scanning electron microscopes (SEMs)** focus a beam of electrons onto the surface of a specimen, providing images that look 3-D
- **Transmission electron microscopes (TEMs)** focus a beam of electrons through a specimen
- TEMs are used mainly to study the internal structure of cells





- SEM

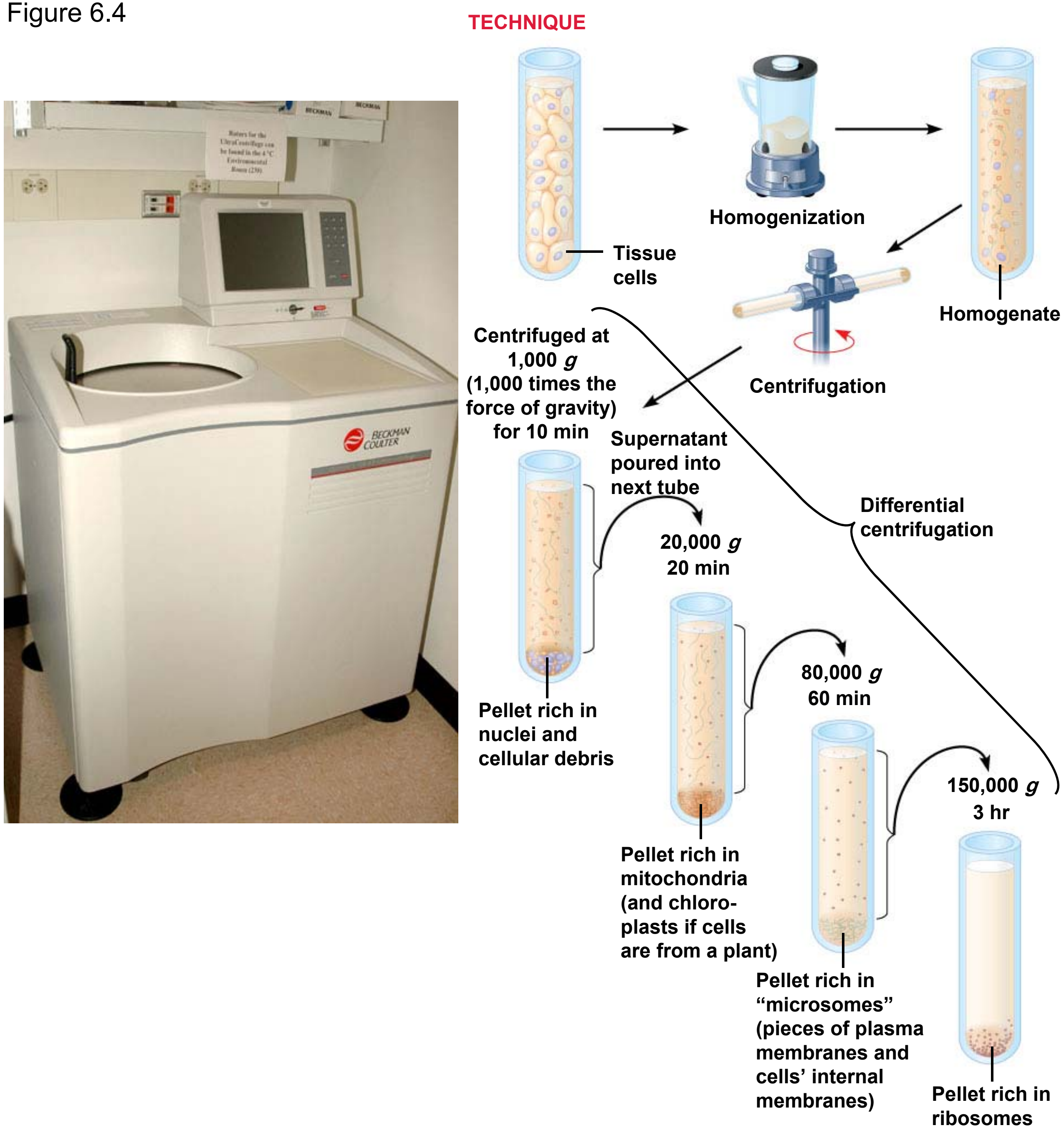
TEM

- LM

Cell Fractionation

- **Cell fractionation** takes cells apart and separates the major organelles from one another
- Ultracentrifuges fractionate cells into their component parts
- Cell fractionation enables scientists to determine the functions of organelles
- Biochemistry and cytology help correlate cell function with structure

Figure 6.4


TECHNIQUE
Homogenization
Tissue cells
Homogenate
Centrifugation
Centrifuged at 1,000 g (1,000 times the force of gravity) for 10 min
Supernatant poured into next tube
Differential centrifugation
20,000 g 20 min
80,000 g 60 min
150,000 g 3 hr
Pellet rich in nuclei and cellular debris
Pellet rich in mitochondria (and chloro- plasts if cells are from a plant)
Pellet rich in "microsomes" (pieces of plasma membranes and cells' internal membranes)
Pellet rich in ribosomes

Concept 6.2: Eukaryotic cells have internal membranes that compartmentalize their functions

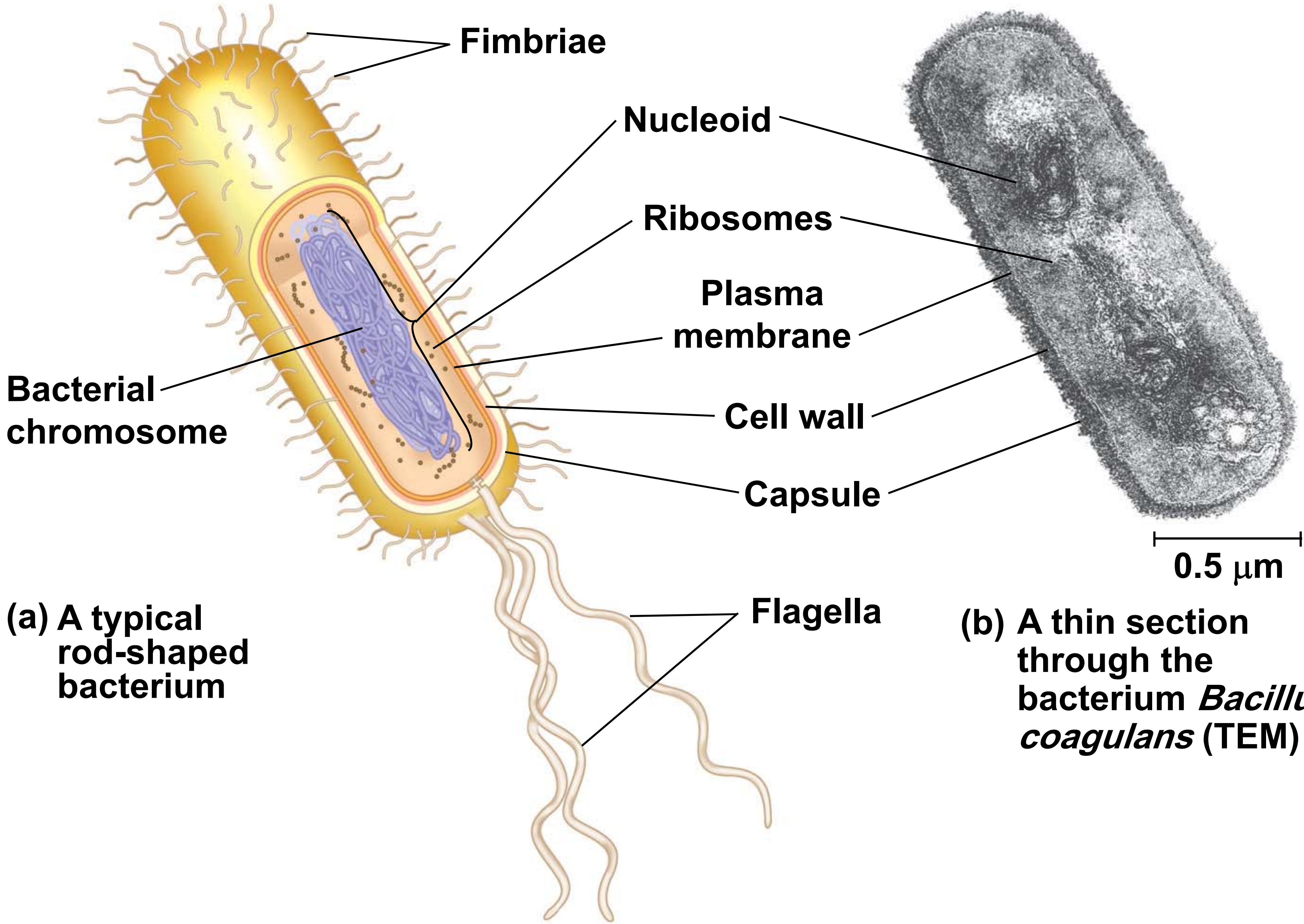
- The basic structural and functional unit of every organism is one of two types of cells: **prokaryotic** or **eukaryotic**
- Only organisms of the domains **Bacteria** and **Archaea** consist of prokaryotic cells
- Protists, fungi, animals, and plants all consist of **eukaryotic cells**

Comparing Prokaryotic and Eukaryotic Cells

- **Basic features of all cells:**
  - Plasma membrane
  - Semifluid substance called cytosol
  - Chromosomes (carry genes)
  - Ribosomes (make proteins)

- **Prokaryotic cells** are characterized by having
  - No nucleus
  - DNA in an unbound region called the **nucleoid**
  - No membrane-bound organelles
  - **Cytoplasm** bound by the plasma membrane

Figure 6.5



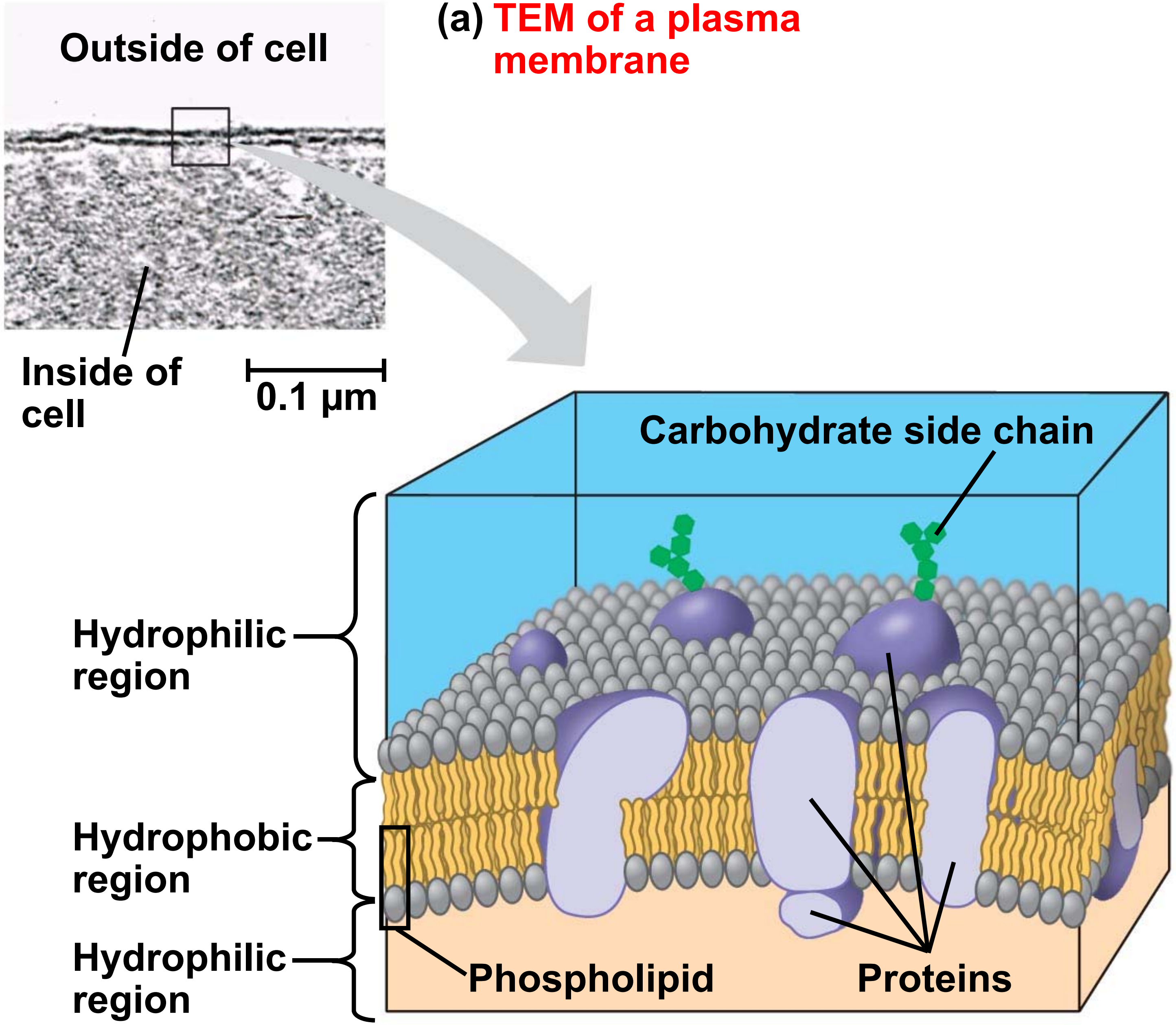
(a) A typical rod-shaped bacterium

(b) A thin section through the bacterium *Bacillus coagulans* (TEM)

- **Eukaryotic cells** are characterized by having
  - DNA in a nucleus that is bounded by a membranous nuclear envelope
  - Membrane-bound organelles
  - Cytoplasm in the region between the plasma membrane and nucleus
- *Eukaryotic cells are generally much larger than prokaryotic cells*

- The **plasma membrane** is a *selective barrier that allows sufficient passage of oxygen, nutrients, and waste to service the volume of every cell*
- The general structure of a biological membrane is a double layer of phospholipids

Fig. 6-7

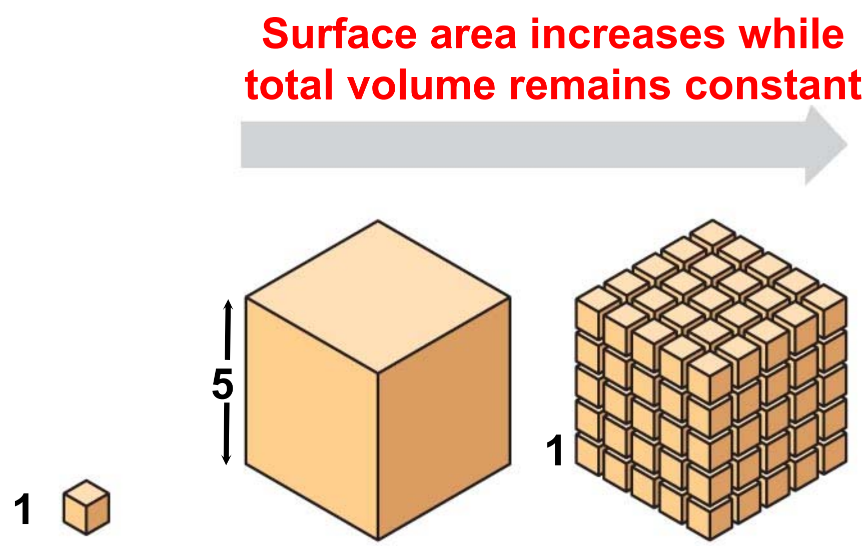


(a) TEM of a plasma membrane

(b) Structure of the plasma membrane

- **Metabolic requirements** set upper limits on the size of cells
- The surface area to volume ratio of a cell is critical
- **Small cells** *have a greater surface area relative to volume*

Fig. 6-8



Total surface area [Sum of the surface areas (height × width) of all boxes sides × number of boxes]	6	150	750
Total volume [height × width × length × number of boxes]	1	125	125
Surface-to-volume (S-to-V) ratio [surface area ÷ volume]	6	1.2	6

A Panoramic View of the Eukaryotic Cell

- A eukaryotic cell has internal membranes that partition the cell into organelles
- Plant and animal cells have most of the same organelles

PLAY BioFlix: Tour Of An Animal Cell

PLAY BioFlix: Tour Of A Plant Cell

Fig. 6-9a

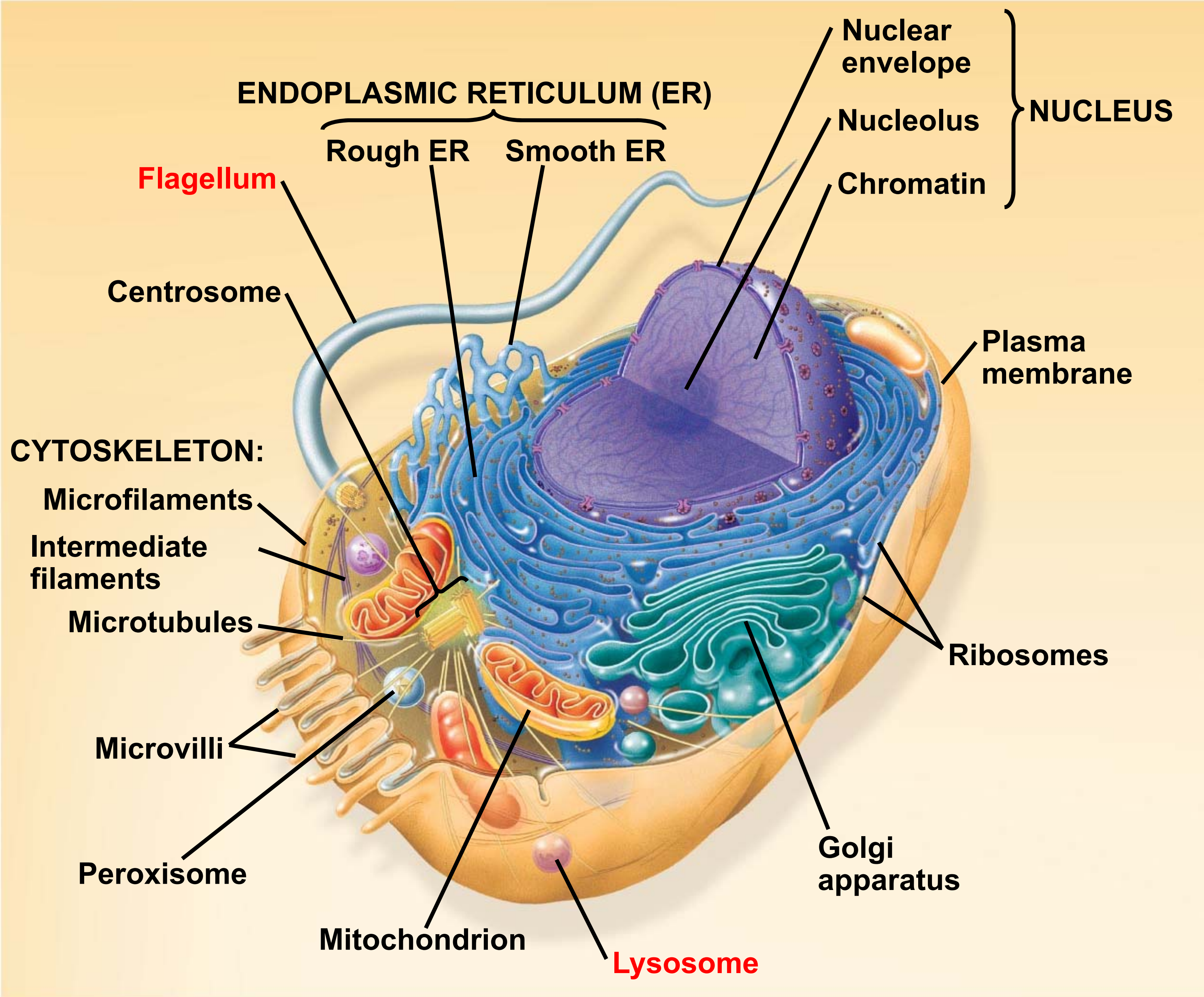
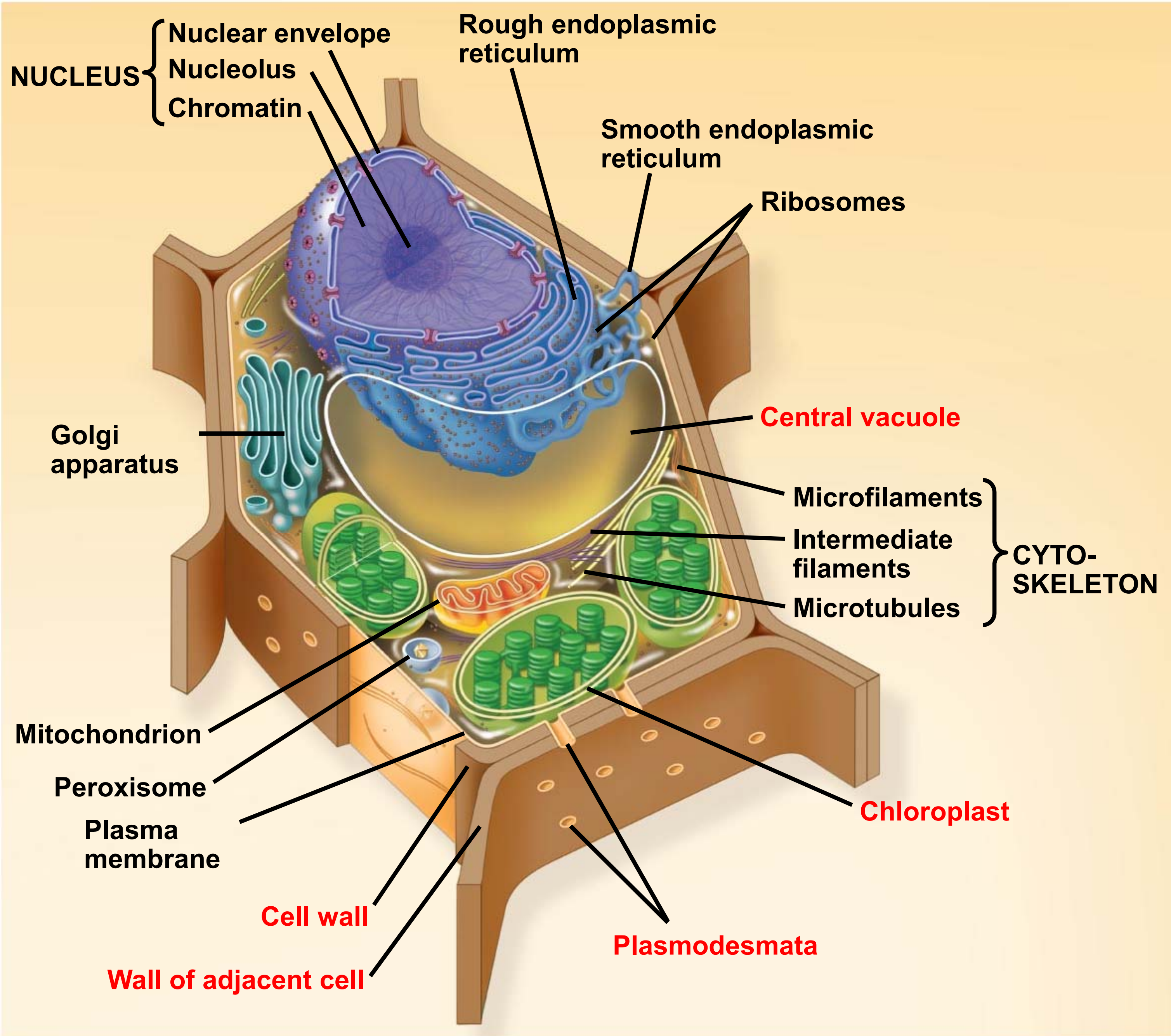

ENDOPLASMIC RETICULUM (ER)
Rough ER
Smooth ER
Flagellum
Nuclear envelope
Nucleolus
Chromatin
NUCLEUS
Centrosome
Plasma membrane
CYTOSKELETON:
Microfilaments
Intermediate filaments
Microtubules
Ribosomes
Microvilli
Peroxisome
Golgi apparatus
Mitochondrion
Lysosome

Fig. 6-9b


NUCLEUS
Nuclear envelope
Nucleolus
Chromatin
Rough endoplasmic reticulum
Smooth endoplasmic reticulum
Ribosomes
Central vacuole
Microfilaments
Intermediate filaments
Microtubules
CYTO-SKELETON
Golgi apparatus
Mitochondrion
Peroxisome
Plasma membrane
Cell wall
Wall of adjacent cell
Plasmodesmata
Chloroplast

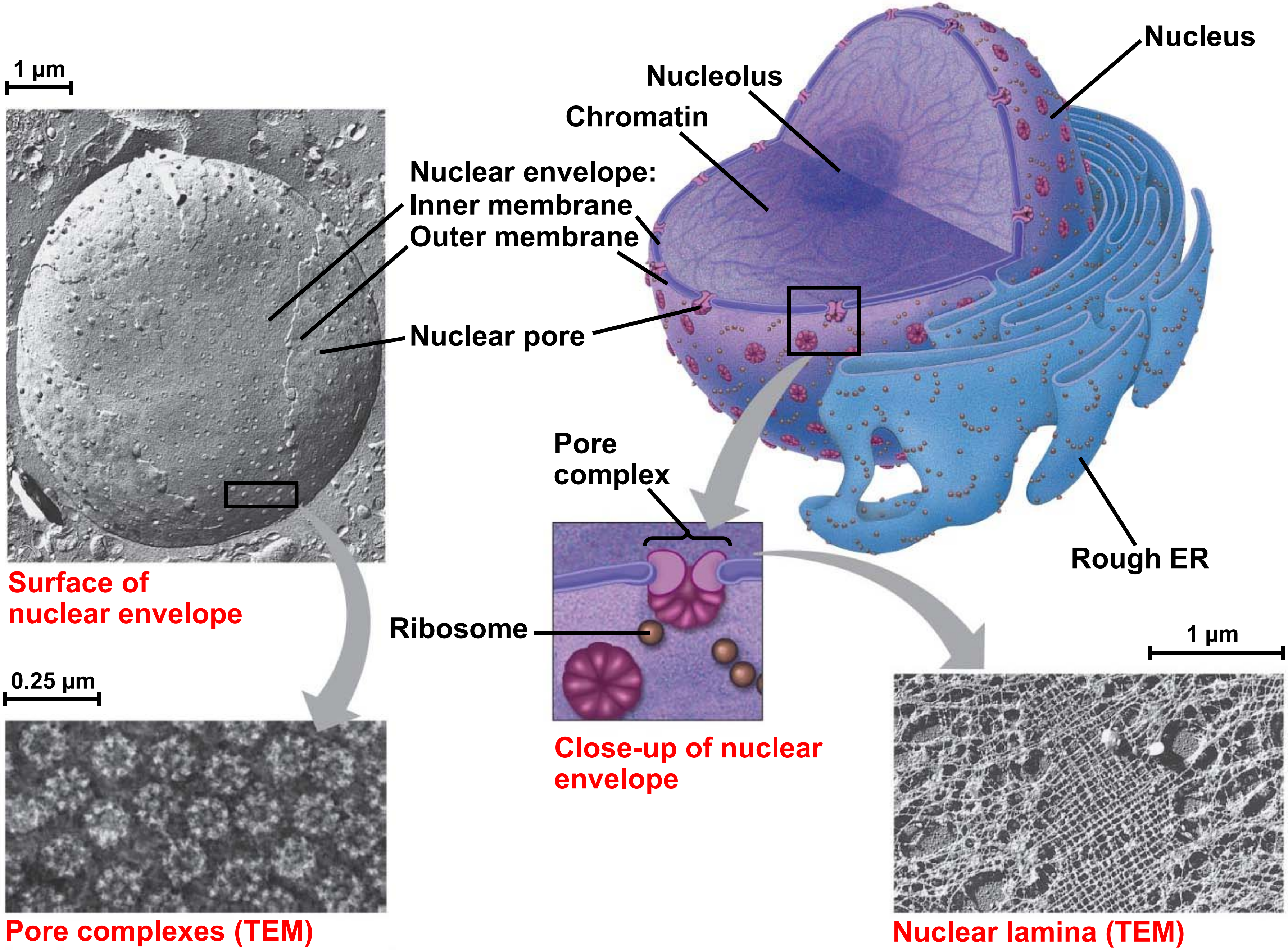
Concept 6.3: The eukaryotic cell's genetic instructions are housed in the nucleus and carried out by the ribosomes

- The **nucleus** contains most of the DNA in a eukaryotic cell
- Ribosomes use the information from the DNA to make proteins

The Nucleus: Information Central

- The **nucleus is** usually the most conspicuous organelle
- The **nuclear envelope** encloses the nucleus, separating it from the cytoplasm
- The nuclear membrane is a double membrane; each membrane consists of a lipid bilayer

Fig. 6-10


1 µm
Nucleus
Nucleolus
Chromatin
Nuclear envelope:
Inner membrane
Outer membrane
Nuclear pore
Pore
complex
Surface of
nuclear envelope
Ribosome
Rough ER
1 µm
0.25 µm
Close-up of nuclear
envelope
Pore complexes (TEM)
Nuclear lamina (TEM)

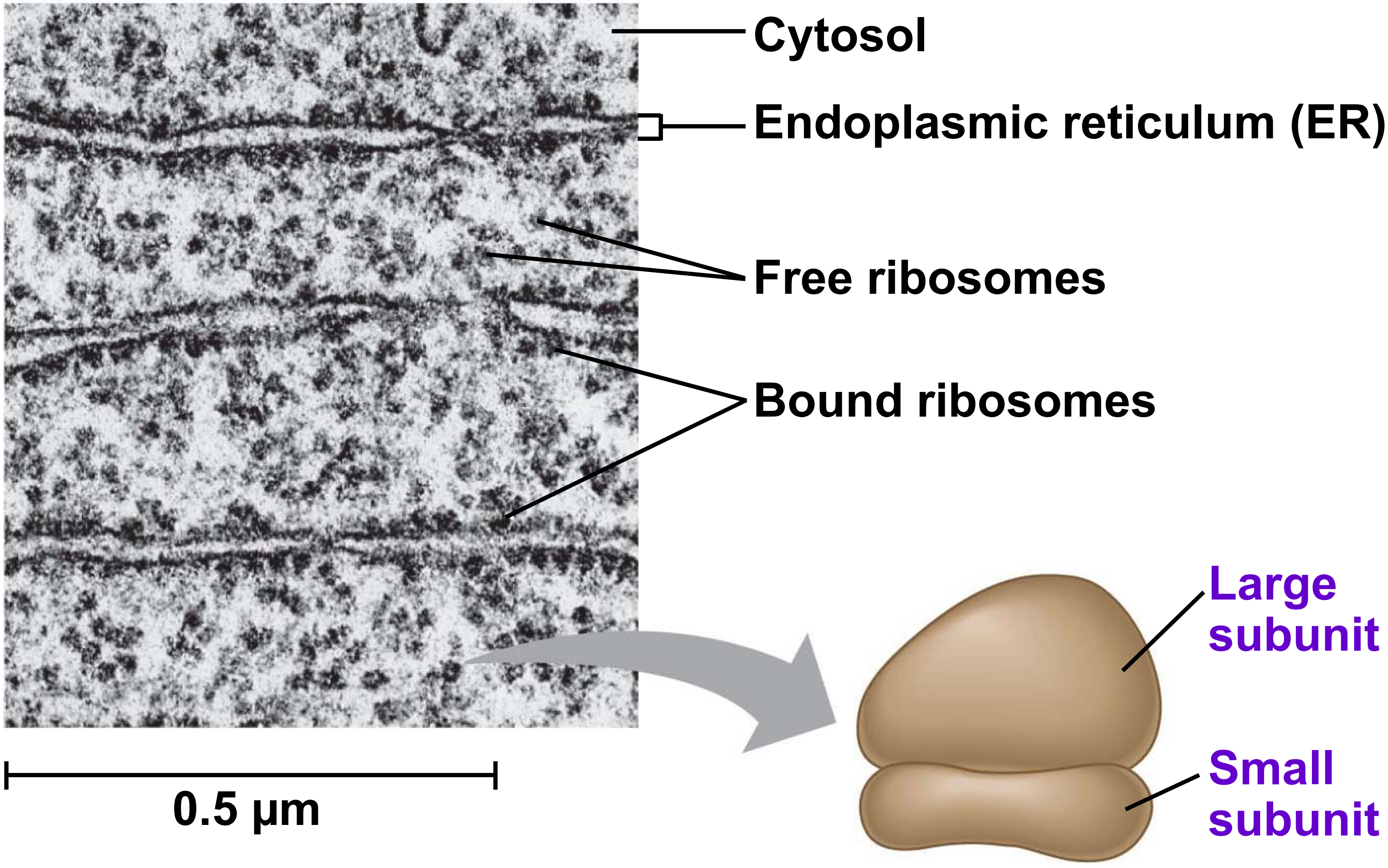
- **Pores** regulate the entry and exit of molecules from the nucleus
- The shape of the nucleus is maintained by the **nuclear lamina**, which is composed of protein

- In the nucleus, DNA is organized into discrete units called **chromosomes.**
- Each chromosome is composed of a single DNA molecule associated with proteins
- **DNA and proteins** form genetic material called **chromatin.**
- Chromatin condenses to form discrete **chromosomes** as a cell prepares to divide.
- The **nucleolus** is located within the nucleus and is the **site of ribosomal RNA (rRNA) synthesis**

Ribosomes: Protein Factories

- **Ribosomes** are particles **made of ribosomal RNA and protein**
- Ribosomes carry out protein synthesis in two locations:
  - **In the cytosol (free ribosomes)**
  - **On the outside of the endoplasmic reticulum** or the **nuclear envelope** **(bound ribosomes)**

Fig. 6-11



TEM showing ER and ribosomes

Diagram of a ribosome

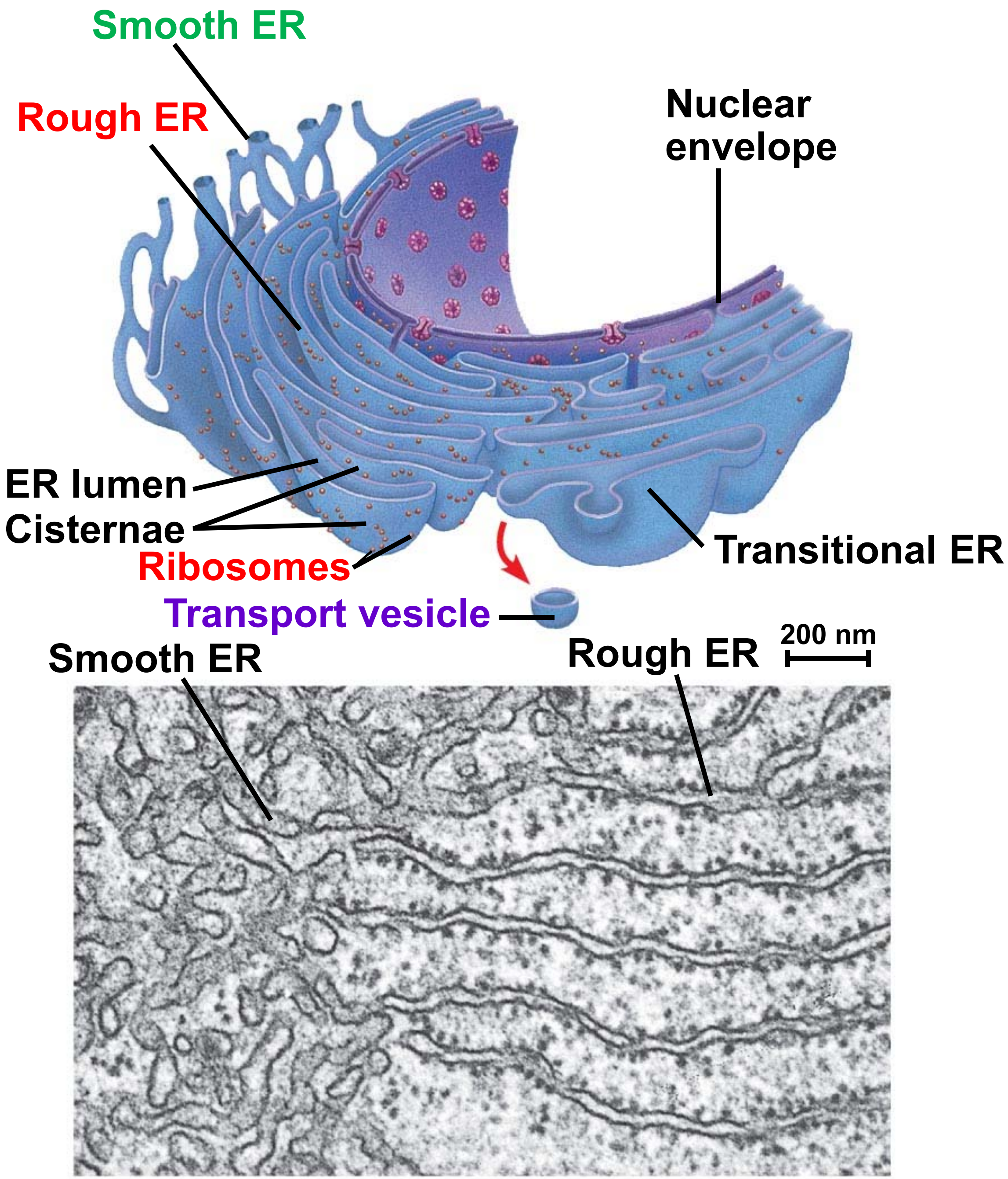
Concept 6.4: The endomembrane system regulates protein traffic and performs metabolic functions in the cell

- Components of the **endomembrane system**:
  - **Nuclear envelope**
  - **Endoplasmic reticulum**
  - **Golgi apparatus**
  - **Lysosomes**
  - **Vacuoles**
  - **Plasma membrane**
- These components are either continuous or connected via transfer by **vesicles**

The Endoplasmic Reticulum: Biosynthetic Factory

- The **endoplasmic reticulum (ER)** accounts for more than half of the total membrane in many eukaryotic cells
- The ER membrane is continuous with the nuclear envelope
- There are **two distinct regions of ER**:
  - **Smooth ER**, which lacks ribosomes
  - **Rough ER**, with ribosomes studding its surface

Fig. 6-12


Smooth ER
Rough ER
Nuclear envelope
ER lumen
Cisternae
Ribosomes
Transport vesicle
Transitional ER
Smooth ER
Rough ER
200 nm

Functions of Smooth ER

- The smooth ER
  - **Synthesizes lipids**
  - **Metabolizes carbohydrates**
  - **Detoxifies poison**
  - **Stores calcium**

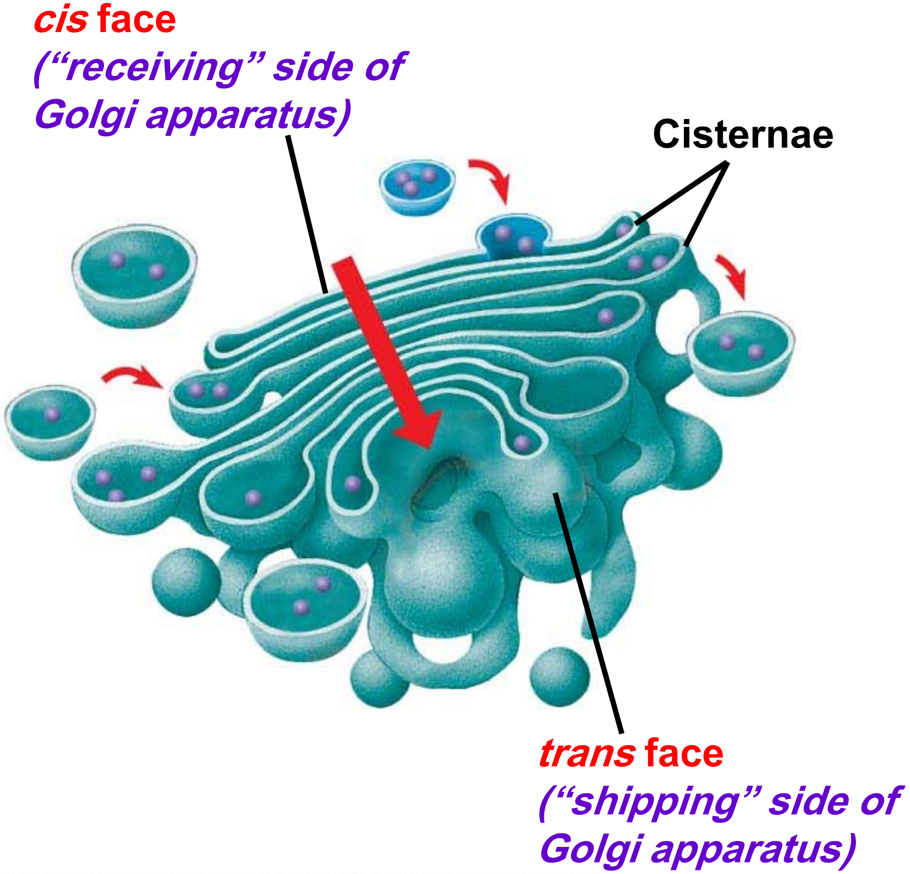
Functions of Rough ER

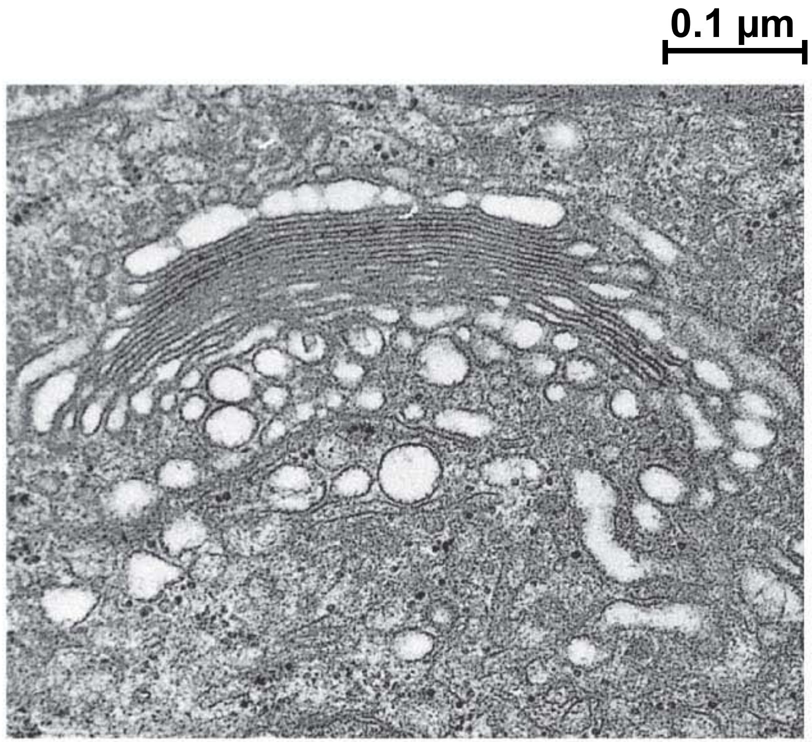
- The rough ER
  - Has bound ribosomes, which **secrete glycoproteins** (proteins covalently bonded to carbohydrates)
  - Distributes **transport vesicles,** proteins surrounded by membranes
  - Is a **membrane factory** for the cell

The Golgi Apparatus: *Shipping and Receiving Center*

- The **Golgi apparatus** *consists of flattened membranous sacs* ***called cisternae***
- **Functions of the Golgi apparatus:**
  - Modifies products of the ER
  - Manufactures certain macromolecules
  - Sorts and packages materials into transport vesicles

Fig. 6-13





TEM of Golgi apparatus

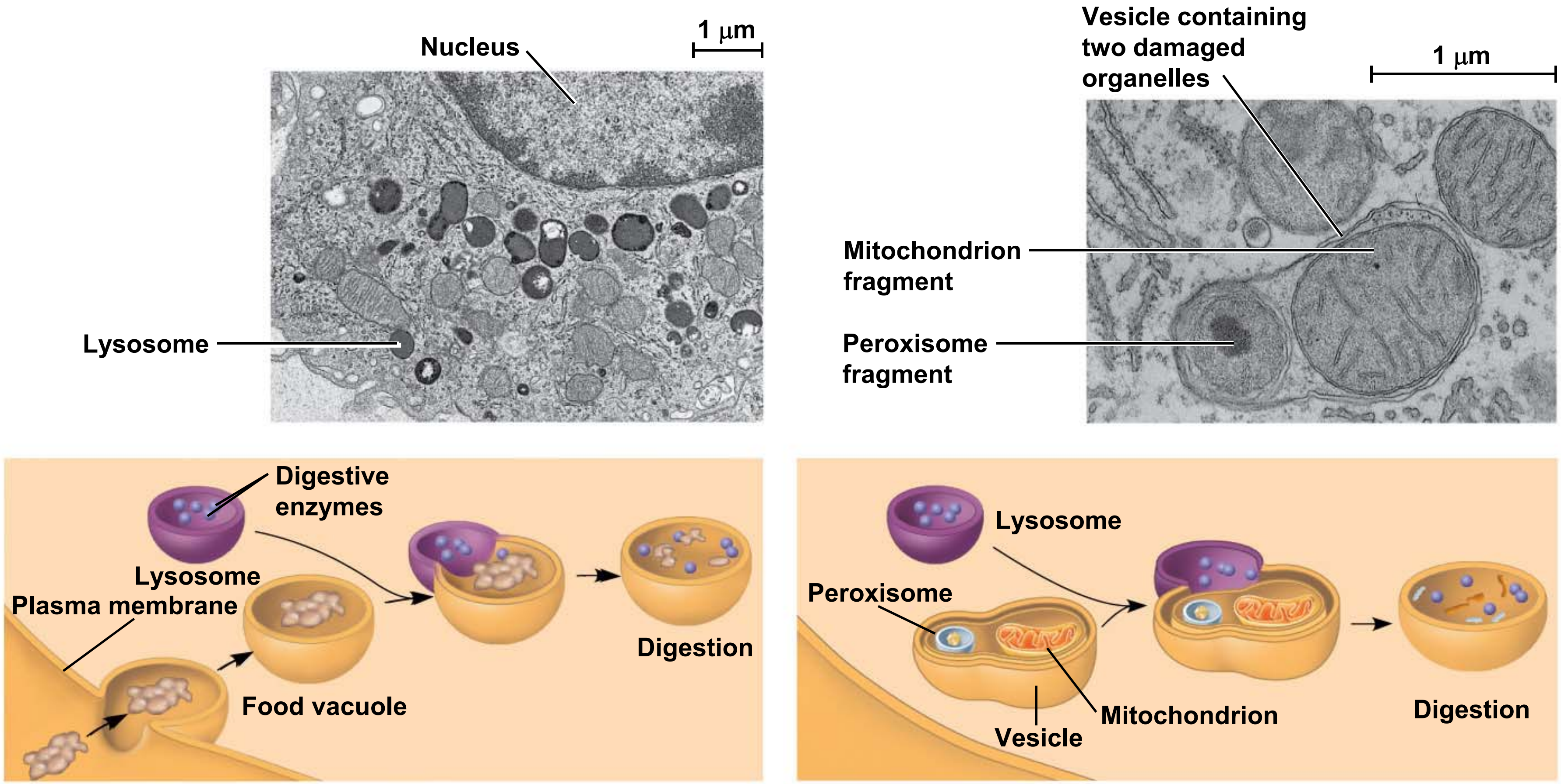
Lysosomes: Digestive Compartments

- A **lysosome** is a membranous sac of **hydrolytic enzymes** that can digest macromolecules
- Lysosomal enzymes can hydrolyze proteins, fats, polysaccharides, and nucleic acids.
- Lysosomal enzymes work best in the **acidic environment** inside the lysosome

PLAY Animation: Lysosome Formation

- Some types of cell can engulf another cell by **phagocytosis**; this forms a food vacuole
- A lysosome fuses with the food vacuole and digests the molecules
- Lysosomes also use enzymes to recycle the cell's own organelles and macromolecules, a process **called autophagy**

Figure 6.13



(a) Phagocytosis

(b) Autophagy

Vacuoles: Diverse Maintenance Compartments

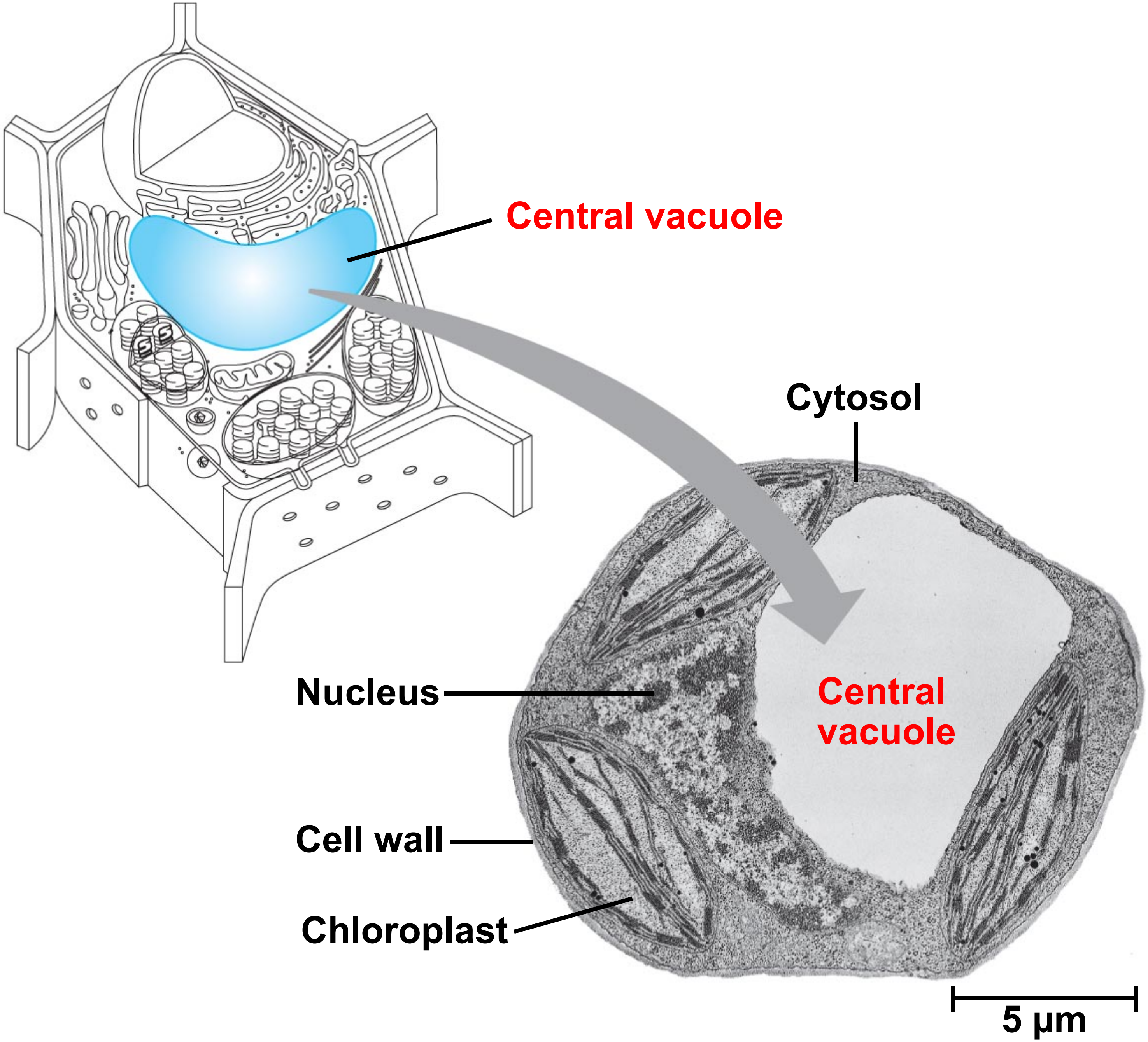
- A plant cell or fungal cell may have **one or several vacuoles** derived from endoplasmic reticulum and Golgi apparatus

- **Types of Vacuoles:**

- **Food vacuoles** are formed by phagocytosis
- **Contractile vacuoles**, found in many freshwater protists, pump excess water out of cells
- **Central vacuoles**, found in many mature plant cells, hold organic compounds and water

PLAY Video: Paramecium Vacuole

Fig. 6-15


Central vacuole
Cytosol
Nucleus
Central vacuole
Cell wall
Chloroplast
5 µm

The **Endomembrane System**: ***A Review***

- The endomembrane system is a complex and dynamic player in the cell's compartmental organization

Figure 6.15-1

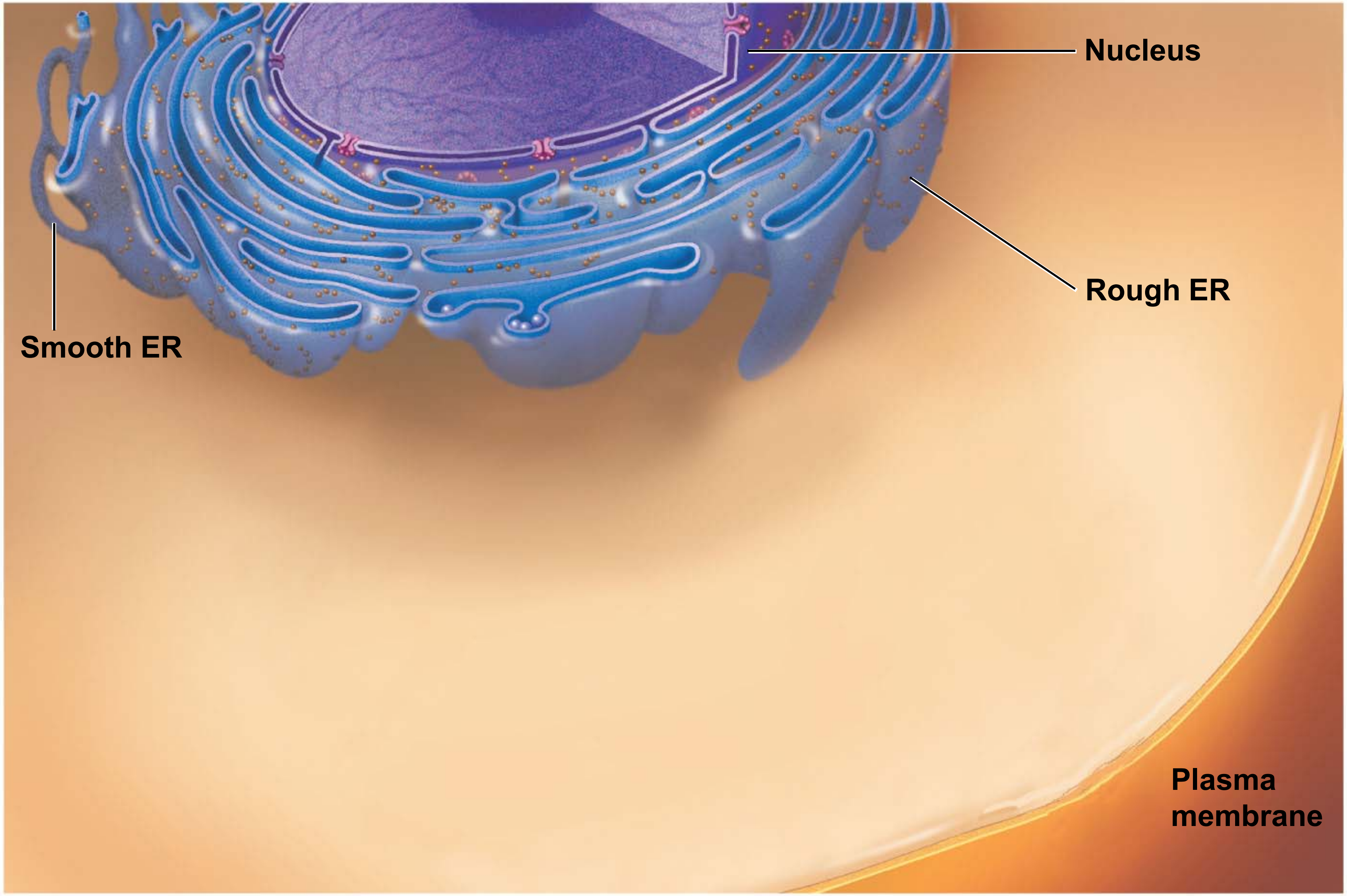
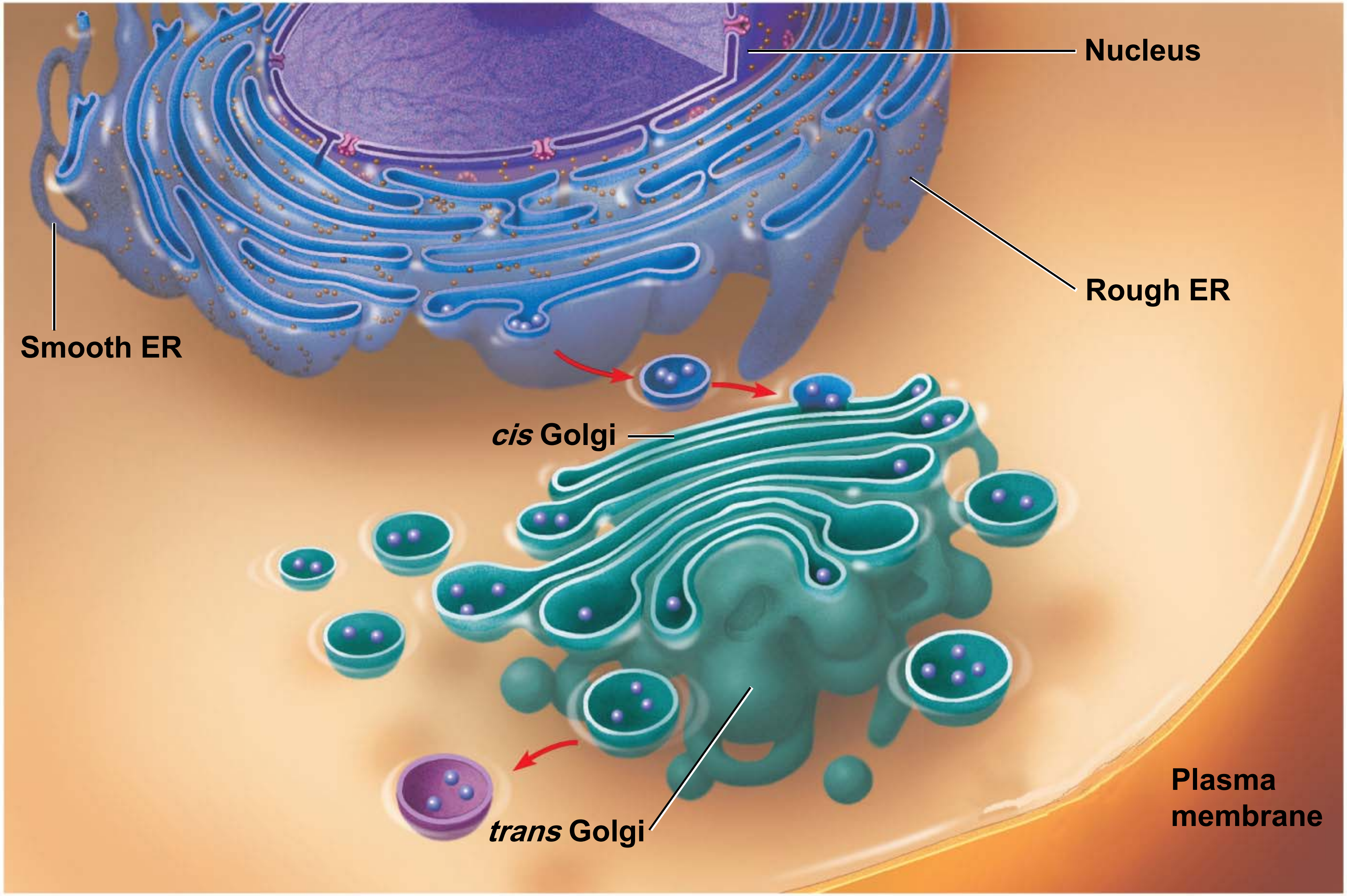
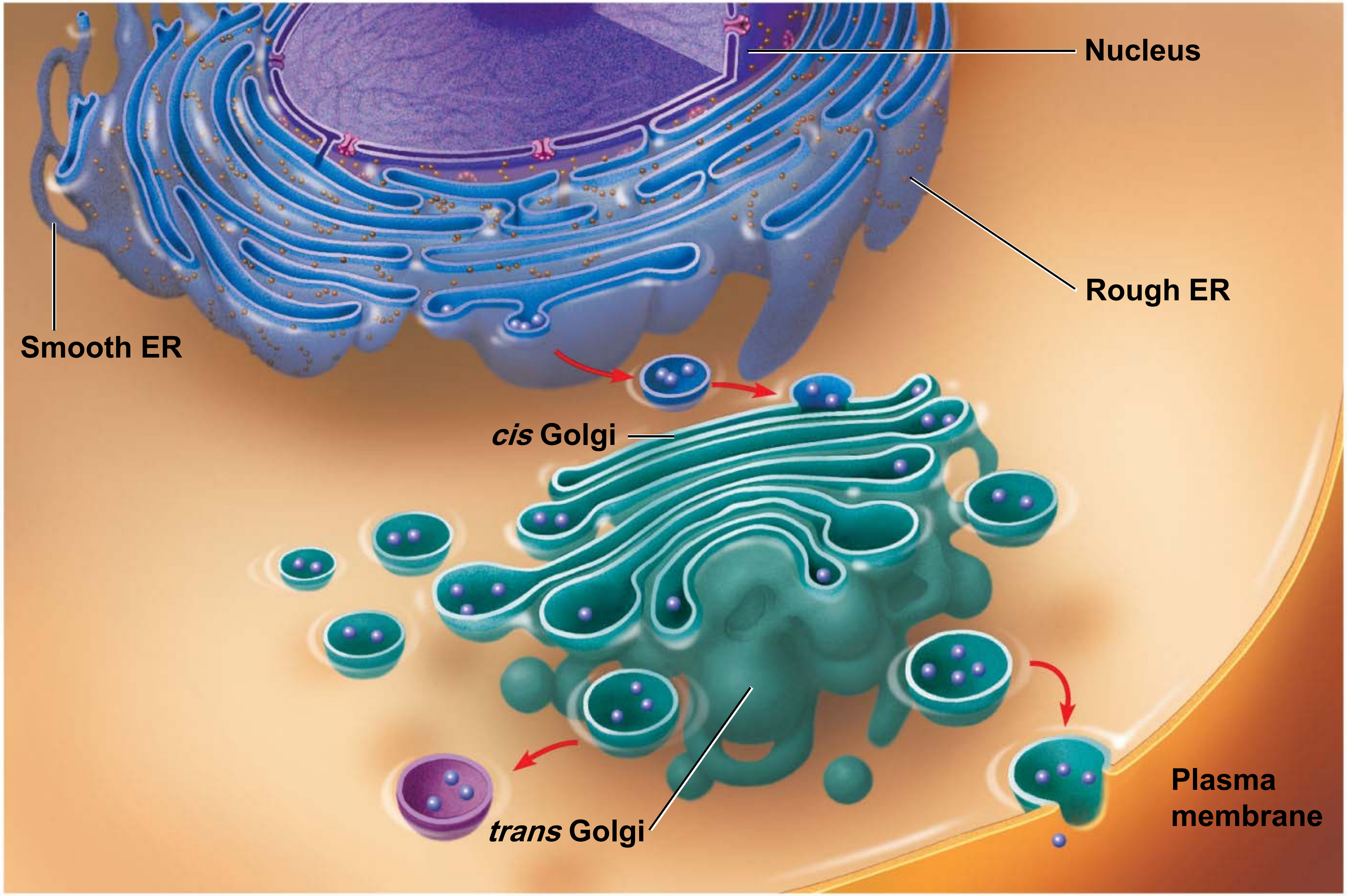


Figure 6.15-2



Nucleus
Rough ER
Smooth ER
cis Golgi
trans Golgi
Plasma membrane

Figure 6.15-3


Nucleus
Rough ER
Smooth ER
cis Golgi
trans Golgi
Plasma membrane

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

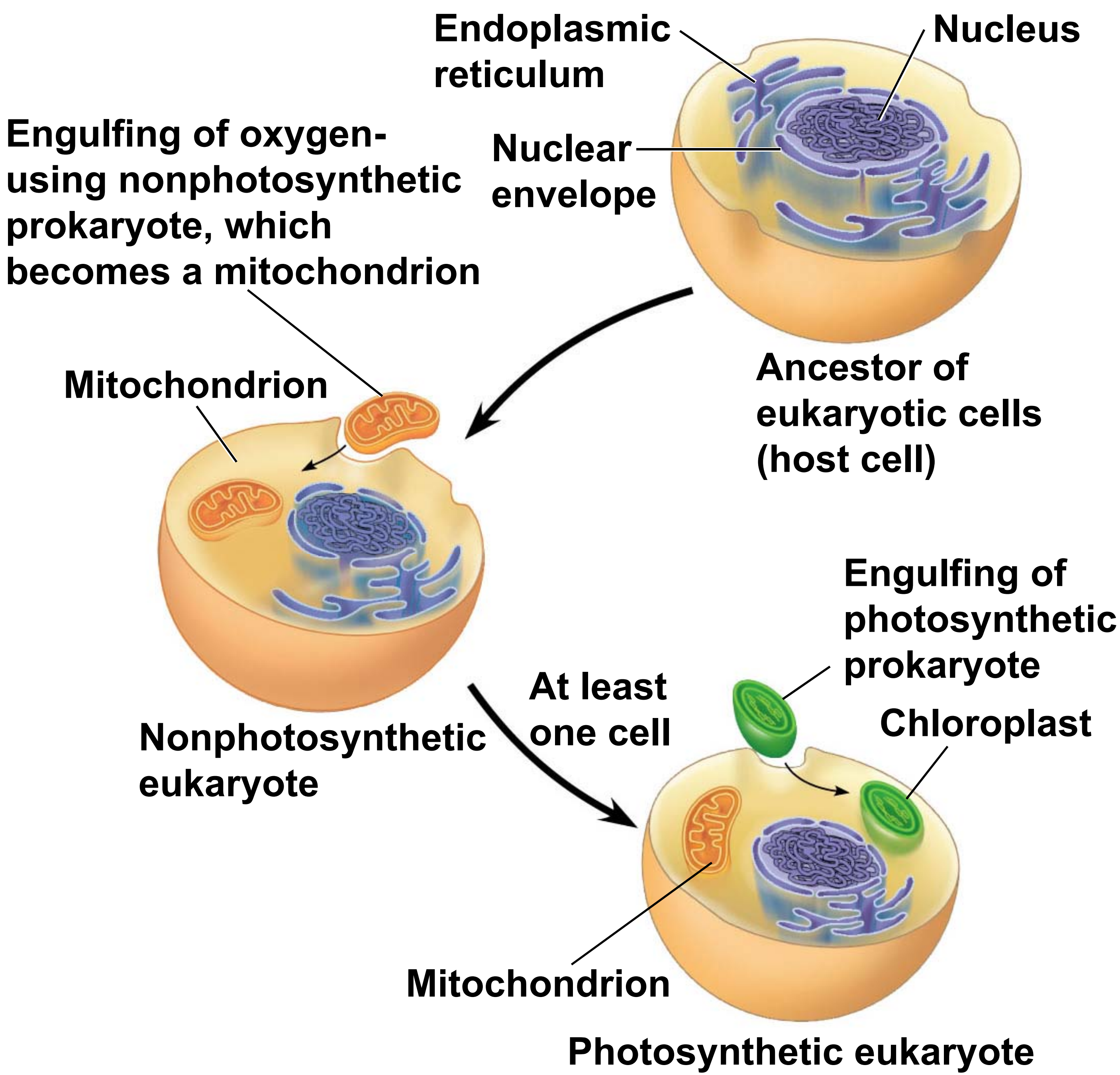
- **Mitochondria** are the sites of cellular respiration, a metabolic process that generates ATP
- **Chloroplasts**, found in plants and algae, are the sites of photosynthesis

The Evolutionary Origins of Mitochondria and Chloroplasts

- Mitochondria and chloroplasts have similarities with bacteria:
  - Enveloped by a **double membrane**
  - Contain **free ribosomes** and circular DNA molecules
  - Grow and reproduce somewhat **independently in cells**

- The **Endosymbiont theory**
  - An early ancestor of eukaryotic cells **engulfed a nonphotosynthetic prokaryotic cell**, which formed an **endosymbiont relationship with its host**
  - The host cell and endosymbiont merged into a single organism, a eukaryotic cell with a mitochondrion
  - At least one of these cells **may have taken up a photosynthetic prokaryote**, becoming the ancestor of cells that contain chloroplasts

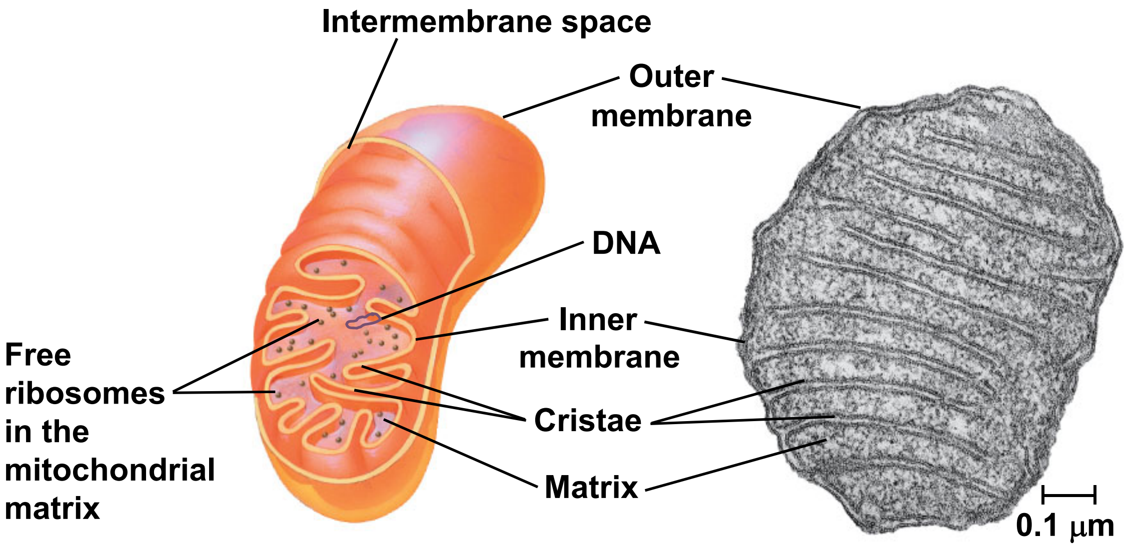
Figure 6.16


Endoplasmic reticulum
Nucleus
Engulfing of oxygen-using nonphotosynthetic prokaryote, which becomes a mitochondrion
Nuclear envelope
Ancestor of eukaryotic cells (host cell)
Mitochondrion
Nonphotosynthetic eukaryote
At least one cell
Engulfing of photosynthetic prokaryote
Chloroplast
Mitochondrion
Photosynthetic eukaryote

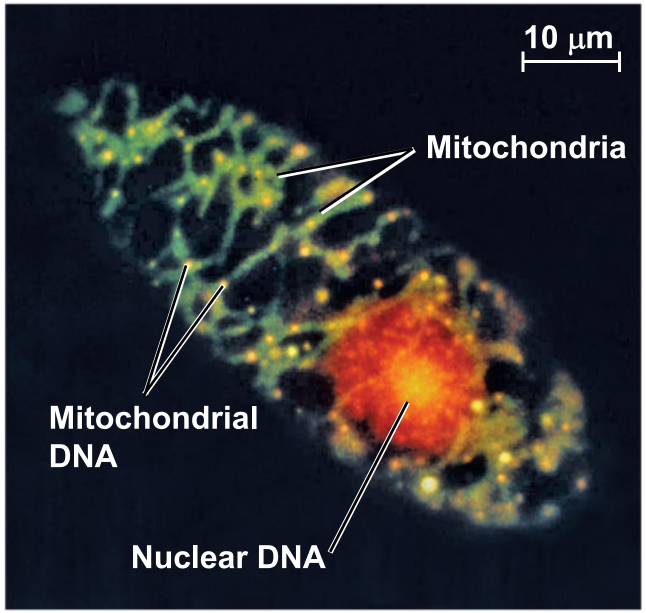
Mitochondria: Chemical Energy Conversion

- Mitochondria are in nearly all eukaryotic cells
- They have a smooth outer membrane and an inner membrane folded into **cristae**
- The inner membrane creates **two compartments**: **intermembrane space** and **mitochondrial matrix**
- Some metabolic steps of cellular respiration are catalyzed in the mitochondrial matrix
- Cristae present a large surface area for enzymes that synthesize ATP

Figure 6.17



(a) Diagram and TEM of mitochondrion



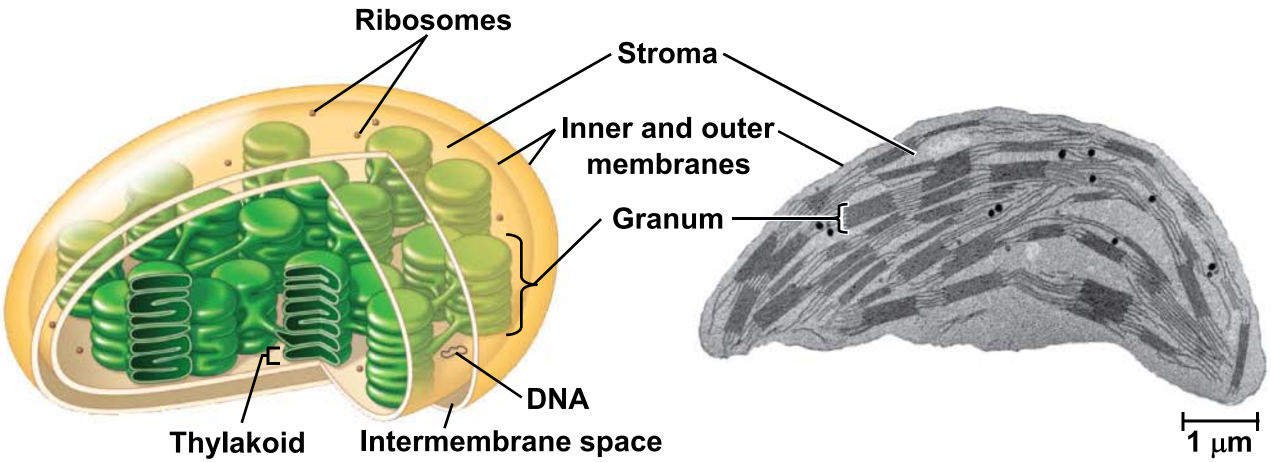
(b) Network of mitochondria in a protist cell (LM)

Chloroplasts: **Capture of Light Energy**

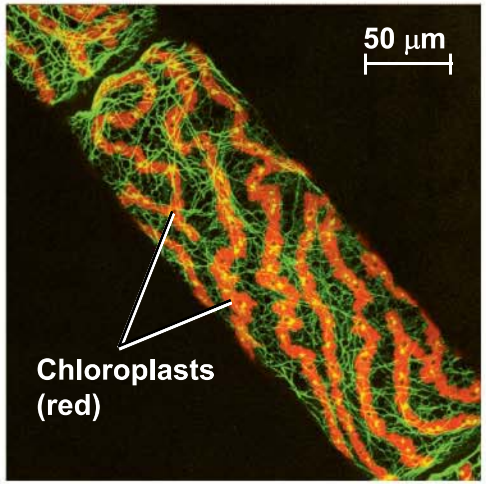
- Chloroplasts contain the **green pigment chlorophyll,** as well as **enzymes** and **other molecules** that function in photosynthesis
- **Chloroplasts** are found **in leaves** and other **green organs** of plants and in algae

- **Chloroplast structure** includes
  - **Thylakoids**, membranous sacs, stacked to form a **granum**
  - **Stroma**, the internal fluid
- The chloroplast is one of a group of plant organelles, called **plastids**

Figure 6.18



(a) Diagram and TEM of chloroplast

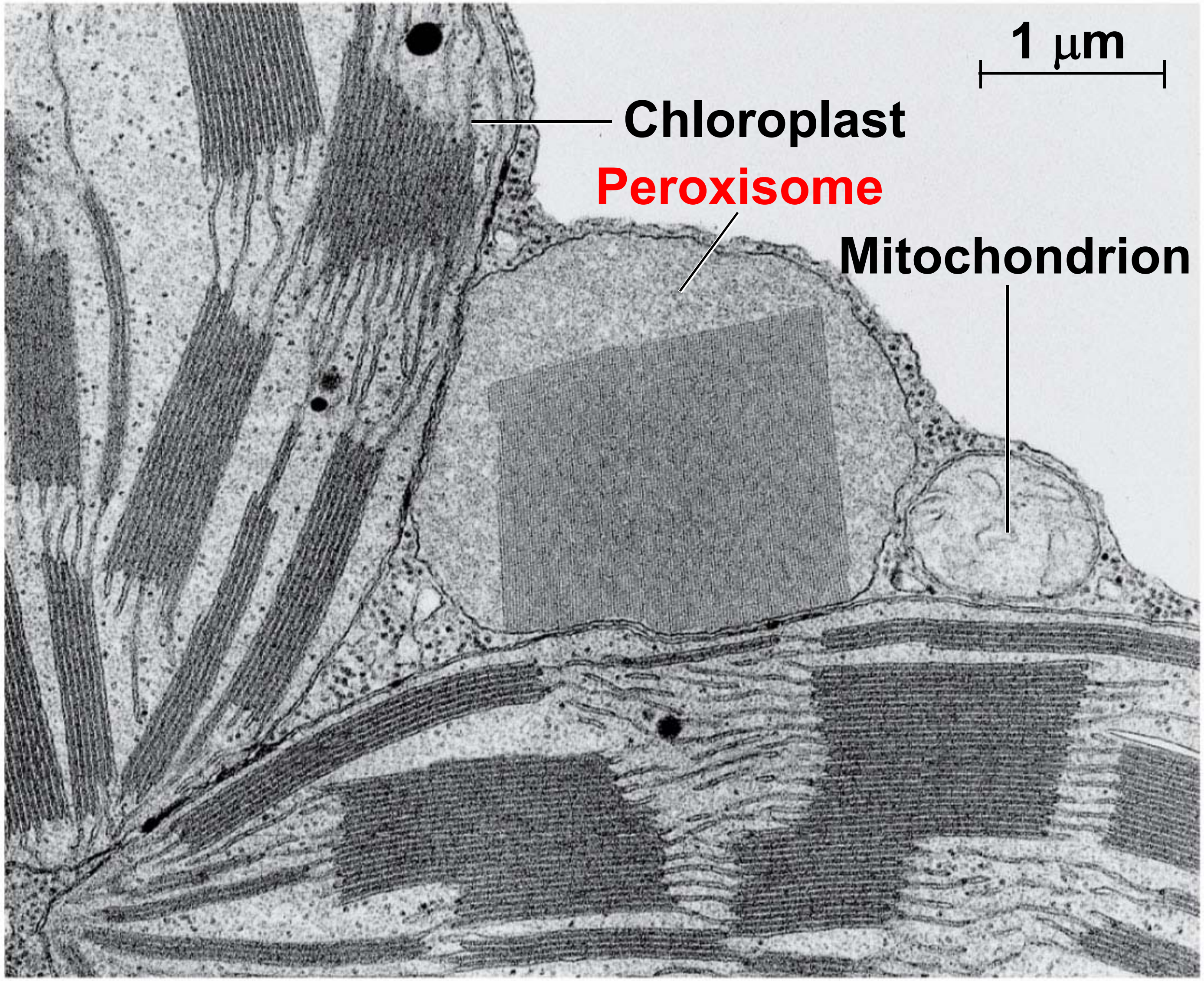


(b) Chloroplasts in an algal cell

Peroxisomes: Oxidation

- **Peroxisomes** are specialized metabolic compartments bounded by a **single membrane**
- **Peroxisomes** produce **hydrogen peroxide** and convert it to water
- Peroxisomes perform reactions with many different functions
- How peroxisomes are related to other organelles is still unknown

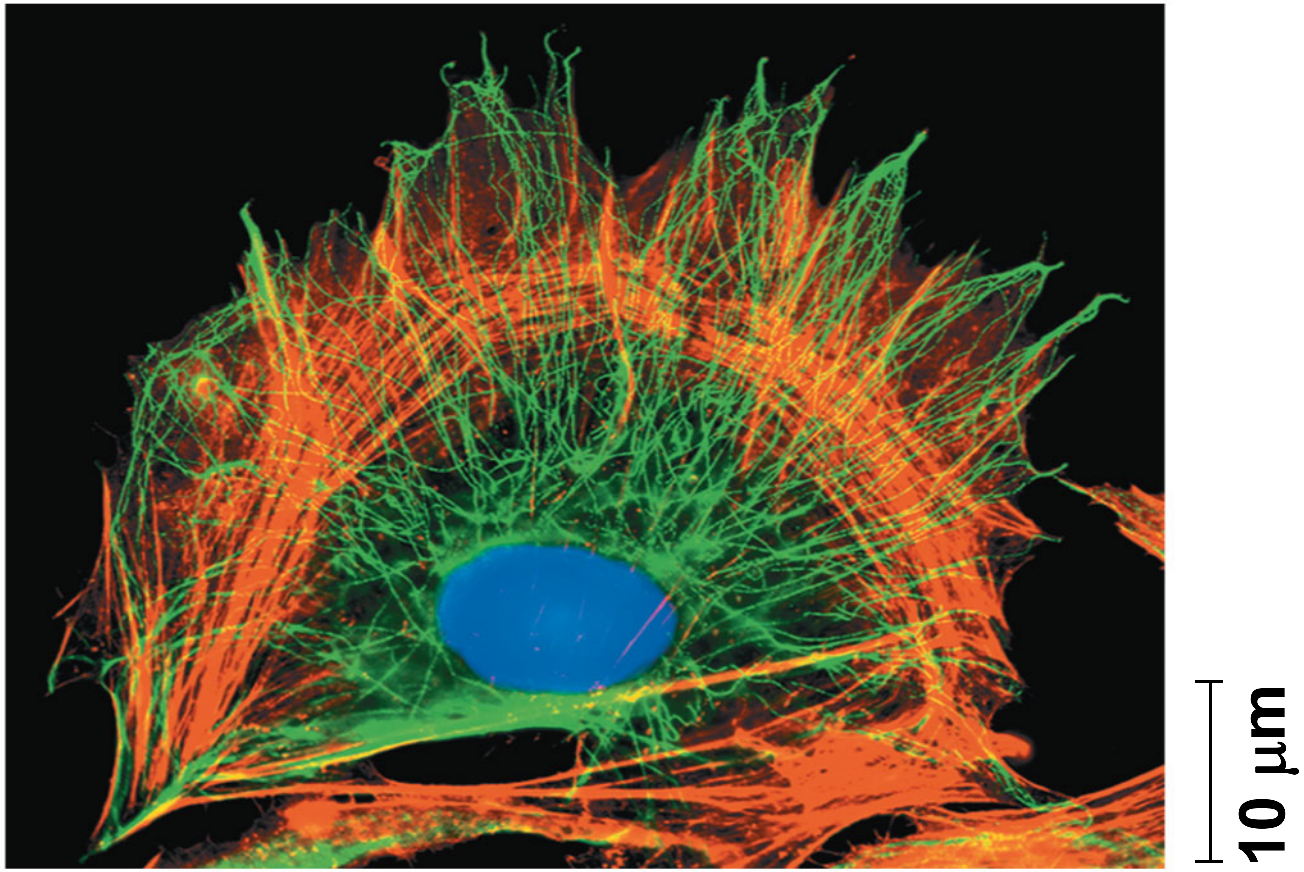
Figure 6.19



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

- The **cytoskeleton** *is a network of fibers extending throughout the cytoplasm*
- It **organizes the cell's structures and activities, anchoring many organelles**
- It is composed of **three types of molecular structures.**

Figure 6.20



- **Three main types of fibers** make up the cytoskeleton
  - ***Microtubules*** are the thickest of the three components of the cytoskeleton
  - ***Microfilaments***, also called actin filaments, are the thinnest components
  - ***Intermediate filaments*** are fibers with diameters in a middle range

Table 6.1a

Property	Microtubules (Tubulin Polymers)
Structure	Hollow tubes; wall consists of 13 columns of tubulin molecules
Diameter	25 nm with 15-nm lumen
Protein subunits	Tubulin, a dimer consisting of α-tubulin and β-tubulin
Main functions	Maintenance of cell shape (compression-resisting "girders") Cell motility (as in cilia or flagella) Chromosome movements in cell division Organelle movements

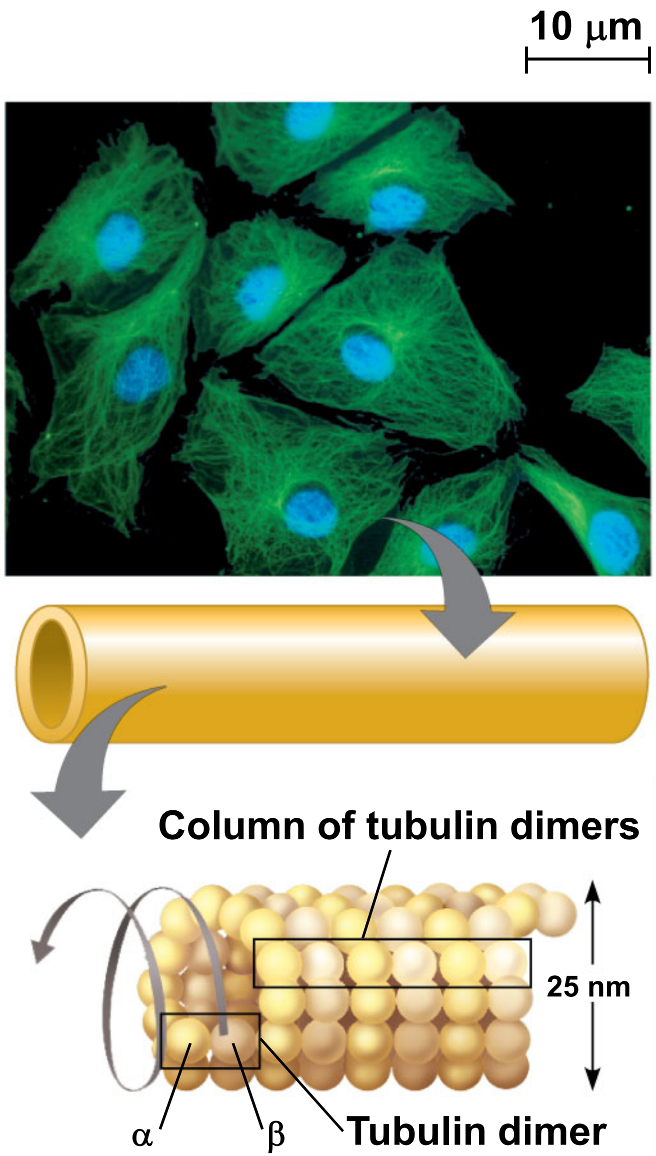


Table 6.1b

Property	Microfilaments (Actin Filaments)
Structure	Two intertwined strands of actin, each a polymer of actin subunits
Diameter	7 nm
Protein subunits	Actin
Main functions	Maintenance of cell shape (tension-bearing elements) Changes in cell shape Muscle contraction Cytoplasmic streaming Cell motility (as in pseudopodia) Cell division (cleavage furrow formation)

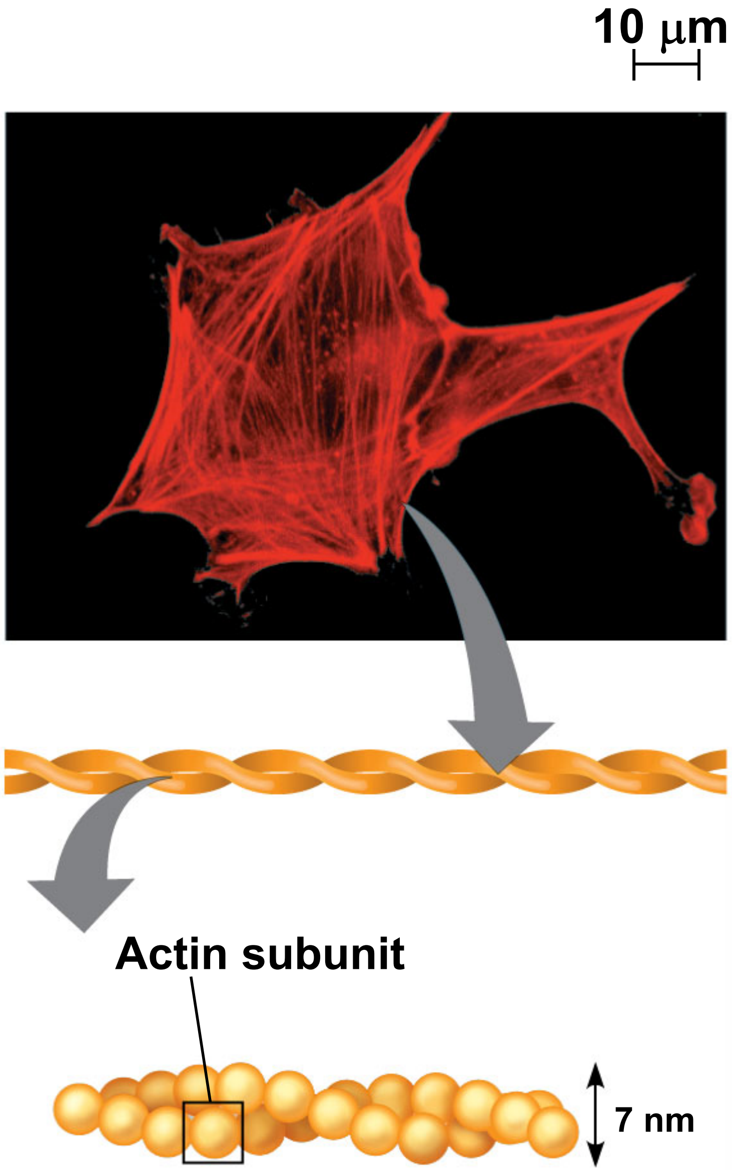
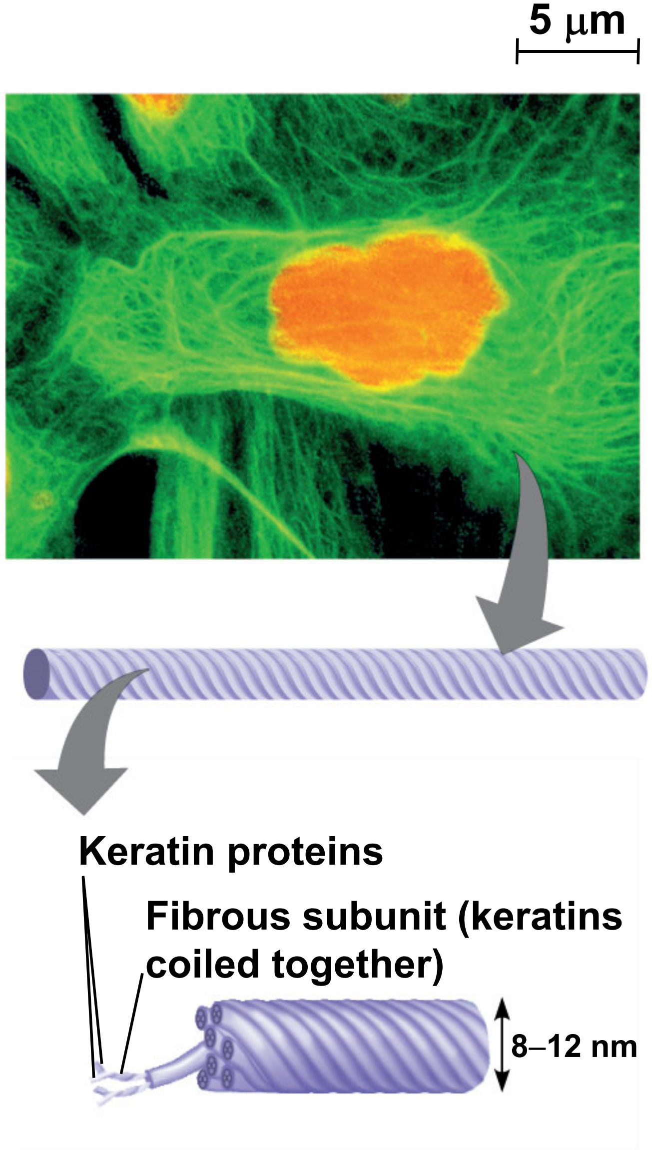


Table 6.1c

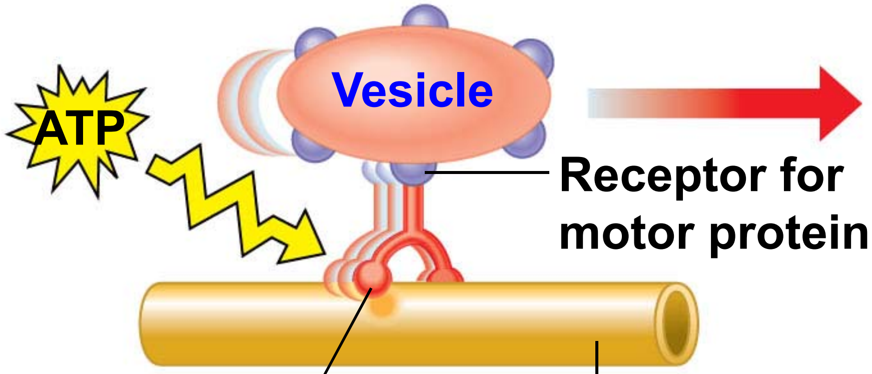
Property	Intermediate Filaments
Structure	Fibrous proteins supercoiled into thicker cables
Diameter	8–12 nm
Protein subunits	One of several different proteins (such as keratins), depending on cell type
Main functions	Maintenance of cell shape (tension-bearing elements) Anchorage of nucleus and certain other organelles Formation of nuclear lamina



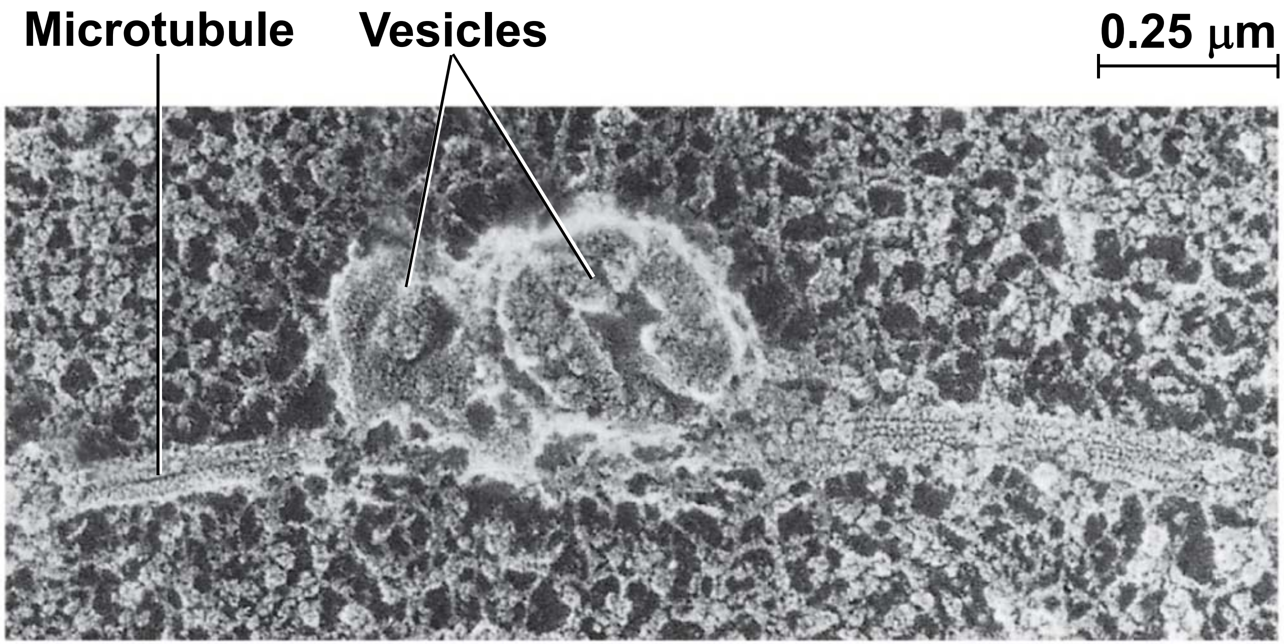
Roles of the Cytoskeleton: Support and Motility

- The cytoskeleton helps to support the cell and maintain its shape
- It interacts with **motor proteins** to produce motility
- Inside the cell, vesicles can travel along "**monorails**" provided by the cytoskeleton
- Recent evidence suggests that the **cytoskeleton may help regulate biochemical activities**

Figure 6.21



(a)

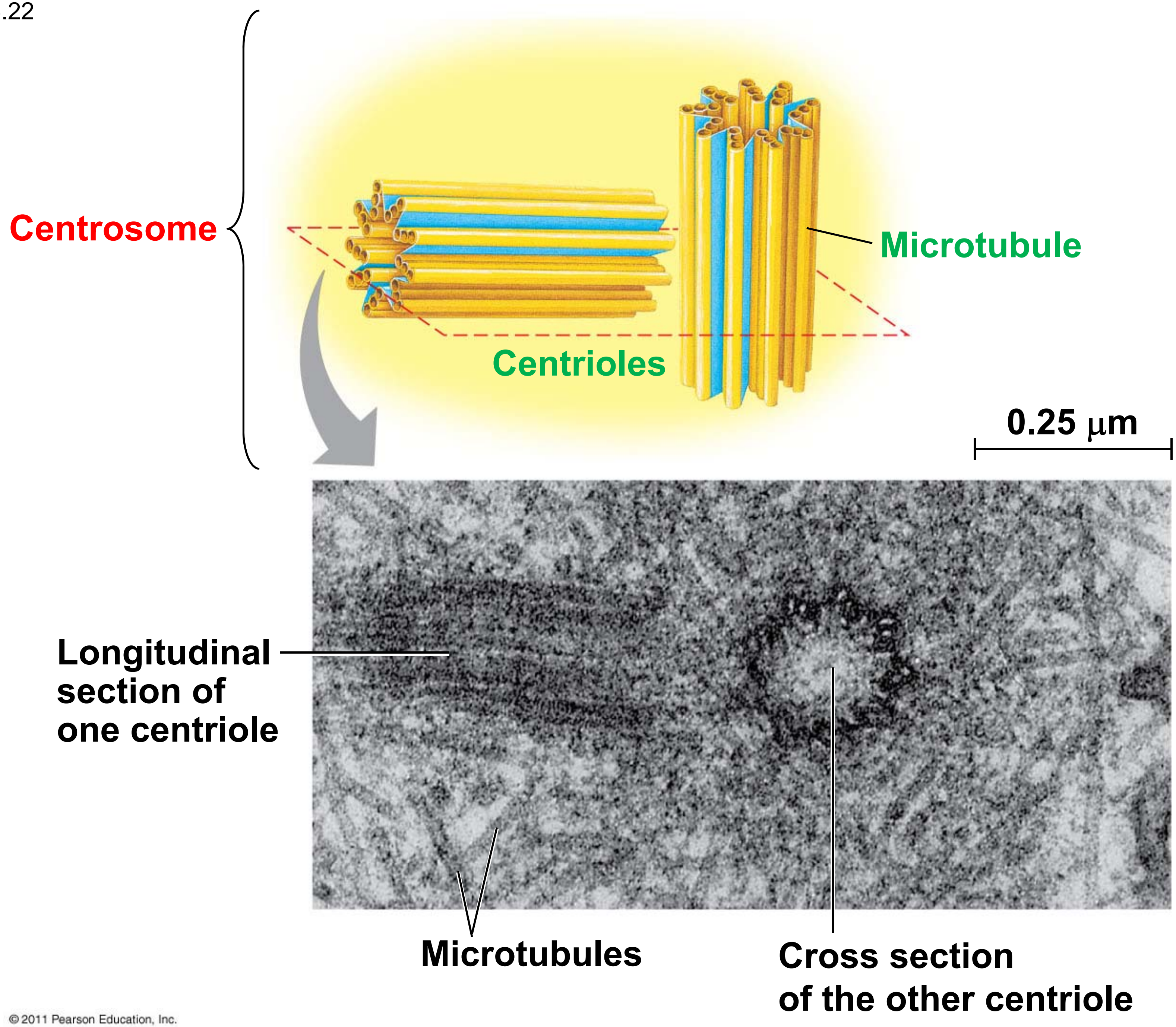


(b)

Centrosomes and Centrioles

- In many cells, microtubules grow out from a **centrosome** near the nucleus
- The centrosome is a "microtubule-organizing center"
- **In animal cells**, the **centrosome has a pair of centrioles**, each with *nine triplets of microtubules arranged in a ring*

Figure 6.22


Centrosome
Microtubule
Centrioles
0.25 µm
Longitudinal section of one centriole
Microtubules
Cross section of the other centriole

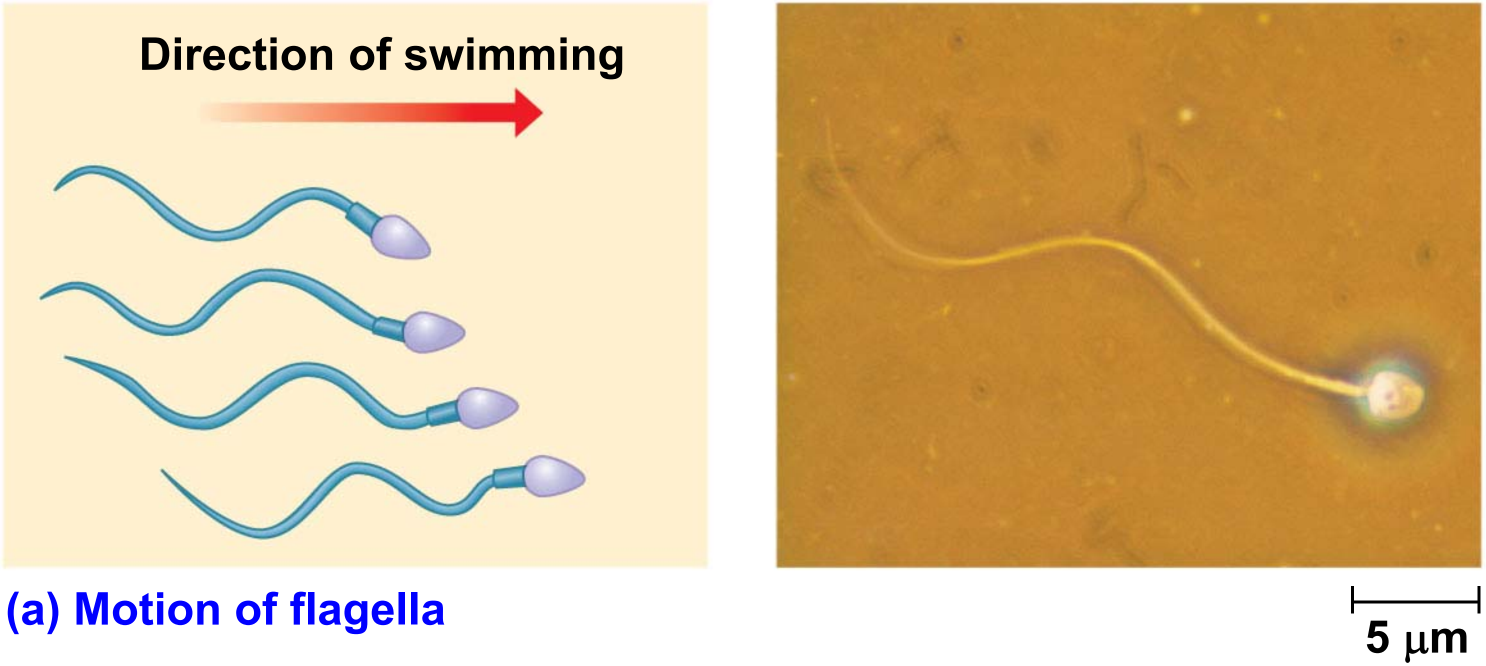
Cilia and Flagella

- **Microtubules** *control the beating of* ***cilia*** *and* ***flagella***, locomotor appendages of some cells
- Cilia and flagella differ in their beating patterns

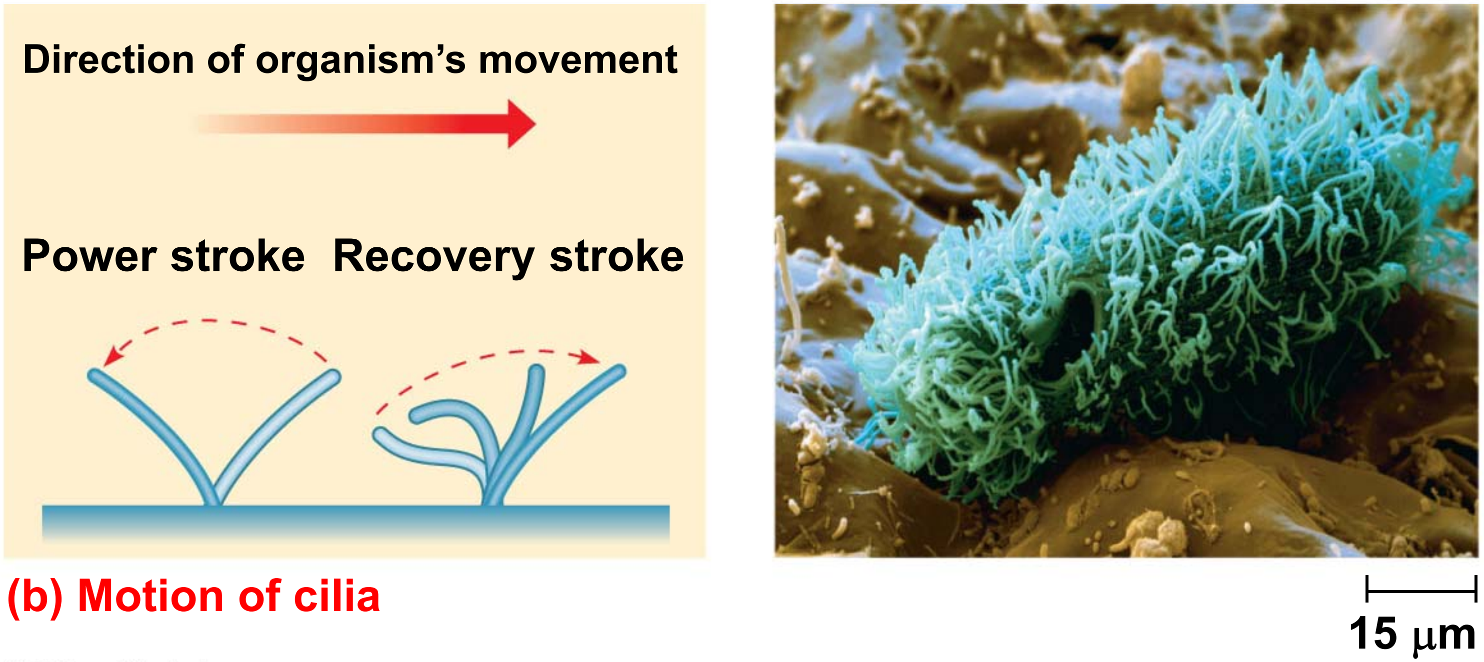
PLAY Video: *Chlamydomonas*

PLAY Video: *Paramecium* Cilia

Figure 6.23



(a) Motion of flagella

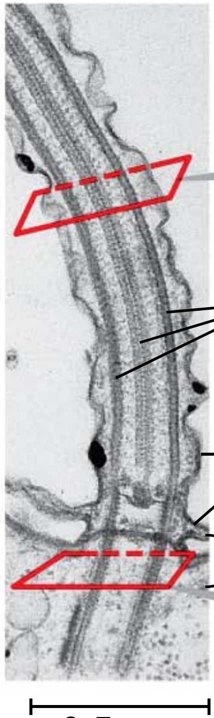


(b) Motion of cilia

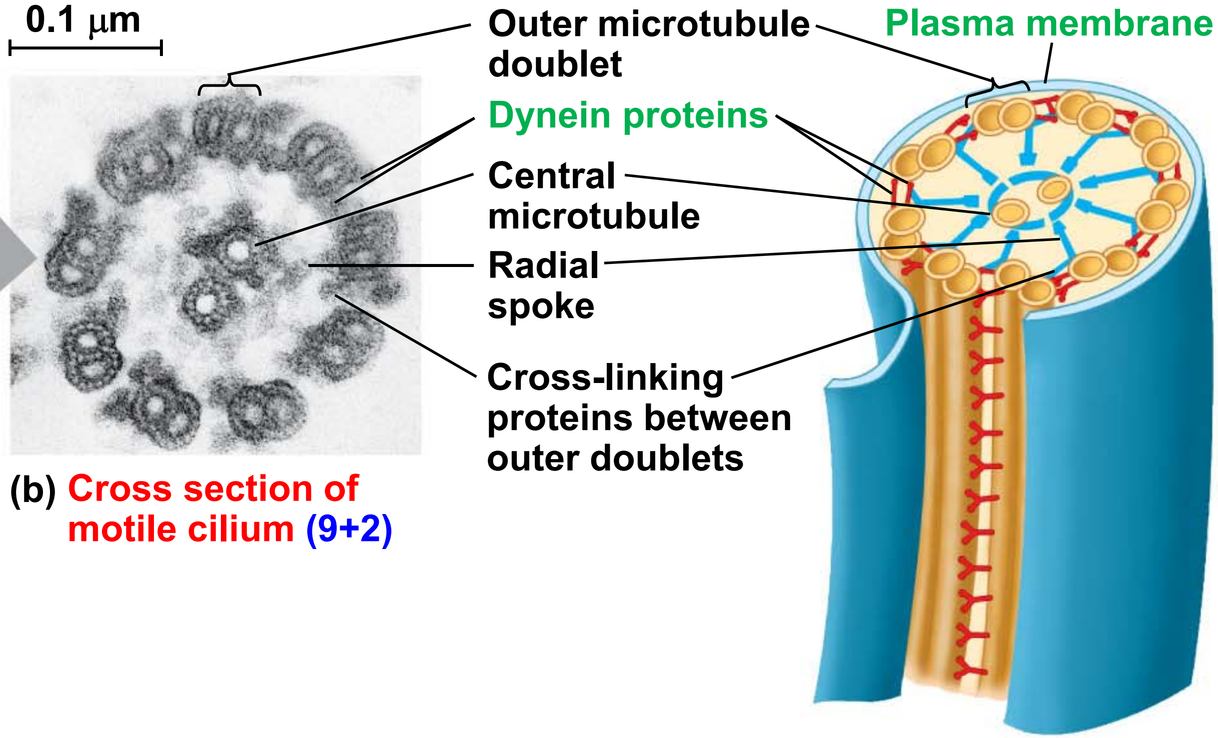
- **Cilia and flagella share a common structure**
  - A **core of microtubules** sheathed by the plasma membrane
  - A **basal body** that anchors the cilium or flagellum
  - A motor protein called **dynein**, which drives the bending movements of a cilium or flagellum

PLAY Animation: Cilia and Flagella

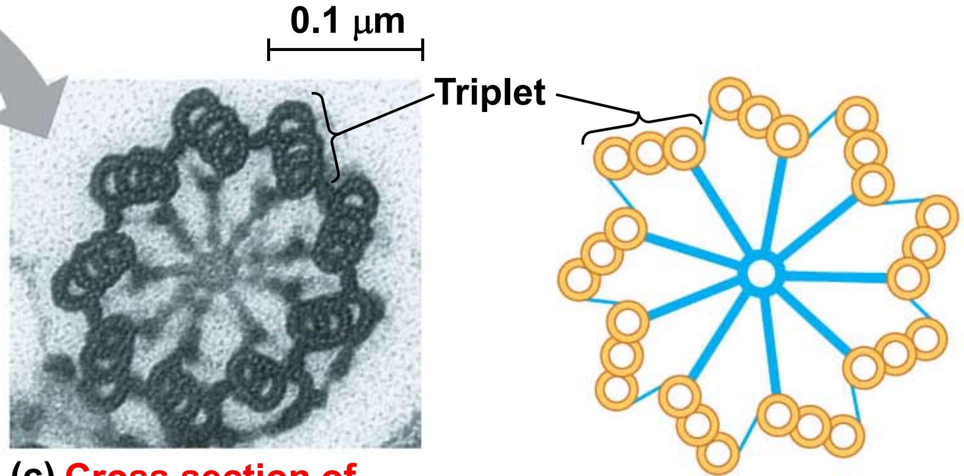
Figure 6.24



(a) Longitudinal section of motile cilium



(b) Cross section of motile cilium (9+2)



(c) Cross section of basal body (9+0)

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

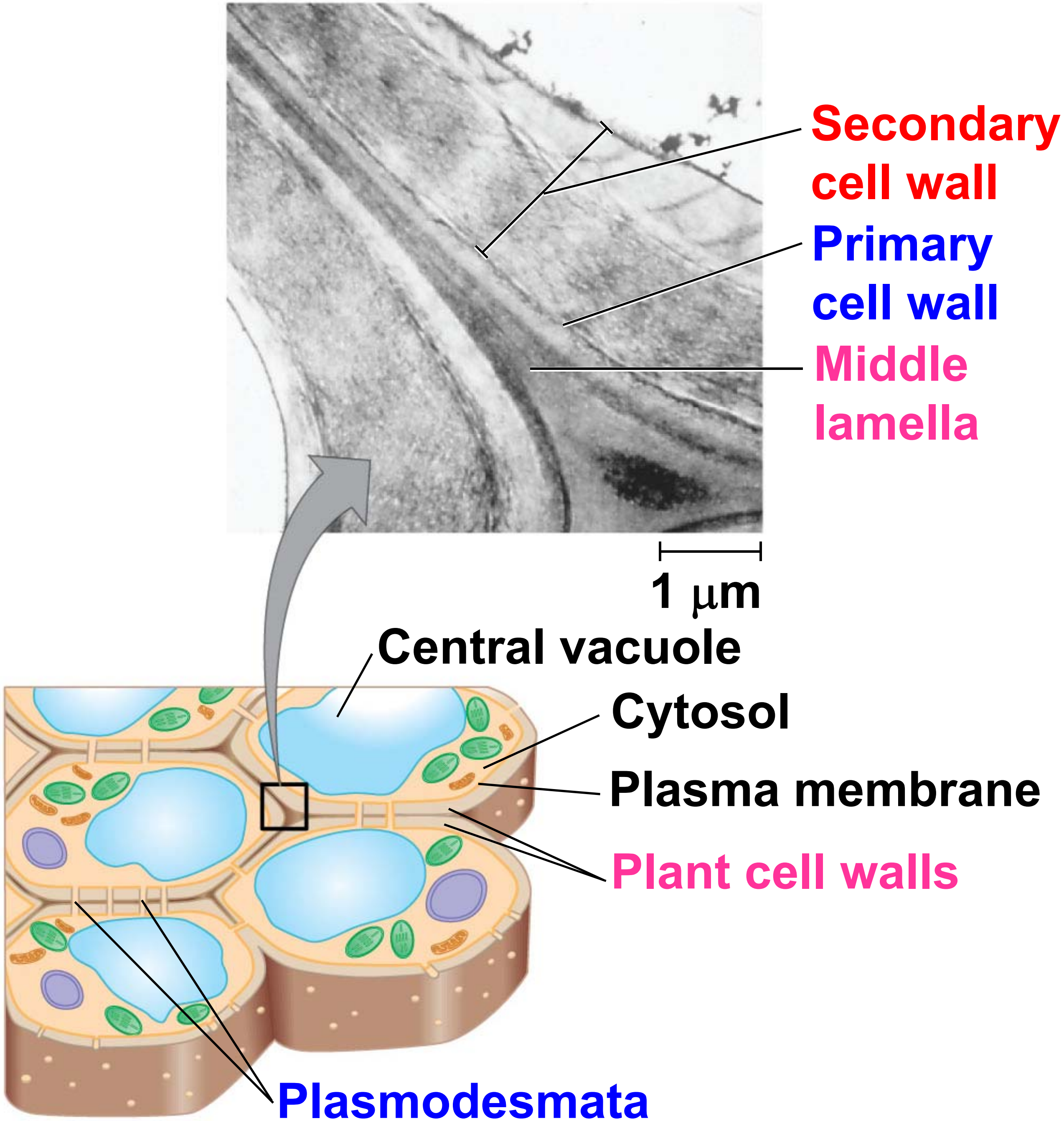
- Most cells synthesize and secrete materials that **are external to the plasma membrane**
- These extracellular structures include
  - **Cell walls of plants**
  - **The extracellular matrix (ECM) of animal cells**
  - **Intercellular junctions**

Cell Walls of Plants

- The **cell wall** is an extracellular structure that distinguishes plant cells from animal cells
- Prokaryotes, fungi, and some protists also have cell walls
- The cell wall **protects the plant cell**, **maintains its shape**, and **prevents excessive uptake of water**
- Plant cell walls are made of **cellulose fibers** embedded in other **polysaccharides and protein**

- **Plant cell walls** may have **multiple layers**
  - **Primary cell wall**: relatively thin and flexible
  - **Middle lamella**: thin layer between primary walls of adjacent cells
  - **Secondary cell wall** (in some cells): added *between the plasma membrane and the primary cell wall*
- **Plasmodesmata** are channels between adjacent plant cells

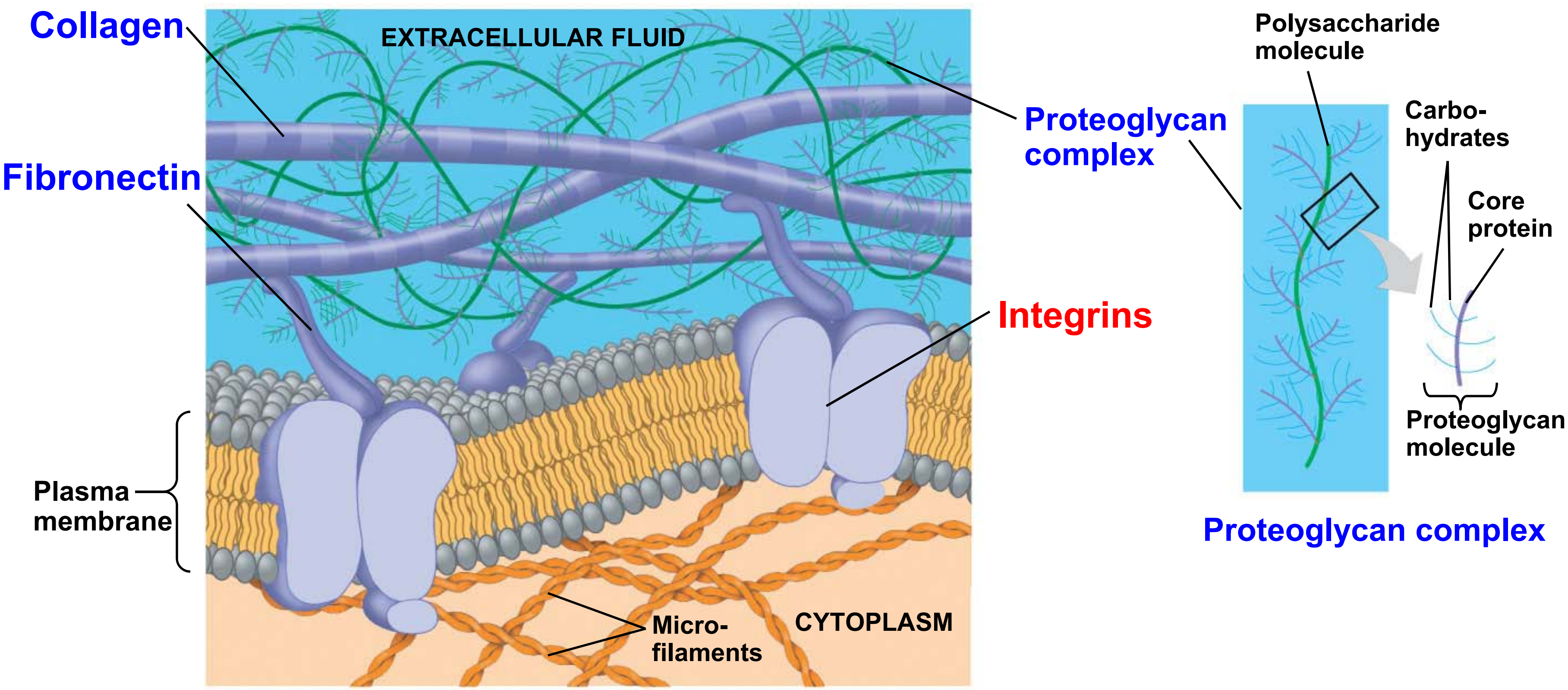
Figure 6.28


Secondary cell wall
Primary cell wall
Middle lamella
1 µm
Central vacuole
Cytosol
Plasma membrane
Plant cell walls
Plasmodesmata

The Extracellular Matrix (ECM) of Animal Cells

- **Animal cells lack cell walls** but are covered by an elaborate **extracellular matrix (ECM).**
- The ECM is made up of **glycoproteins** such as **collagen**, **proteoglycans**, and **fibronectin**
- ECM proteins bind to receptor proteins in the plasma membrane called **integrins**

Figure 6.30



Collagen
EXTRACELLULAR FLUID
Fibronectin
Proteoglycan complex
Integrins
Plasma membrane
Micro-filaments
CYTOPLASM
Polysaccharide molecule
Carbo-hydrates
Core protein
Proteoglycan molecule
Proteoglycan complex

- **Functions of the ECM**
  - *Support*
  - *Adhesion*
  - *Movement*
  - *Regulation*

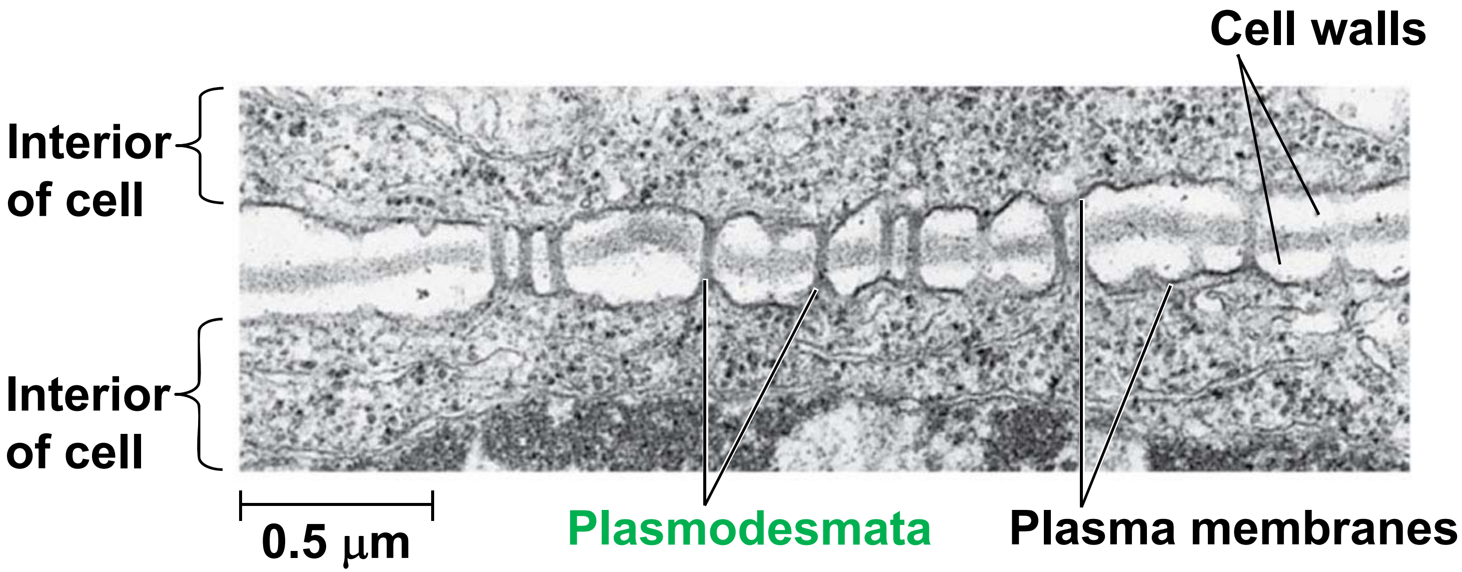
Cell Junctions

- *Neighboring cells in tissues, organs, or organ systems often adhere, interact, and communicate through direct physical contact*
- **Intercellular junctions** facilitate this contact
- There are **several types of intercellular junctions**
  - **Plasmodesmata**
  - **Tight junctions**
  - **Desmosomes**
  - **Gap junctions**

Plasmodesmata: in Plant Cells

- **Plasmodesmata** are channels that perforate **plant cell walls**
- Through plasmodesmata, water and small solutes (and sometimes proteins and RNA) can pass from cell to cell

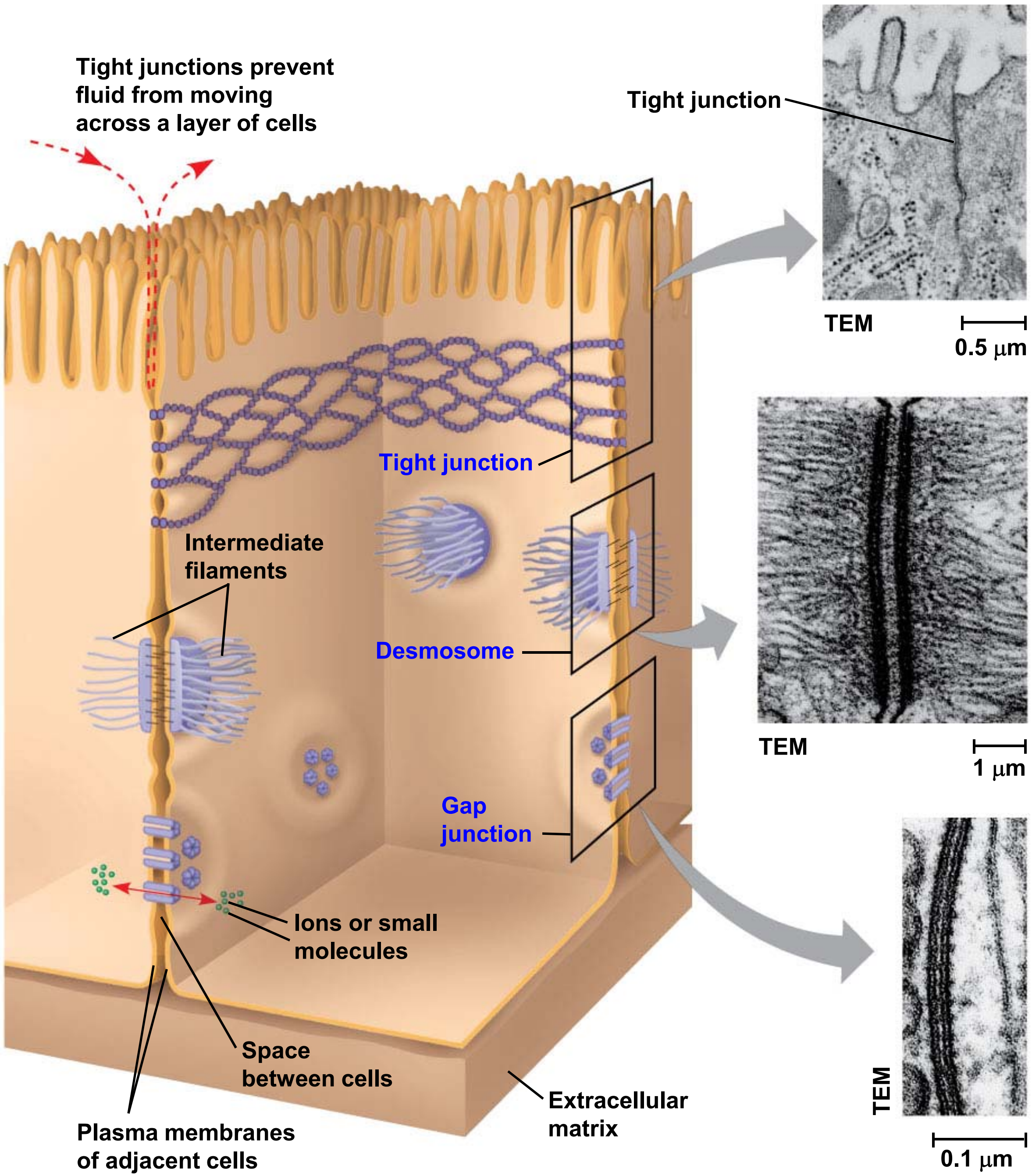
Figure 6.31


Cell walls
Interior of cell
Interior of cell
0.5 µm
Plasmodesmata
Plasma membranes

Tight Junctions, Desmosomes, and Gap Junctions in Animal Cells

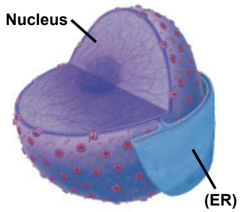
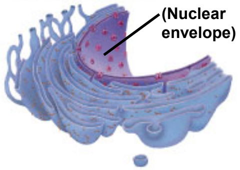
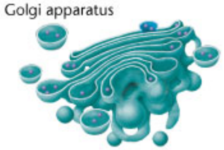
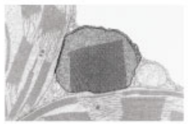
- At **tight junctions**, *membranes of neighboring cells are pressed together, preventing leakage of extracellular fluid*
- **Desmosomes** (anchoring junctions) *fasten cells together into strong sheets*
- **Gap junctions** (communicating junctions) *provide cytoplasmic channels between adjacent cells*

Figure 6.32



Tight junctions prevent fluid from moving across a layer of cells
Tight junction
TEM
0.5 µm
Tight junction
Intermediate filaments
Desmosome
TEM
1 µm
Gap junction
Ions or small molecules
Space between cells
Plasma membranes of adjacent cells
Extracellular matrix
TEM
0.1 µm

Figure 6.UN01

	Cell Component	Structure	Function
CONCEPT 6.3 The eukaryotic cell's genetic instructions are housed in the nucleus and carried out by the ribosomes		Surrounded by nuclear envelope (double membrane) perforated by nuclear pores; nuclear envelope continuous with endoplasmic reticulum (ER)	Houses chromosomes, which are made of chromatin (DNA and proteins); contains nucleoli, where ribosomal subunits are made; pores regulate entry and exit of materials
	Ribosome 	Two subunits made of ribosomal RNA and proteins; can be free in cytosol or bound to ER	Protein synthesis
CONCEPT 6.4 The endomembrane system regulates protein traffic and performs metabolic functions in the cell	Endoplasmic reticulum 	Extensive network of membrane-bounded tubules and sacs; membrane separates lumen from cytosol; continuous with nuclear envelope	Smooth ER: synthesis of lipids, metabolism of carbohydrates, Ca^{2+} storage, detoxification of drugs and poisons Rough ER: aids in synthesis of secretory and other proteins from bound ribosomes; adds carbohydrates to proteins to make glycoproteins; produces new membrane
	Golgi apparatus 	Stacks of flattened membranous sacs; has polarity (*cis* and *trans* faces)	Modification of proteins, carbohydrates on proteins, and phospholipids; synthesis of many polysaccharides; sorting of Golgi products, which are then released in vesicles
	Lysosome 	Membranous sac of hydrolytic enzymes (in animal cells)	Breakdown of ingested substances, cell macromolecules, and damaged organelles for recycling
	Vacuole 	Large membrane-bounded vesicle	Digestion, storage, waste disposal, water balance, cell growth, and protection
CONCEPT 6.5 Mitochondria and chloroplasts change energy from one form to another	Mitochondrion 	Bounded by double membrane; inner membrane has infoldings (cristae)	Cellular respiration
	Chloroplast 	Typically two membranes around fluid stroma, which contains thylakoids stacked into grana (in cells of photosynthetic eukaryotes, including plants)	Photosynthesis
	Peroxisome 	Specialized metabolic compartment bounded by a single membrane	Contains enzymes that transfer hydrogen atoms from substrates to oxygen, producing hydrogen peroxide (H_2O_2) as a by-product; H_2O_2 is converted to water by another enzyme

LECTURE PRESENTATIONS
For CAMPBELL BIOLOGY, NINTH EDITION
Jane B. Reece, Lisa A. Urry, Michael L. Cain, Steven A. Wasserman, Peter V. Minorsky, Robert B. Jackson

Chapter 7

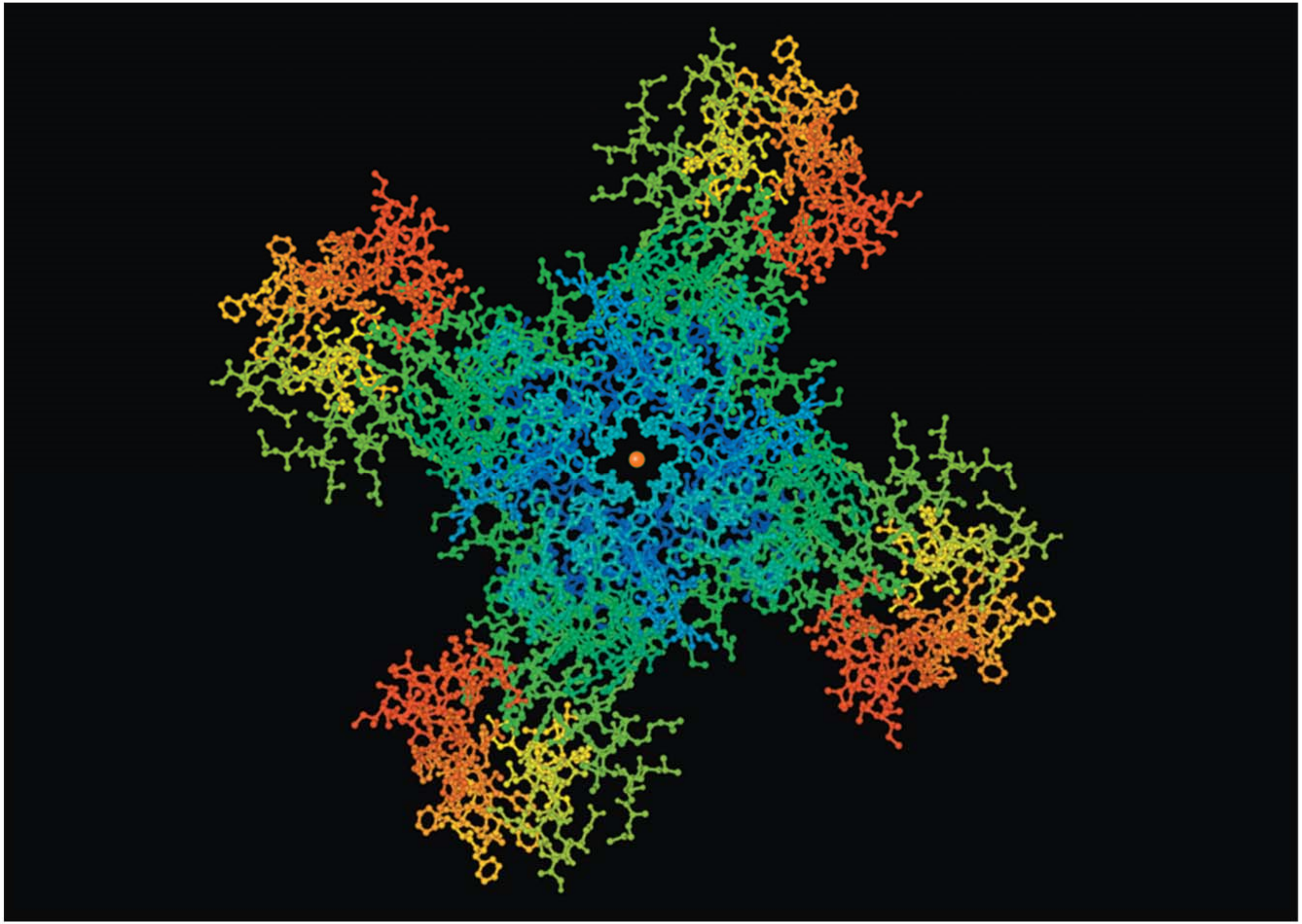
Membrane Structure and Function

Lectures by
Erin Barley
Kathleen Fitzpatrick

Overview: Life at the Edge

- The plasma membrane is the boundary that separates the living cell from its surroundings
- The plasma membrane exhibits **selective permeability**, allowing some substances to cross it more easily than others

Figure 7.1



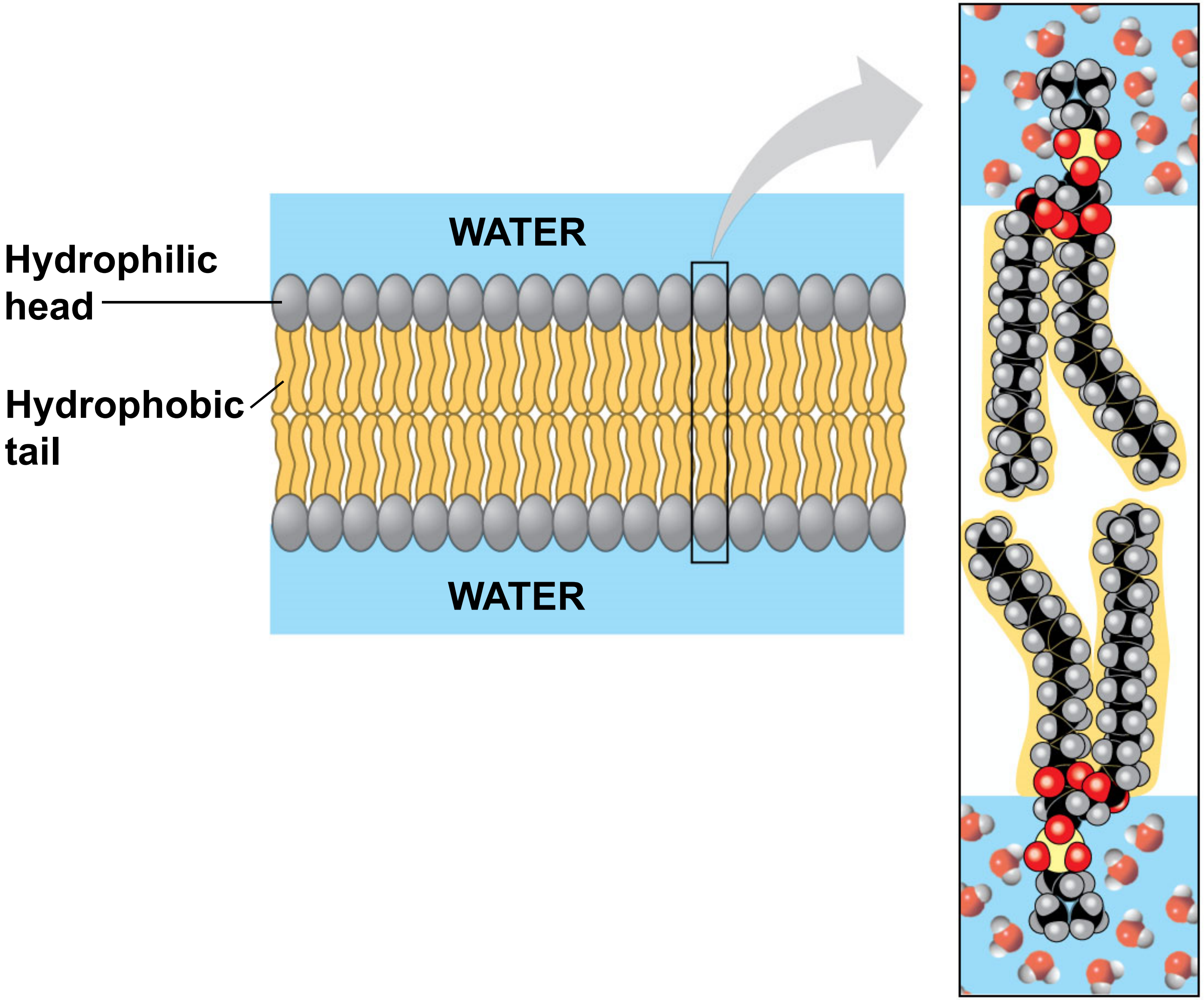
Concept 7.1: Cellular membranes are fluid mosaics of lipids and proteins

- Phospholipids are the most abundant lipid in the plasma membrane
- Phospholipids are **amphipathic molecules**, containing hydrophobic and hydrophilic regions
- The **fluid mosaic model** *states that a membrane is a fluid structure with a "mosaic" of various proteins embedded in it*

Membrane Models: *Scientific Inquiry*

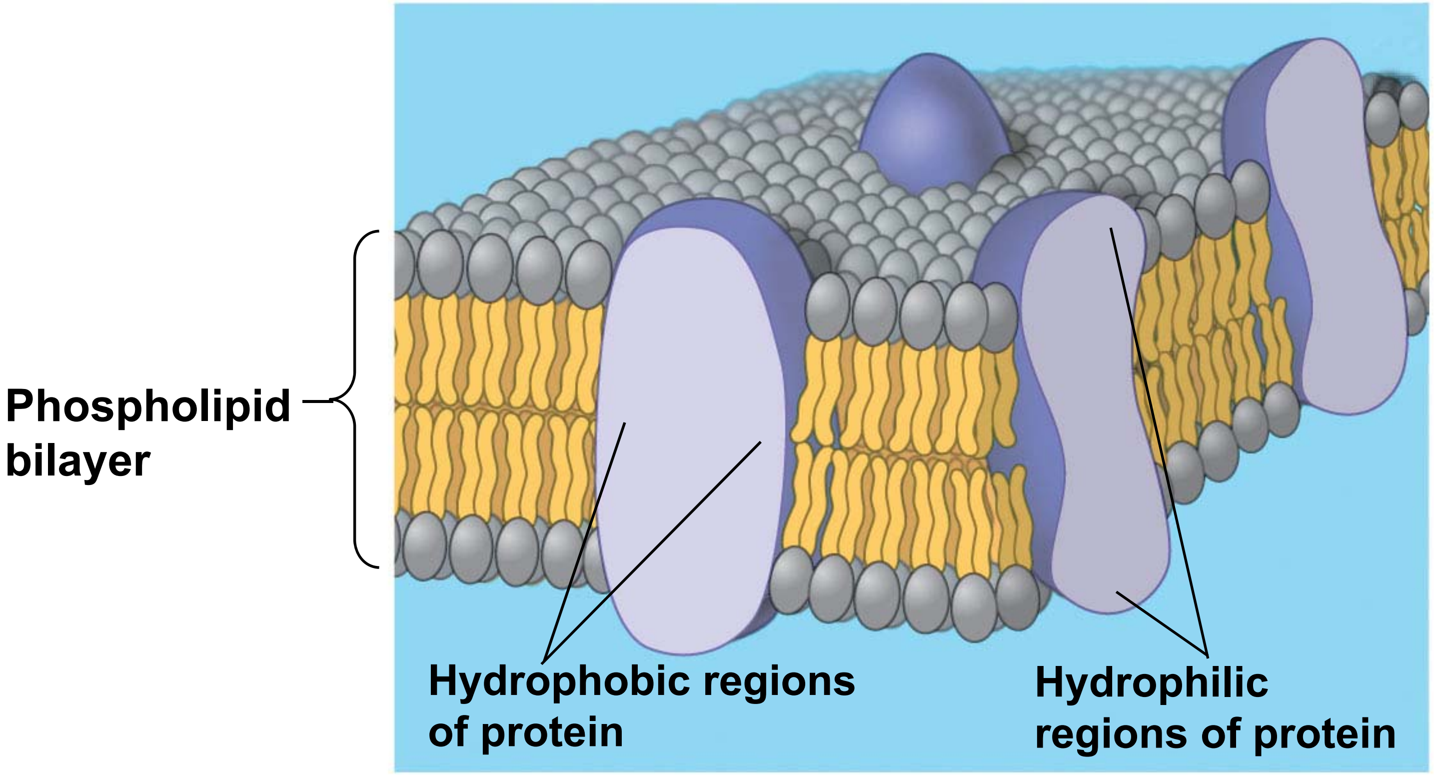
- Membranes have been chemically analyzed and found to be made of proteins and lipids
- Scientists studying the plasma membrane reasoned that it must be a phospholipid bilayer

Figure 7.2



- In 1935, Hugh Davson and James Danielli proposed a **sandwich model** in which the phospholipid bilayer lies between two layers of globular proteins
- Later studies found problems with this model, particularly the placement of membrane proteins, which have hydrophilic and hydrophobic regions
- In 1972, J. **Singer and G. Nicolson** proposed the **fluid mosaic model** which states that the membrane is a *mosaic of proteins dispersed within the bilayer, with only the hydrophilic regions exposed to water*

Figure 7.3

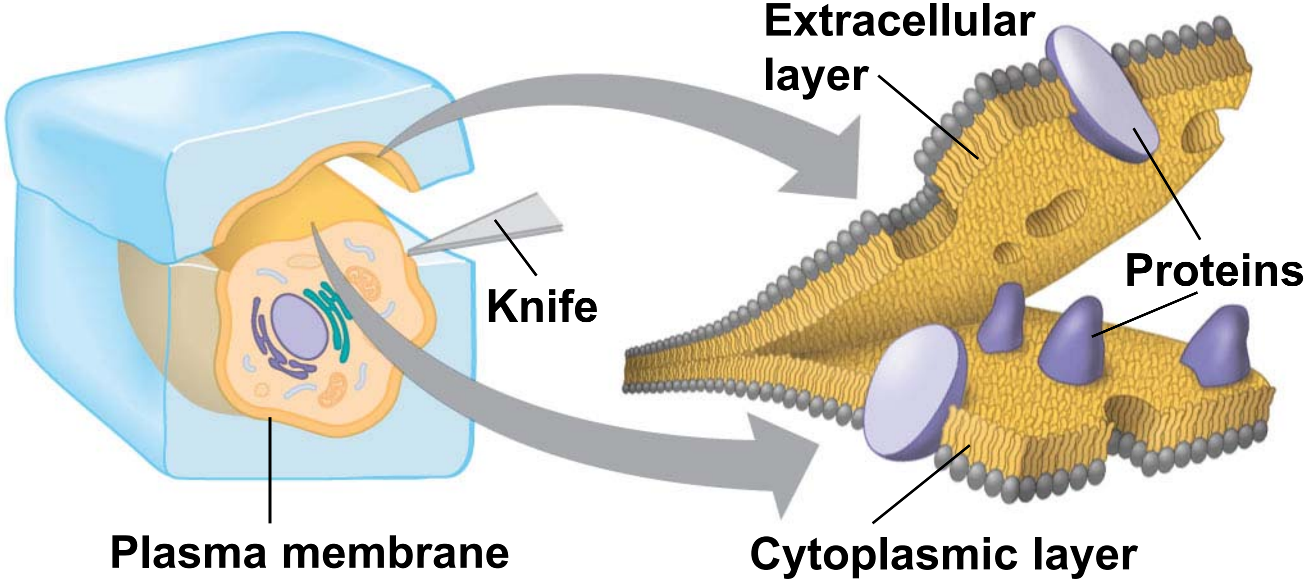


Phospholipid bilayer
Hydrophobic regions of protein
Hydrophilic regions of protein

- Freeze-fracture studies of the plasma membrane supported the fluid mosaic model
- Freeze-fracture is a specialized preparation technique that splits a membrane along the middle of the phospholipid bilayer

Figure 7.4

TECHNIQUE



RESULTS


Inside of extracellular layer


Inside of cytoplasmic layer

Figure 7.4a

Inside of extracellular layer

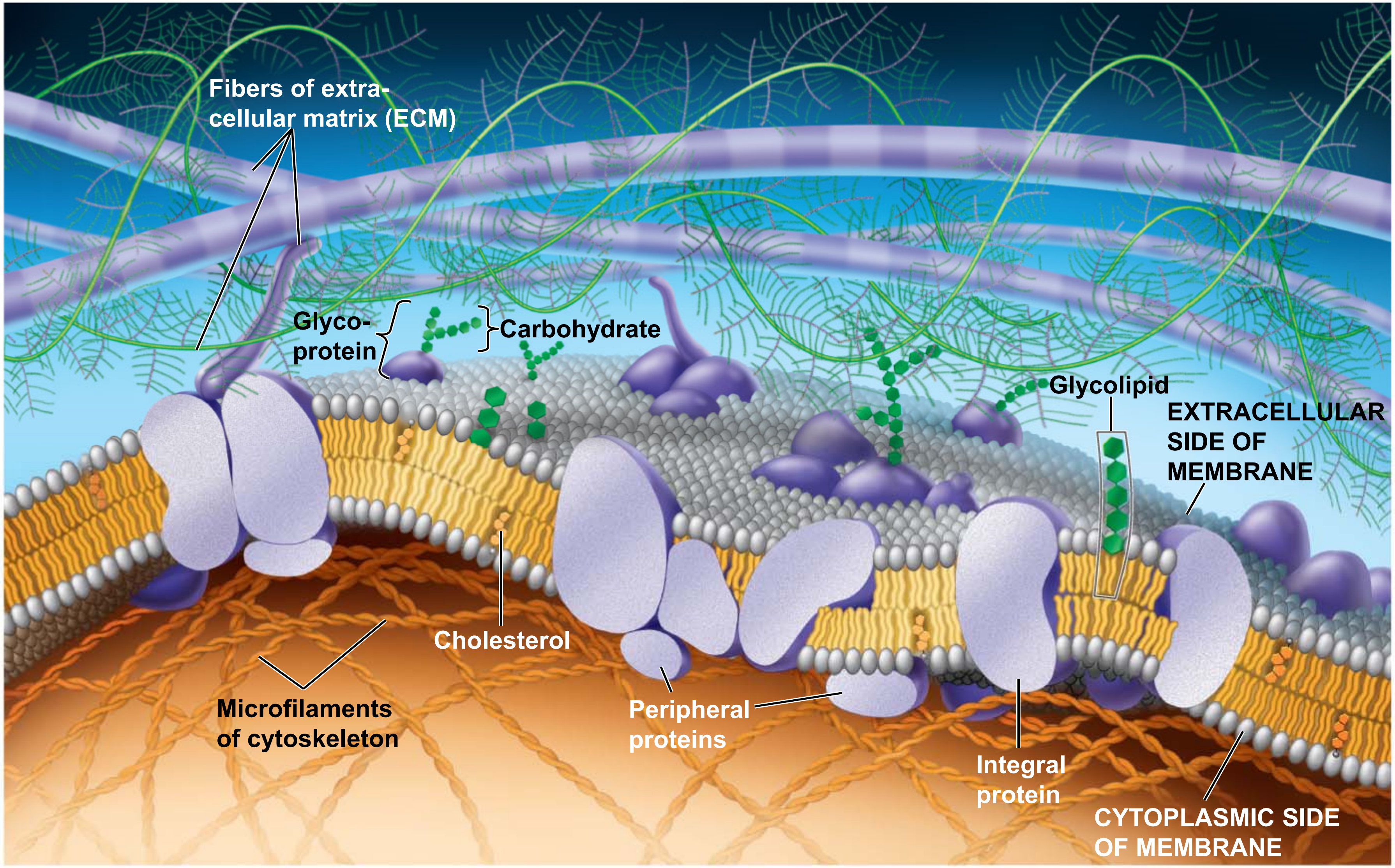
Figure 7.4b

Inside of cytoplasmic layer

The Fluidity of Membranes

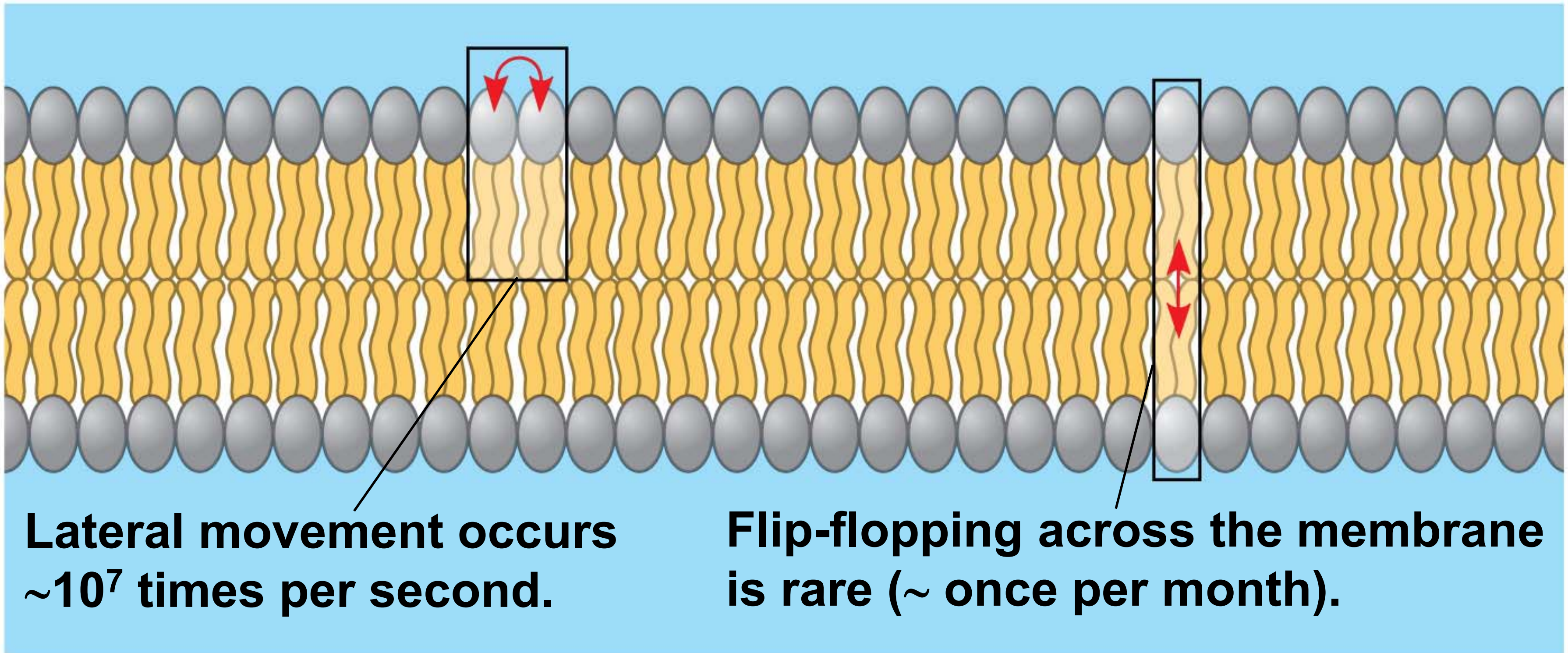
- *Phospholipids* in the plasma membrane *can move within the bilayer*
- Most of the lipids, and some proteins, drift laterally
- Rarely does a molecule flip-flop transversely across the membrane

Figure 7.5



Fibers of extra-
cellular matrix (ECM)
Glyco-
protein
Carbohydrate
Glycolipid
EXTRACELLULAR
SIDE OF
MEMBRANE
Cholesterol
Microfilaments
of cytoskeleton
Peripheral
proteins
Integral
protein
CYTOPLASMIC SIDE
OF MEMBRANE

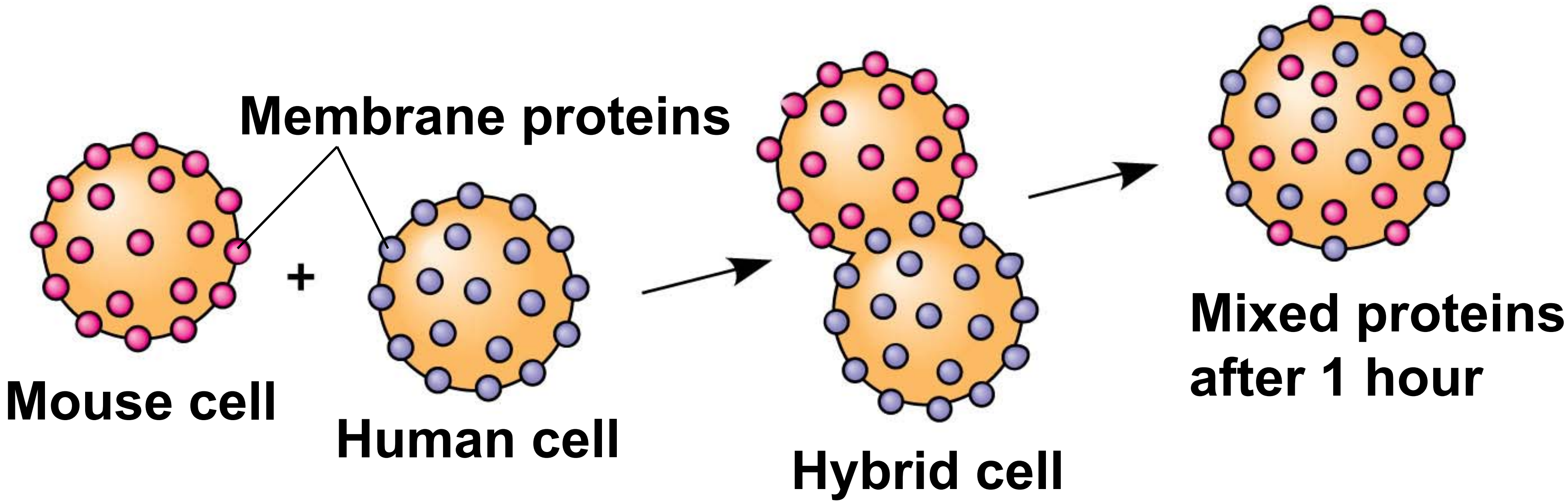
Figure 7.6



Lateral movement occurs ~10^7 times per second.
Flip-flopping across the membrane is rare (~ once per month).

Figure 7.7

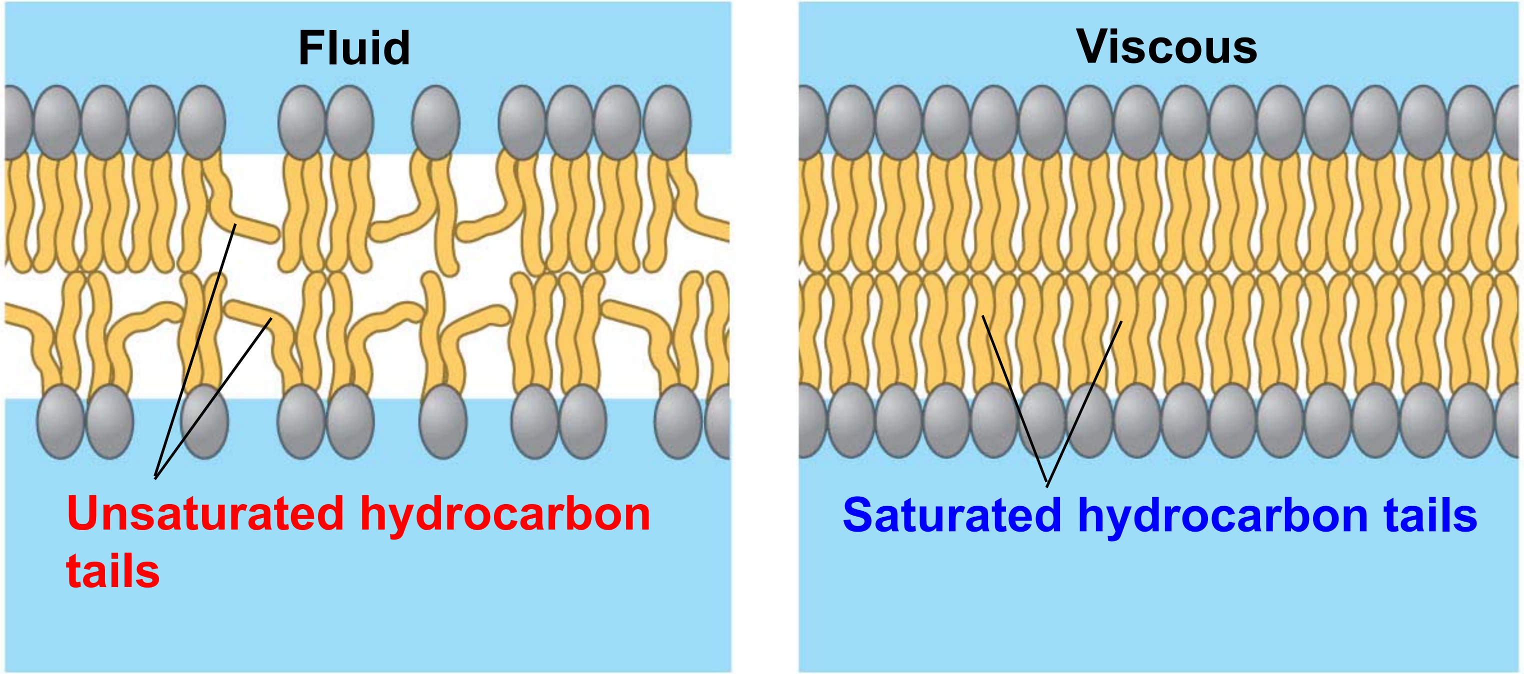
RESULTS



- As temperatures cool, *membranes switch from a fluid state to a solid state*
- The temperature at which a membrane solidifies depends on the types of lipids
- Membranes rich in unsaturated fatty acids are more fluid than those rich in saturated fatty acids
- Membranes must be fluid to work properly; they are usually about as fluid as salad oil

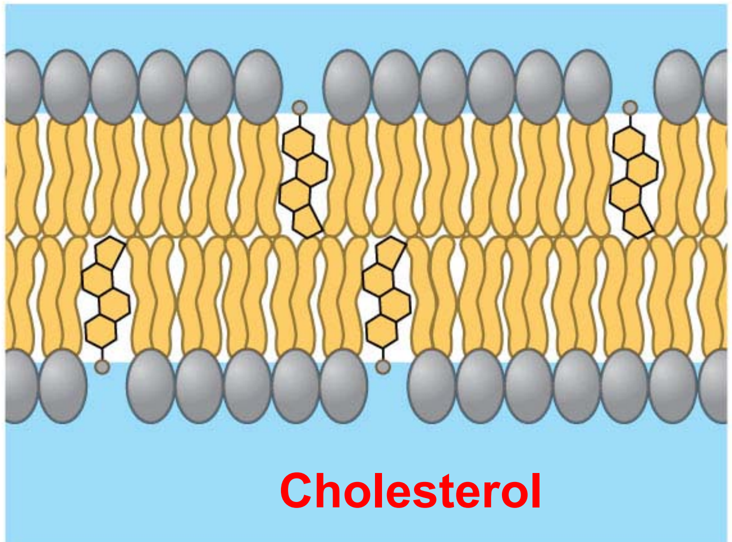
- The steroid cholesterol has different effects on membrane fluidity at different temperatures
- At warm temperatures (such as 37° C), cholesterol restrains movement of phospholipids
- At cool temperatures, it maintains fluidity by preventing tight packing

Figure 7.8



(a) Unsaturated versus saturated hydrocarbon tails

(b) Cholesterol within the animal cell membrane

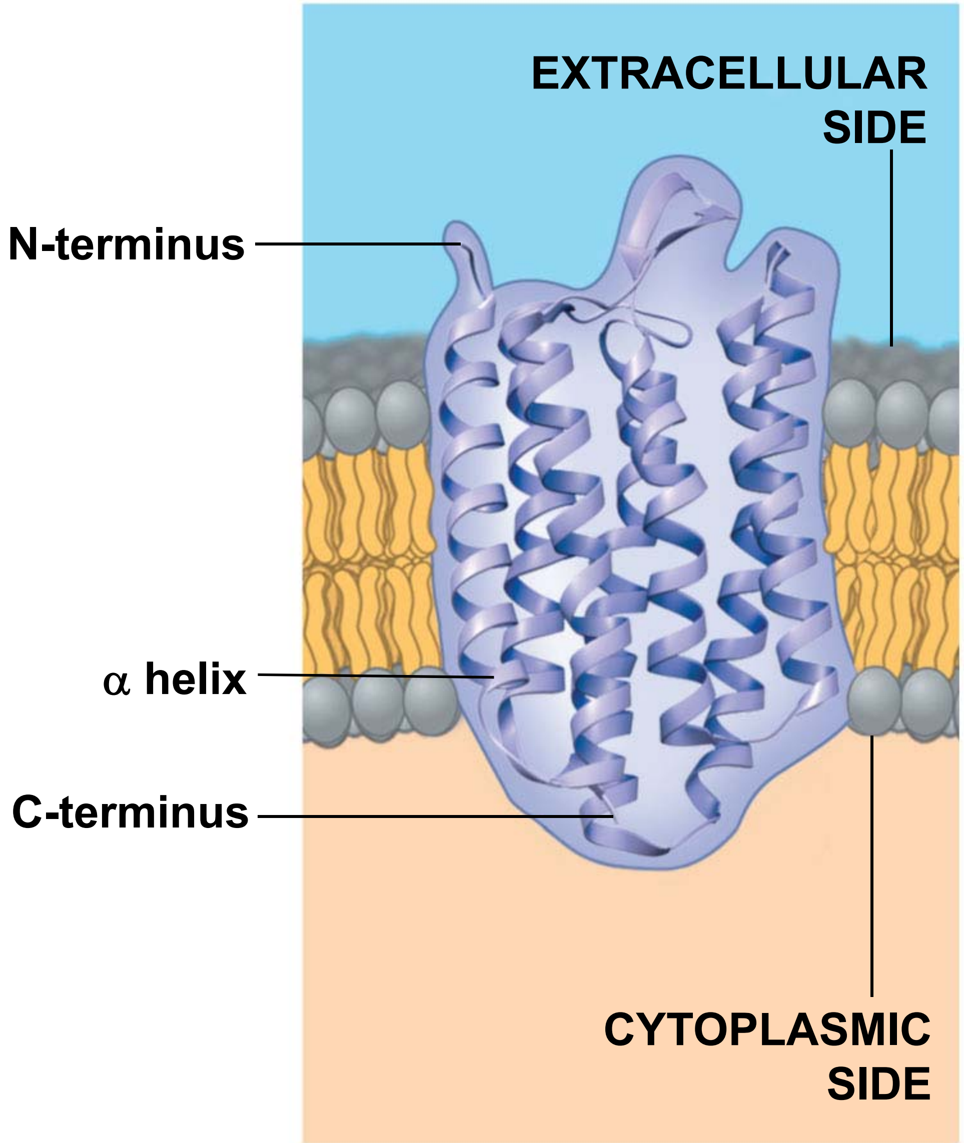


Membrane Proteins and Their Functions

- A membrane is a collage of different proteins embedded in the fluid matrix of the lipid bilayer
- Proteins determine most of the membrane's specific functions

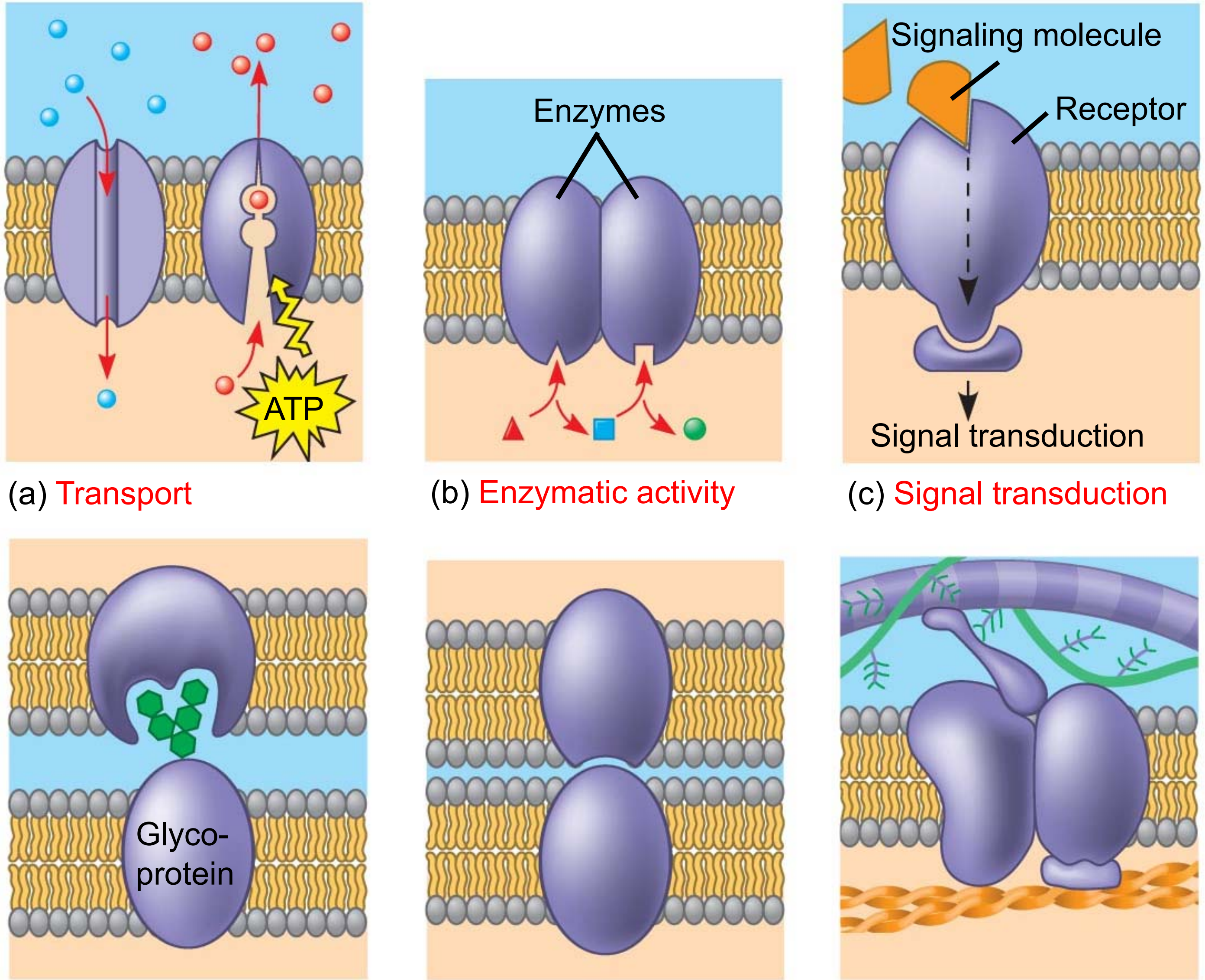
- **Peripheral proteins** are bound to the surface of the membrane
- **Integral proteins** penetrate the hydrophobic core
- Integral proteins that span the membrane are called transmembrane proteins
- The hydrophobic regions of an integral protein consist of one or more stretches of nonpolar amino acids, *often coiled into alpha helices*

Figure 7.9


EXTRACELLULAR SIDE
N-terminus
α helix
C-terminus
CYTOPLASMIC SIDE

- **Six major functions** of membrane proteins:
  - **Transport**
  - **Enzymatic activity**
  - **Signal transduction**
  - **Cell-cell recognition**
  - **Intercellular joining**
  - **Attachment to the cytoskeleton and extracellular matrix (ECM)**

Fig. 7-9



(a) Transport

(b) Enzymatic activity

(c) Signal transduction

(d) Cell-cell recognition

(e) Intercellular joining

(f) Attachment to the cytoskeleton and extracellular matrix (ECM)

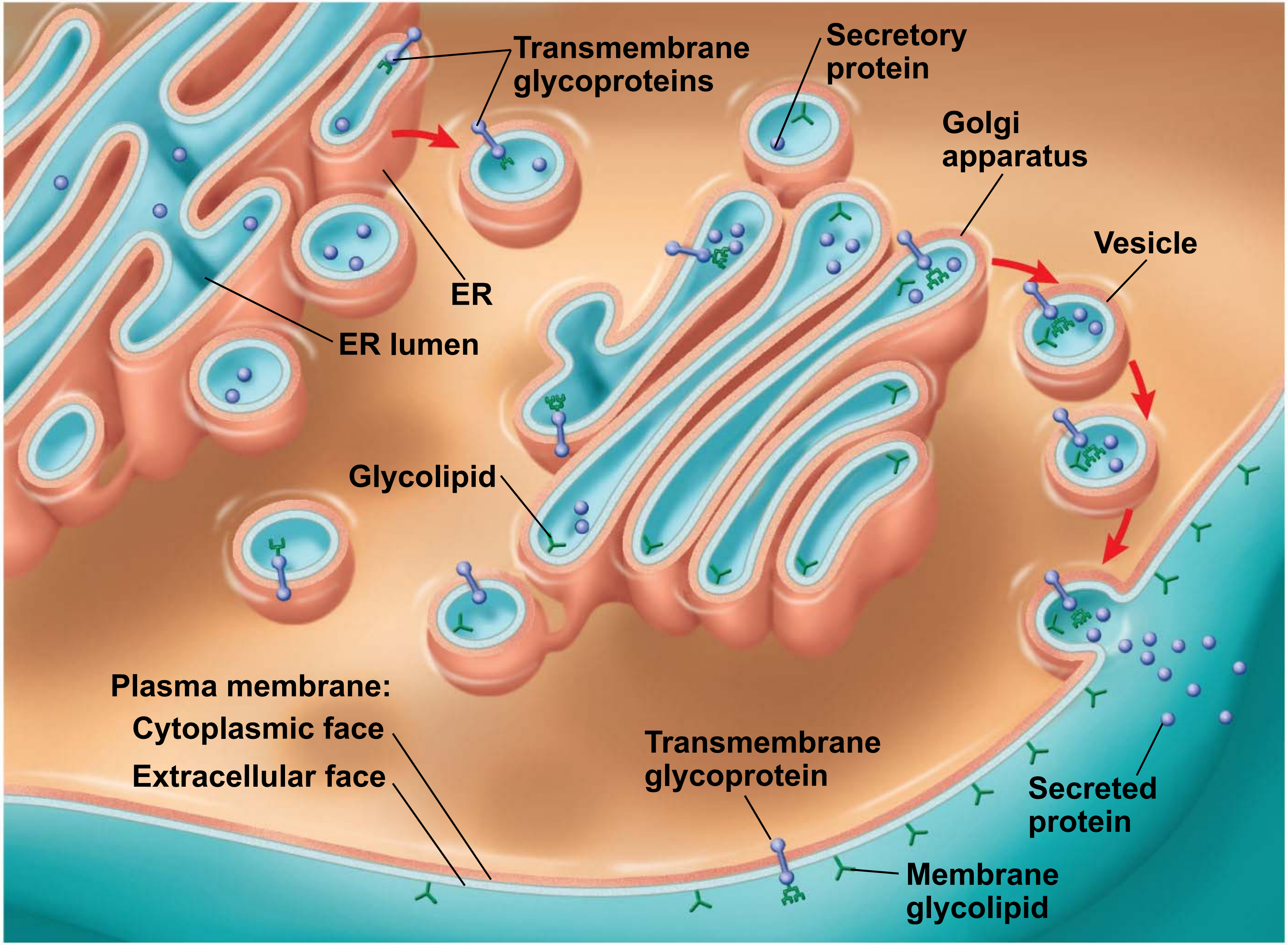
The Role of Membrane Carbohydrates in Cell-Cell Recognition

- Cells recognize each other by binding to surface molecules, often carbohydrates, on the plasma membrane
- Membrane carbohydrates may be covalently bonded to lipids (forming **glycolipids**) or more commonly to proteins (forming **glycoproteins**)

Synthesis and Sidedness of Membranes

- Membranes have distinct inside and outside faces
- The asymmetrical distribution of proteins, lipids, and associated carbohydrates in the plasma membrane is determined when the membrane is built by the ER and Golgi apparatus

Figure 7.12



Transmembrane glycoproteins
Secretory protein
Golgi apparatus
Vesicle
ER
ER lumen
Glycolipid
Plasma membrane:
Cytoplasmic face
Extracellular face
Transmembrane glycoprotein
Secreted protein
Membrane glycolipid

Concept 7.2: Membrane structure results in selective permeability

- A cell must exchange materials with its surroundings, a process controlled by the plasma membrane
- Plasma membranes are selectively permeable, regulating the cell's molecular traffic

The Permeability of the Lipid Bilayer

- Hydrophobic (nonpolar) molecules, such as hydrocarbons, can dissolve in the lipid bilayer and pass through the membrane rapidly
- Polar molecules, such as sugars, do not cross the membrane easily

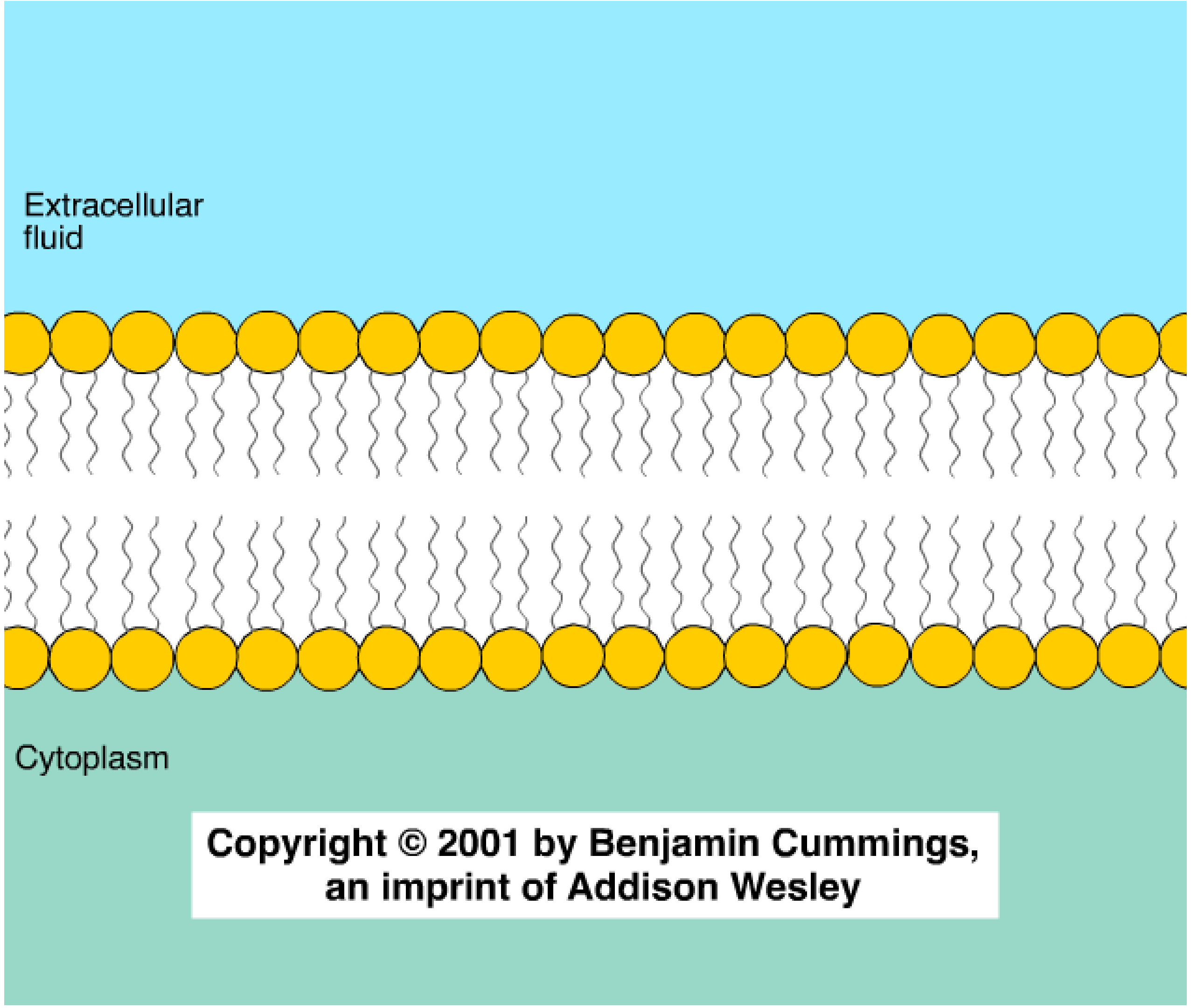
Transport Proteins

- **Transport proteins** allow passage of hydrophilic substances across the membrane
- Some transport proteins, called 1) **channel proteins**, have a hydrophilic channel that certain molecules or ions can use as a tunnel
- Channel proteins called **aquaporins** facilitate the passage of water

- Other transport proteins, called **2) carrier proteins**, *bind to molecules and change shape to shuttle them across the membrane*
- A transport protein is **specific** for the substance it moves

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

- **Diffusion** is the tendency for molecules to spread out evenly into the available space
- Although each molecule moves randomly, diffusion of a population of molecules may exhibit a net movement in one direction
- At dynamic equilibrium, as many molecules cross one way as cross in the other direction



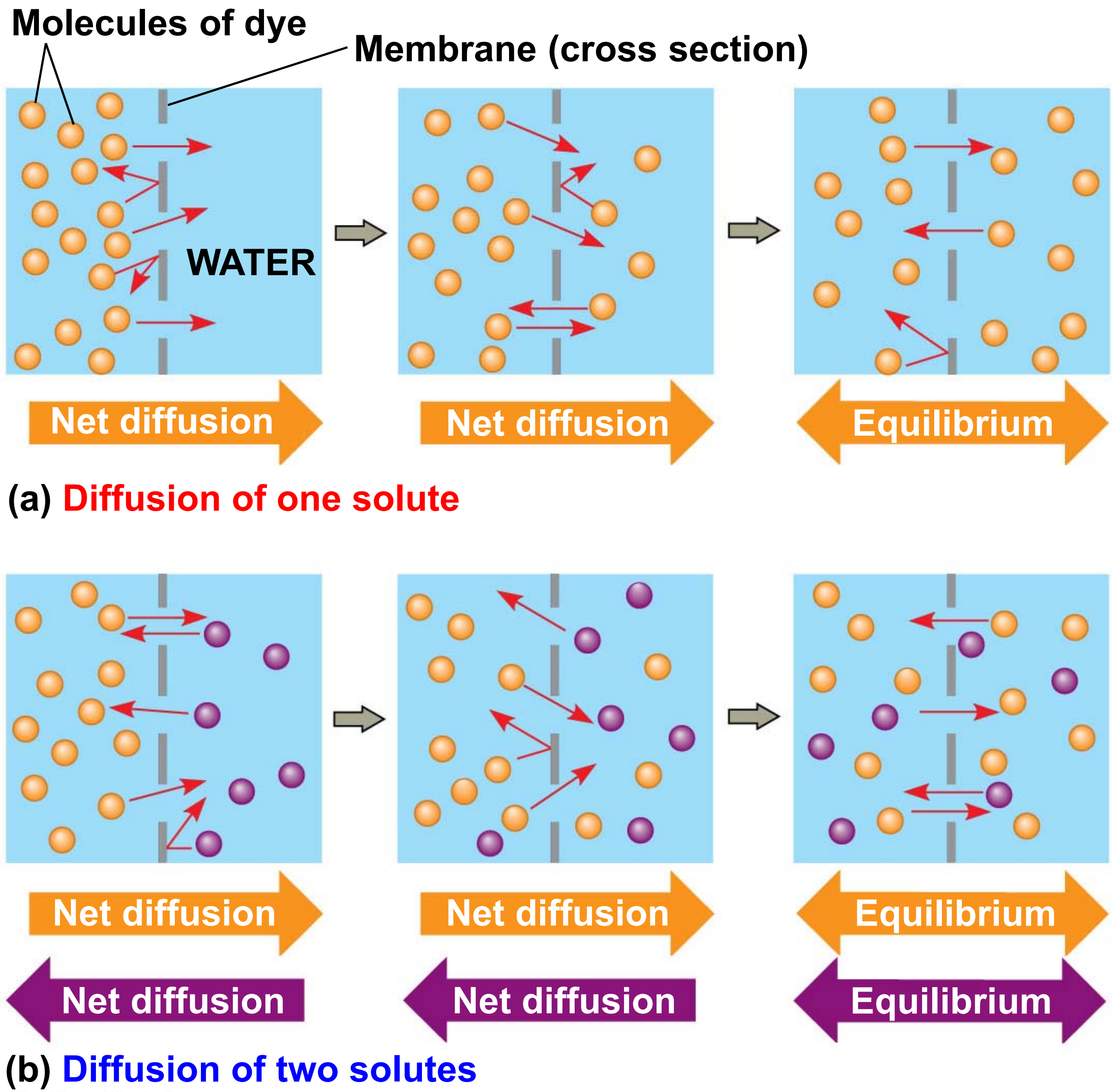
Animation: Membrane Selectivity

Right-click slide / select “Play”

Animation: Diffusion

Right-click slide / select “Play”

Figure 7.13



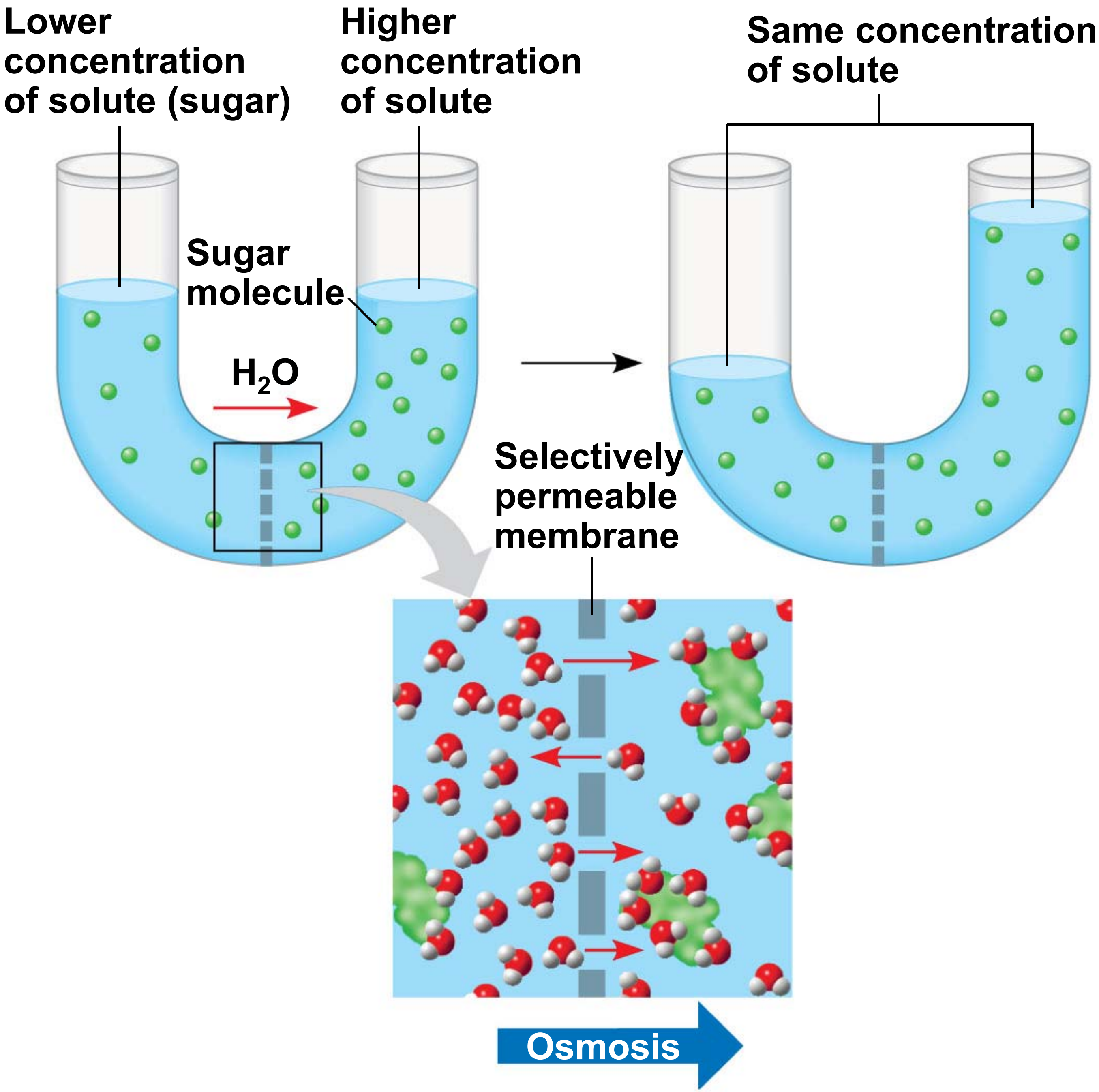
Molecules of dye
Membrane (cross section)
WATER
Net diffusion
Net diffusion
Equilibrium
(a) Diffusion of one solute
Net diffusion
Net diffusion
Equilibrium
Net diffusion
Net diffusion
Equilibrium
(b) Diffusion of two solutes

- Substances diffuse **down their concentration gradient**, the difference in concentration of a substance from one area to another
- No work must be done to move substances down the concentration gradient
- The diffusion of a substance across a biological membrane is **passive transport** because it requires no energy from the cell to make it happen

Effects of Osmosis on Water Balance

- **Osmosis** is the diffusion of water across a selectively permeable membrane
- Water diffuses across a membrane from the region of lower solute concentration to the region of higher solute concentration

Figure 7.14

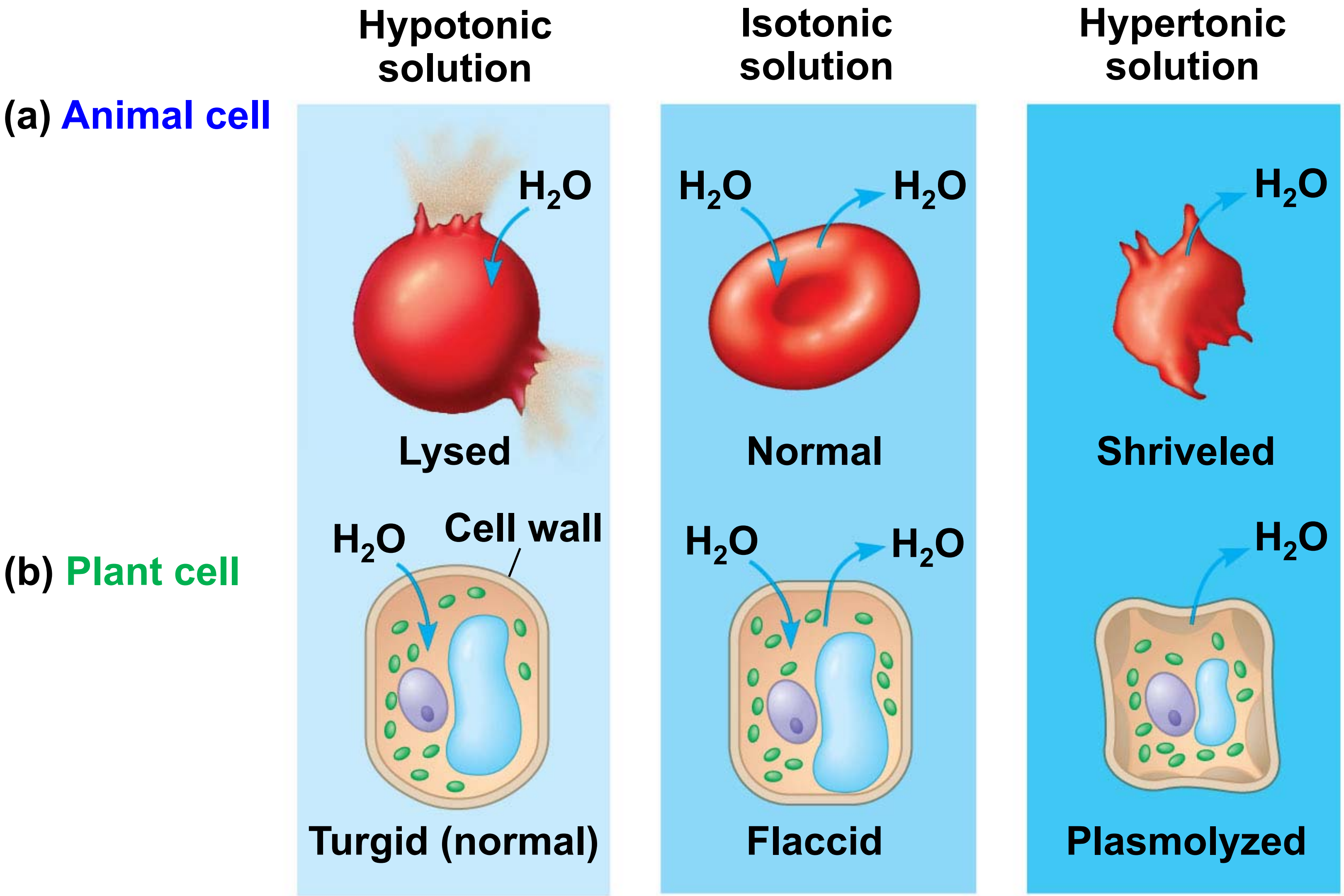


Lower concentration of solute (sugar)
Higher concentration of solute
Same concentration of solute
Sugar molecule
H_2O
Selectively permeable membrane
Osmosis

Water Balance of Cells Without Walls

- **Tonicity** *is the ability of a solution to cause a cell to gain or lose water*
- **Isotonic** solution: Solute concentration is the same as that inside the cell; no net water movement across the plasma membrane
- **Hypertonic** solution: Solute concentration is greater than that inside the cell; cell loses water
- **Hypotonic** solution: Solute concentration is less than that inside the cell; cell gains water

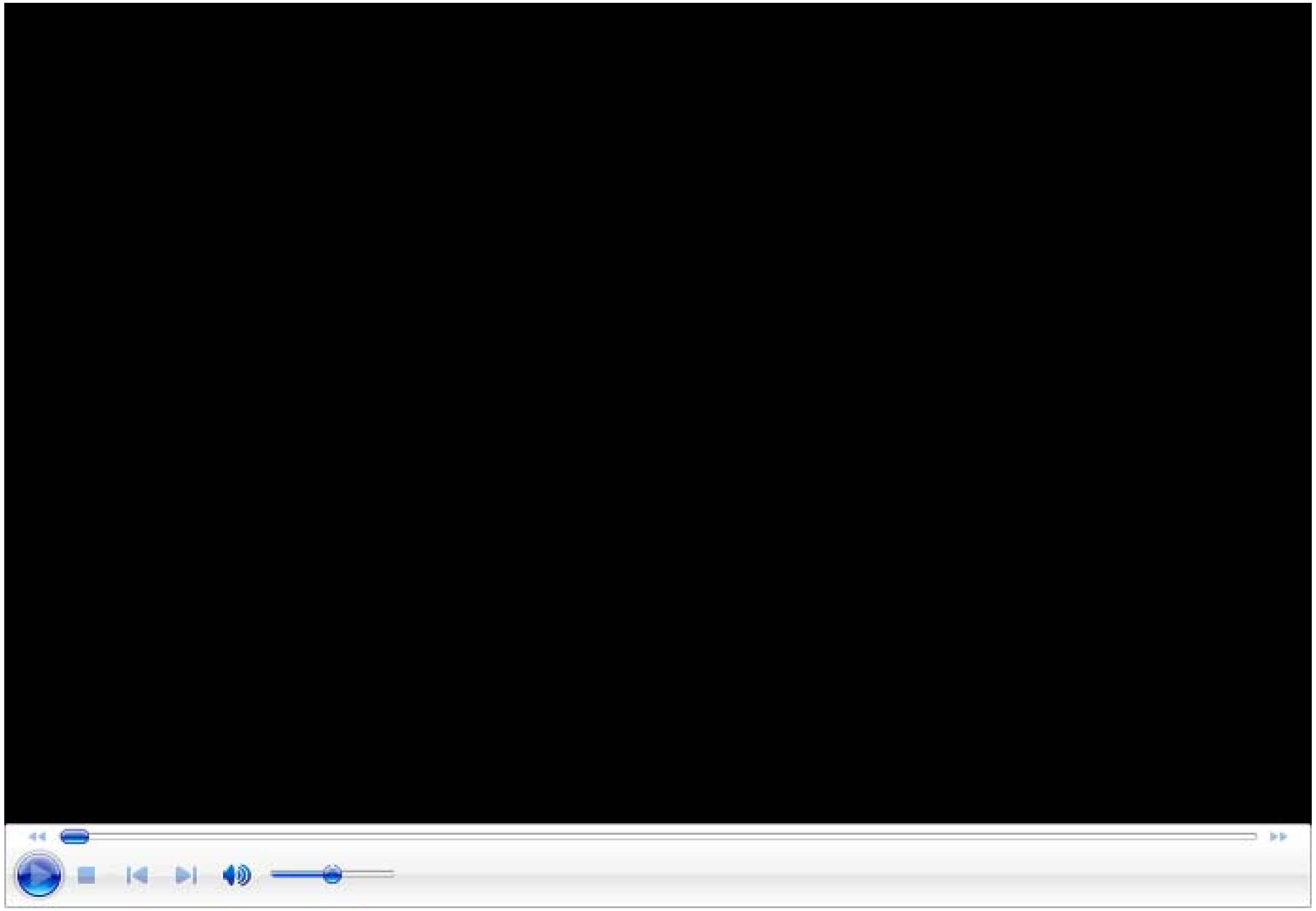
Figure 7.15


Hypotonic solution
Isotonic solution
Hypertonic solution
(a) Animal cell
H_2O
H_2O
H_2O
H_2O
Lysed
Normal
Shriveled
(b) Plant cell
H_2O
Cell wall
H_2O
H_2O
H_2O
Turgid (normal)
Flaccid
Plasmolyzed

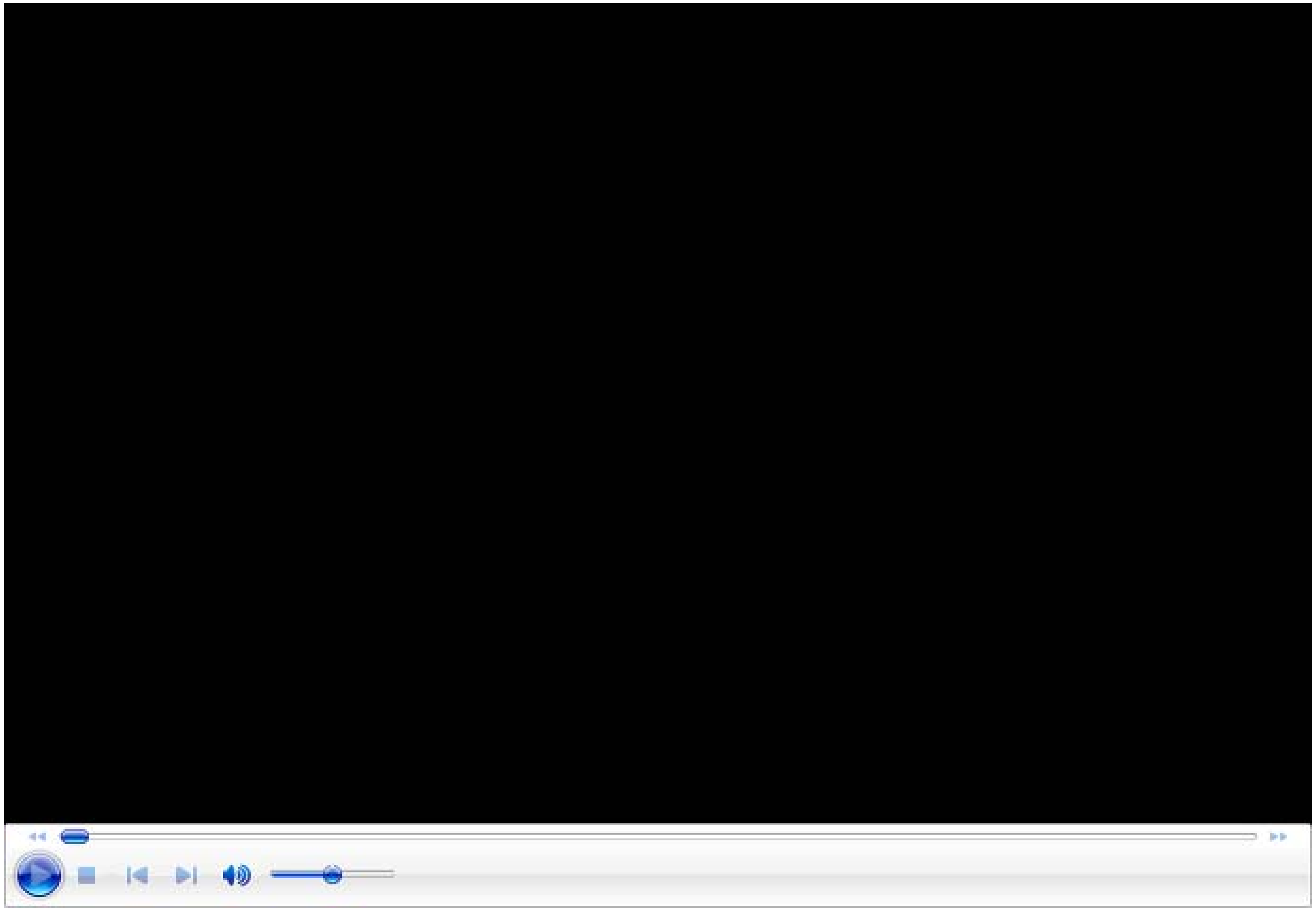
- **Hypertonic** or **hypotonic** environments create osmotic problems for organisms
- **Osmoregulation**, the control of water balance, is a necessary adaptation for life in such environments
- The protist *Paramecium,* which is hypertonic to its pond water environment, has a contractile vacuole that acts as a pump

PLAY Video: *Chlamydomonas*

PLAY Video: *Paramecium* Vacuole

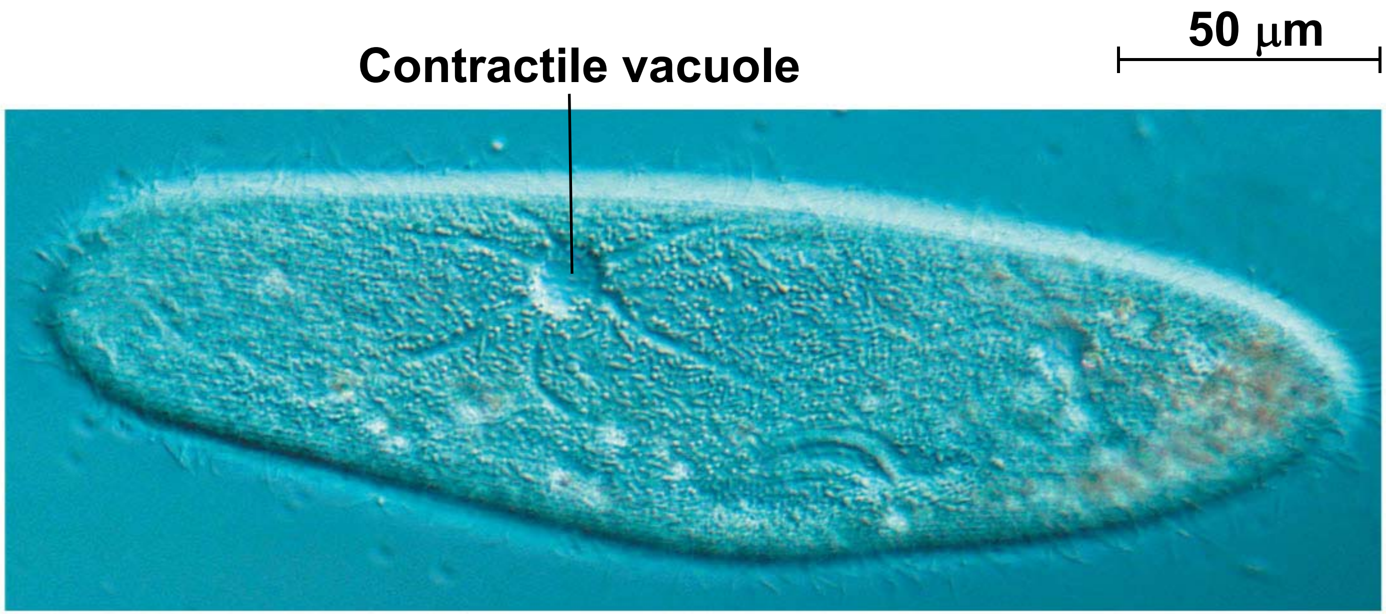


Video: *Chlamydomonas*



Video: *Paramecium* Vacuole

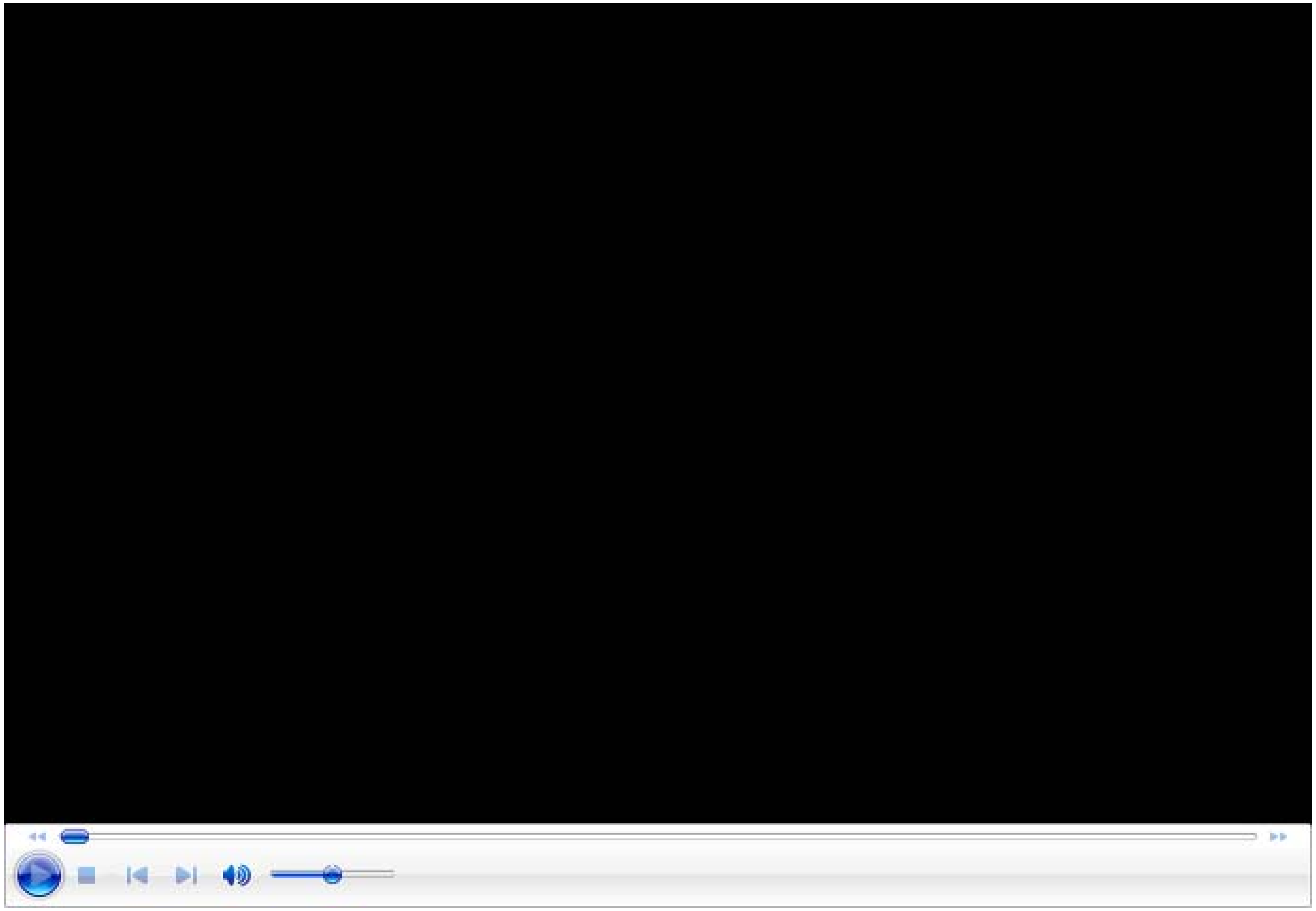
Figure 7.16



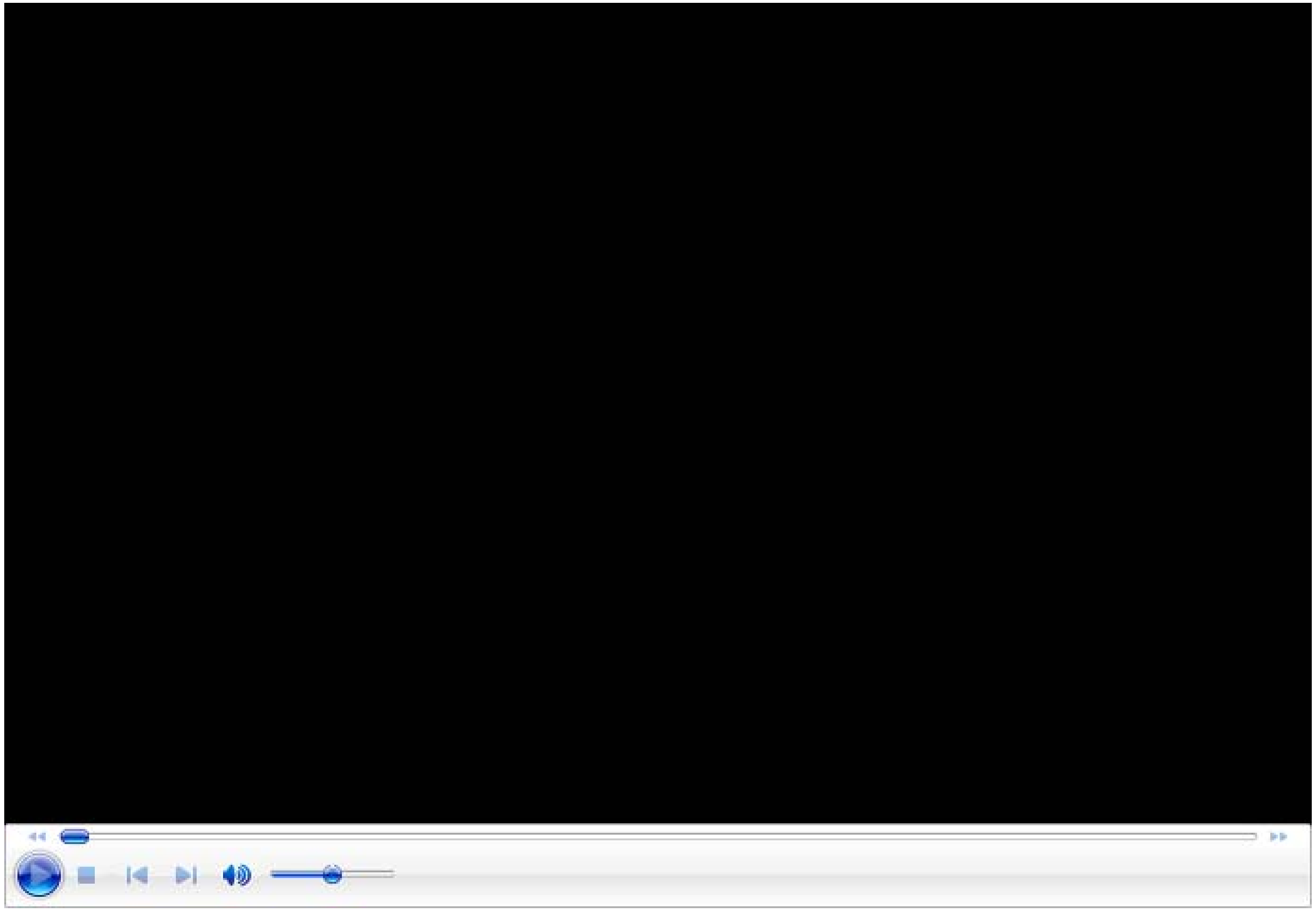
Water Balance of Cells with Walls

- Cell walls help maintain water balance
- A plant cell in a hypotonic solution swells until the wall opposes uptake; the cell is now **turgid** (firm)
- If a plant cell and its surroundings are isotonic, there is no net movement of water into the cell; the cell becomes **flaccid** (limp), and the plant may wilt

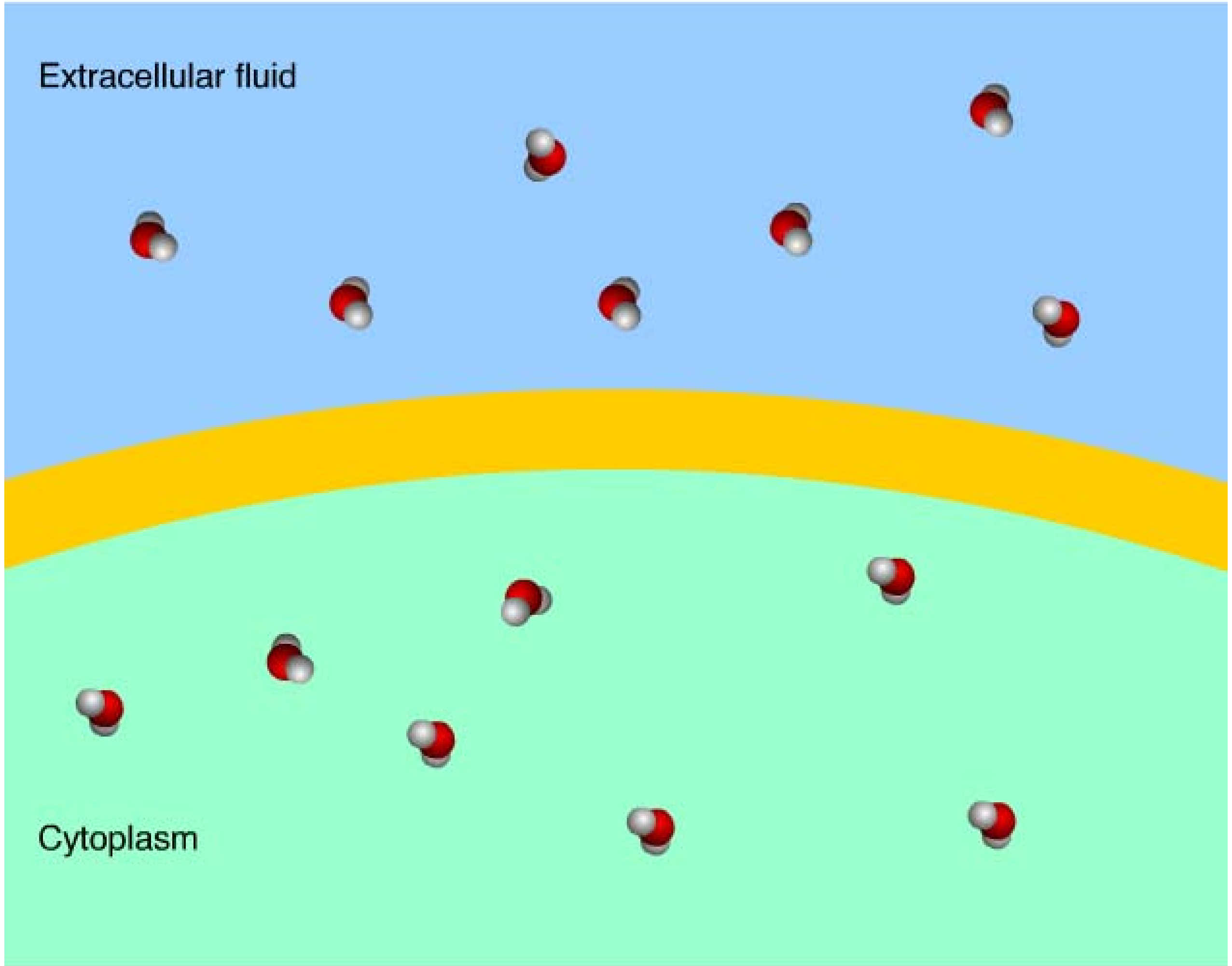
- In a hypertonic environment, plant cells lose water; eventually, the membrane pulls away from the wall, a usually lethal effect called **plasmolysis**



Video: Plasmolysis



Video: Turgid *Elodea*



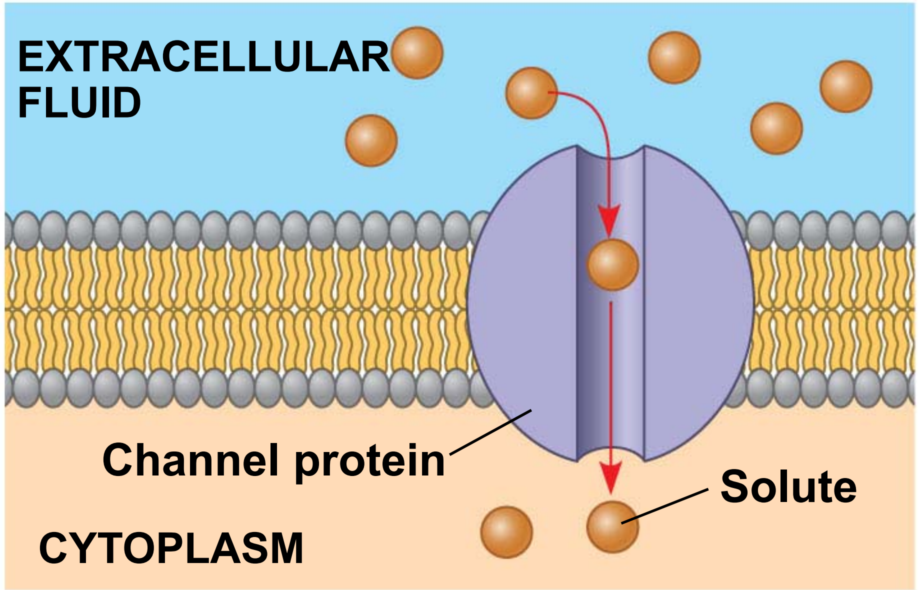
Animation: Osmosis

Right-click slide / select "Play"

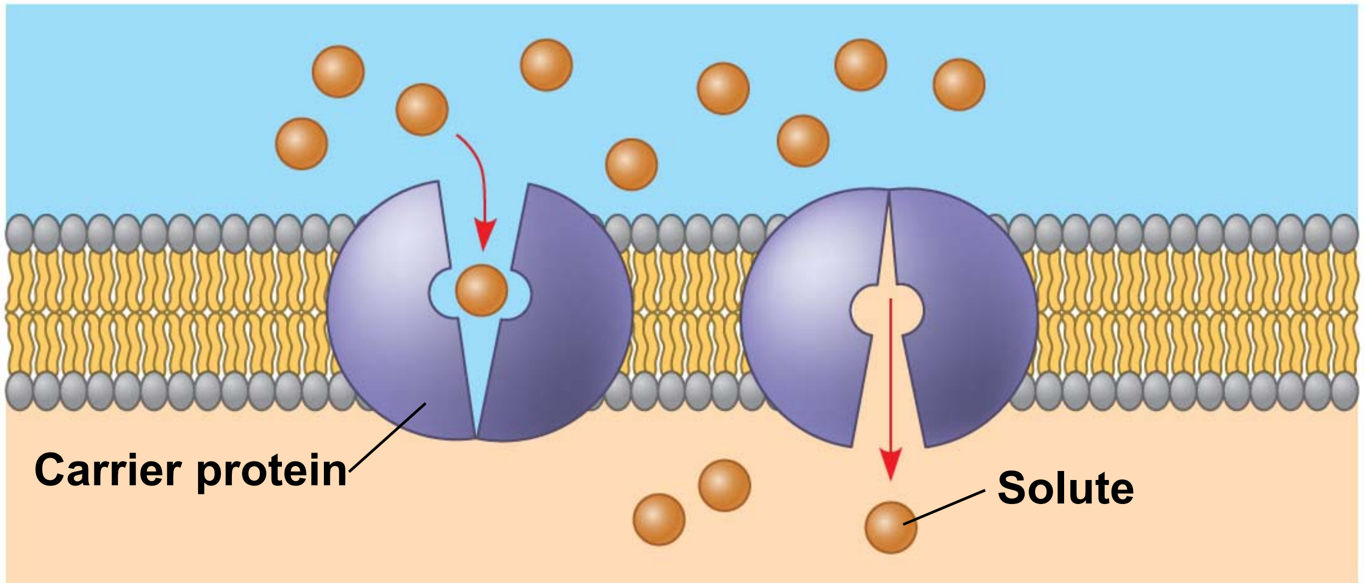
Facilitated Diffusion: Passive Transport Aided by Proteins

- In **facilitated diffusion**, transport proteins speed the passive movement of molecules across the plasma membrane
- Channel proteins provide corridors that allow a specific molecule or ion to cross the membrane
- Channel proteins include
  - **Aquaporins**, for facilitated diffusion of water
  - **Ion channels** that open or close in response to a stimulus (**gated channels**)

Figure 7.17



(a) A channel protein

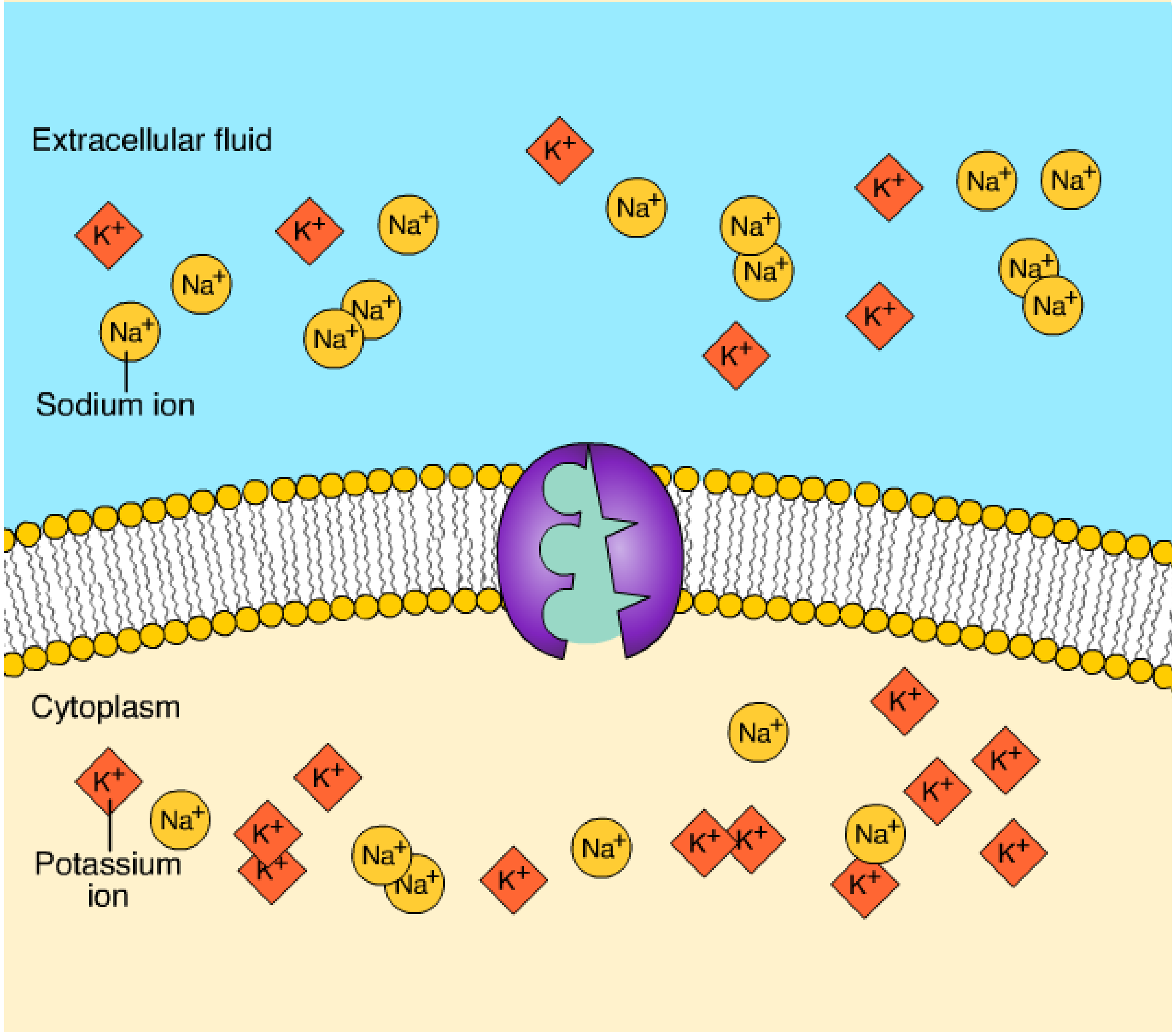


(b) A carrier protein

- **Carrier proteins** undergo a subtle change in shape that translocates the solute-binding site across the membrane

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

- Facilitated diffusion is still passive because the solute moves down its concentration gradient
- Some transport proteins, however, can move solutes against their concentration gradients
- Active transport requires energy, usually in the form of ATP
- Active transport is performed by **specific proteins** embedded **in the membranes**



Animation: Active Transport

Right-click slide / select "Play"

- Active transport allows cells to maintain concentration gradients that differ from their surroundings
- The **sodium-potassium pump** is one type of active transport system

Figure 7.18-1

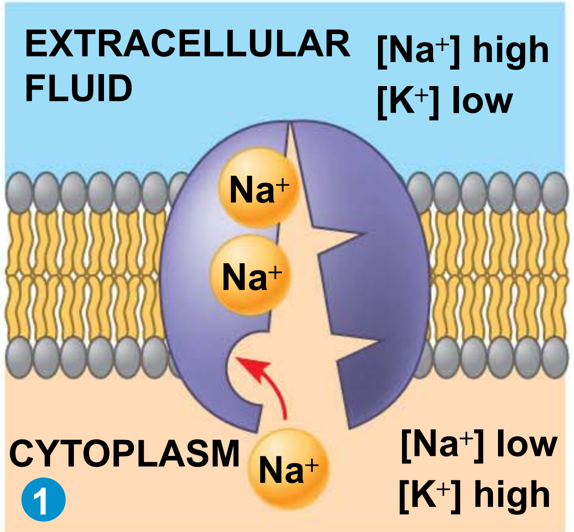
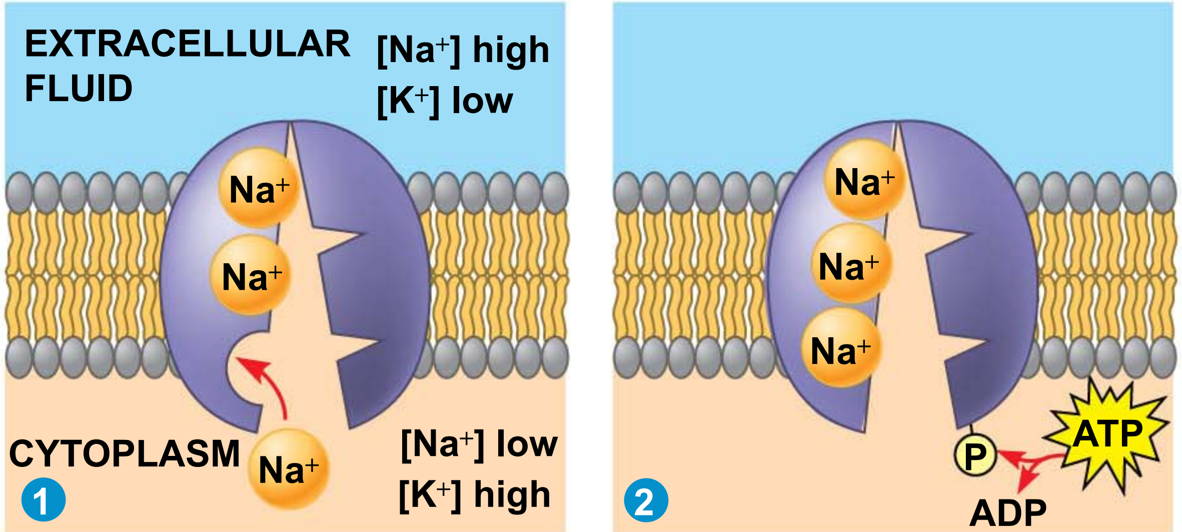
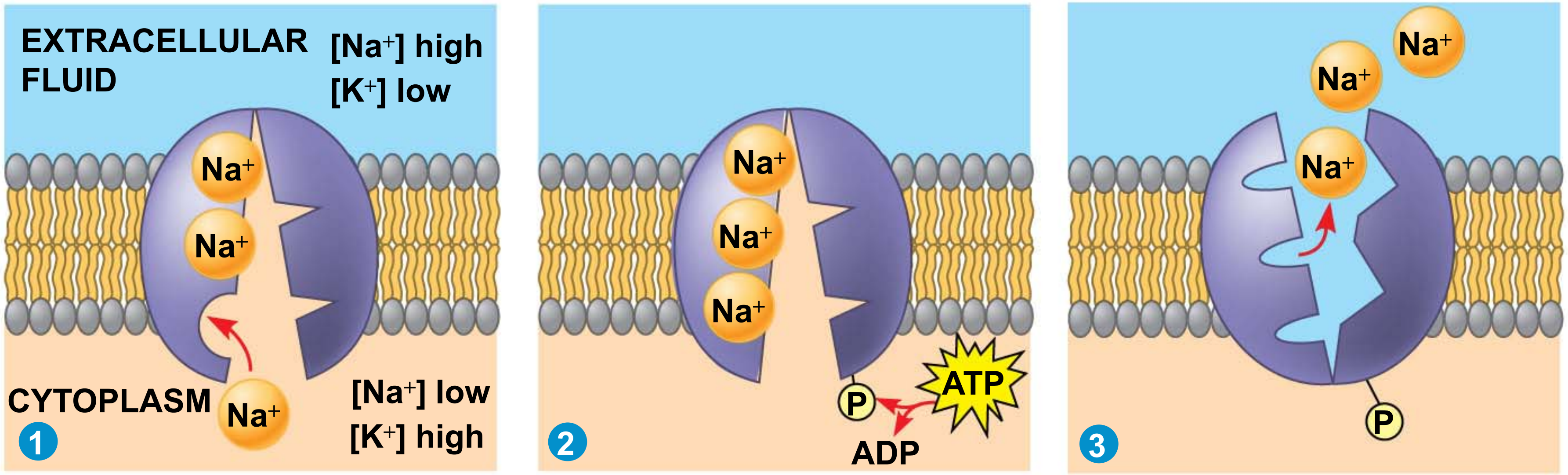

EXTRACELLULAR FLUID
[Na+] high
[K+] low
Na+
Na+
CYTOPLASM
Na+
[Na+] low
[K+] high
1

Figure 7.18-2



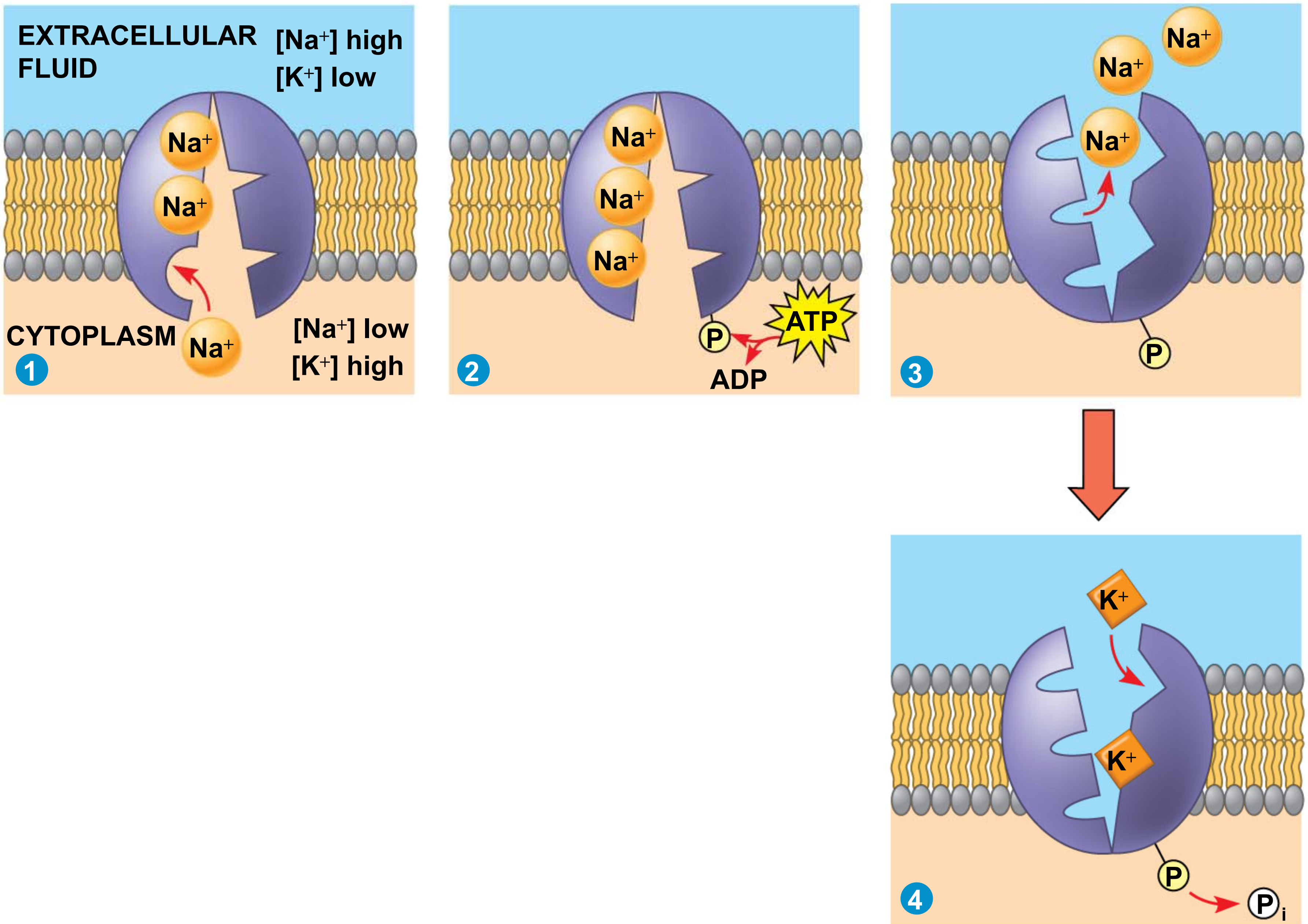
EXTRACELLULAR FLUID
[Na+] high
[K+] low
Na+
Na+
CYTOPLASM
Na+
[Na+] low
[K+] high
1
Na+
Na+
Na+
ATP
P
ADP
2

Figure 7.18-3



EXTRACELLULAR FLUID
[Na+] high
[K+] low
Na+
Na+
CYTOPLASM
Na+
[Na+] low
[K+] high
1
Na+
Na+
Na+
P
ATP
ADP
2
Na+
Na+
Na+
P
3

Figure 7.18-4



EXTRACELLULAR FLUID
[Na+] high
[K+] low
Na+
Na+
CYTOPLASM
Na+
[Na+] low
[K+] high
1
Na+
Na+
Na+
P
ATP
ADP
2
Na+
Na+
Na+
P
3
K+
K+
P
P i
4

Figure 7.18-5

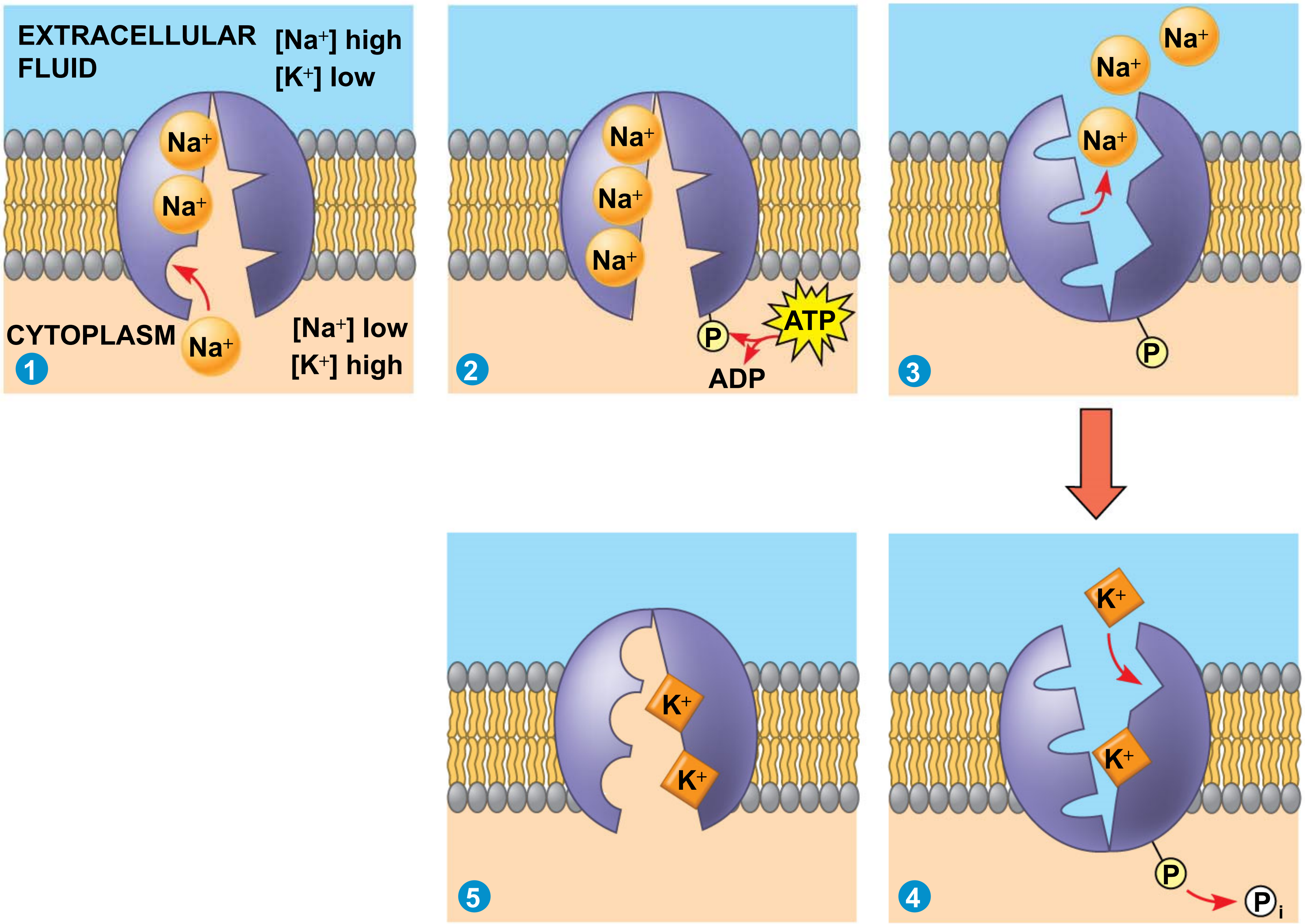

EXTRACELLULAR FLUID
[Na+] high
[K+] low
Na+
Na+
CYTOPLASM
Na+
[Na+] low
[K+] high
1
Na+
Na+
Na+
P
ATP
ADP
2
Na+
Na+
Na+
P
3
K+
K+
5
K+
K+
P
Pi
4

Figure 7.18-6

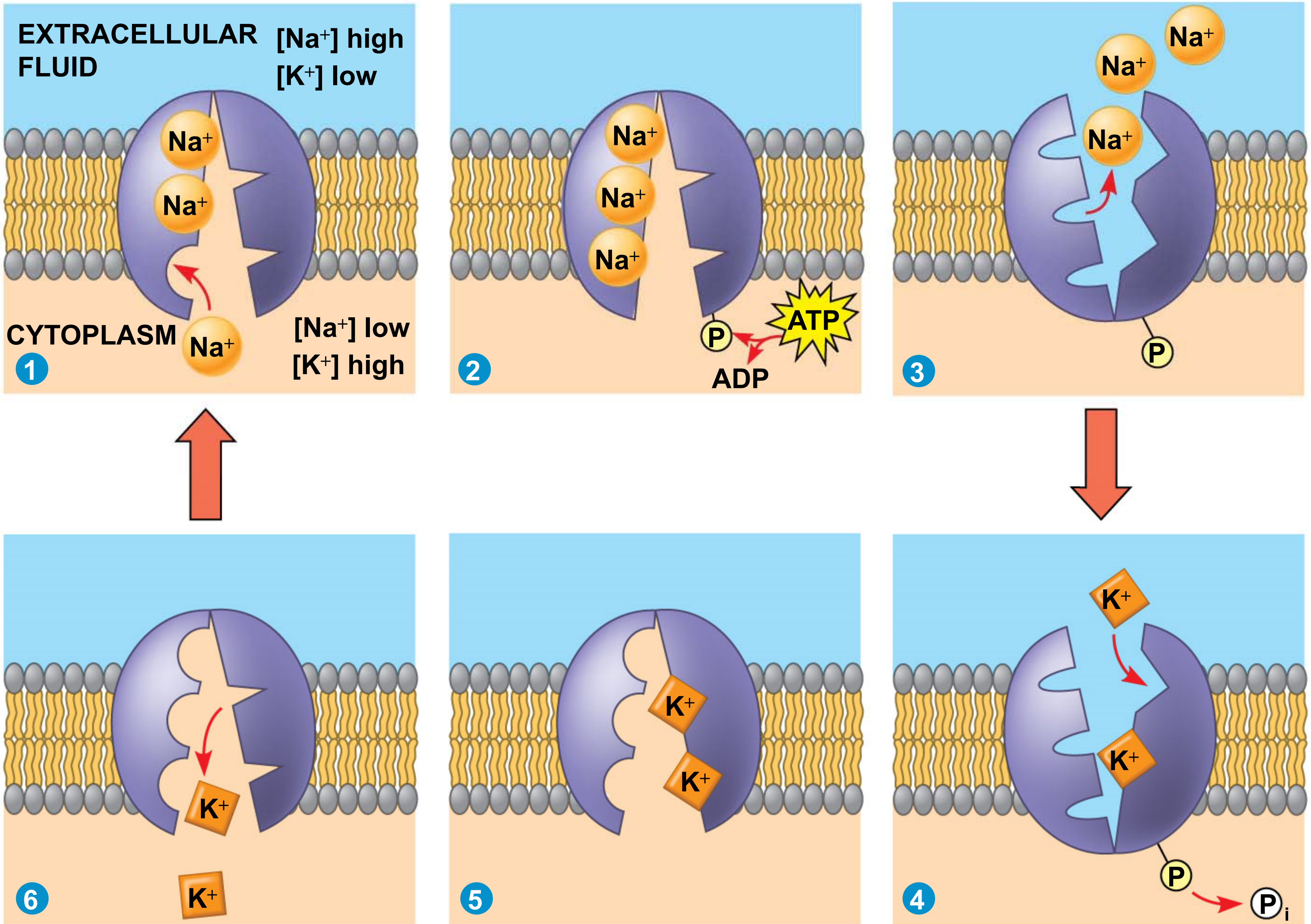
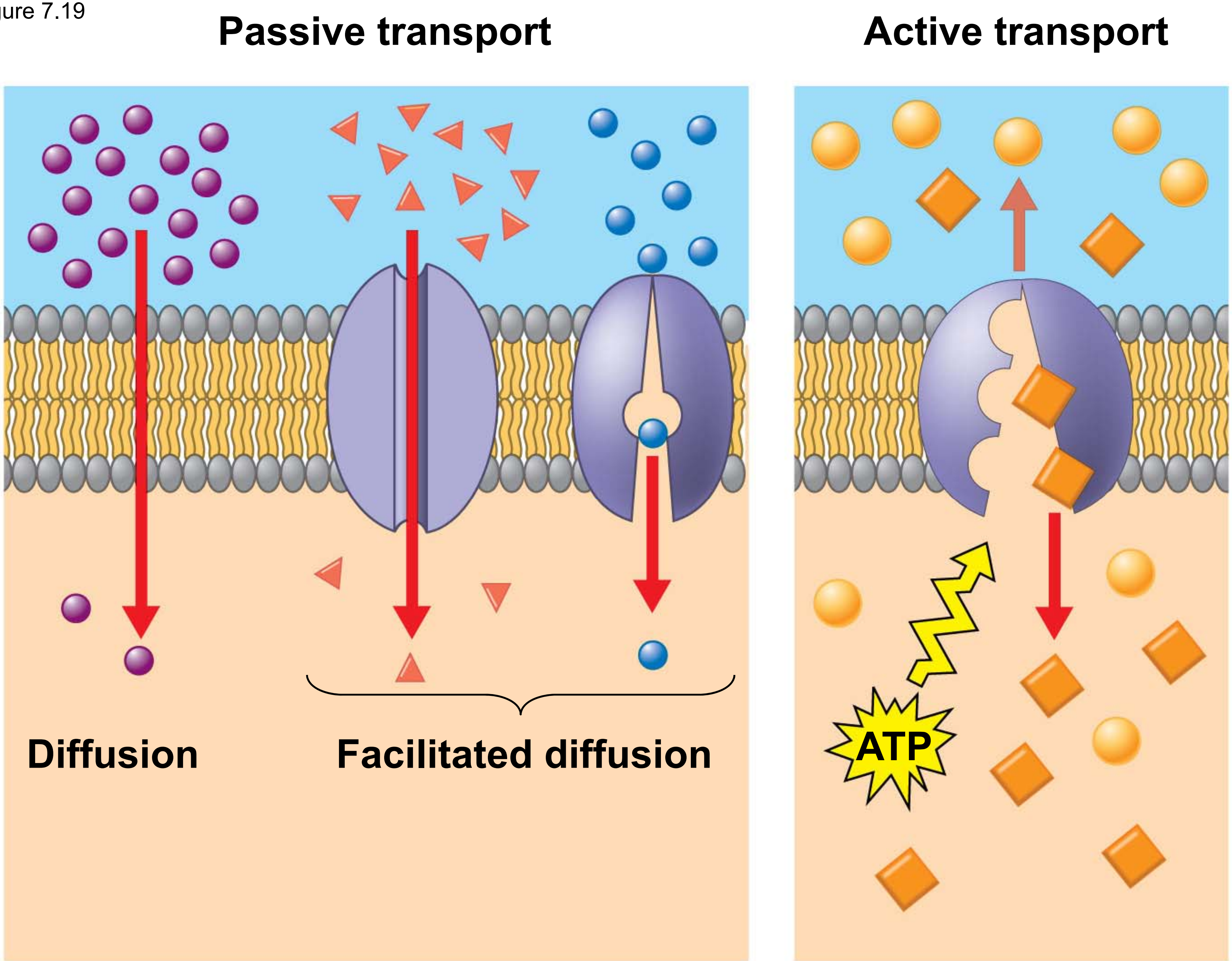

EXTRACELLULAR FLUID
[Na+] high
[K+] low
Na+
Na+
CYTOPLASM
Na+
[Na+] low
[K+] high
1
Na+
Na+
Na+
P
ATP
ADP
2
Na+
Na+
Na+
P
3
K+
K+
P
Pi
4
K+
K+
5
K+
K+
6

Figure 7.19



Passive transport
Active transport
Diffusion
Facilitated diffusion
ATP

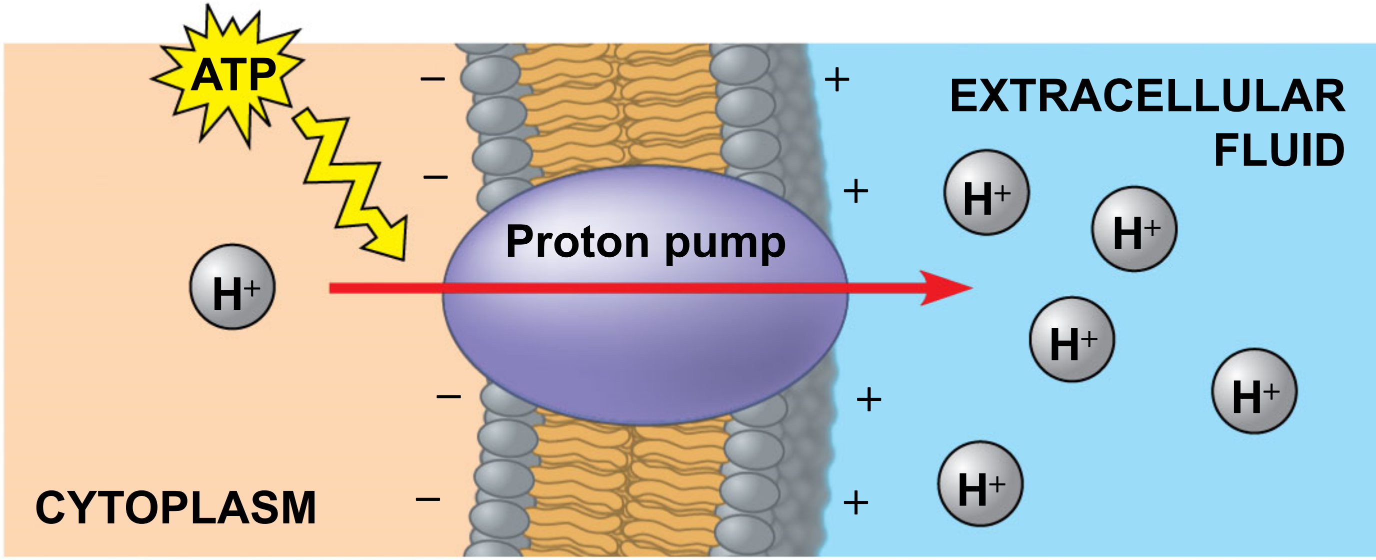
How Ion Pumps Maintain Membrane Potential

- **Membrane potential** is the voltage difference across a membrane
- Voltage is created by differences in the distribution of **positive and negative ions** across a membrane.

- Two combined forces, collectively called the **electrochemical gradient**, drive the diffusion of ions across a membrane:
  - A chemical force (the ion's concentration gradient)
  - An electrical force (the effect of the membrane potential on the ion's movement)

- An **electrogenic pump** is a transport protein that generates voltage across a membrane
- The **sodium-potassium pump** is the major electrogenic pump of animal cells
- The main electrogenic pump of plants, fungi, and bacteria is a **proton pump**

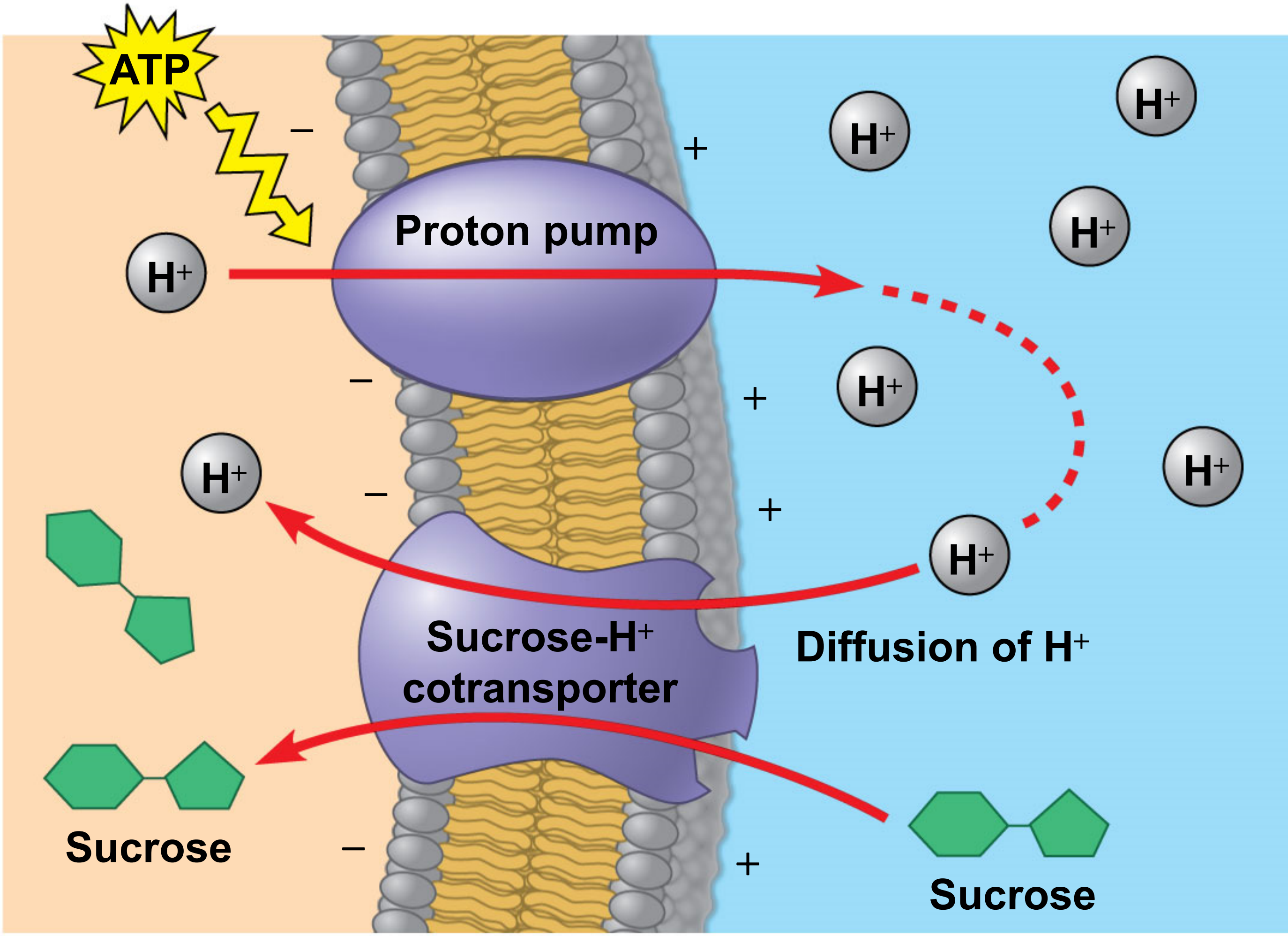
Figure 7.20



Cotransport: Coupled Transport by a Membrane Protein

- **Cotransport** *occurs when active transport of a solute indirectly drives transport of another solute*
- Plants commonly use the gradient of hydrogen ions generated by proton pumps to drive active transport of nutrients into the cell

Figure 7.21



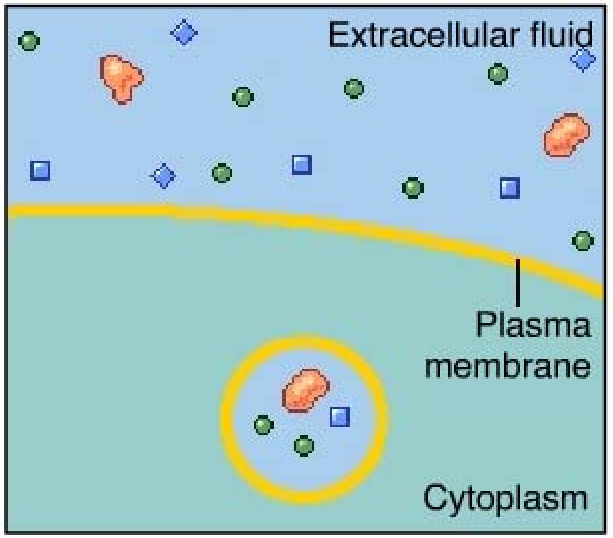
ATP
Proton pump
Sucrose-H+
cotransporter
Diffusion of H+
Sucrose
Sucrose

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

- Small molecules and water enter or leave the cell through the lipid bilayer or by transport proteins
- Large molecules, such as polysaccharides and proteins, cross the membrane in bulk via vesicles
- Bulk transport requires energy

Exocytosis

- In **exocytosis**, transport vesicles migrate to the membrane, fuse with it, and release their contents
- Many secretory cells use exocytosis to export their products

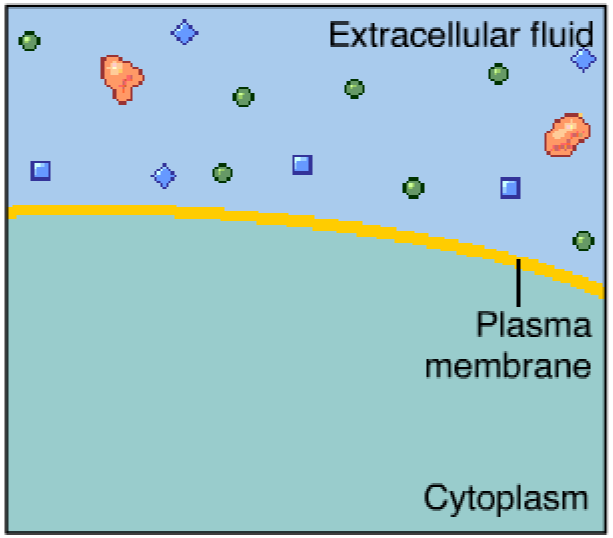


Animation: Exocytosis

Right-click slide / select “Play”

Endocytosis

- In **endocytosis**, the cell takes in macromolecules by forming vesicles from the plasma membrane
- Endocytosis is a reversal of exocytosis, involving different proteins
- There are **three types of endocytosis**:
  - Phagocytosis (“cellular eating”)
  - Pinocytosis (“cellular drinking”)
  - Receptor-mediated endocytosis



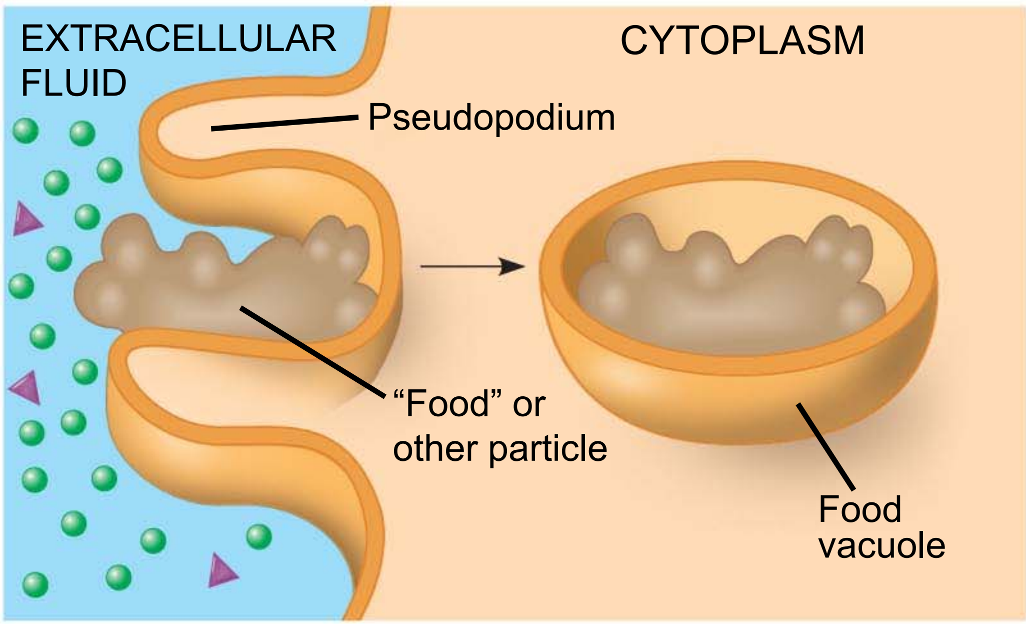
Animation: Exocytosis and Endocytosis Introduction

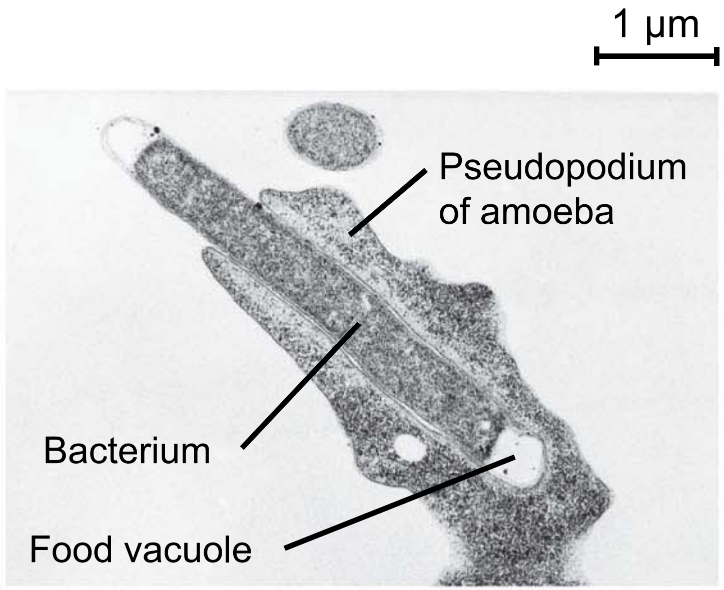
Right-click slide / select “Play”

- In **phagocytosis** a cell engulfs a particle in a vacuole
- The vacuole fuses with a lysosome to digest the particle

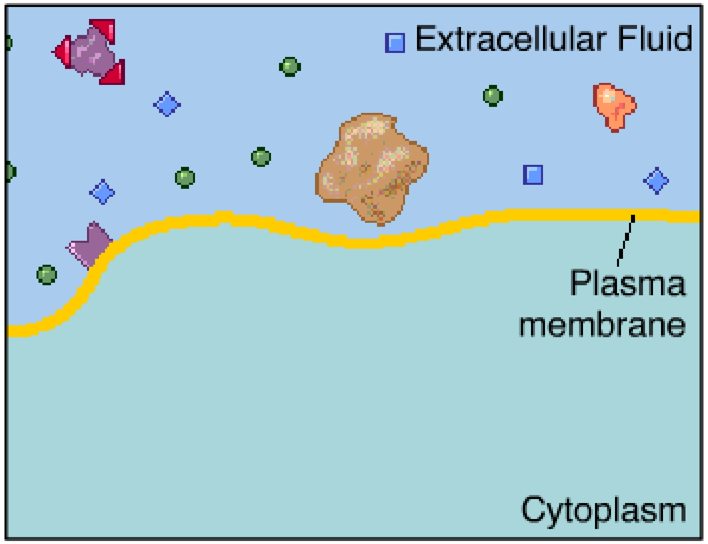
Fig. 7-20a

PHAGOCYTOSIS





An amoeba engulfing a bacterium
via phagocytosis (TEM)



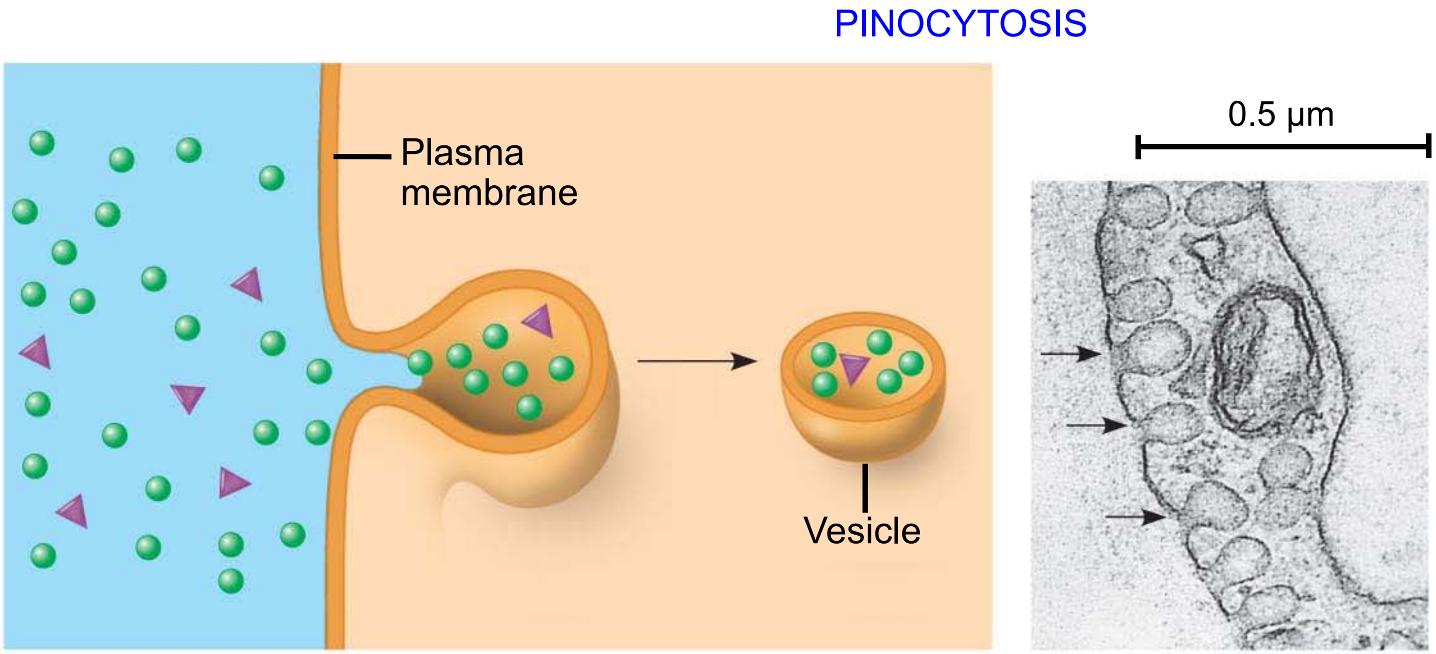
Animation: Phagocytosis

Right-click slide / select "Play"

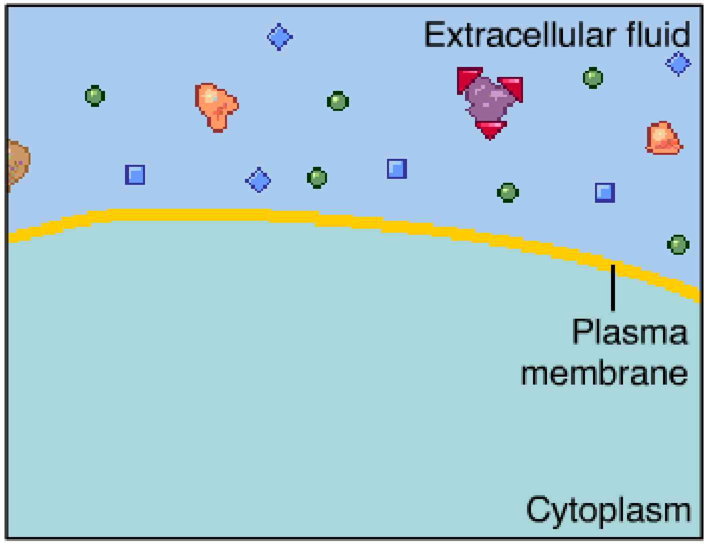
- In **pinocytosis**, molecules are taken up when extracellular fluid is "gulped" into tiny vesicles

PLAY Animation: Pinocytosis

Fig. 7-20b



Pinocytosis vesicles forming (arrows) in a cell lining a small blood vessel (TEM)

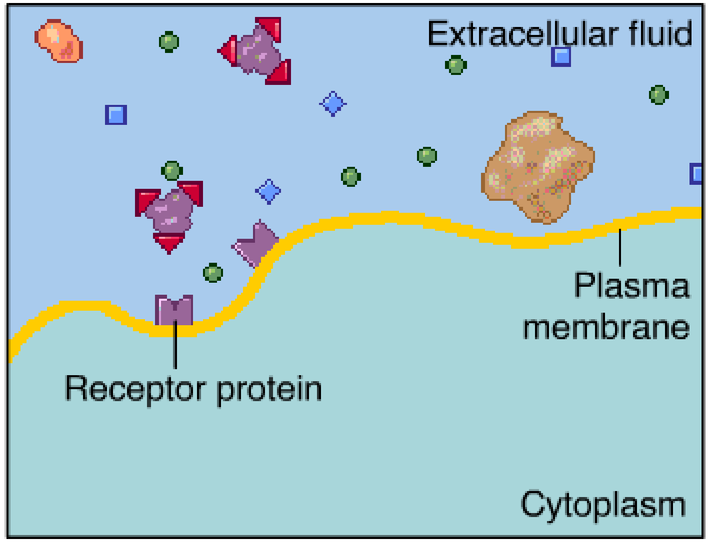


Animation: Pinocytosis

Right-click slide / select "Play"

- In **receptor-mediated endocytosis**, binding of ligands to receptors triggers vesicle formation
- A **ligand** is any molecule that binds specifically to a receptor site of another molecule

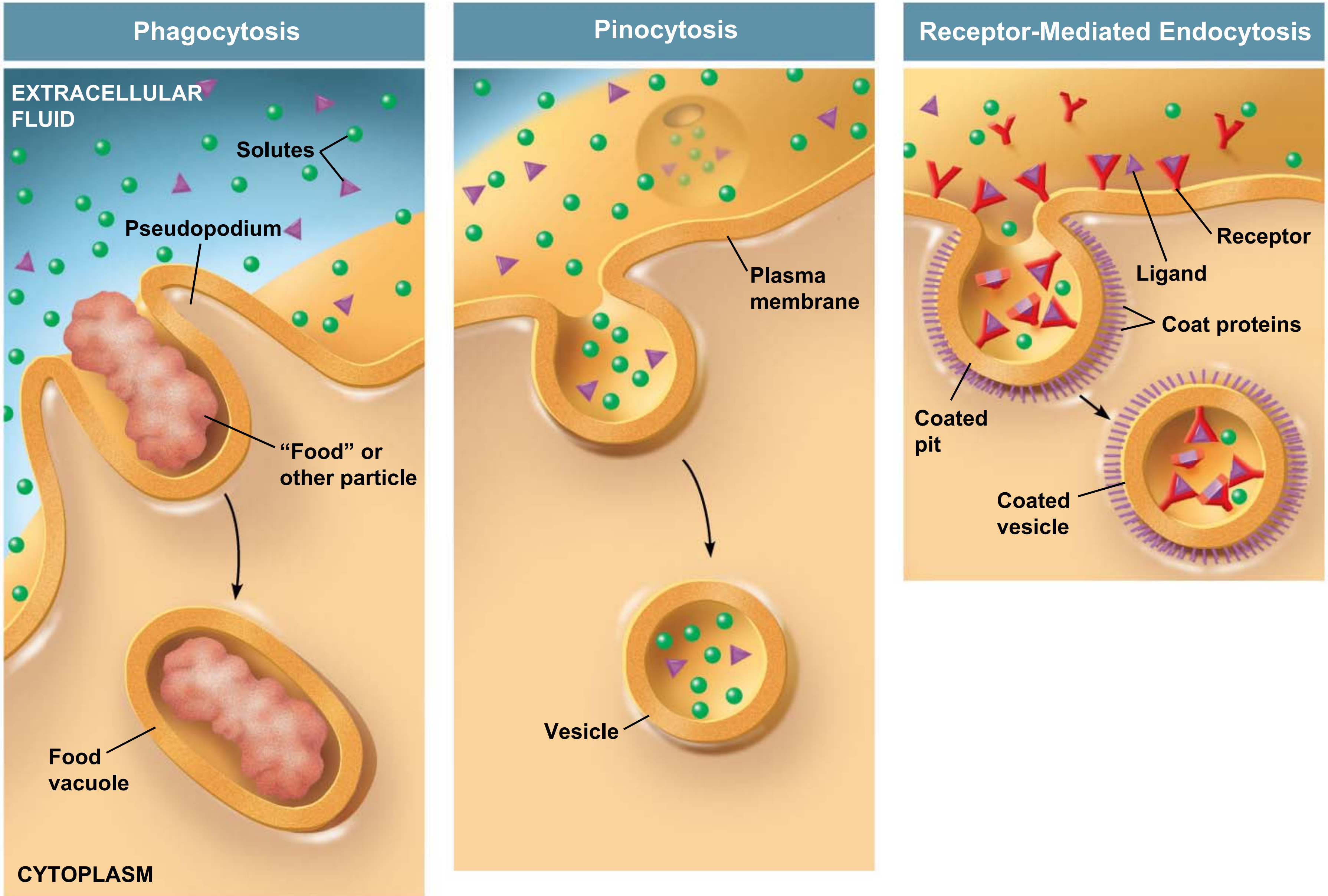
PLAY Animation: Receptor-Mediated Endocytosis



Animation: Receptor-Mediated Endocytosis

Right-click slide / select “Play”

Figure 7.22



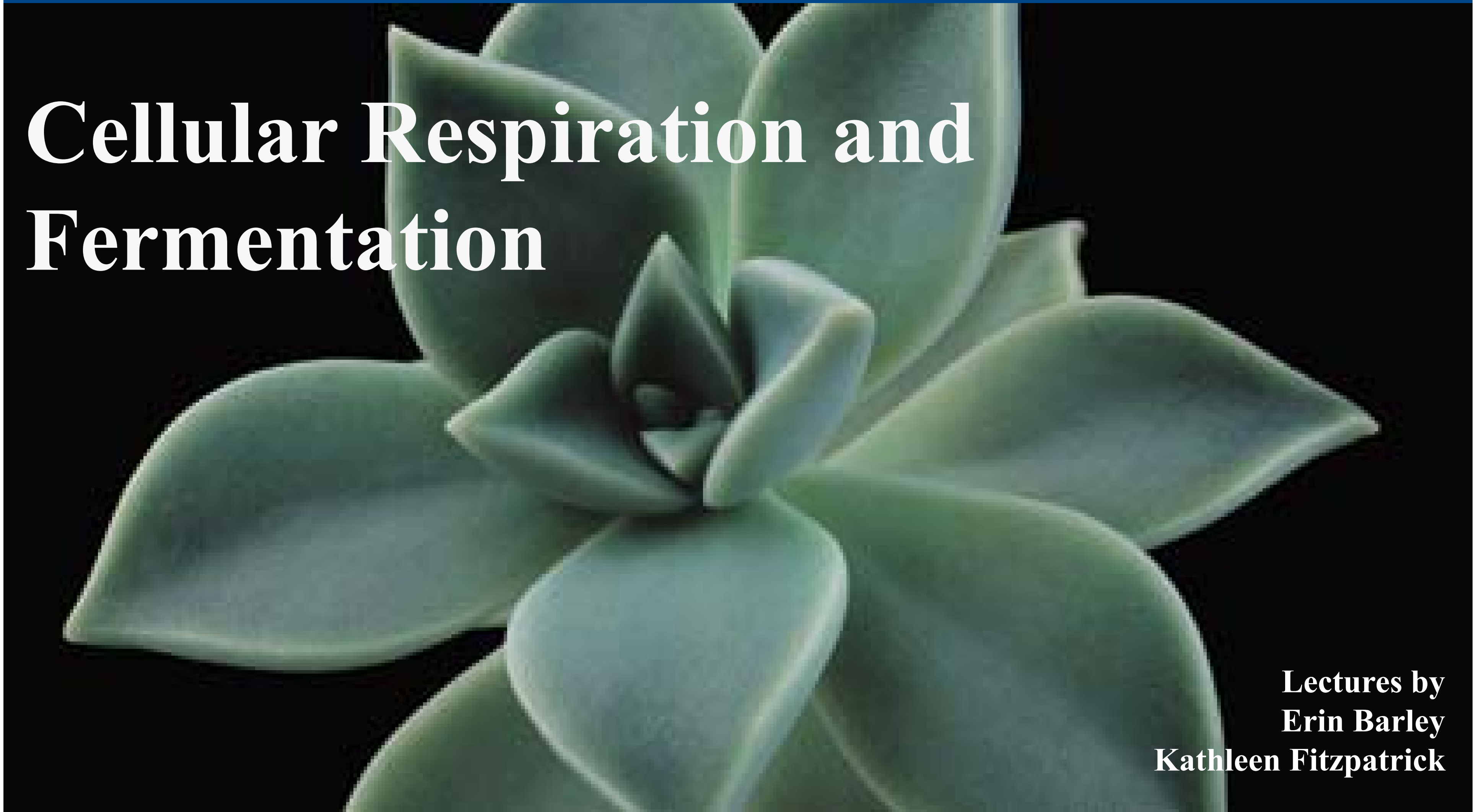
Phagocytosis
EXTRACELLULAR
FLUID
Solutes
Pseudopodium
"Food" or
other particle
Food
vacuole
CYTOPLASM
Pinocytosis
Plasma
membrane
Vesicle
Receptor-Mediated Endocytosis
Receptor
Ligand
Coat proteins
Coated
pit
Coated
vesicle

LECTURE PRESENTATIONS

For CAMPBELL BIOLOGY, NINTH EDITION

Jane B. Reece, Lisa A. Urry, Michael L. Cain, Steven A. Wasserman, Peter V. Minorsky, Robert B. Jackson

Chapter 9



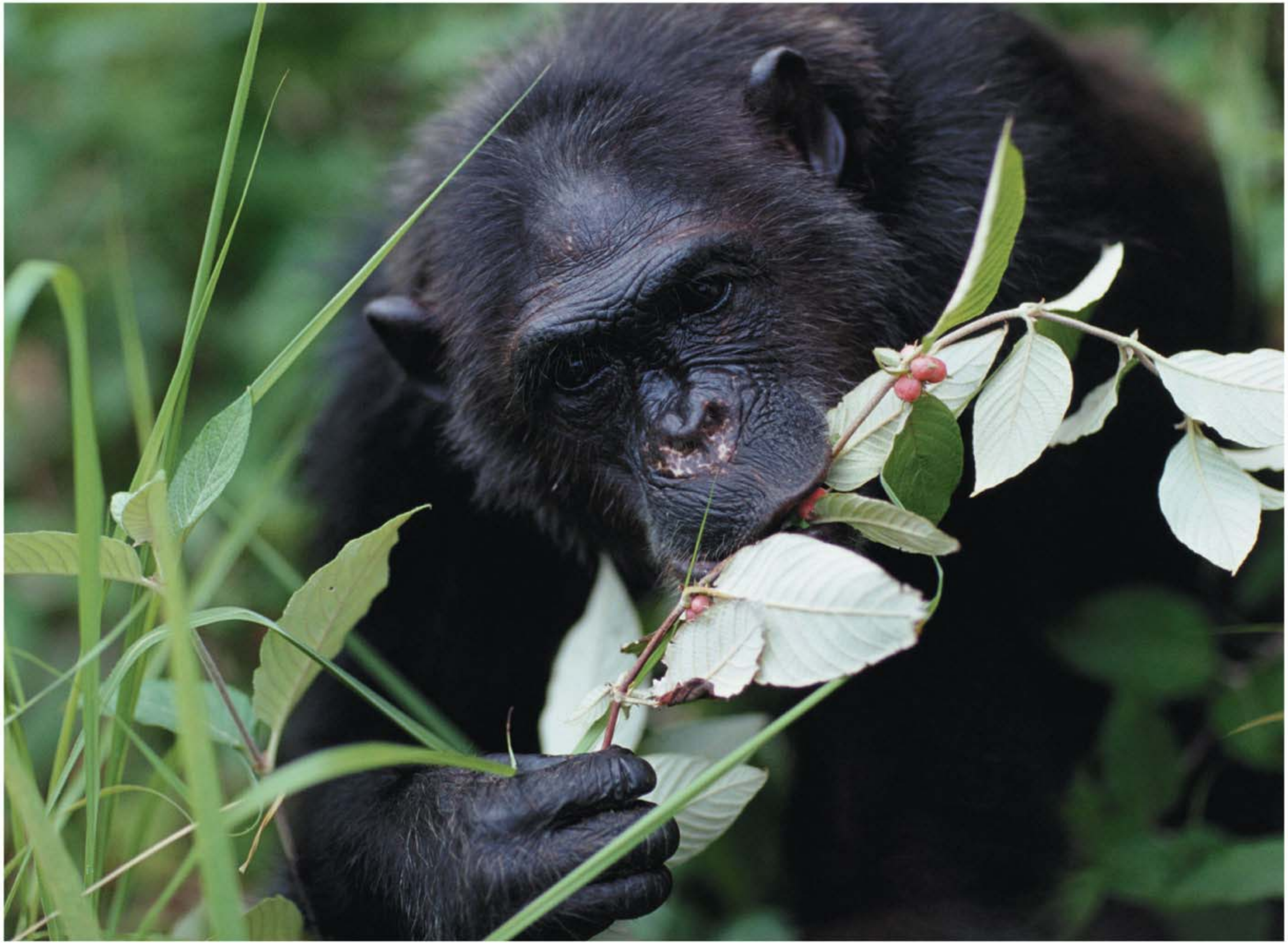
Cellular Respiration and Fermentation

Lectures by
Erin Barley
Kathleen Fitzpatrick

Overview: Life Is Work

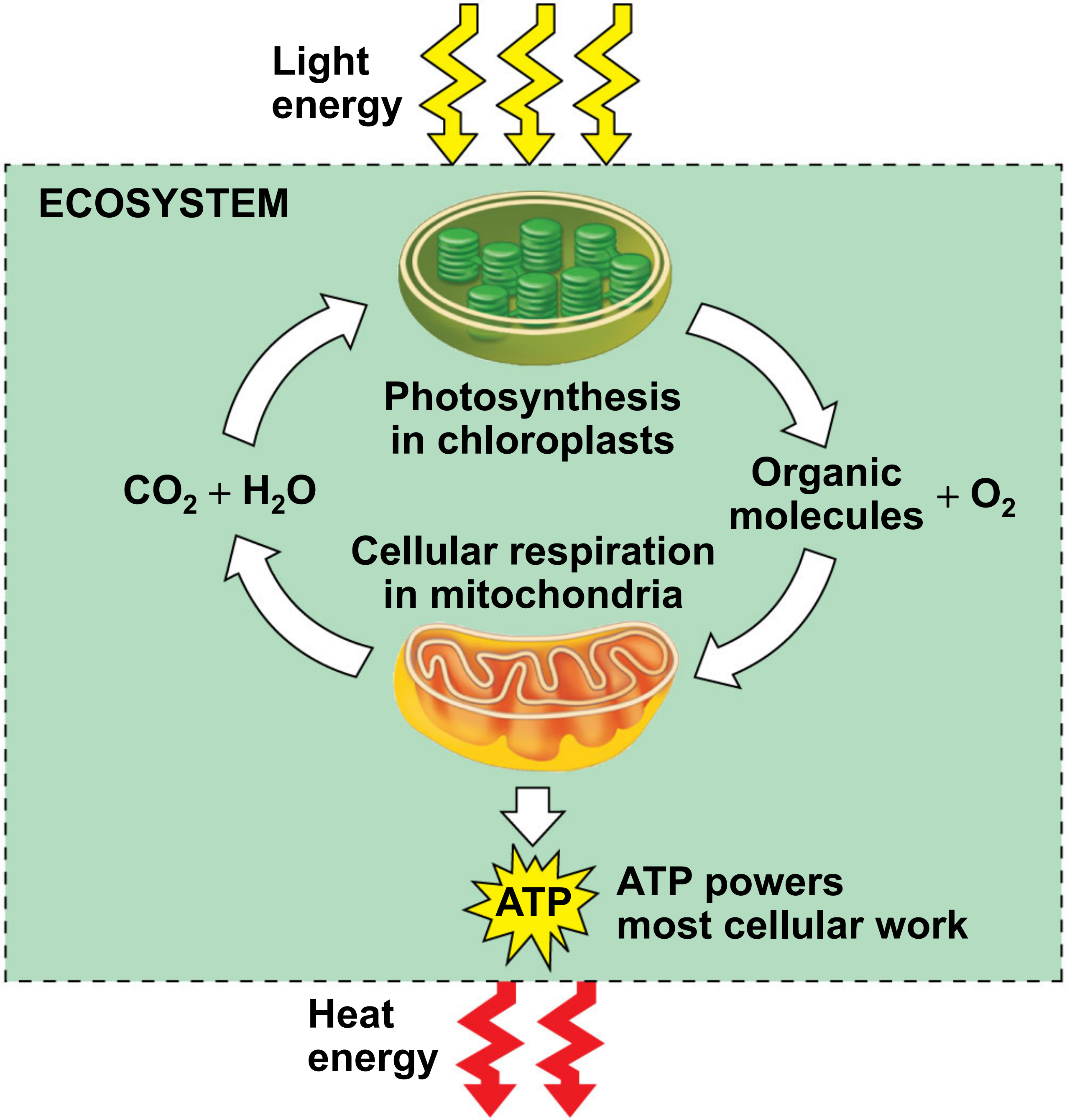
- Living cells require energy from outside sources
- Some animals, such as the giant panda, obtain energy by eating plants, and some animals feed on other organisms that eat plants

Figure 9.1



- Energy flows **into an ecosystem as sunlight** and leaves as heat
- Photosynthesis generates O_2 and organic molecules, which are used in cellular respiration
- Cells use chemical energy stored in organic molecules to regenerate ATP, which powers work

Figure 9.2



Light energy
ECOSYSTEM
Photosynthesis in chloroplasts
$CO_2 + H_2O$
Organic molecules
$+ O_2$
Cellular respiration in mitochondria
ATP
ATP powers most cellular work
Heat energy

Concept 9.1: Catabolic pathways yield energy by oxidizing organic fuels

- The breakdown of organic molecules is exergonic
- **Fermentation** is a partial degradation of sugars that occurs without O_2
- **Aerobic respiration** consumes organic molecules and O_2 and yields ATP
- Anaerobic respiration is similar to aerobic respiration but consumes compounds other than O_2

- **Cellular respiration** includes both aerobic and anaerobic respiration but is often used to refer to aerobic respiration
- Although carbohydrates, fats, and proteins are all consumed as fuel, it is helpful to trace cellular respiration with the sugar glucose:

$$C_6H_{12}O_6 + 6\ O_2 \rightarrow 6\ CO_2 + 6\ H_2O + \text{Energy (ATP + heat)}$$

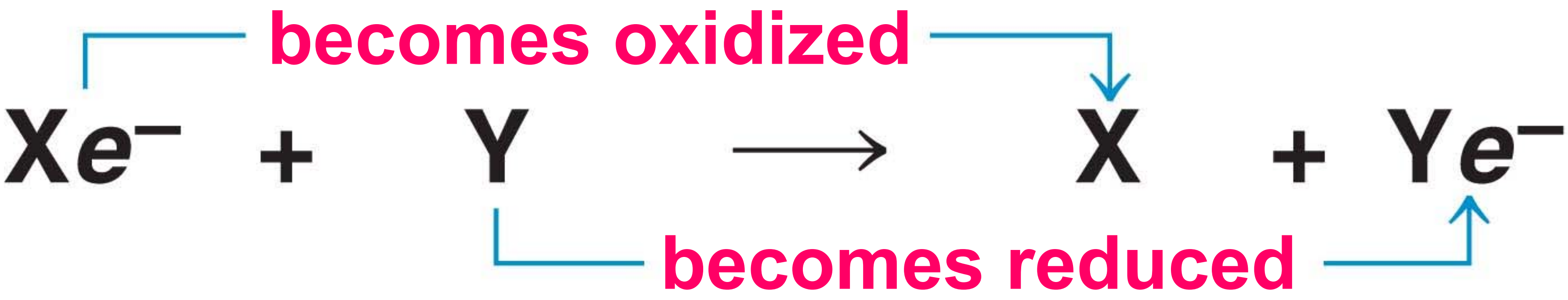
Redox Reactions: Oxidation and Reduction

- The transfer of electrons during chemical reactions releases energy stored in organic molecules
- This released energy is ultimately used to synthesize ATP

The Principle of Redox

- Chemical reactions that transfer electrons between reactants are called oxidation-reduction reactions, or **redox reactions**
- In **oxidation**, a substance loses electrons, or is oxidized
- In **reduction**, a substance gains electrons, or is reduced (*the amount of positive charge is reduced*)

Fig. 9-UN2



The electron donor is called the **reducing agent**

The electron receptor is called the **oxidizing agent**

Oxidation of Organic Fuel Molecules During Cellular Respiration

- During cellular respiration, the fuel (such as glucose) is oxidized, and O_2 is reduced:

Fig. 9-UN3

becomes oxidized

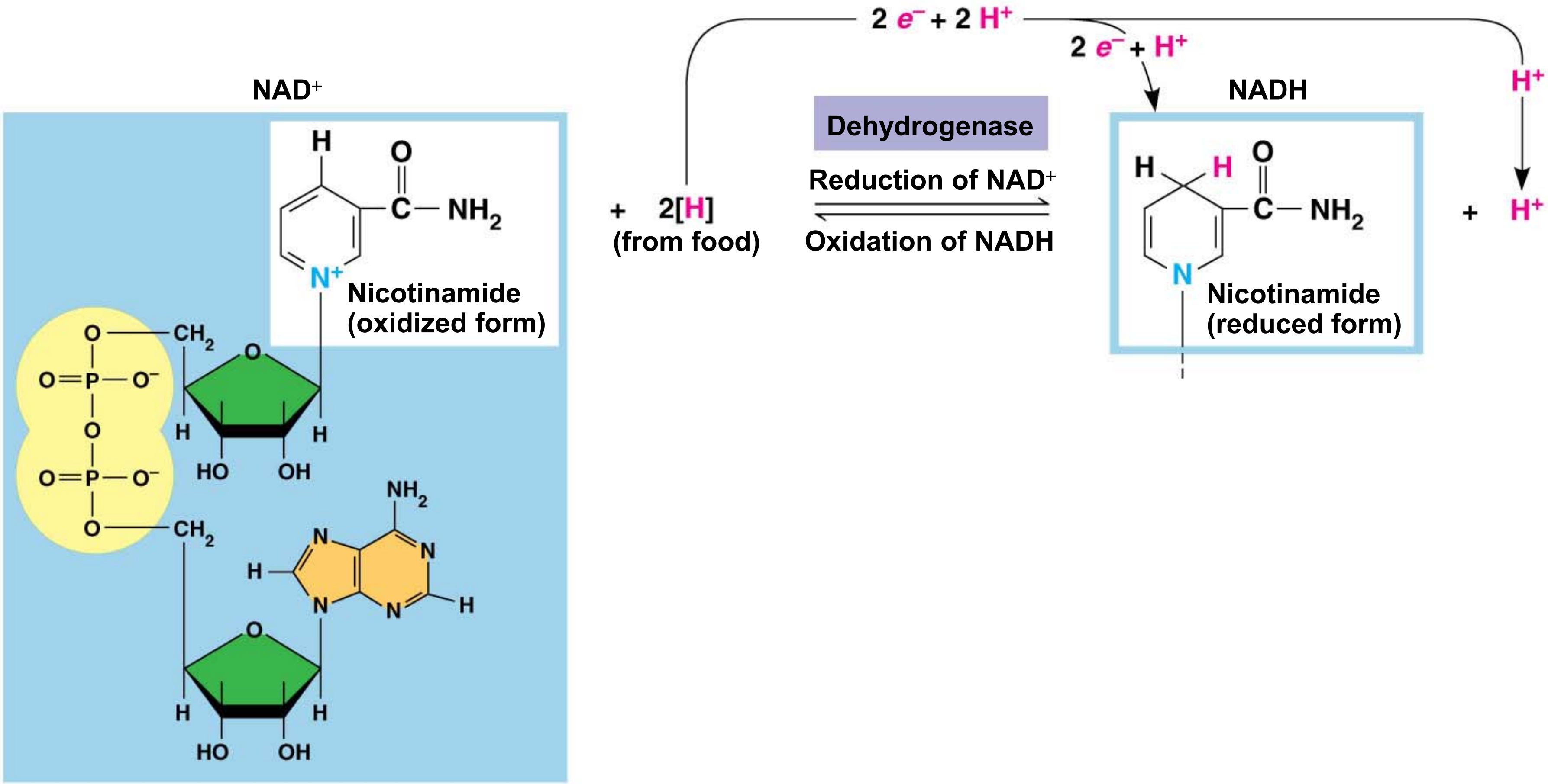
$$C_6H_{12}O_6 + 6\,O_2 \longrightarrow 6\,CO_2 + 6\,H_2O + \text{Energy}$$

becomes reduced

Stepwise Energy Harvest via NAD^+ and the Electron Transport Chain

- In cellular respiration, glucose and other organic molecules are broken down in a series of steps
- Electrons from organic compounds are usually first transferred to **NAD^+**, a coenzyme
- As an electron acceptor, NAD^+ functions as an oxidizing agent during cellular respiration
- Each NADH (the reduced form of NAD^+) represents stored energy that is tapped to synthesize ATP

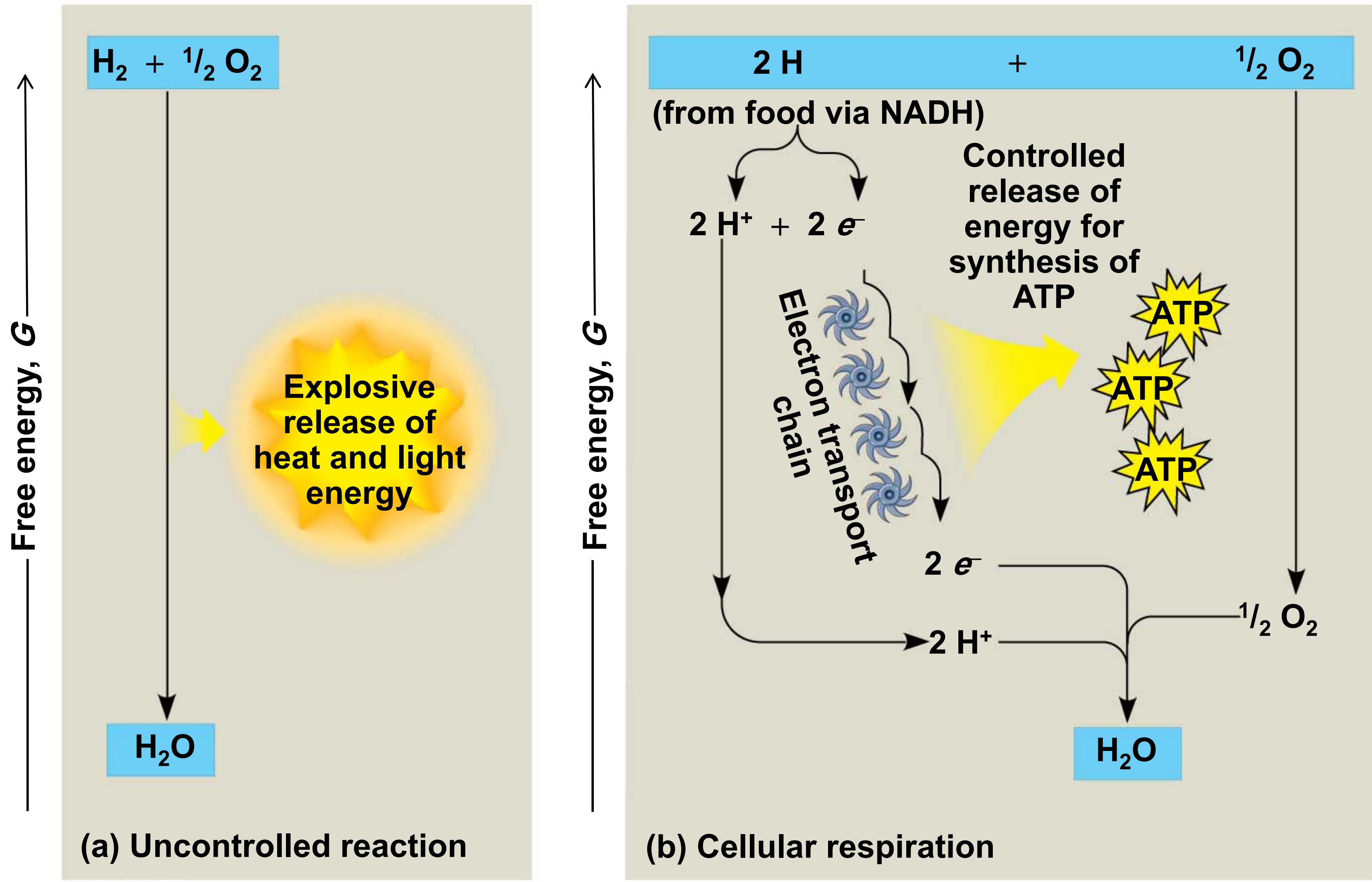
Figure 9.4



2 e⁻ + 2 H⁺
2 e⁻ + H⁺
NAD+
NADH
H⁺
Dehydrogenase
Reduction of NAD+
Oxidation of NADH
+ 2[H]
(from food)
+ H⁺
Nicotinamide
(oxidized form)
Nicotinamide
(reduced form)

- NADH passes the electrons to the **electron transport chain**
- Unlike an uncontrolled reaction, *the electron transport chain passes electrons in a series of steps instead of one explosive reaction*
- O_2 pulls electrons down the chain in an energy-yielding tumble (fall).
- The energy yielded is used to regenerate ATP

Figure 9.5



$H_2 + 1/2 O_2$
Free energy, G
Explosive release of heat and light energy
H_2O
(a) Uncontrolled reaction
2 H
+
$1/2 O_2$
(from food via NADH)
$2 H^+ + 2 e^-$
Controlled release of energy for synthesis of ATP
Electron transport chain
ATP
ATP
ATP
$2 e^-$
$1/2 O_2$
$2 H^+$
H_2O
(b) Cellular respiration

The Stages of Cellular Respiration: *A Preview*

- Cellular respiration has three stages:
  - **Glycolysis** (breaks down glucose into two molecules of pyruvate)
  - The **citric acid cycle** (completes the breakdown of glucose)
  - **Oxidative phosphorylation** (accounts for most of the ATP synthesis)

Figure 9.UN05

1. Glycolysis (color-coded teal throughout the chapter)
2. Pyruvate oxidation and the citric acid cycle (color-coded salmon)
3. Oxidative phosphorylation: electron transport and chemiosmosis (color-coded violet)

Figure 9.6-1

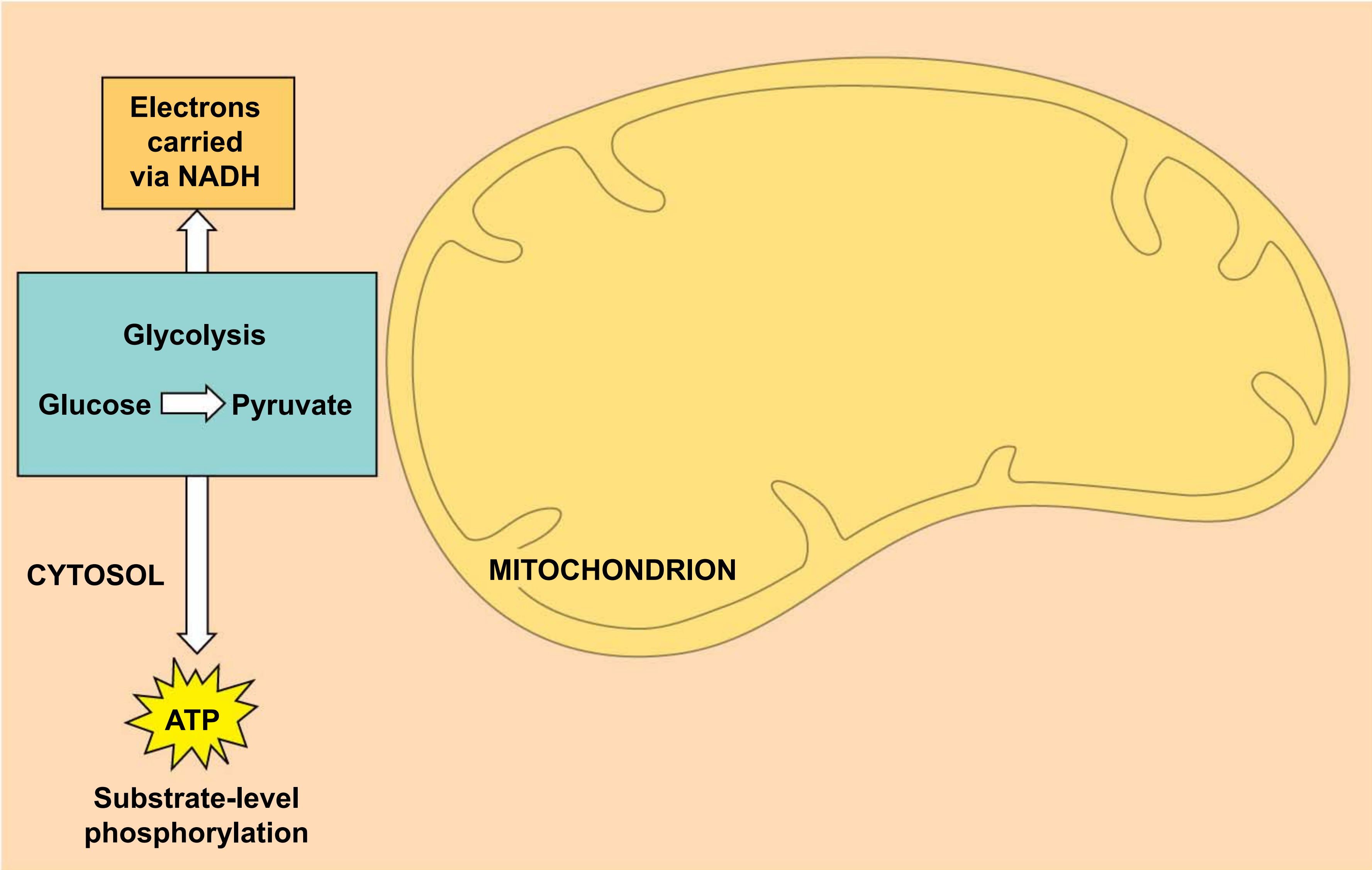
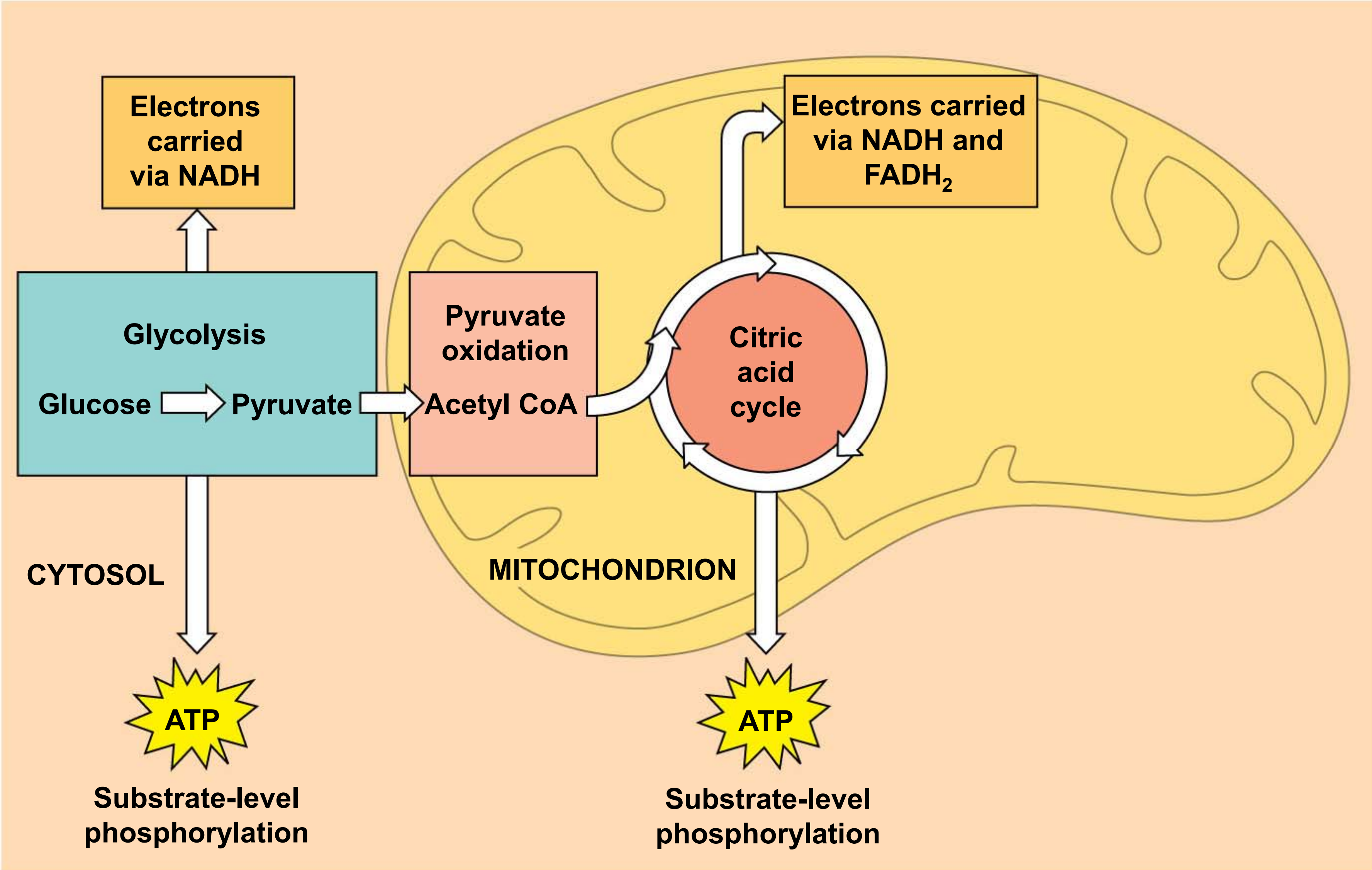
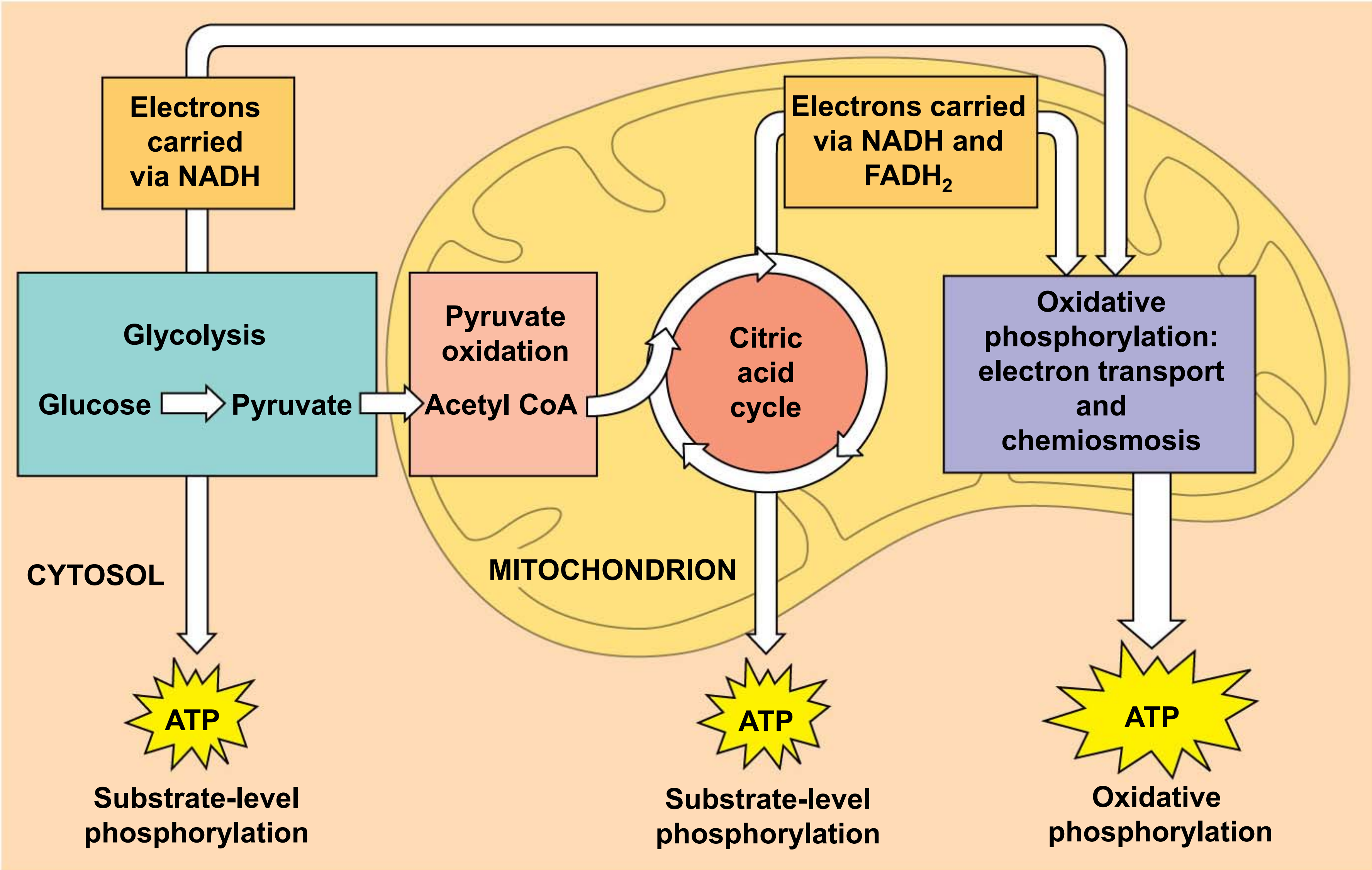

Electrons carried via NADH
Glycolysis
Glucose
Pyruvate
CYTOSOL
MITOCHONDRION
ATP
Substrate-level phosphorylation

Figure 9.6-2



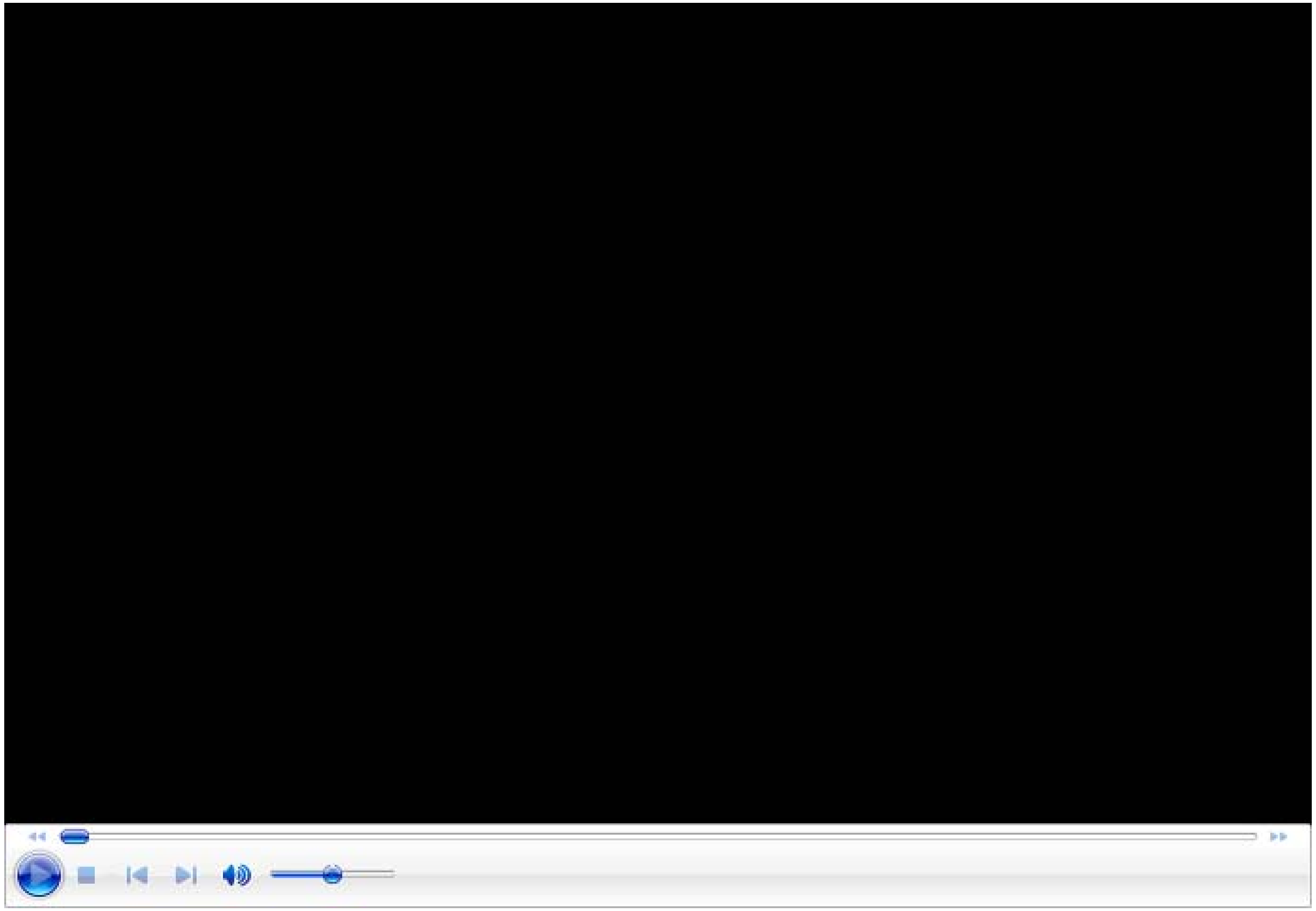
Electrons carried via NADH
Glycolysis
Glucose
Pyruvate
Pyruvate oxidation
Acetyl CoA
Citric acid cycle
Electrons carried via NADH and FADH$_2$
CYTOSOL
MITOCHONDRION
ATP
ATP
Substrate-level phosphorylation
Substrate-level phosphorylation

Figure 9.6-3



Electrons carried via NADH
Electrons carried via NADH and $FADH_2$
Glycolysis
Glucose
Pyruvate
Pyruvate oxidation
Acetyl CoA
Citric acid cycle
Oxidative phosphorylation: electron transport and chemiosmosis
CYTOSOL
MITOCHONDRION
ATP
ATP
ATP
Substrate-level phosphorylation
Substrate-level phosphorylation
Oxidative phosphorylation

- The process that generates most of the ATP is called **oxidative phosphorylation.**

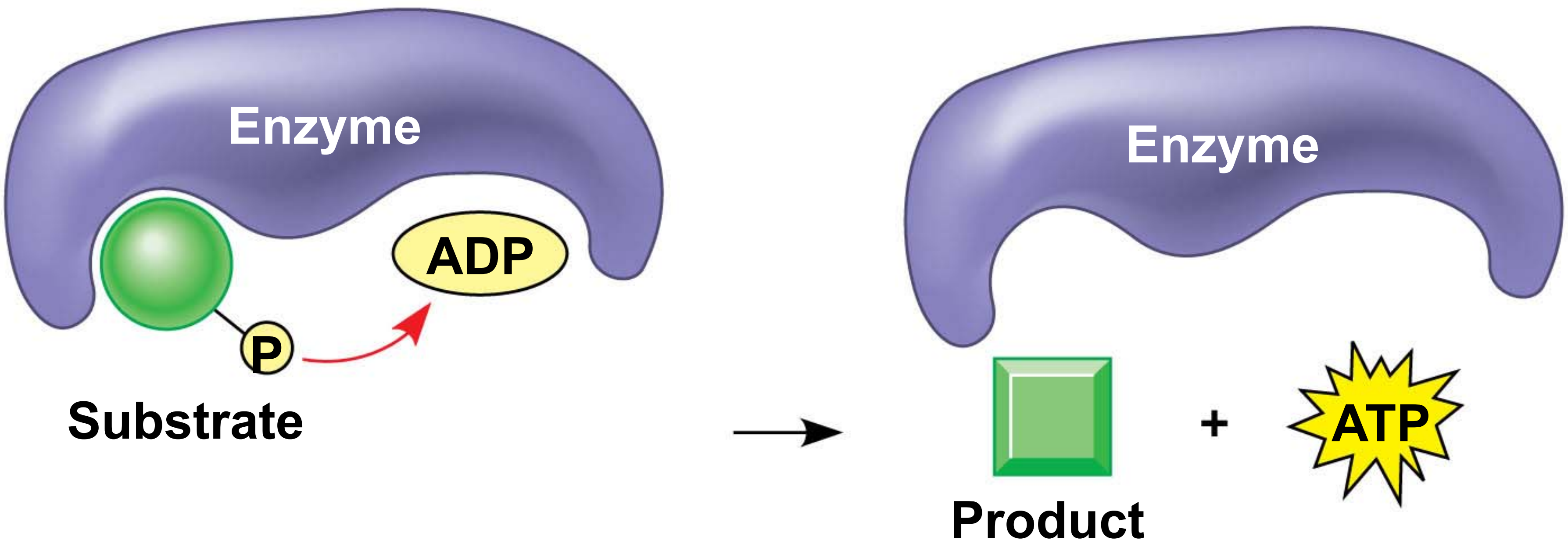


BioFlix: Cellular Respiration

Right-clickslide/ select”Play”

- The process that generates most of the ATP is called **oxidative phosphorylation.**
- Oxidative phosphorylation accounts for almost **90% of the ATP** generated by cellular respiration
- A smaller amount of ATP is formed in **glycolysis** and the **citric acid cycle** by **substrate-level phosphorylation**
- For **each molecule of glucose** degraded to CO_2 and water by respiration, **the cell makes up to 32 molecules of ATP**

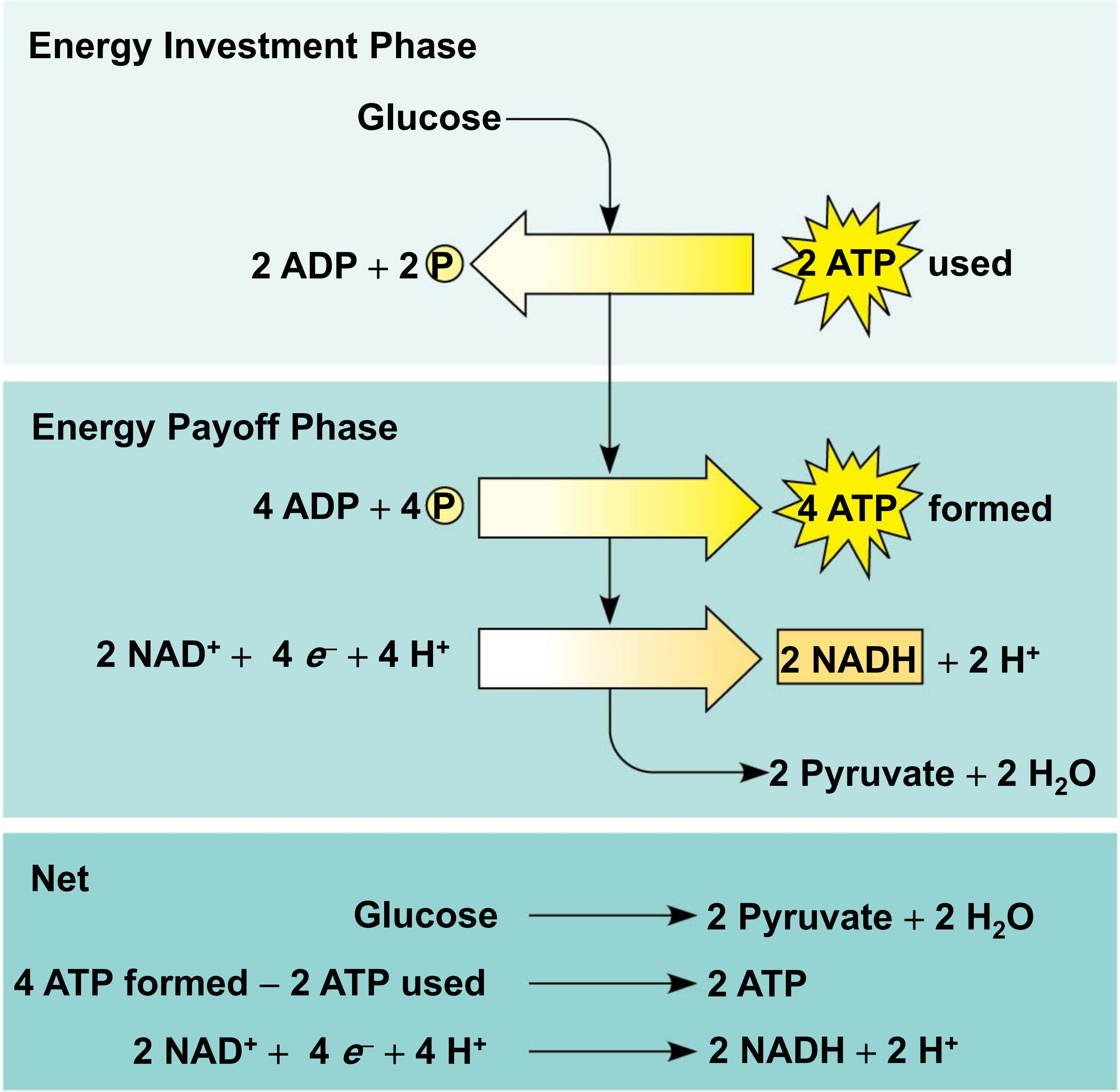
Figure 9.7



Concept 9.2: Glycolysis harvests chemical energy by oxidizing glucose to pyruvate

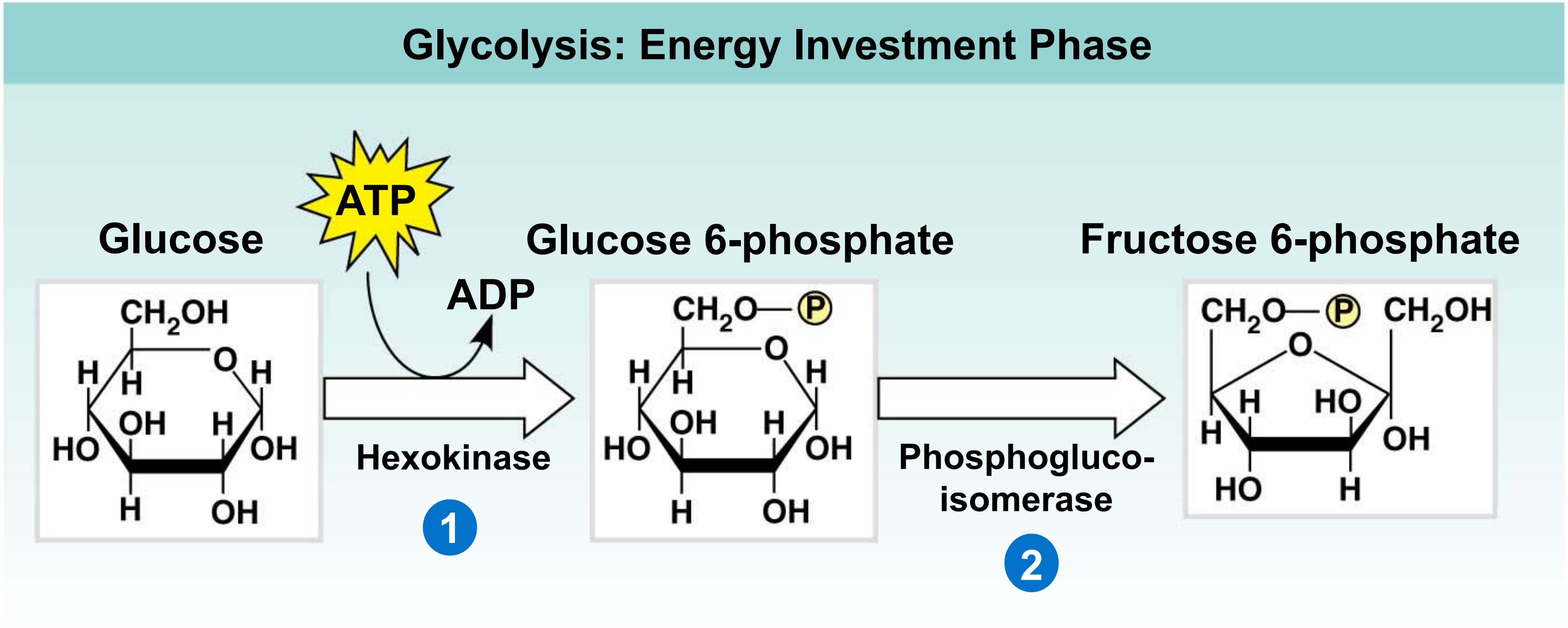
- Glycolysis ("splitting of sugar") breaks down glucose into two molecules of pyruvate
- Glycolysis occurs in the cytoplasm and has two major phases:
  - Energy investment phase
  - Energy payoff phase

Figure 9.8



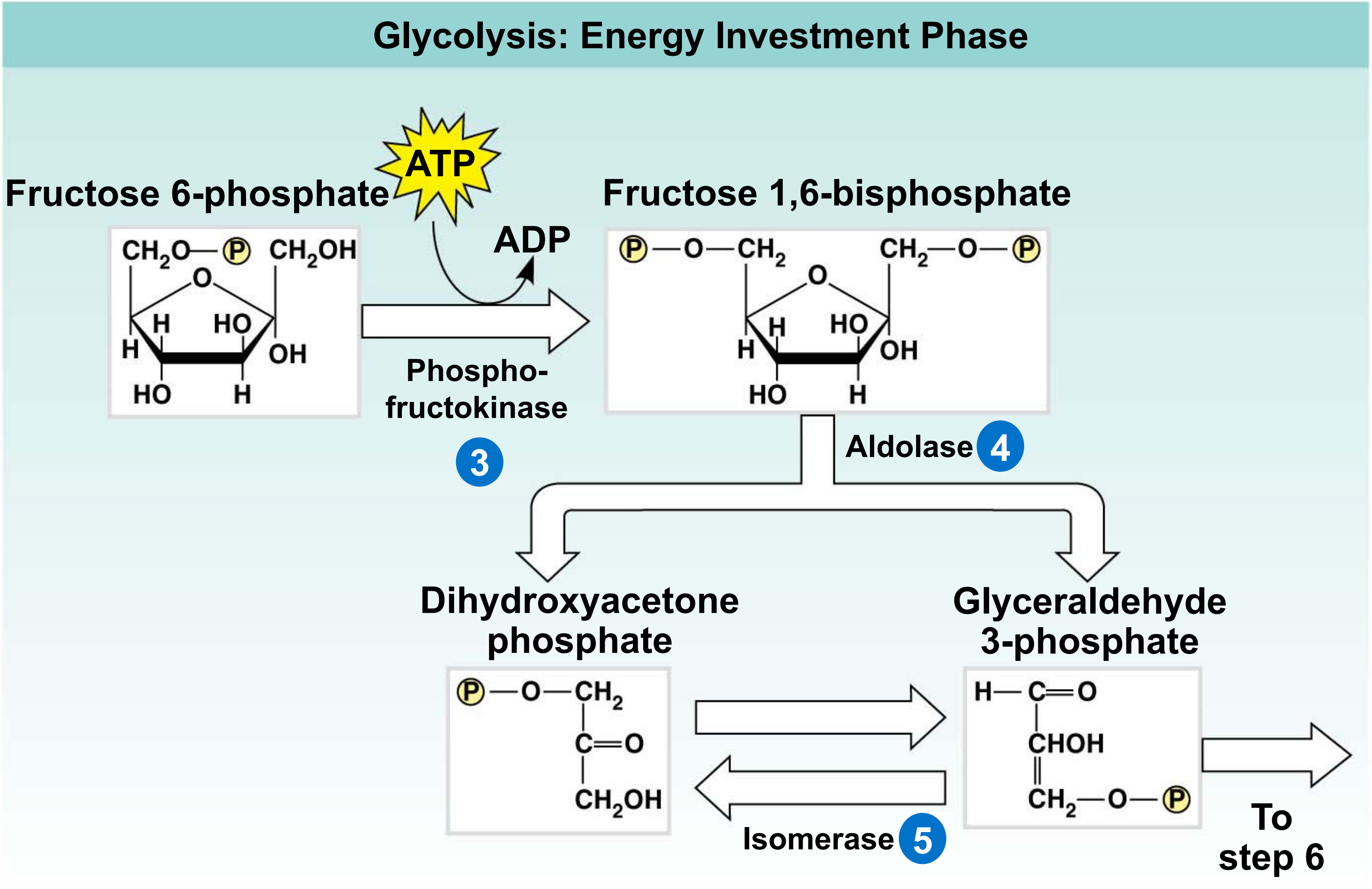
Energy Investment Phase
Glucose
2 ADP + 2 P
2 ATP used
Energy Payoff Phase
4 ADP + 4 P
4 ATP formed
2 NAD+ + 4 e- + 4 H+
2 NADH + 2 H+
2 Pyruvate + 2 H2O
Net
Glucose → 2 Pyruvate + 2 H2O
4 ATP formed – 2 ATP used → 2 ATP
2 NAD+ + 4 e- + 4 H+ → 2 NADH + 2 H+

Figure 9.9a



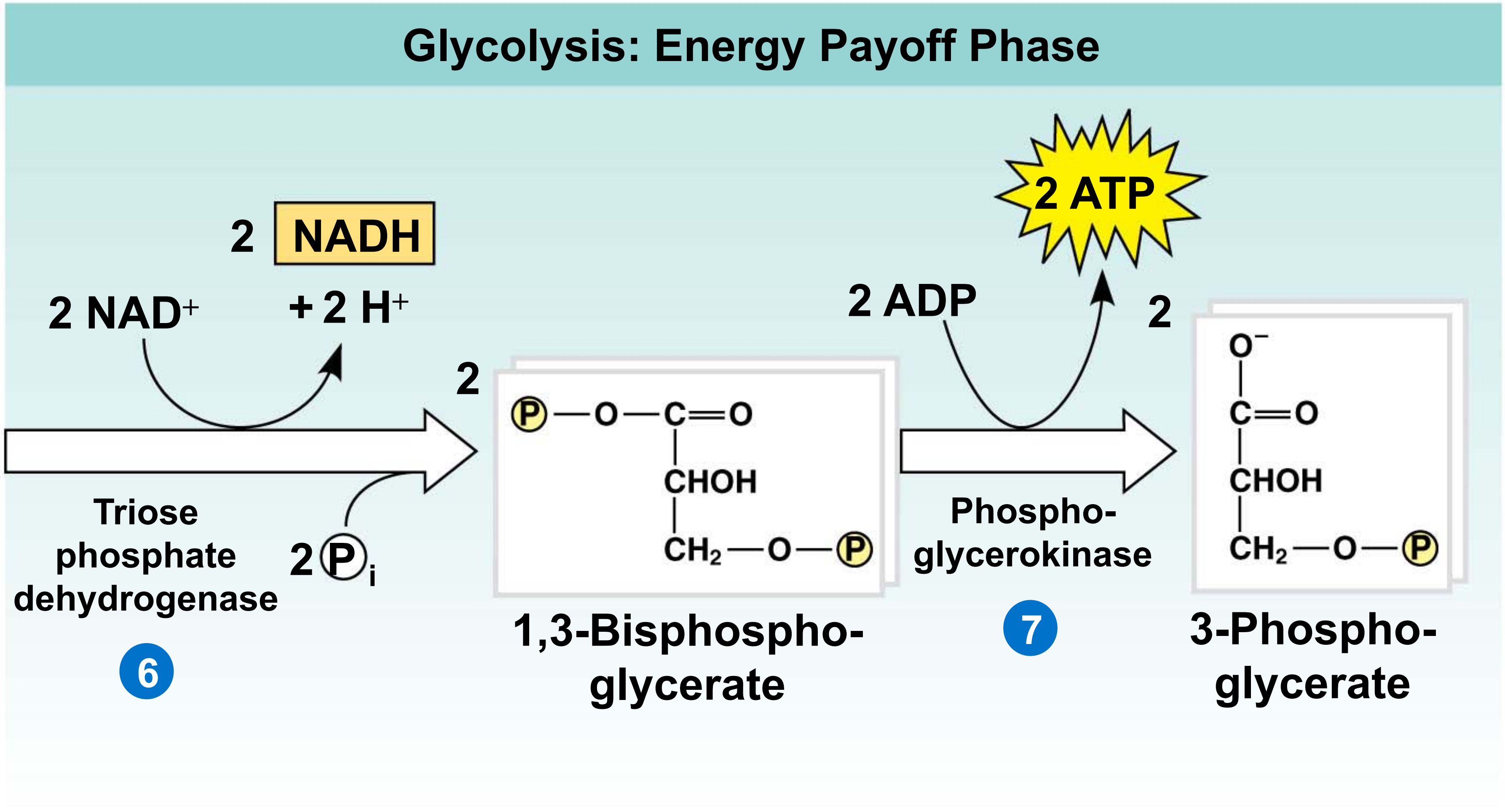
Glycolysis: Energy Investment Phase
ATP
Glucose
ADP
Glucose 6-phosphate
Fructose 6-phosphate
CH2OH
H
H
O
H
OH
H
HO
OH
H
OH
Hexokinase
1
CH2O—P
Phosphogluco-
isomerase
2
HO
H

Figure 9.9b



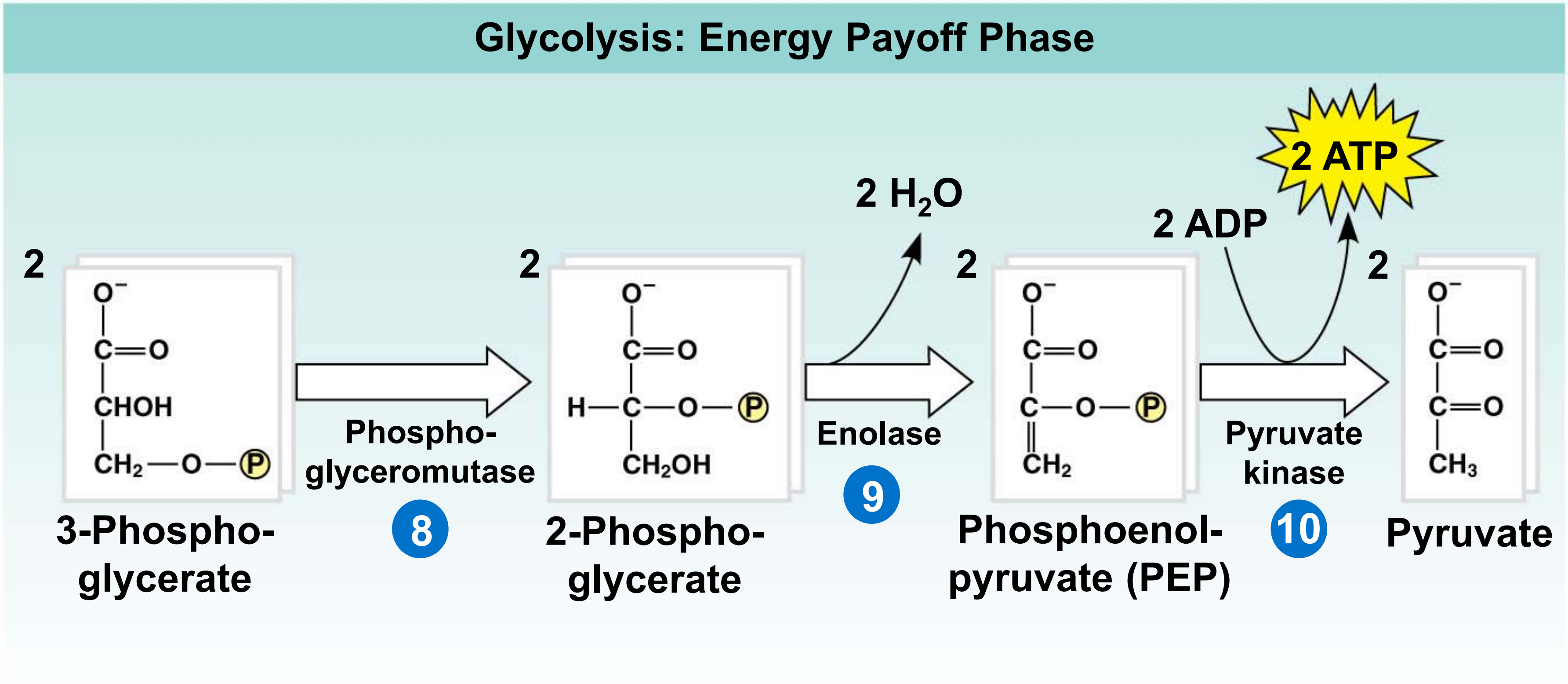
Glycolysis: Energy Investment Phase
Fructose 6-phosphate
ATP
ADP
Fructose 1,6-bisphosphate
CH2O—P
CH2OH
O
H
HO
H
OH
HO
H
P—O—CH2
CH2—O—P
Phospho-
fructokinase
3
Aldolase
4
Dihydroxyacetone
phosphate
Glyceraldehyde
3-phosphate
P—O—CH2
C=O
CH2OH
H—C=O
CHOH
CH2—O—P
Isomerase
5
To
step 6

Figure 9.9c



Glycolysis: Energy Payoff Phase
2 NADH
2 NAD+
+ 2 H+
2
Triose
phosphate
dehydrogenase
6
2 P i
P—O—C=O
CHOH
CH2—O—P
1,3-Bisphospho-
glycerate
2 ADP
2 ATP
2
Phospho-
glycerokinase
7
O−
C=O
CHOH
CH2—O—P
3-Phospho-
glycerate

Figure 9.9d



Glycolysis: Energy Payoff Phase
2
O⁻
C═O
CHOH
CH₂—O—P
3-Phospho-
glycerate
Phospho-
glyceromutase
8
2
O⁻
C═O
H—C—O—P
CH₂OH
2-Phospho-
glycerate
2 H₂O
Enolase
9
2
O⁻
C═O
C—O—P
CH₂
Phosphoenol-
pyruvate (PEP)
2 ADP
2 ATP
Pyruvate
kinase
10
2
O⁻
C═O
C═O
CH₃
Pyruvate

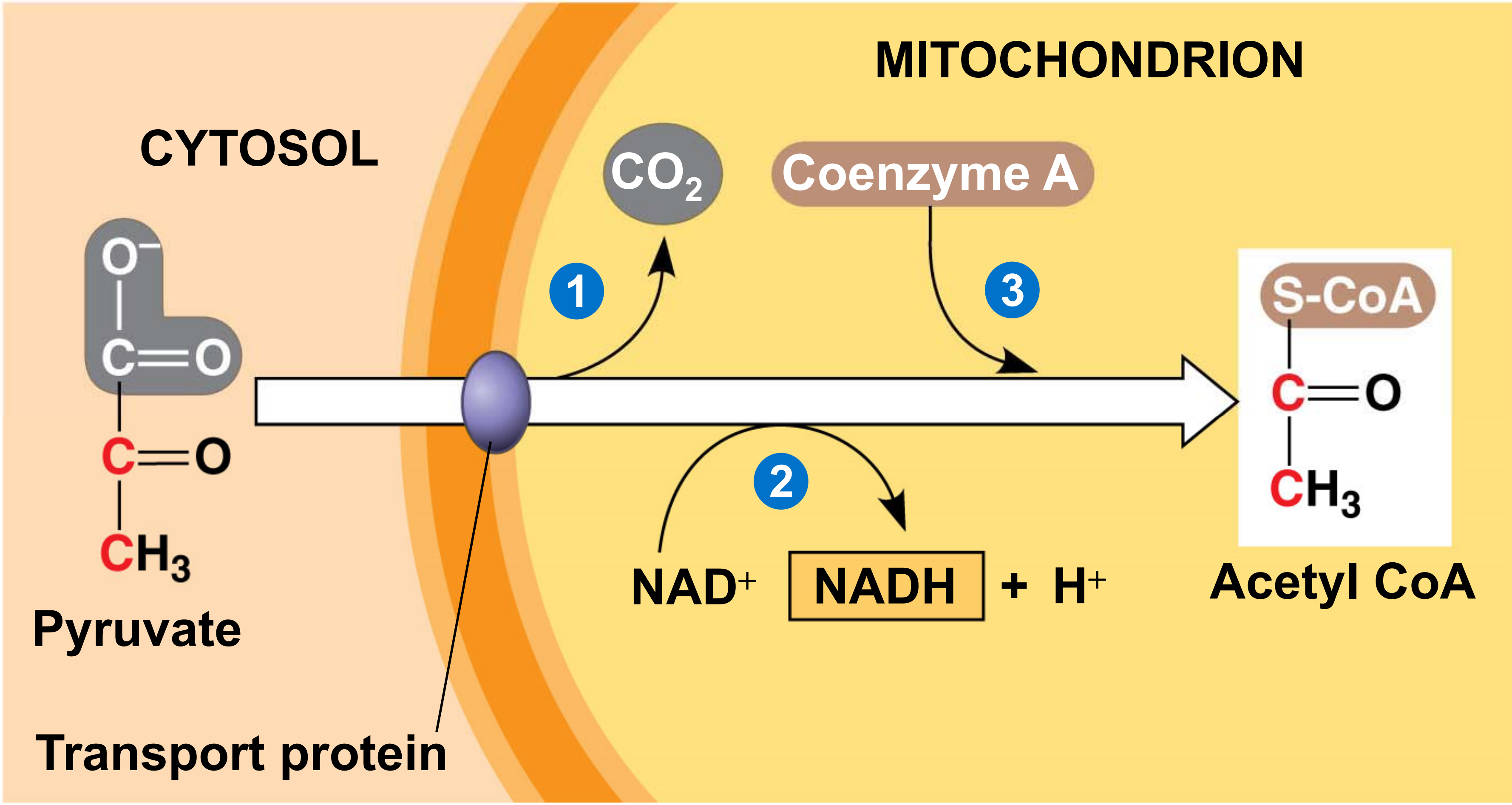
Concept 9.3: The citric acid cycle completes the energy-yielding oxidation of organic molecules

- In the presence of O_2, pyruvate enters the mitochondrion

Oxidation of Pyruvate to Acetyl CoA

- Before the citric acid cycle can begin, **pyruvate must be converted to acetyl Coenzyme A (acetyl CoA)**, which **links glycolysis to the citric acid cycle**
- This step is carried out by a **multienzyme complex** that catalyses **three reactions**

Figure 9.10

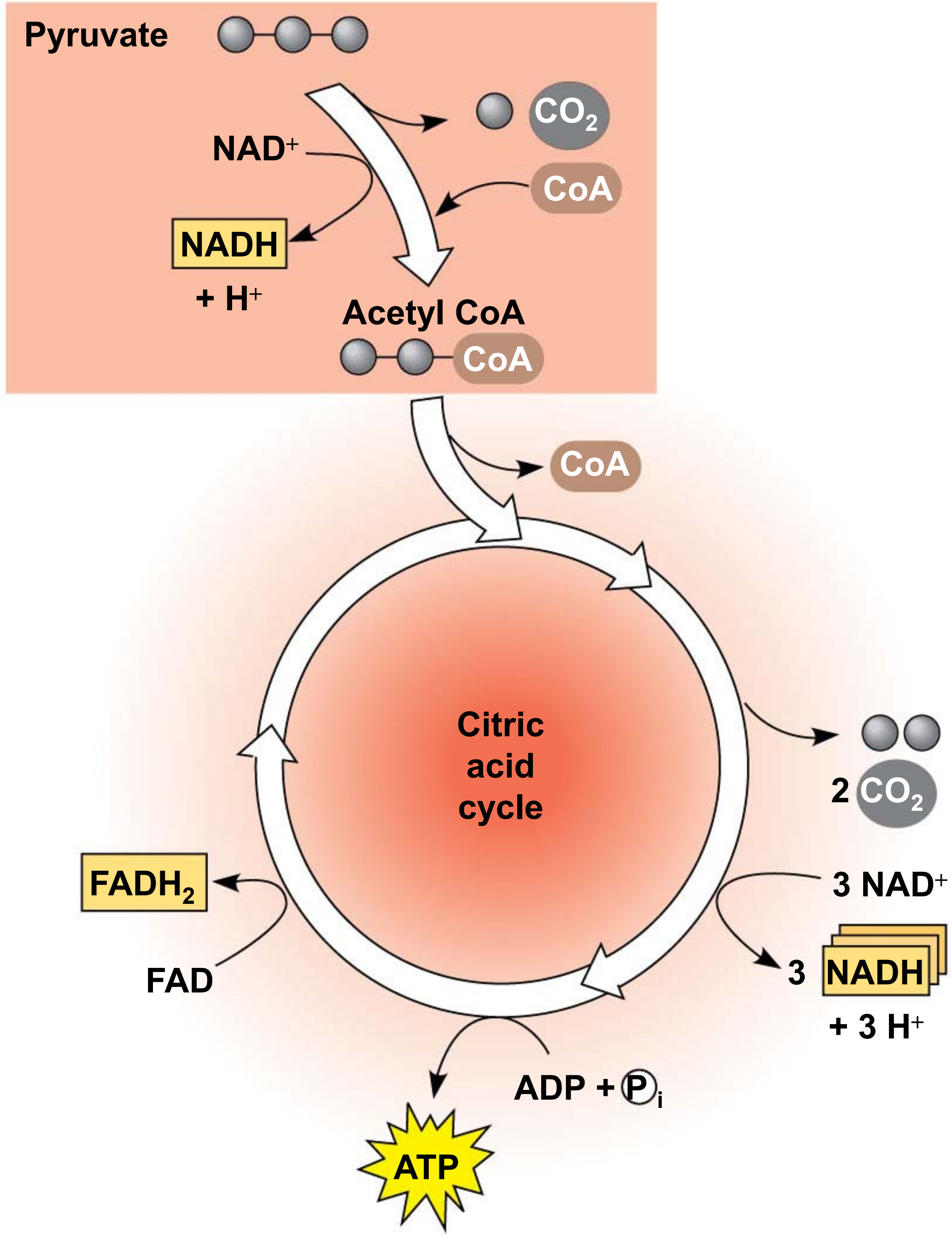


MITOCHONDRION
CYTOSOL
CO2
Coenzyme A
1
3
2
O⁻
C═O
C═O
CH3
Pyruvate
S-CoA
C═O
CH3
NAD+
NADH
+ H+
Acetyl CoA
Transport protein

The Citric Acid Cycle

- The citric acid cycle, also called the Krebs cycle, takes place within the mitochondrial matrix
- The citric acid cycle has eight steps, each catalyzed by a specific enzyme
- The cycle oxidizes organic fuel derived from pyruvate, generating 1 ATP, 3 NADH, and 1 $FADH_2$ per turn (*Each glucose makes 2 turns*)

Figure 9.11



Pyruvate
NAD+
CO_2
CoA
NADH
+ H+
Acetyl CoA
CoA
CoA
Citric
acid
cycle
2 CO_2
3 NAD+
3 NADH
+ 3 H+
$FADH_2$
FAD
ADP + Ⓟi
ATP

- In the first step, acetyl group of acetyl CoA joins the cycle by **combining with oxaloacetate**, forming **citrate**
- The **next seven steps** ***decompose the citrate back to oxaloacetate***, making the process a cycle
- The **NADH and $FADH_2$** produced by the cycle relay electrons extracted from food **to the electron transport chain**

Figure 9.12-1

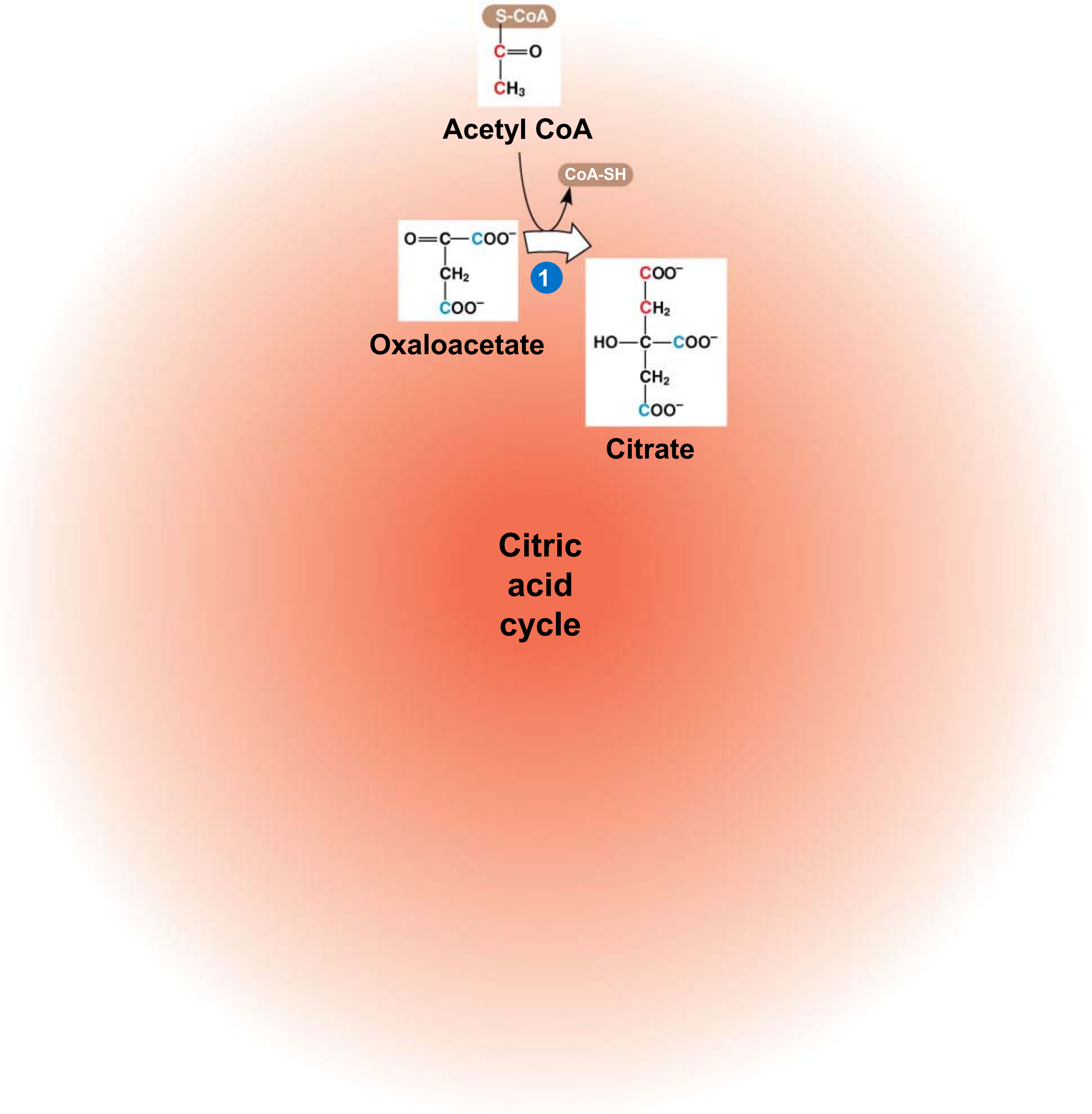

S-CoA
C═O
CH3
Acetyl CoA
CoA-SH
O═C—COO⁻
CH2
COO⁻
Oxaloacetate
1
COO⁻
CH2
HO—C—COO⁻
CH2
COO⁻
Citrate
Citric
acid
cycle

Figure 9.12-2

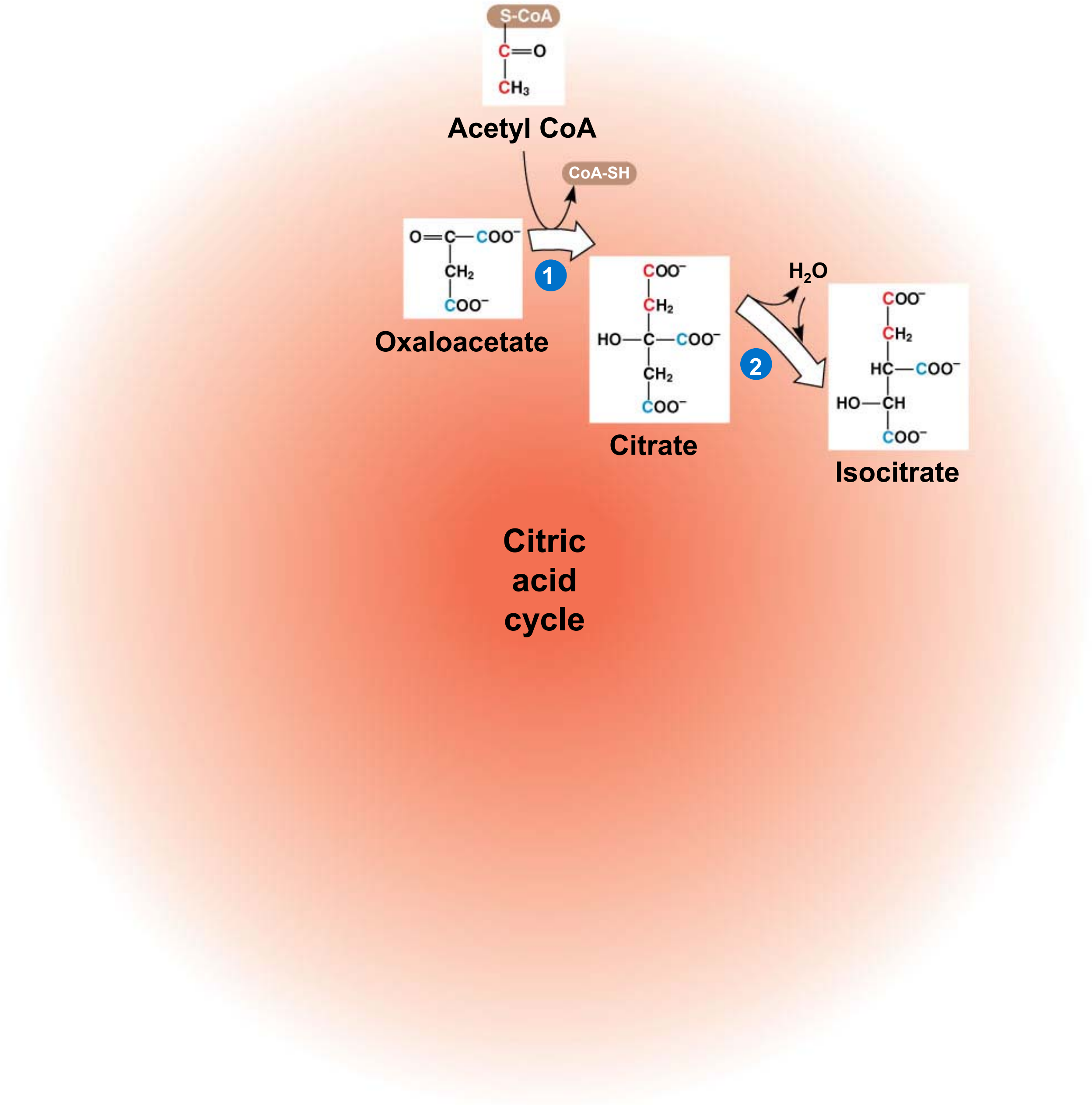

S-CoA
C=O
CH3
Acetyl CoA
CoA-SH
O=C—COO⁻
CH2
COO⁻
Oxaloacetate
1
COO⁻
CH2
HO—C—COO⁻
CH2
COO⁻
Citrate
H2O
2
COO⁻
CH2
HC—COO⁻
HO—CH
COO⁻
Isocitrate
Citric acid cycle

Figure 9.12-3

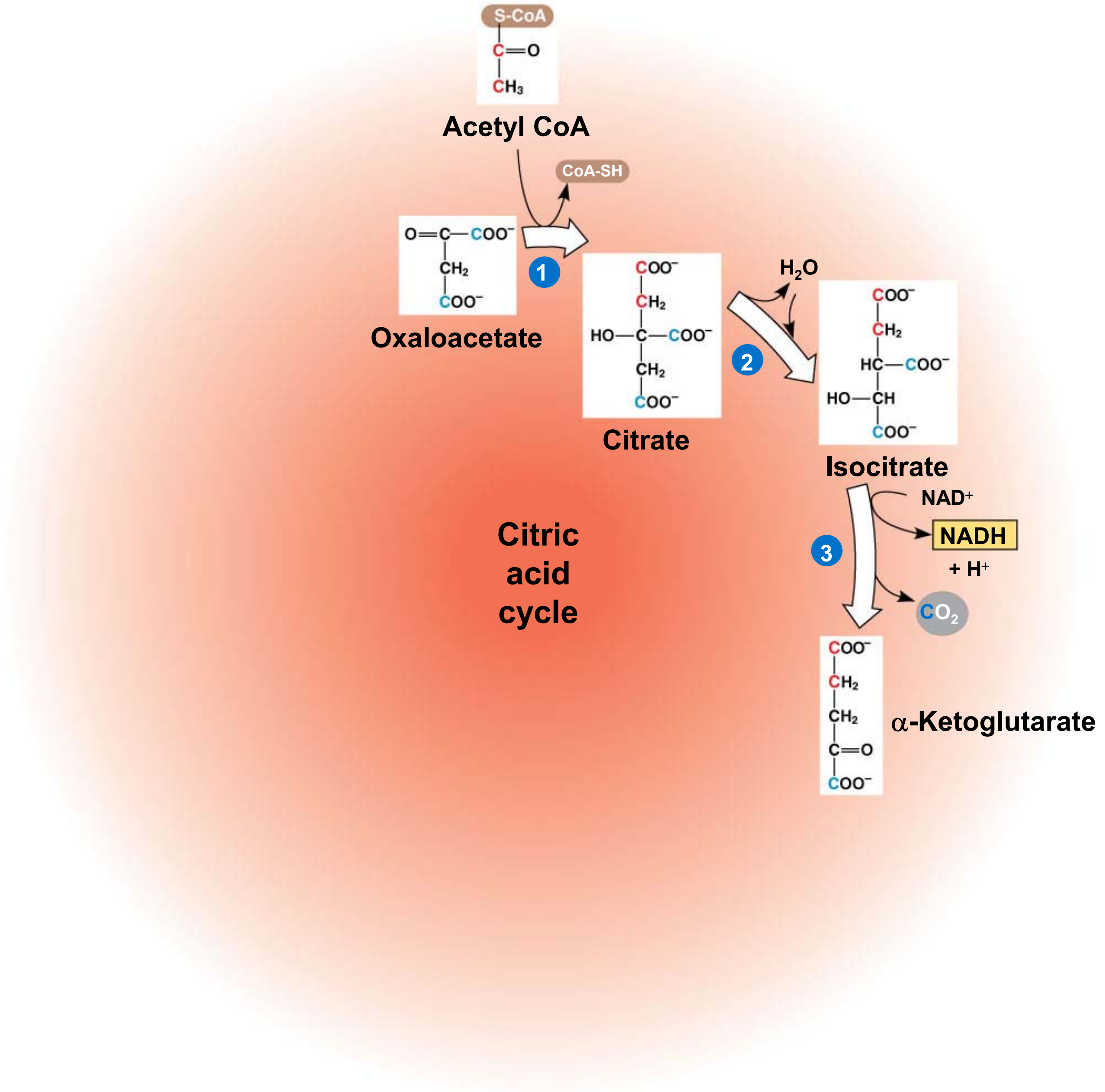
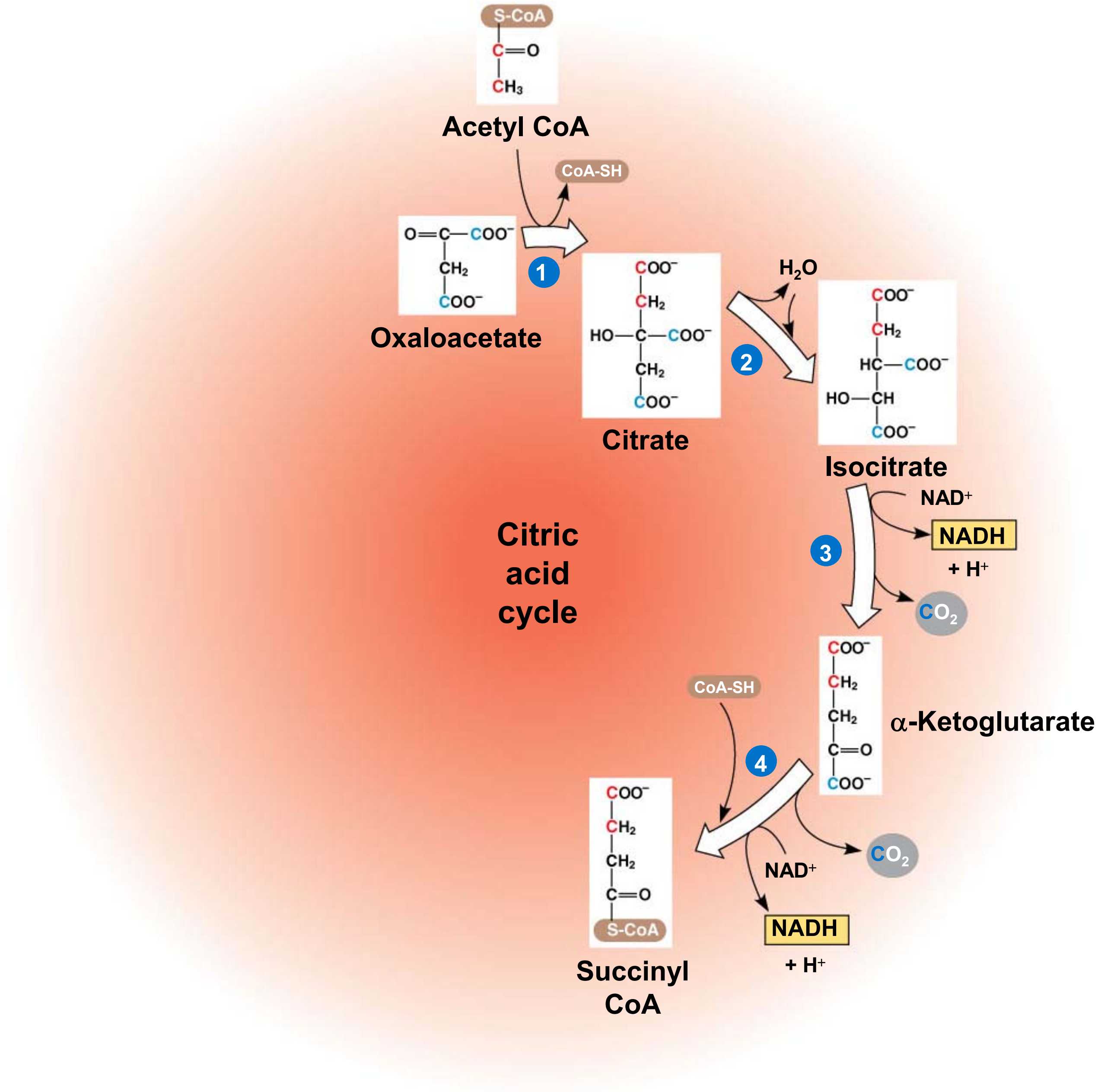
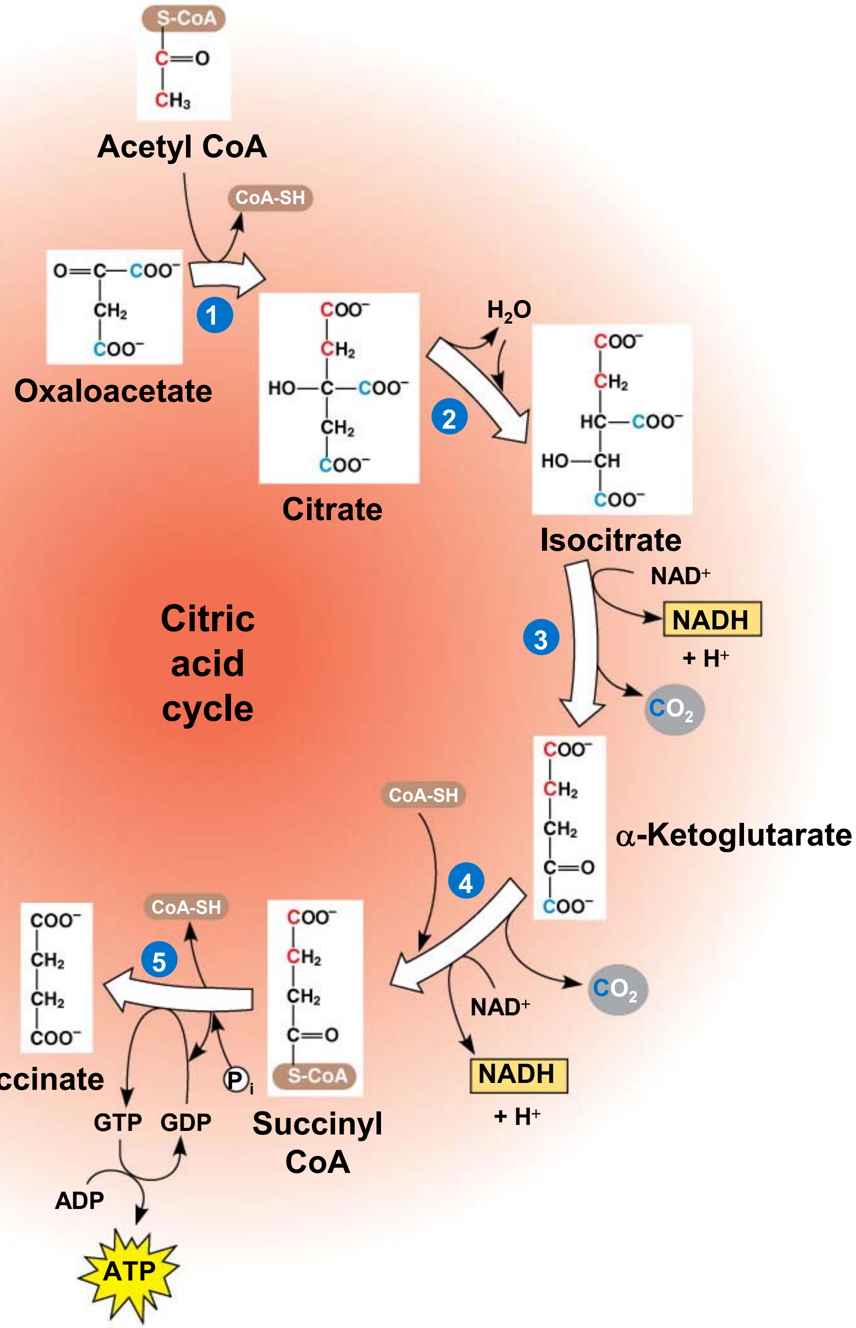

S-CoA
C=O
CH3
Acetyl CoA
CoA-SH
Oxaloacetate
1
Citrate
H_2O
2
Isocitrate
NAD^+
NADH
$+ H^+$
3
CO_2
α-Ketoglutarate
Citric acid cycle

Figure 9.12-4



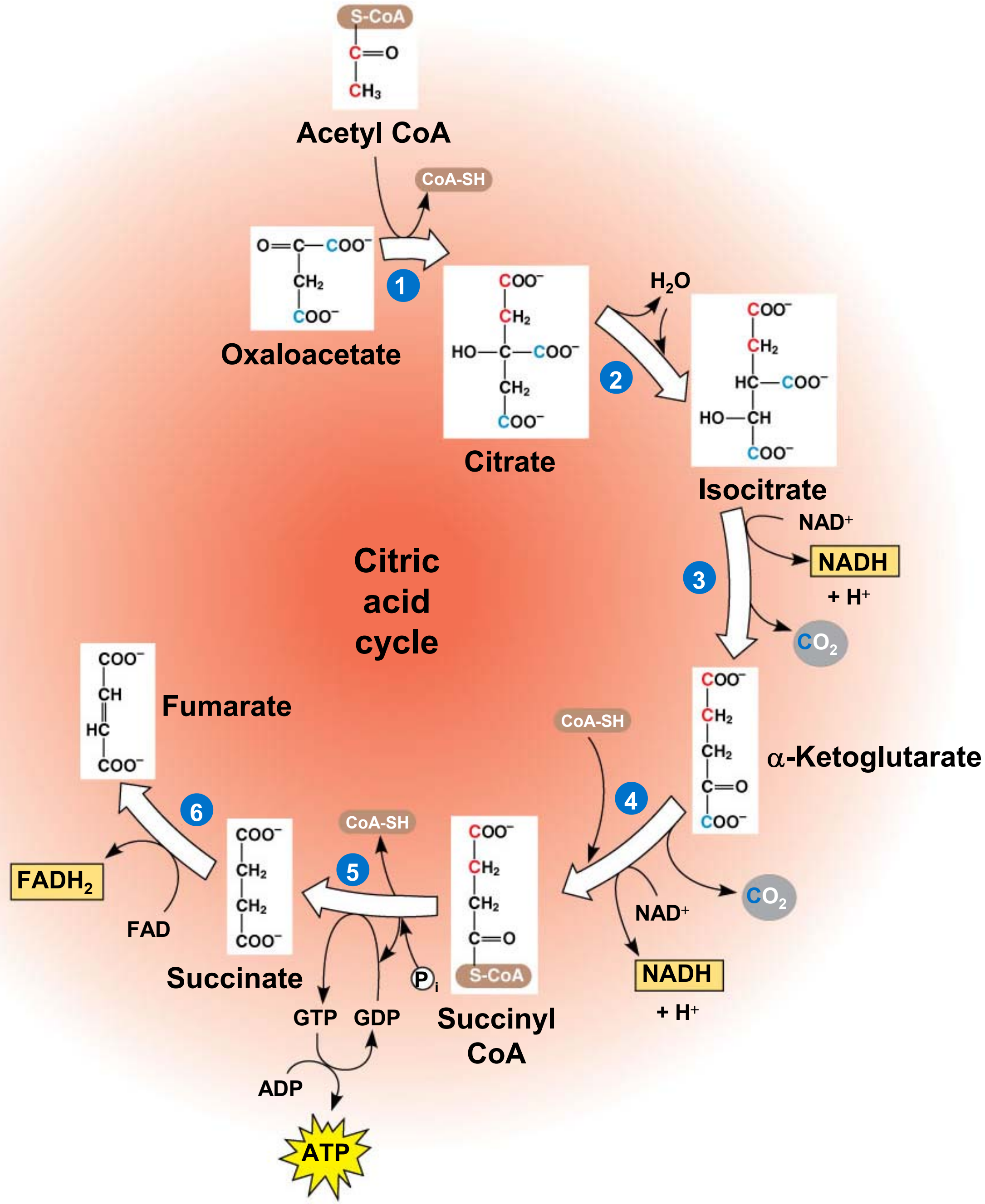
S-CoA
C=O
CH3
Acetyl CoA
CoA-SH
O=C—COO⁻
CH2
COO⁻
Oxaloacetate
1
COO⁻
CH2
HO—C—COO⁻
CH2
COO⁻
Citrate
H2O
2
COO⁻
CH2
HC—COO⁻
HO—CH
COO⁻
Isocitrate
NAD+
NADH
+ H+
3
CO2
Citric
acid
cycle
COO⁻
CH2
CH2
C=O
COO⁻
α-Ketoglutarate
CoA-SH
4
CO2
NAD+
NADH
+ H+
COO⁻
CH2
CH2
C=O
S-CoA
Succinyl
CoA

Figure 9.12-5



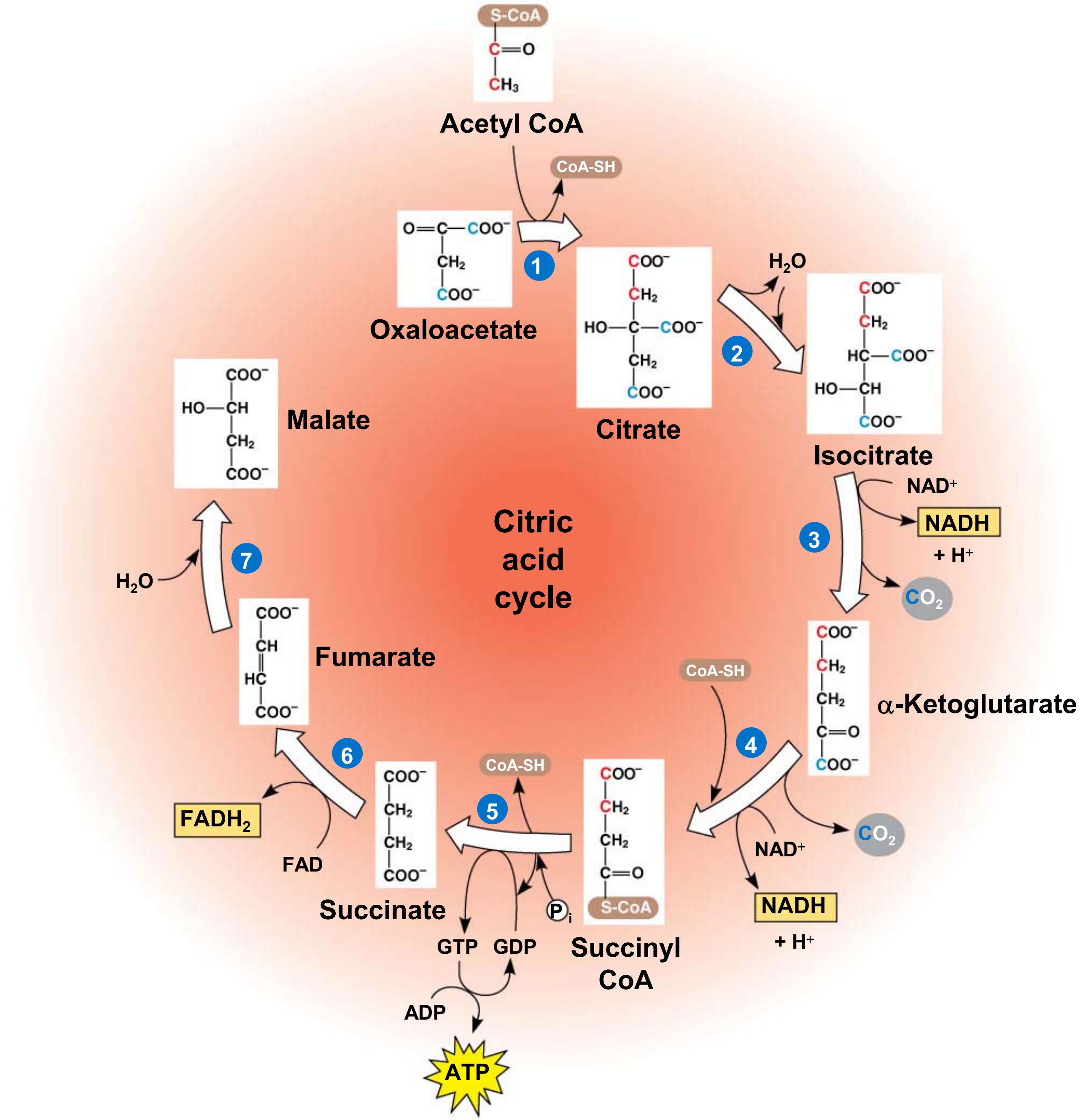
S-CoA
C=O
CH3
Acetyl CoA
CoA-SH
O=C—COO⁻
CH2
COO⁻
Oxaloacetate
1
COO⁻
CH2
HO—C—COO⁻
CH2
COO⁻
Citrate
H2O
2
COO⁻
CH2
HC—COO⁻
HO—CH
COO⁻
Isocitrate
NAD+
NADH
+ H+
3
CO2
Citric acid cycle
COO⁻
CH2
CH2
C=O
COO⁻
α-Ketoglutarate
CoA-SH
4
CO2
NAD+
NADH
+ H+
COO⁻
CH2
CH2
C=O
S-CoA
Succinyl CoA
CoA-SH
5
Pi
COO⁻
CH2
CH2
COO⁻
Succinate
GTP
GDP
ADP
ATP

Figure 9.12-6



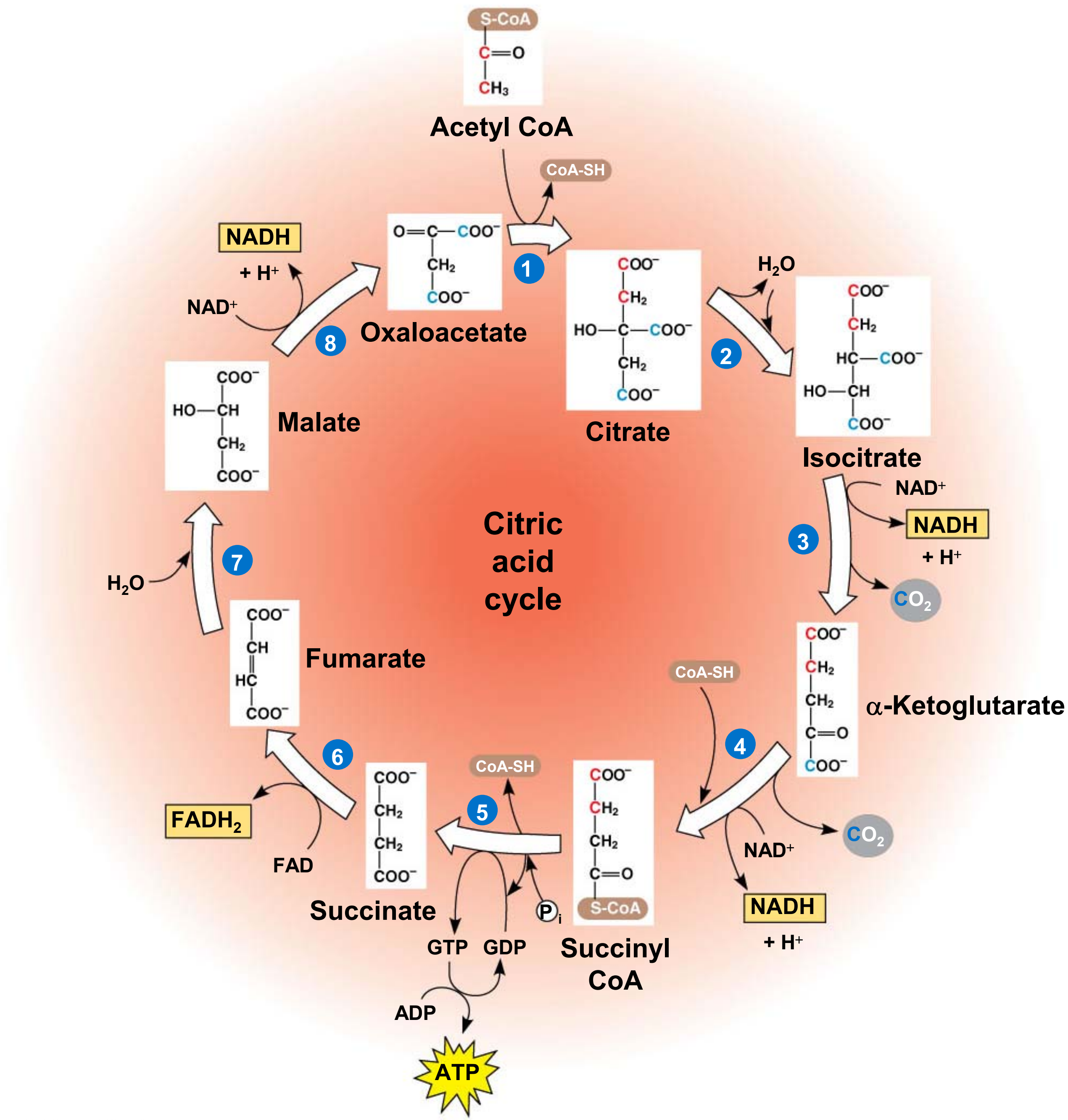
Acetyl CoA
S-CoA
CoA-SH
Oxaloacetate
Citrate
H_2O
Isocitrate
NAD^+
NADH
$+ H^+$
CO_2
α-Ketoglutarate
CoA-SH
NAD^+
NADH
$+ H^+$
CO_2
Succinyl CoA
CoA-SH
P_i
GTP
GDP
ADP
ATP
Succinate
FAD
$FADH_2$
Fumarate
Citric acid cycle
1
2
3
4
5
6

Figure 9.12-7



Acetyl CoA
S-CoA
CoA-SH
Oxaloacetate
1
Citrate
H_2O
2
Isocitrate
NAD^+
NADH
+ H^+
3
CO_2
α-Ketoglutarate
CoA-SH
4
NAD^+
NADH
+ H^+
CO_2
Succinyl CoA
CoA-SH
5
P_i
GTP
GDP
ADP
ATP
Succinate
6
FAD
$FADH_2$
Fumarate
H_2O
7
Malate
Citric acid cycle

Figure 9.12-8



S-CoA
C=O
CH3
Acetyl CoA
CoA-SH
1
Oxaloacetate
Citrate
H2O
2
Isocitrate
NAD+
NADH
+ H+
3
CO2
α-Ketoglutarate
CoA-SH
4
CO2
NAD+
NADH
+ H+
Succinyl CoA
S-CoA
Pi
CoA-SH
5
GTP
GDP
ADP
ATP
Succinate
6
FADH2
FAD
Fumarate
7
H2O
Malate
8
NADH
+ H+
NAD+
Citric acid cycle

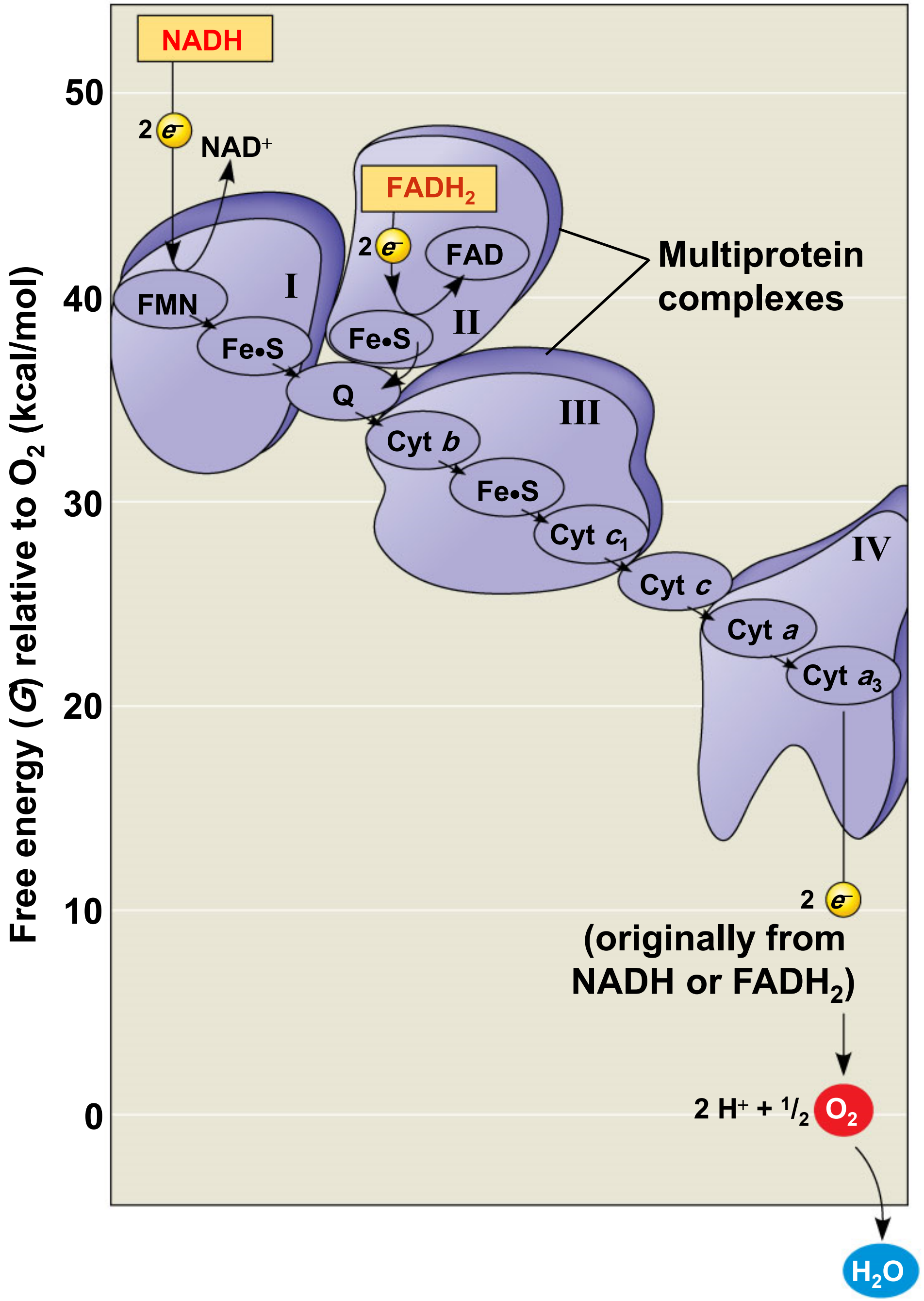
Concept 9.4: During oxidative phosphorylation, chemiosmosis couples electron transport to ATP synthesis

- Following glycolysis and the citric acid cycle, NADH and $FADH_2$ account for most of the energy extracted from food
- These two electron carriers donate electrons to the electron transport chain, which powers ATP synthesis via oxidative phosphorylation

The Pathway of Electron Transport

- The electron transport chain is in the cristae of the mitochondrion
- Most of the chain's components are proteins, which exist in multiprotein complexes
- The electron transport chain generates no ATP
- Electrons drop in free energy as they go down the chain and are finally passed to O_2, forming H_2O

Figure 9.13



NADH
50
2 e⁻
NAD+
FADH2
2 e⁻
FAD
Multiprotein complexes
40
FMN
I
Fe•S
Fe•S
II
Q
III
Cyt b
30
Fe•S
Cyt c1
IV
Cyt c
Cyt a
Cyt a3
20
Free energy (G) relative to O2 (kcal/mol)
10
2 e⁻
(originally from NADH or FADH2)
0
2 H+ + 1/2 O2
H2O

- Electrons are transferred **from NADH or $FADH_2$ to the electron transport chain**
- Electrons are passed through a **number of proteins including cytochromes** (each with an iron atom) **to O_2**
- The **electron transport chain generates no ATP directly**
- It breaks the large free-energy drop from food to O_2 into smaller steps that release energy in manageable amounts

Chemiosmosis: The Energy-Coupling Mechanism

- Electron transfer in the electron transport chain causes proteins to pump H^+ from the mitochondrial matrix to the intermembrane space
- H^+ then moves back across the membrane, passing through channels in **ATP synthase**
- ATP synthase uses the exergonic flow of H^+ to drive phosphorylation of ATP
- This is an example of **chemiosmosis**, the use of energy in a H^+ gradient to drive cellular work

Figure 9.14

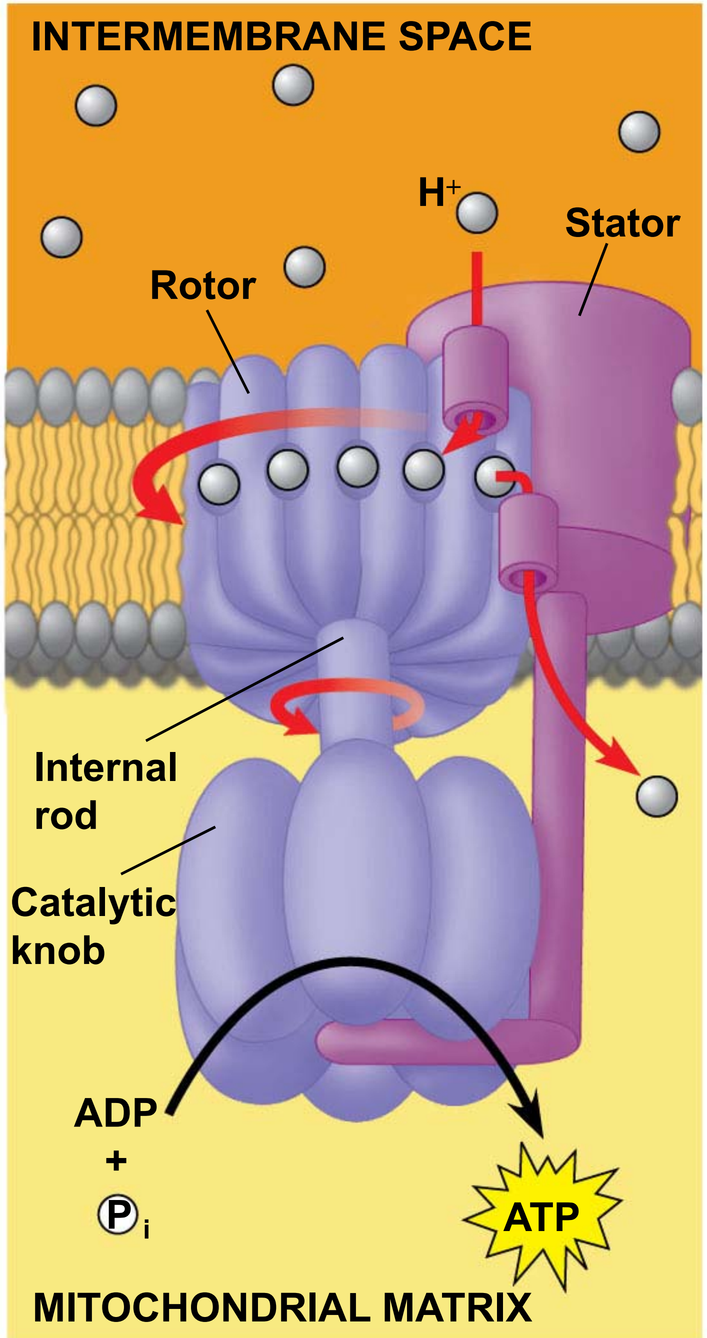
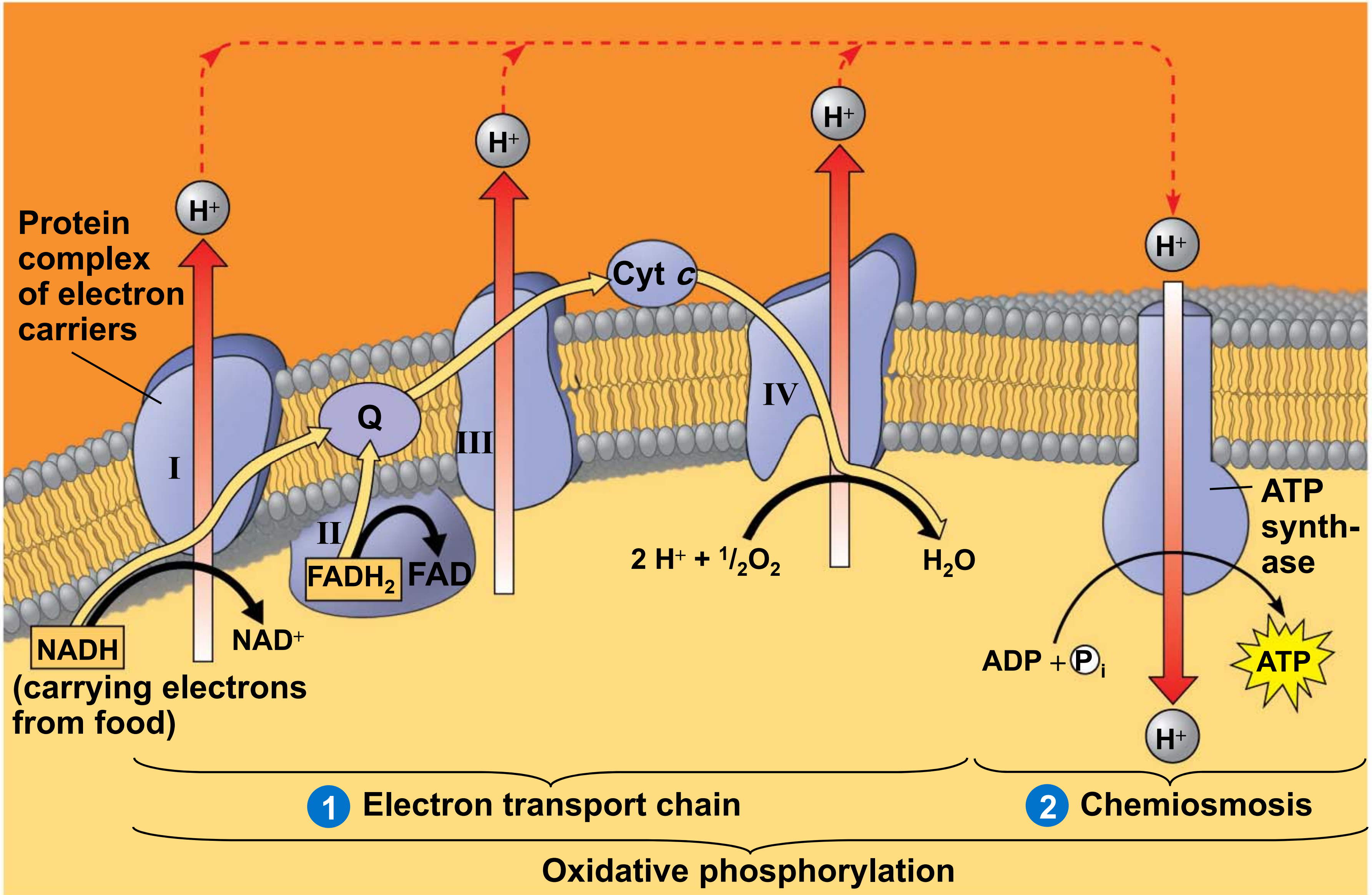

INTERMEMBRANE SPACE
H+
Stator
Rotor
Internal rod
Catalytic knob
ADP
+
P i
ATP
MITOCHONDRIAL MATRIX

Figure 9.15



H+
H+
H+
H+
Protein complex of electron carriers
Cyt c
Q
I
II
III
IV
FADH2
FAD
NADH
NAD+
(carrying electrons from food)
2 H+ + 1/2O2
H2O
ATP synthase
ADP + P i
ATP
H+
1 Electron transport chain
2 Chemiosmosis
Oxidative phosphorylation

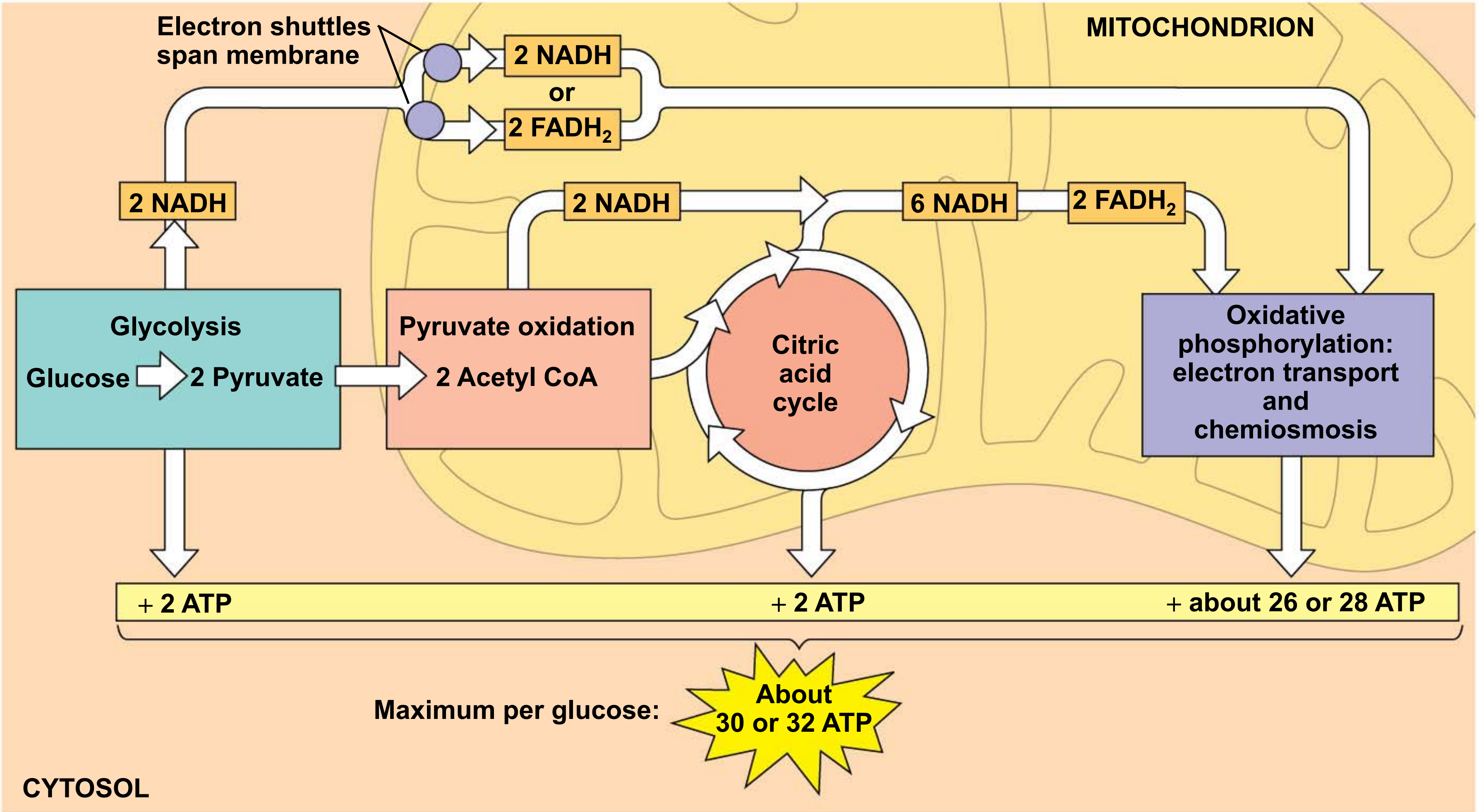
- The **energy stored in a H^+ gradient** across a membrane **couples the redox reactions of the electron transport chain to ATP synthesis**
- The H^+ gradient is referred to as a **proton-motive force**, emphasizing its capacity to do work

An Accounting of ATP Production by Cellular Respiration

- During cellular respiration, most energy flows in this sequence:

  glucose → NADH → electron transport chain → proton-motive force → ATP
- About **34%** of the energy in a glucose molecule is **transferred to ATP** during cellular respiration, making about 32 ATP
- There are several reasons why the **number of ATP is not known exactly**

Figure 9.16



Electron shuttles span membrane
MITOCHONDRION
2 NADH
or
2 FADH$_2$
2 NADH
2 NADH
6 NADH
2 FADH$_2$
Glycolysis
Glucose
2 Pyruvate
Pyruvate oxidation
2 Acetyl CoA
Citric acid cycle
Oxidative phosphorylation: electron transport and chemiosmosis
+ 2 ATP
+ 2 ATP
+ about 26 or 28 ATP
Maximum per glucose:
About 30 or 32 ATP
CYTOSOL

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

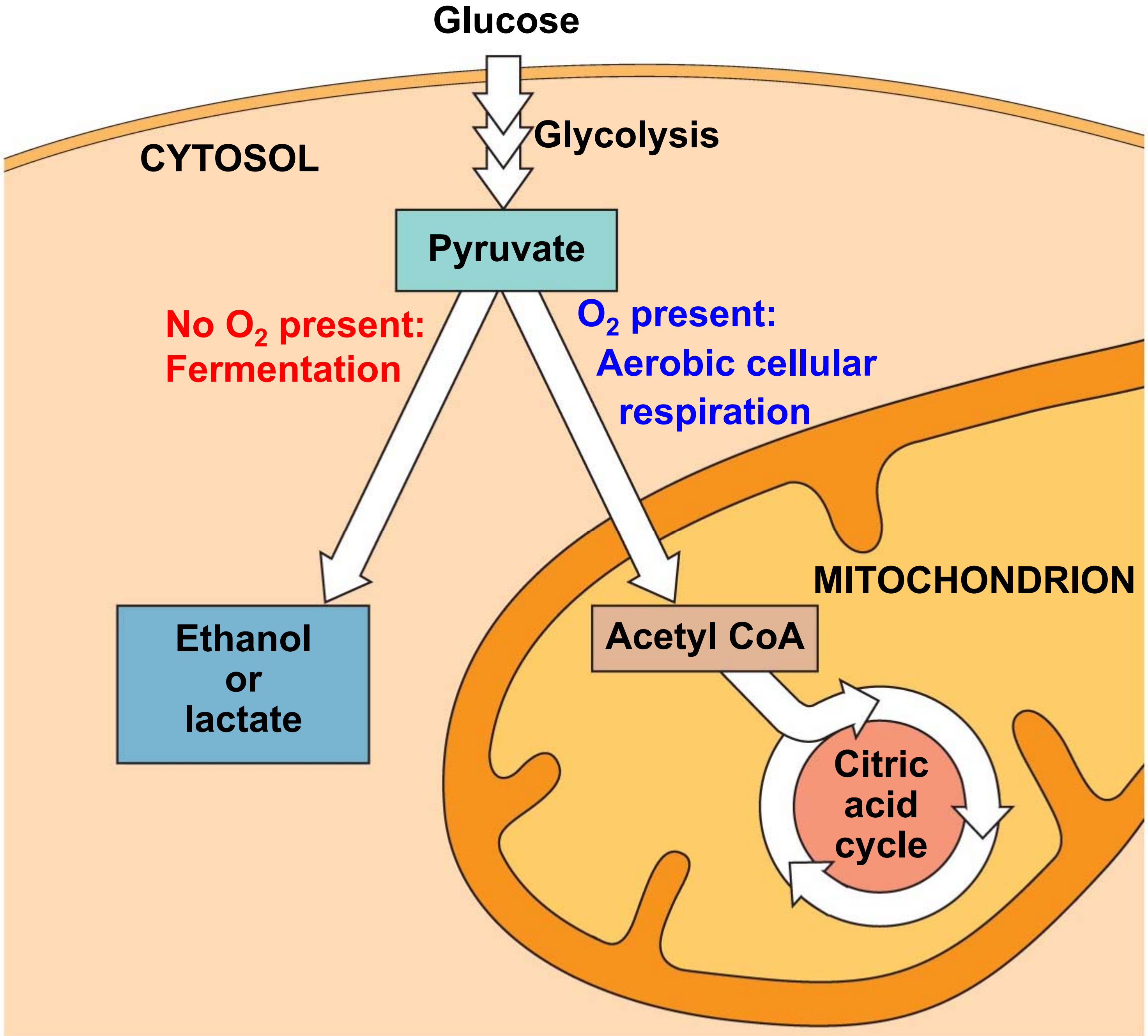
- Most cellular respiration requires O_2 to produce ATP
- Glycolysis can produce ATP with or without O_2 (in aerobic or anaerobic conditions)
- In the absence of O_2, glycolysis couples with fermentation or anaerobic respiration to produce ATP

- **Anaerobic respiration** uses an electron transport chain with a **final electron acceptor other than O_2**, for **example sulfate**
- Fermentation uses **substrate-level phosphorylation** instead of an electron transport chain to generate ATP

Types of Fermentation

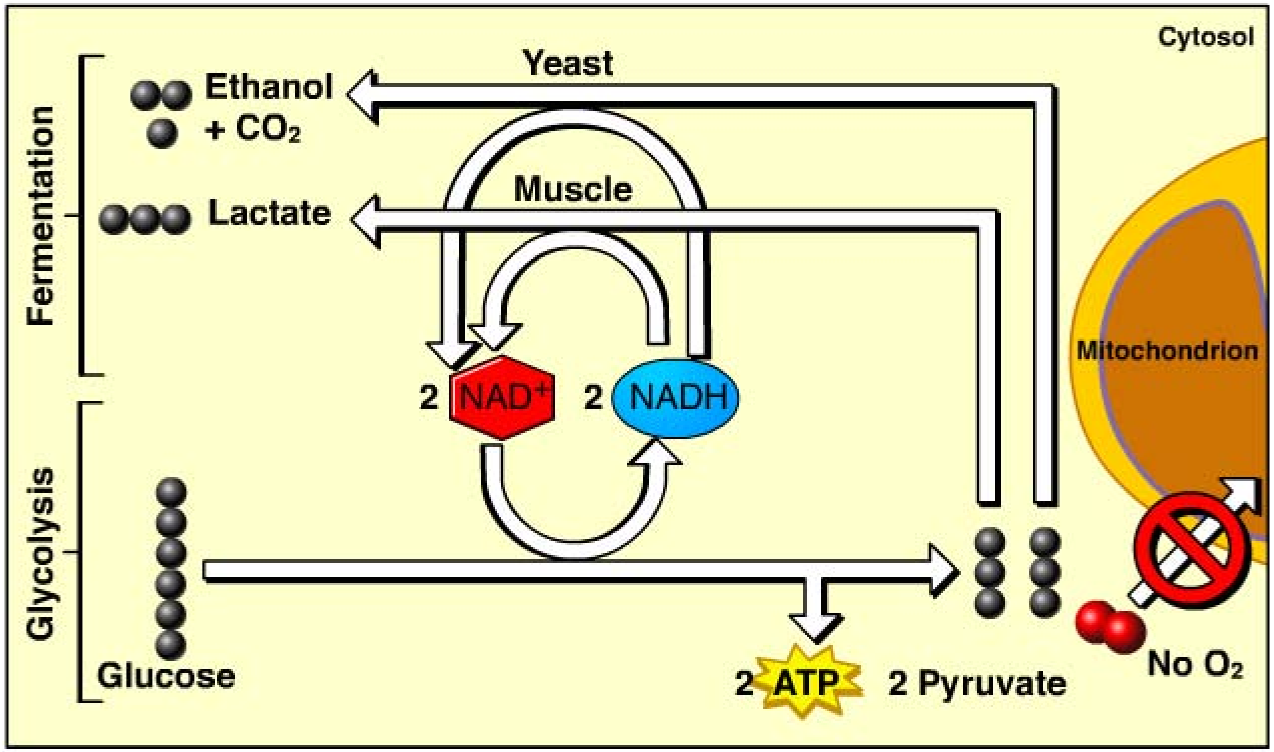
- Fermentation consists of glycolysis plus reactions that regenerate NAD^+, which can be reused by glycolysis
- Two common types are **alcohol fermentation** and **lactic acid fermentation**

Fig. 9-19



Glucose
Glycolysis
CYTOSOL
Pyruvate
No O_2 present:
Fermentation
O_2 present:
Aerobic cellular
respiration
MITOCHONDRION
Ethanol
or
lactate
Acetyl CoA
Citric
acid
cycle

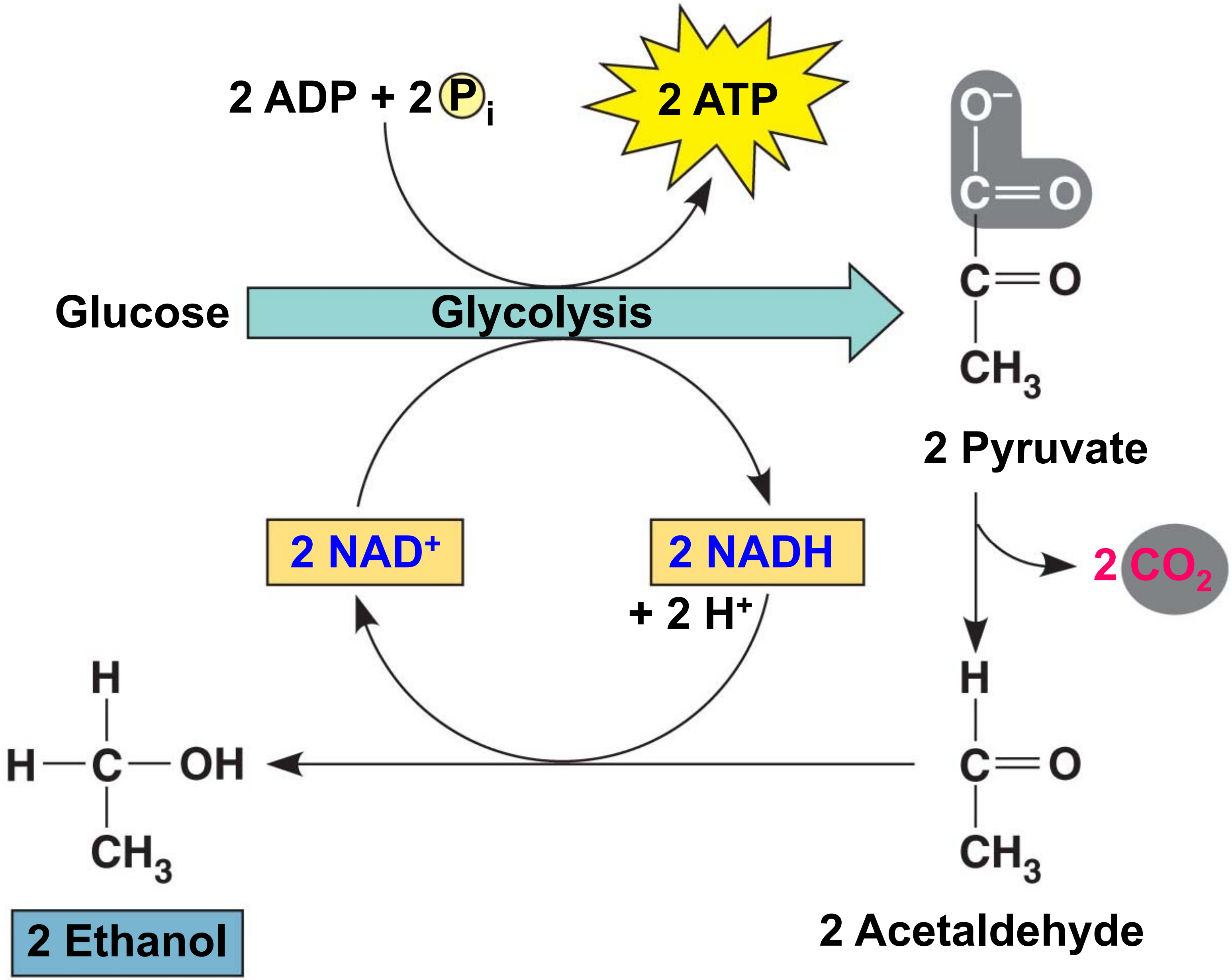
- In **alcohol fermentation**, pyruvate is converted to ethanol in two steps, with the **first releasing CO_2**
- Alcohol fermentation by yeast is used in brewing, winemaking, and baking



Animation: Fermentation Overview

Right-click slide / select "Play"

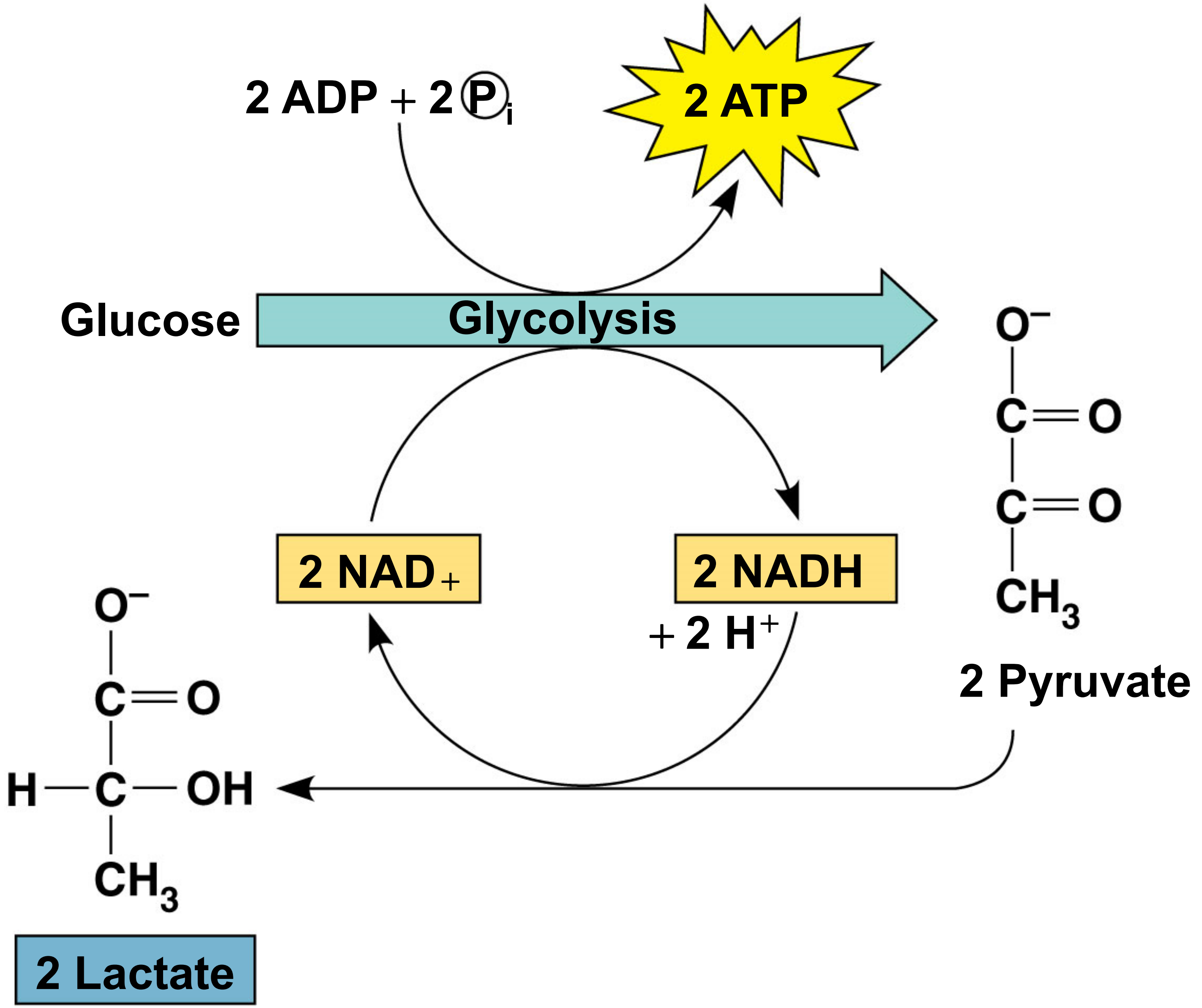
Fig. 9-18a



(a) Alcohol fermentation

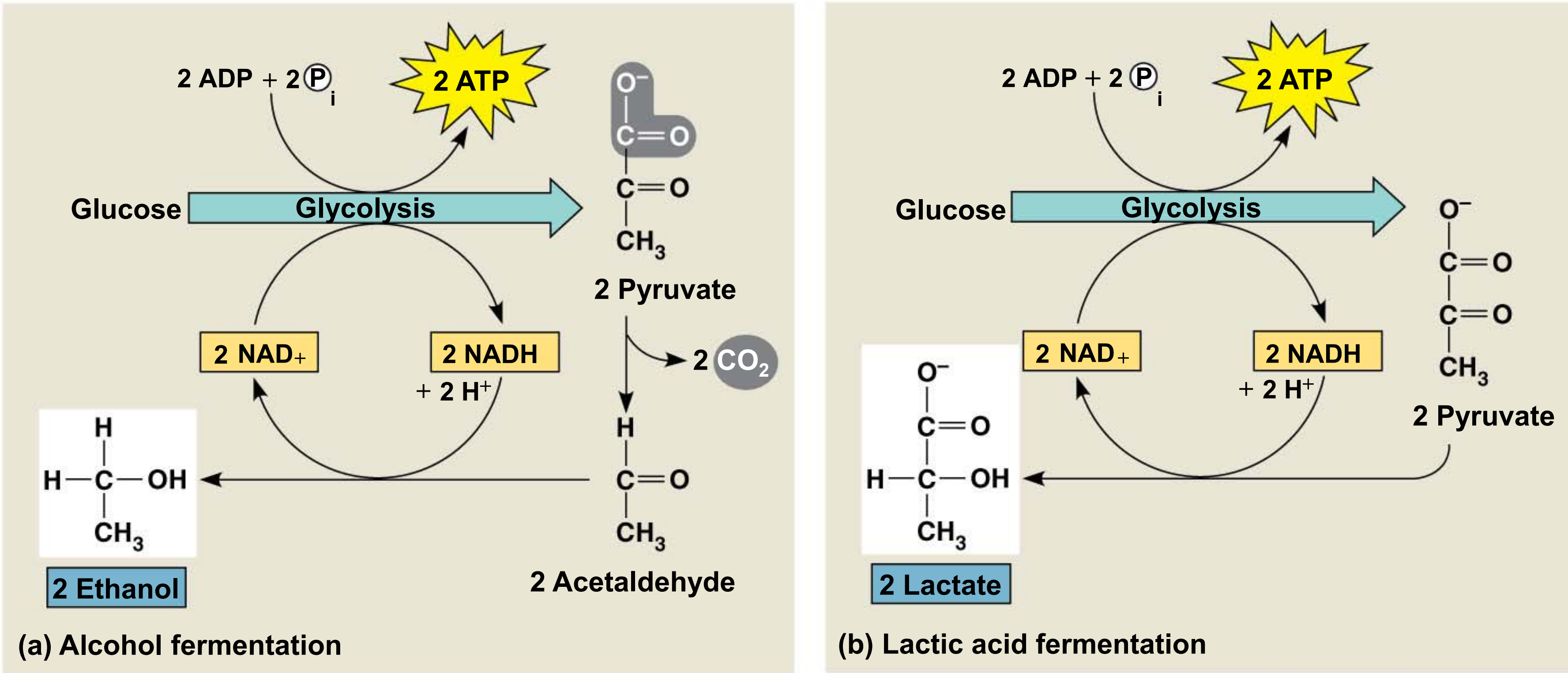
- In **lactic acid fermentation**, pyruvate is reduced to NADH, forming lactate as an end product, **with no release of CO_2**
- Lactic acid fermentation by some fungi and bacteria is used to make cheese and yogurt
- Human muscle cells use lactic acid fermentation to generate ATP when O_2 is scarce

Figure 9.17b



(b) Lactic acid fermentation

Figure 9.17



2 ADP + 2 Ⓟi
2 ATP
Glucose
Glycolysis
2 NAD+
2 NADH
+ 2 H+
2 Pyruvate
2 CO2
2 Acetaldehyde
2 Ethanol
(a) Alcohol fermentation
2 ADP + 2 Ⓟi
2 ATP
Glucose
Glycolysis
2 NAD+
2 NADH
+ 2 H+
2 Pyruvate
2 Lactate
(b) Lactic acid fermentation

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

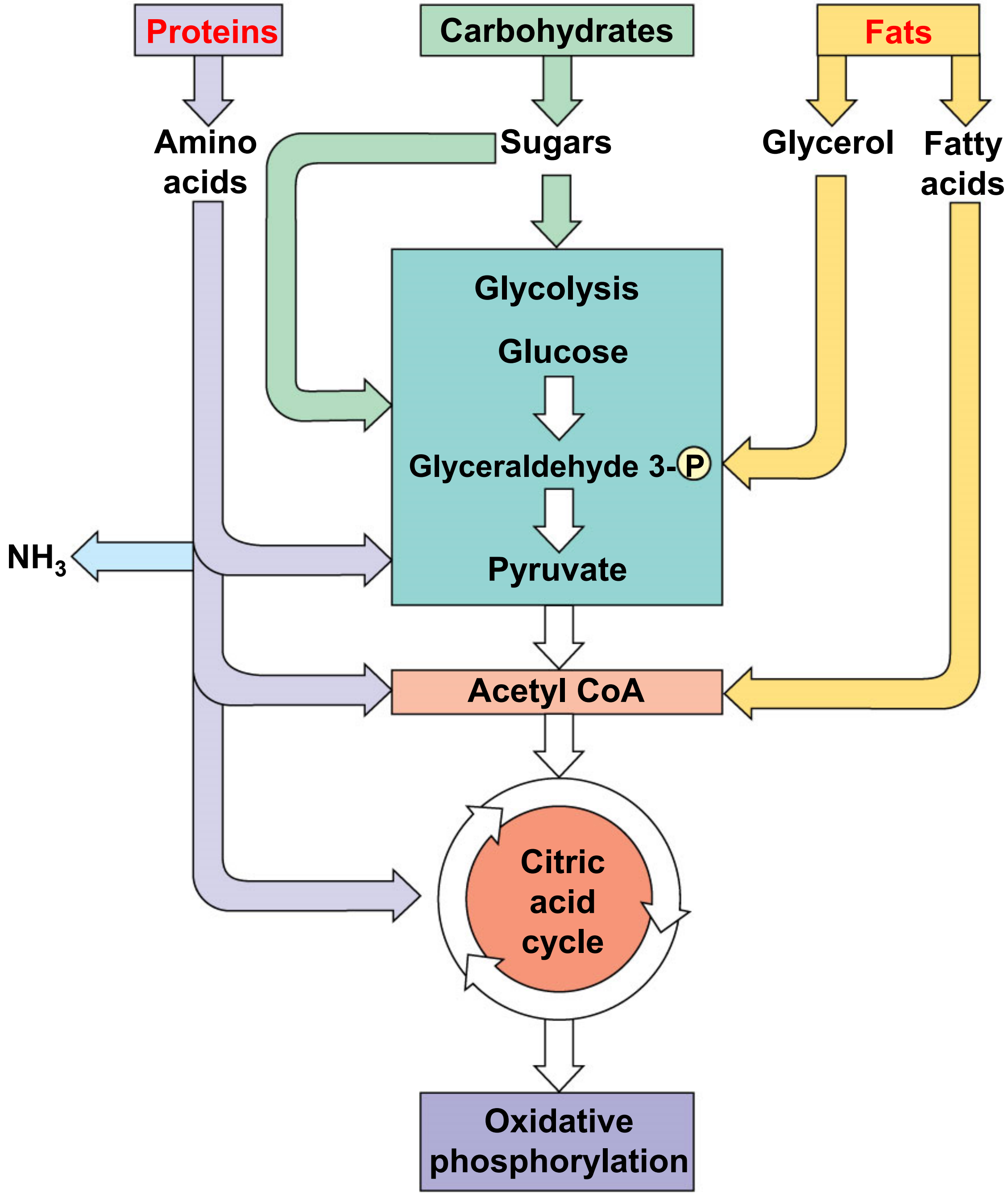
- Gycolysis and the citric acid cycle **are major intersections to various catabolic and anabolic pathways**

The Versatility of Catabolism

- Catabolic pathways funnel electrons from many kinds of organic molecules into cellular respiration
- Glycolysis accepts a wide range of carbohydrates
- Proteins must be digested to amino acids; amino groups can feed glycolysis or the citric acid cycle

- Fats are digested to glycerol (**used in glycolysis**) and fatty acids (**used in generating acetyl CoA)**
- Fatty acids are broken down by **beta oxidation** and yield acetyl CoA
- An oxidized **gram of fat produces more than twice as much ATP as an oxidized gram of carbohydrate**

Figure 9.19



Proteins
Carbohydrates
Fats
Amino acids
Sugars
Glycerol
Fatty acids
Glycolysis
Glucose
Glyceraldehyde 3-P
Pyruvate
NH_3
Acetyl CoA
Citric acid cycle
Oxidative phosphorylation

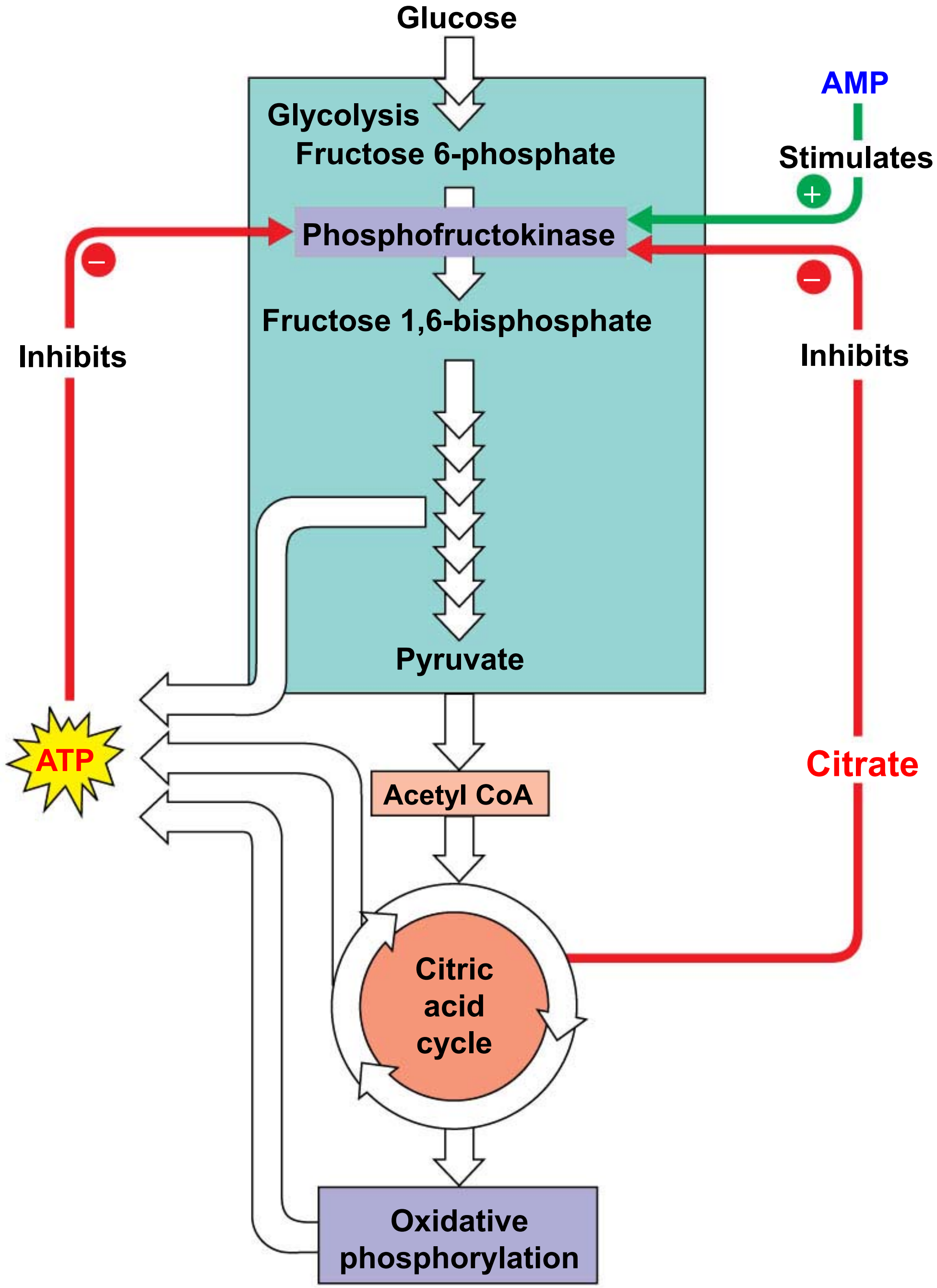
Biosynthesis (Anabolic Pathways)

- The body **uses small molecules to build other substances**
- These small molecules may **come directly from food**, **from glycolysis**, or **from the citric acid cycle**

Regulation of Cellular Respiration via Feedback Mechanisms

- Feedback inhibition is the most common mechanism for control
- If **ATP concentration begins to drop**, **respiration speeds** up; when there is **plenty of ATP, respiration slows down**
- Control of catabolism is based mainly on regulating the activity of enzymes at strategic points in the catabolic pathway

Figure 9.20


Glucose
Glycolysis
Fructose 6-phosphate
AMP
Stimulates
+
Phosphofructokinase
−
Inhibits
−
Inhibits
Fructose 1,6-bisphosphate
Pyruvate
ATP
Acetyl CoA
Citrate
Citric acid cycle
Oxidative phosphorylation

LECTURE PRESENTATIONS

For CAMPBELL BIOLOGY, NINTH EDITION

Jane B. Reece, Lisa A. Urry, Michael L. Cain, Steven A. Wasserman, Peter V. Minorsky, Robert B. Jackson

Chapter 10

Photosynthesis

Lectures by
Erin Barley
Kathleen Fitzpatrick

Overview: The Process That Feeds the Biosphere

- **Photosynthesis** is the process that converts solar energy into chemical energy
- Directly or indirectly, photosynthesis nourishes almost the entire living world

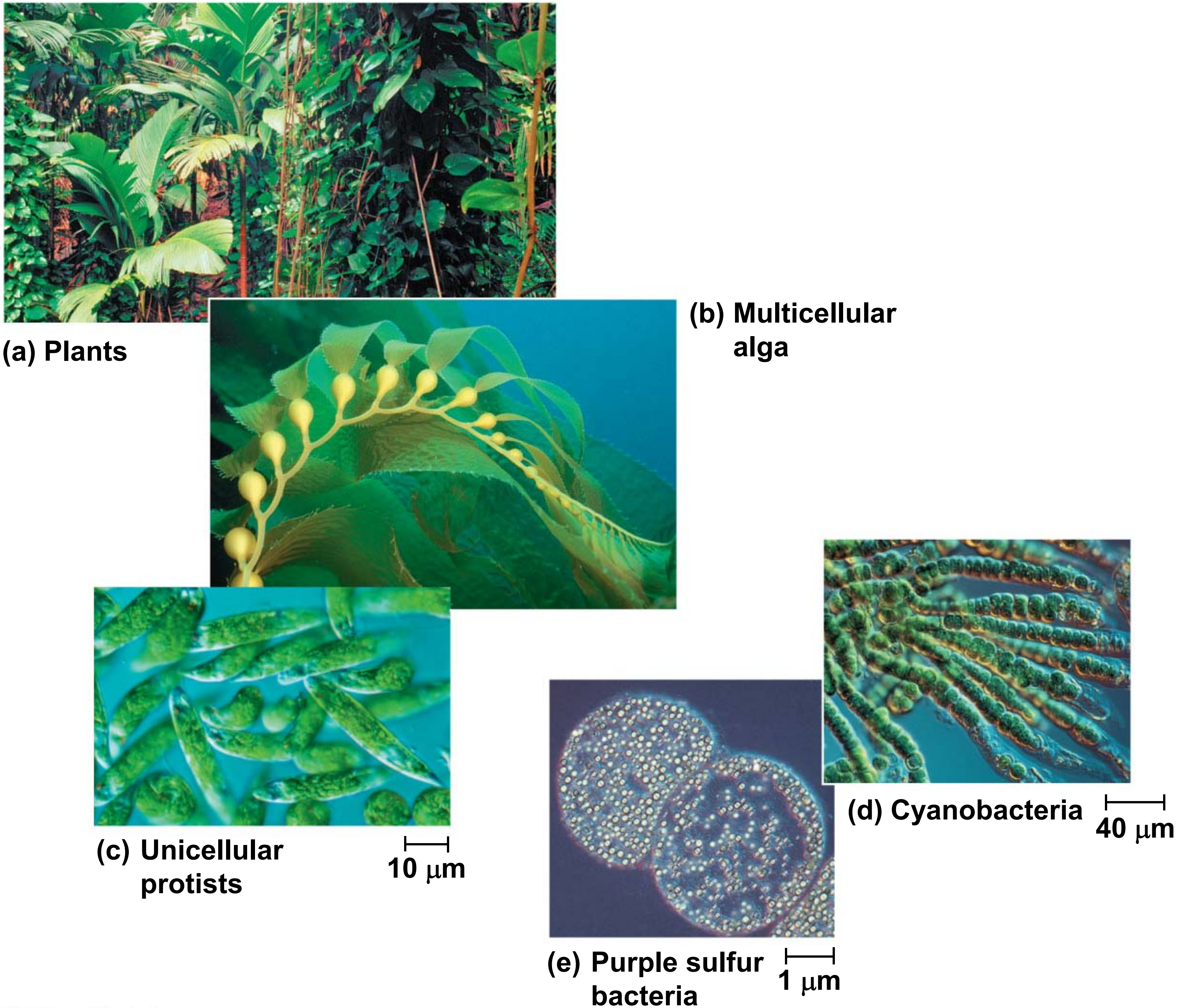
- **Autotrophs** sustain themselves without eating anything derived from other organisms
- Autotrophs are the *producers* of the biosphere, producing organic molecules from CO_2 and other inorganic molecules
- Almost all plants are *photo*autotrophs, using the energy of sunlight to make organic molecules from H_2O and CO_2

Fig. 10-1

- Photosynthesis occurs in plants, algae, certain other protists, and some prokaryotes
- These organisms feed not only themselves but also most of the living world

PLAY BioFlix: Photosynthesis

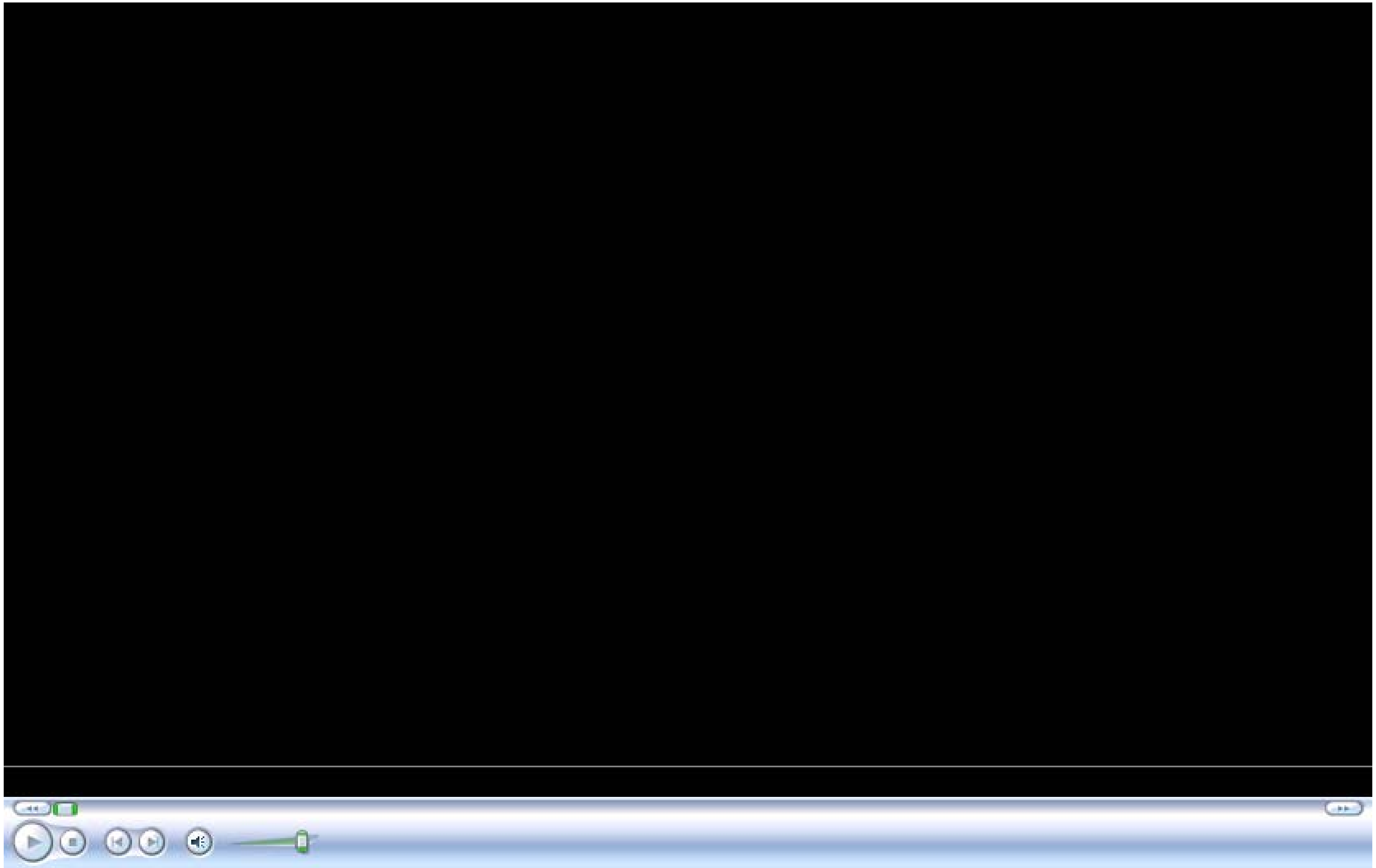
Figure 10.2


(a) Plants
(b) Multicellular alga
(c) Unicellular protists
10 μm
(d) Cyanobacteria
40 μm
(e) Purple sulfur bacteria
1 μm

- **Heterotrophs** obtain their organic material from other organisms
- Heterotrophs are the *consumers* of the biosphere
- Almost all heterotrophs, including humans, depend on photoautotrophs for food and O_2

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

- Chloroplasts are structurally similar to and likely evolved from photosynthetic bacteria
- The structural organization of these cells allows for the chemical reactions of photosynthesis



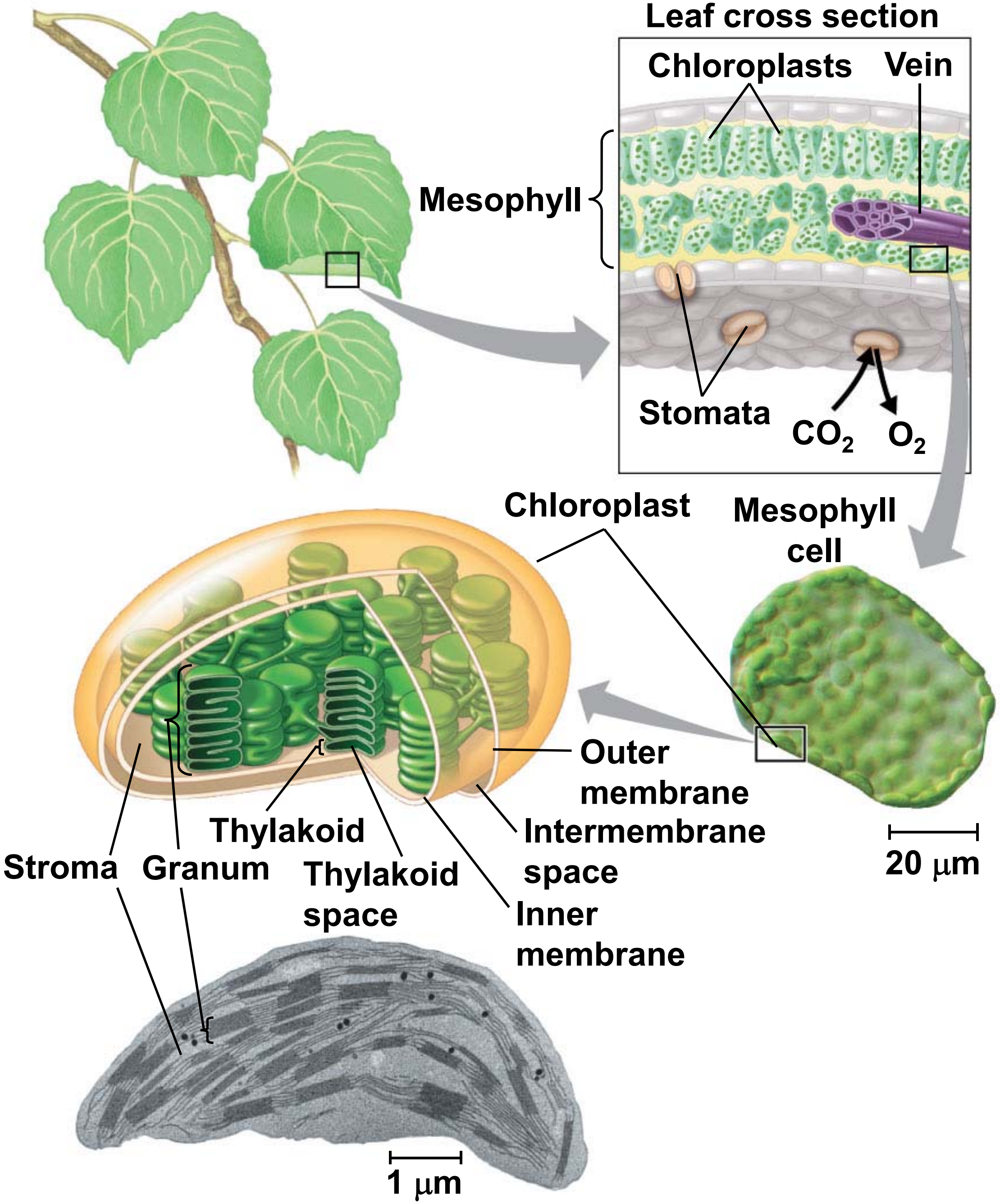
BioFlix: Photosynthesis

Chloroplasts: The Sites of Photosynthesis in Plants

- Leaves are the major locations of photosynthesis
- Their green color is from **chlorophyll**, the green pigment within chloroplasts
- Light energy absorbed by chlorophyll drives the synthesis of organic molecules in the chloroplast
- CO_2 enters and O_2 exits the leaf through microscopic pores called **stomata**

- Chloroplasts are found mainly in cells of the **mesophyll**, the interior tissue of the leaf
- A typical mesophyll cell has 30–40 chloroplasts
- The chlorophyll is in the membranes of **thylakoids** (connected sacs in the chloroplast); thylakoids may be stacked in columns called ***grana***
- Chloroplasts also contain **stroma**, a dense fluid

Figure 10.4

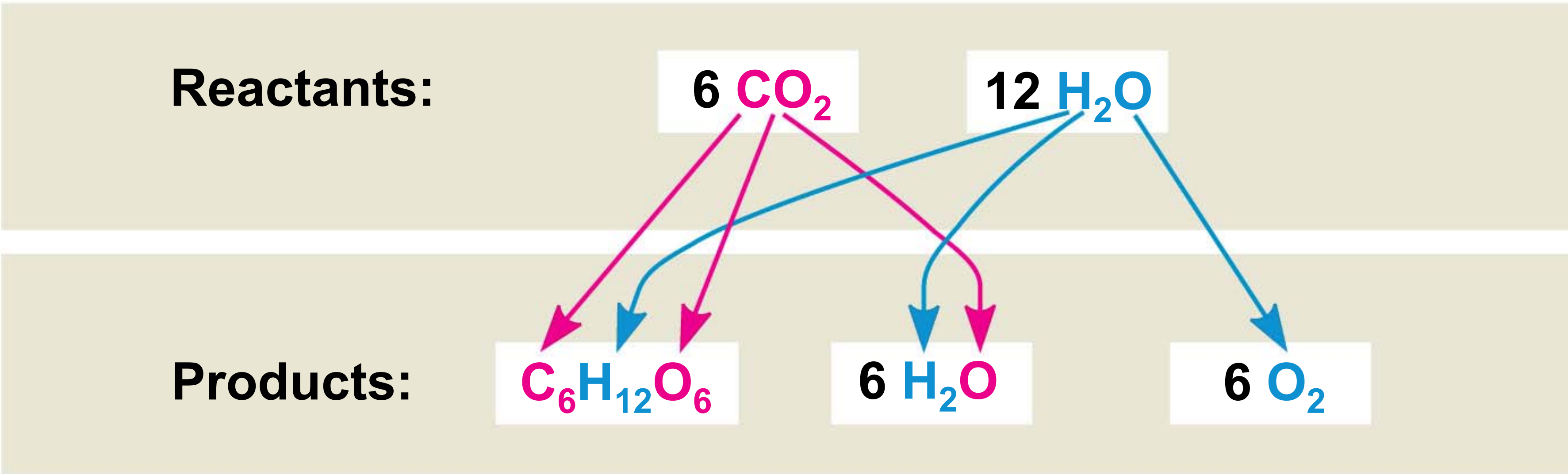

Leaf cross section
Chloroplasts
Vein
Mesophyll
Stomata
CO_2
O_2
Chloroplast
Mesophyll cell
Outer membrane
Intermembrane space
Inner membrane
Thylakoid
Thylakoid space
Stroma
Granum
20 μm
1 μm

Tracking Atoms Through Photosynthesis: *Scientific Inquiry*

- Photosynthesis can be summarized as the following equation:

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

Figure 10.5



The Splitting of Water

- Chloroplasts split H_2O into hydrogen and oxygen, incorporating the electrons of hydrogen into sugar molecules

Photosynthesis as a Redox Process

- Photosynthesis is a redox process in which H_2O is oxidized and CO_2 is reduced

The Two Stages of Photosynthesis: *A Preview*

- Photosynthesis consists of the **light reactions** (the *photo* part) and **Calvin cycle** (the *synthesis* part)
- **The light reactions** (*in the thylakoids*):
  - Split H_2O
  - Release O_2
  - Reduce **$NADP^+$** to NADPH
  - Generate ATP from ADP by **photophosphorylation**

Figure 10.UN01

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

becomes reduced ($CO_2 \rightarrow C_6H_{12}O_6$)

becomes oxidized ($H_2O \rightarrow O_2$)

The Two Stages of Photosynthesis: *A Preview*

- Photosynthesis consists of the **light reactions** (the *photo* part) and **Calvin cycle** (the *synthesis* part)
- **The light reactions** (*in the thylakoids*):
  - Split H_2O
  - Release O_2
  - Reduce **$NADP^+$** to NADPH
  - Generate ATP from ADP by **photophosphorylation**

- **The Calvin cycle** (*in the stroma*) forms sugar from CO_2, using ATP and NADPH
- The Calvin cycle begins with **carbon fixation**, incorporating CO_2 into organic molecules

Fig. 10-5-1

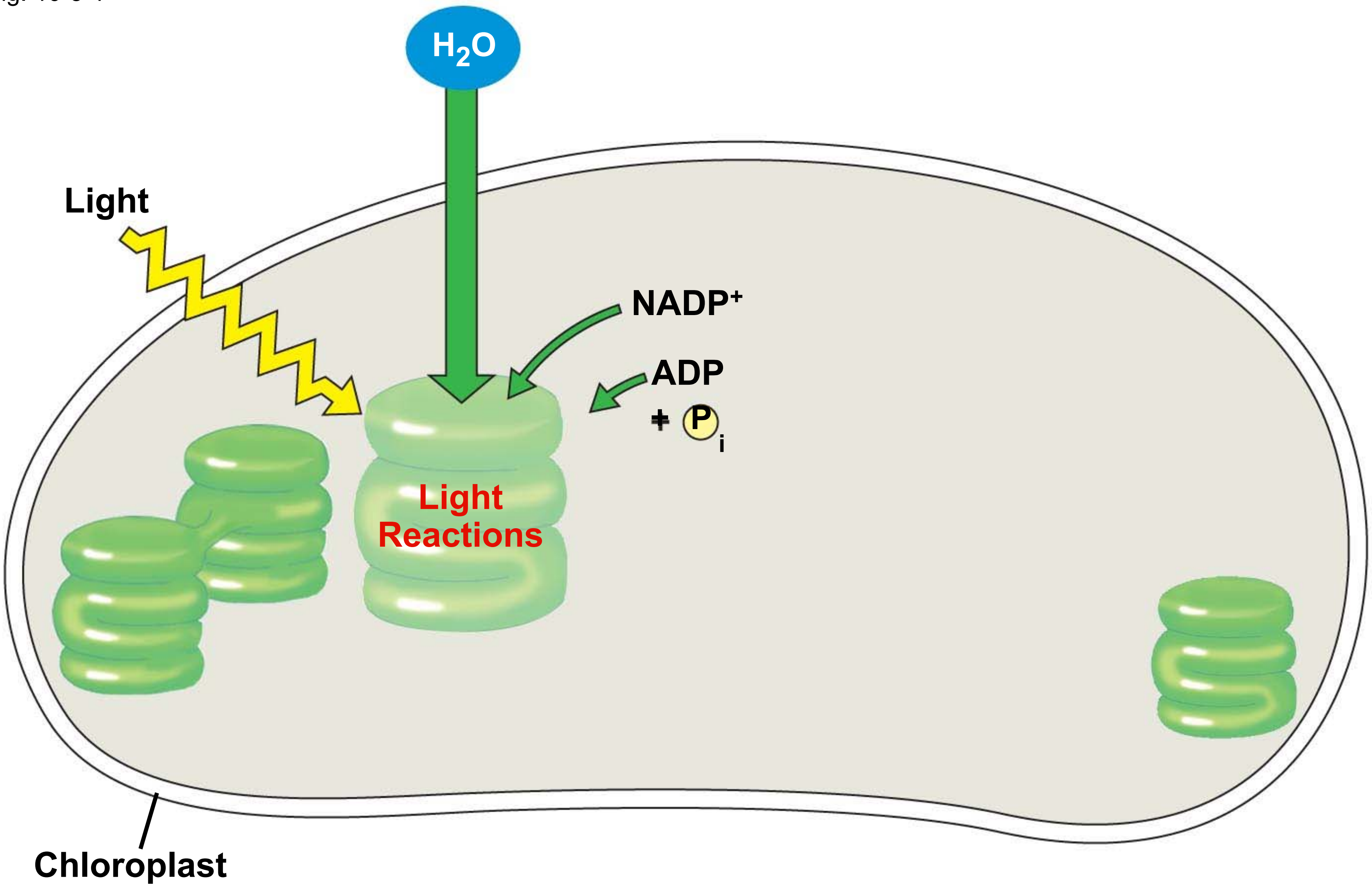
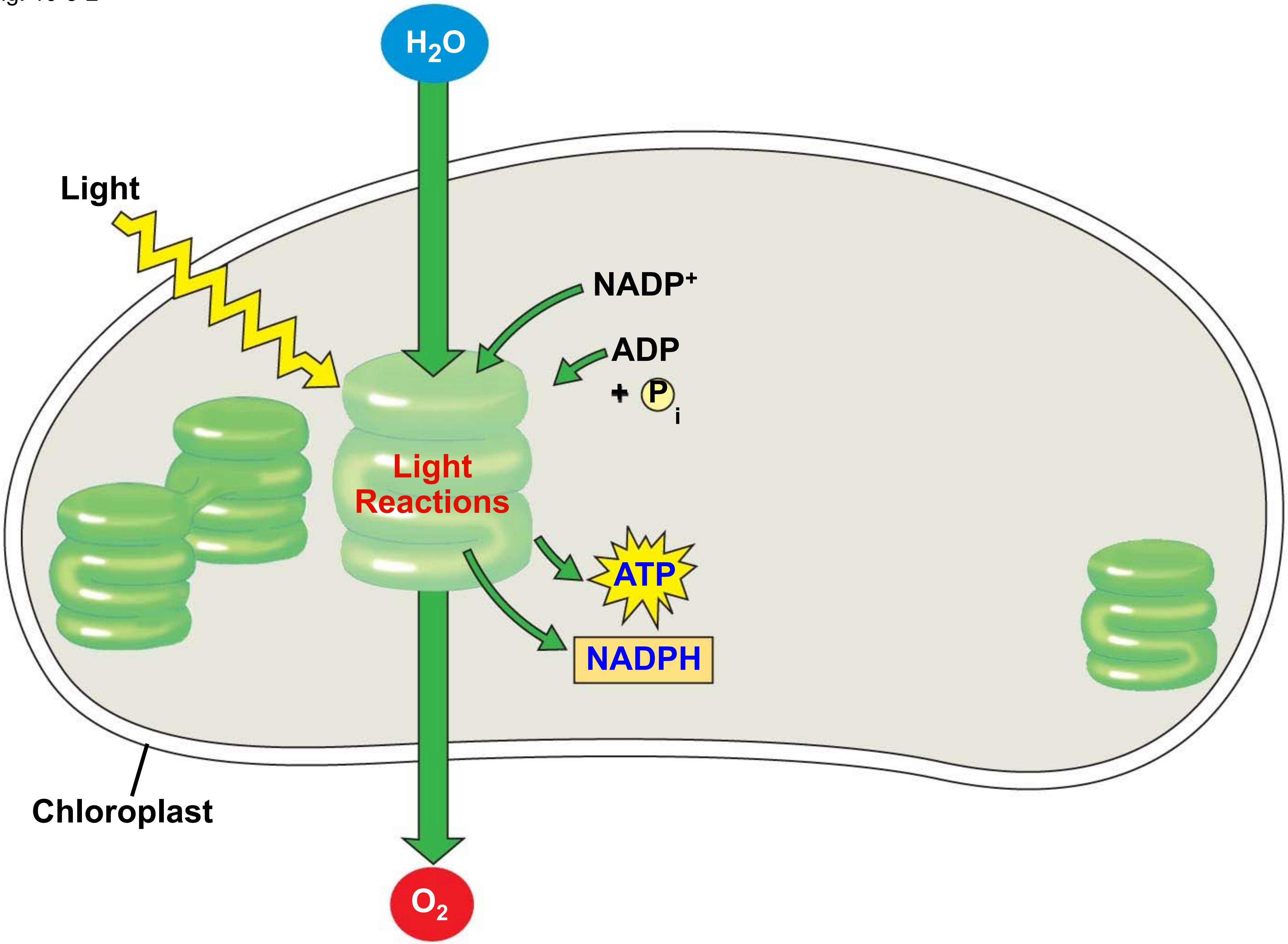
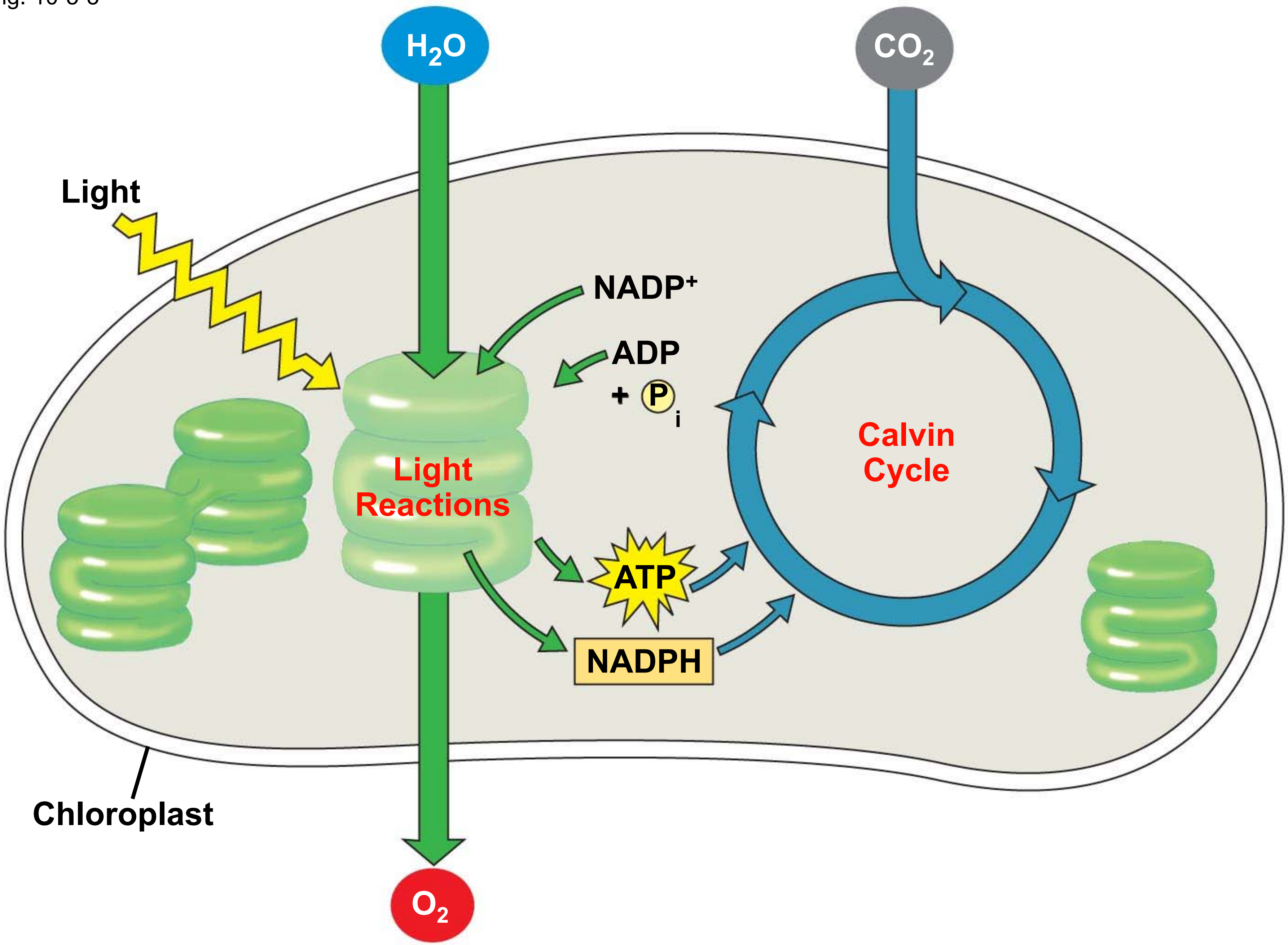


Fig. 10-5-2



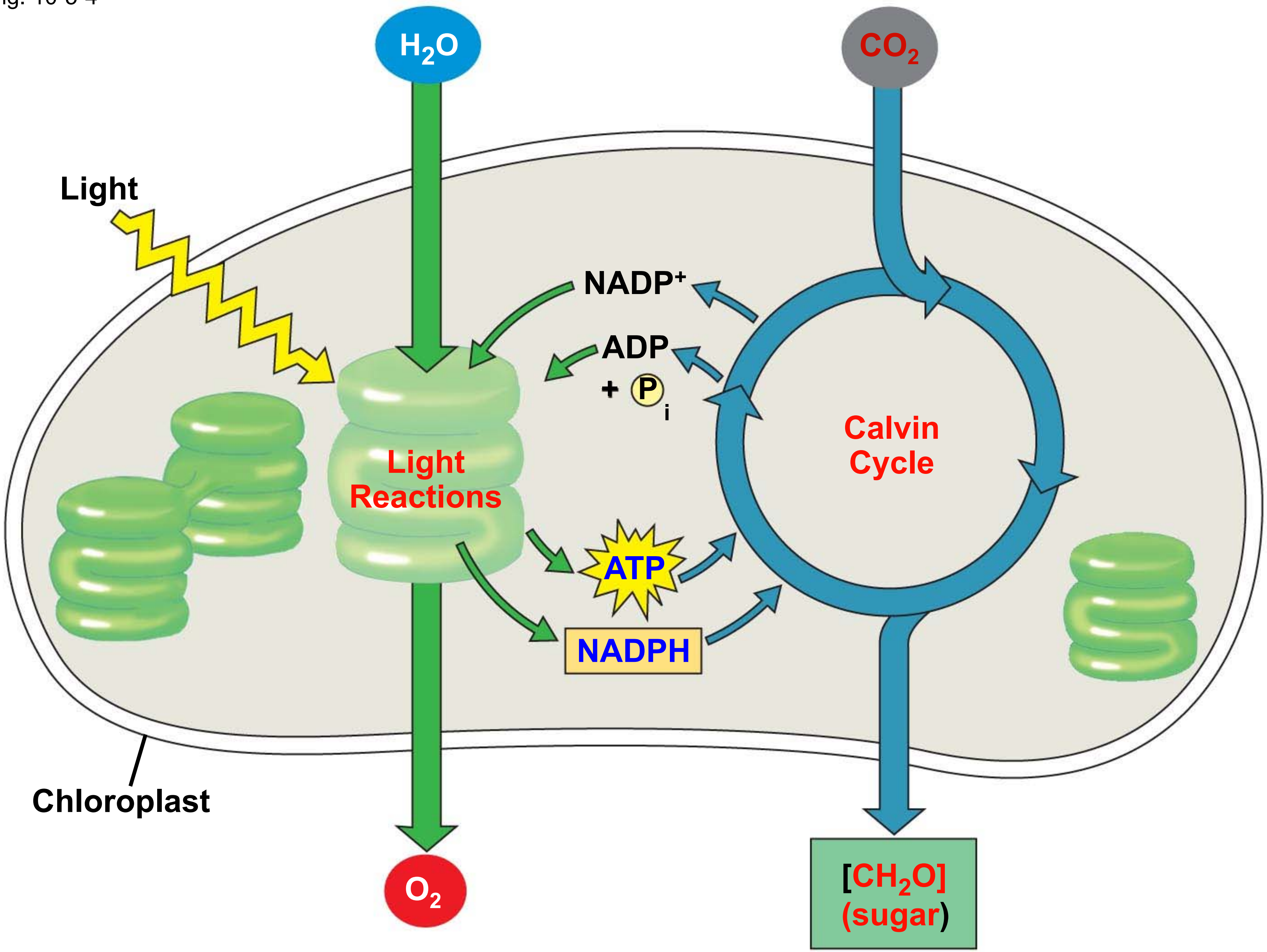
H_2O
Light
$NADP^+$
ADP
+ P
i
Light Reactions
ATP
NADPH
Chloroplast
O_2

Fig. 10-5-3



H_2O
CO_2
Light
$NADP^+$
ADP
+ (P)i
Calvin
Cycle
Light
Reactions
ATP
NADPH
Chloroplast
O_2

Fig. 10-5-4



H_2O
CO_2
Light
$NADP^+$
ADP
+ P_i
Calvin Cycle
Light Reactions
ATP
NADPH
Chloroplast
O_2
$[CH_2O]$ (sugar)

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

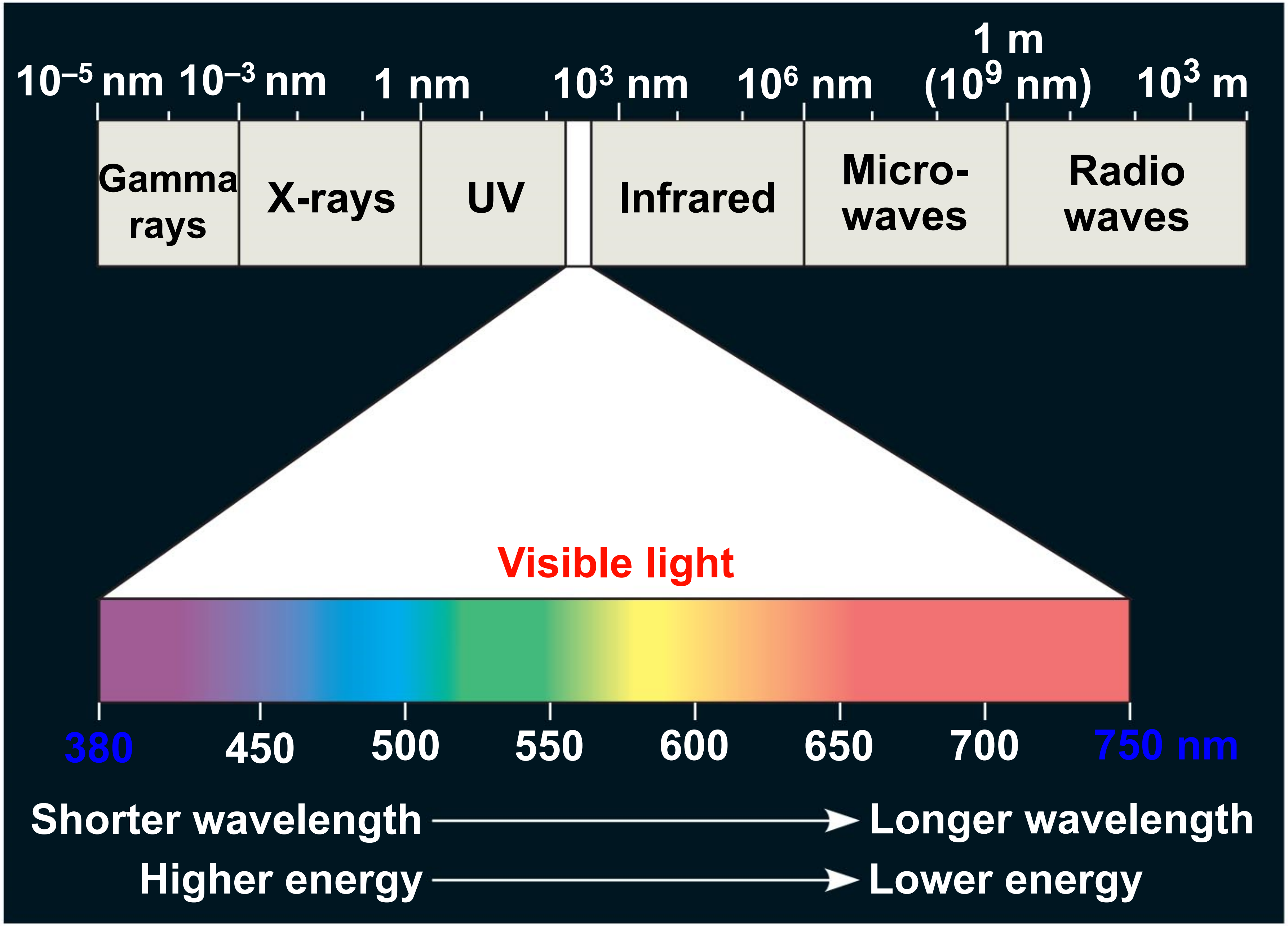
- Chloroplasts are solar-powered chemical factories
- Their thylakoids transform light energy into the chemical energy of ATP and NADPH

The Nature of Sunlight

- Light is a form of electromagnetic energy, also called electromagnetic radiation
- Like other electromagnetic energy, light travels in rhythmic waves
- **Wavelength** is the distance between crests of waves
- Wavelength determines the type of electromagnetic energy

- The **electromagnetic spectrum** is the entire range of electromagnetic energy, or radiation
- **Visible light** consists of wavelengths (including those that drive photosynthesis) that produce colors we can see
- Light also behaves as though it consists of discrete particles, called **photons**

Fig. 10-6

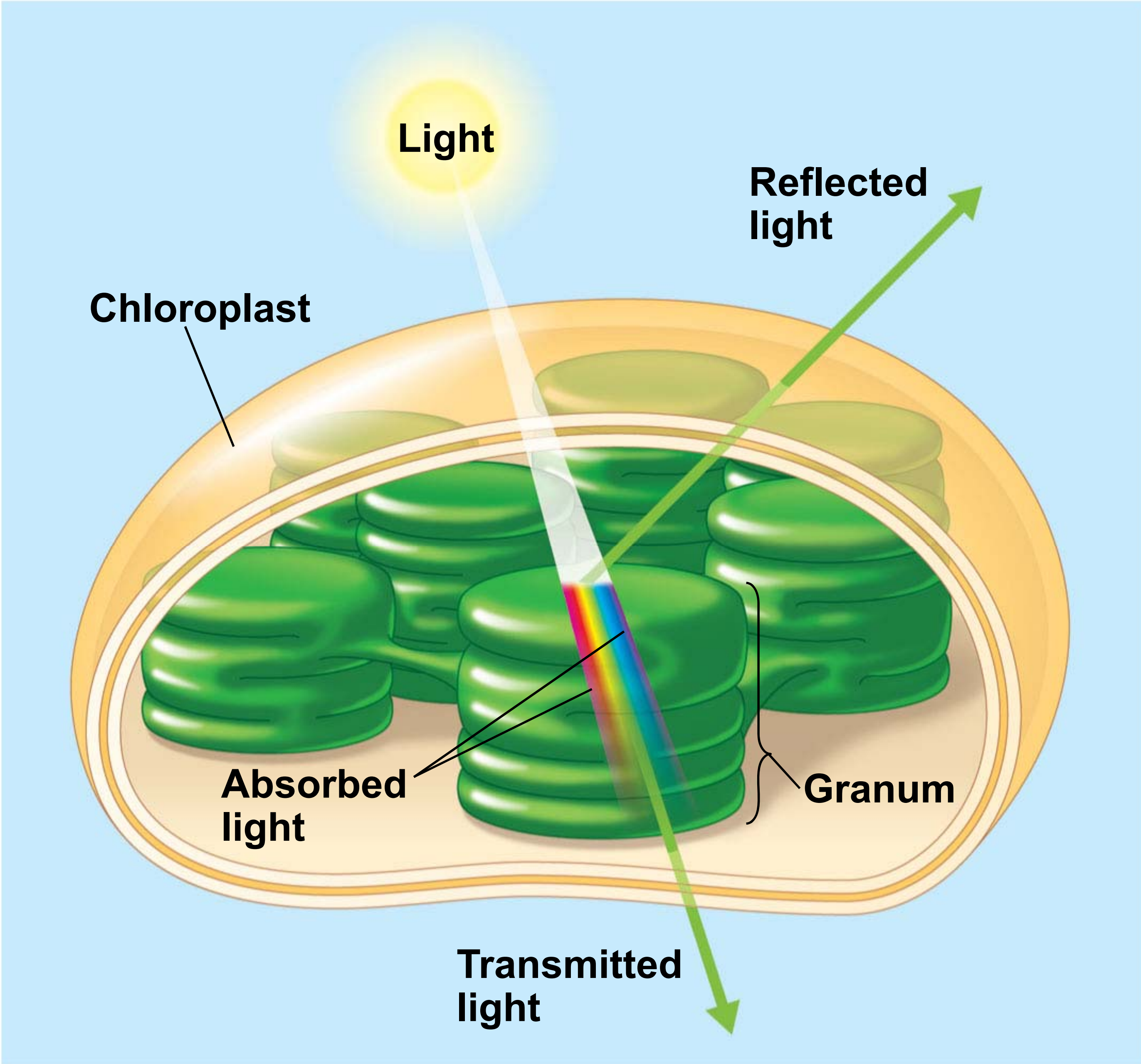

10⁻⁵ nm
10⁻³ nm
1 nm
10³ nm
10⁶ nm
1 m
(10⁹ nm)
10³ m
Gamma rays
X-rays
UV
Infrared
Micro-waves
Radio waves
Visible light
380
450
500
550
600
650
700
750 nm
Shorter wavelength
Longer wavelength
Higher energy
Lower energy

Photosynthetic Pigments: The Light Receptors

- Pigments are substances that absorb visible light
- Different pigments absorb different wavelengths
- Wavelengths that are not absorbed are reflected or transmitted
- Leaves appear green because chlorophyll **reflects** and **transmits** green light

PLAY Animation: Light and Pigments

Figure 10.8



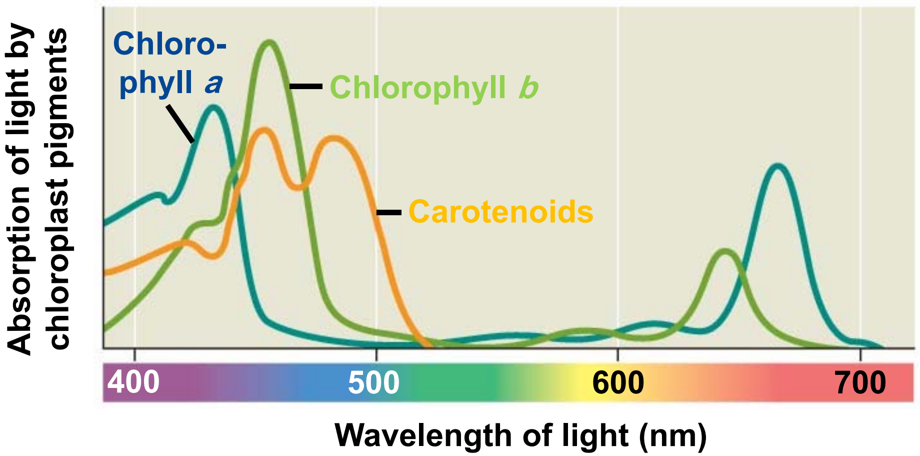
Light
Reflected light
Chloroplast
Absorbed light
Granum
Transmitted light

- A **spectrophotometer** measures a pigment's ability to absorb various wavelengths
- This machine sends light through pigments and measures the fraction of light transmitted at each wavelength

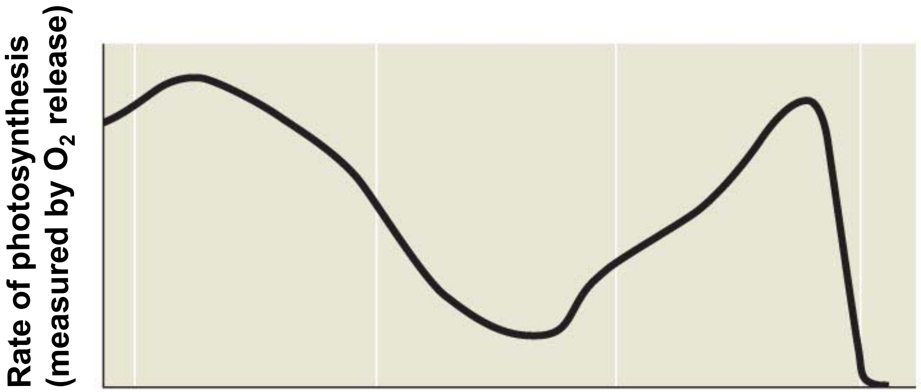
- An **absorption spectrum** is a graph plotting a pigment's light absorption versus wavelength
- The absorption spectrum of **chlorophyll *a*** suggests that violet-blue and red light work best for photosynthesis

Fig. 10-9

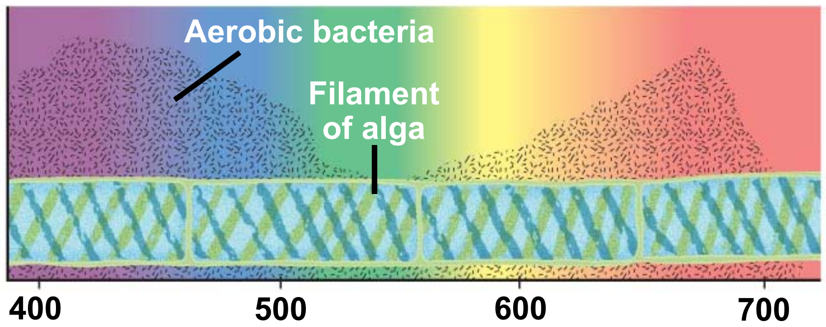
RESULTS



(a) Absorption spectra



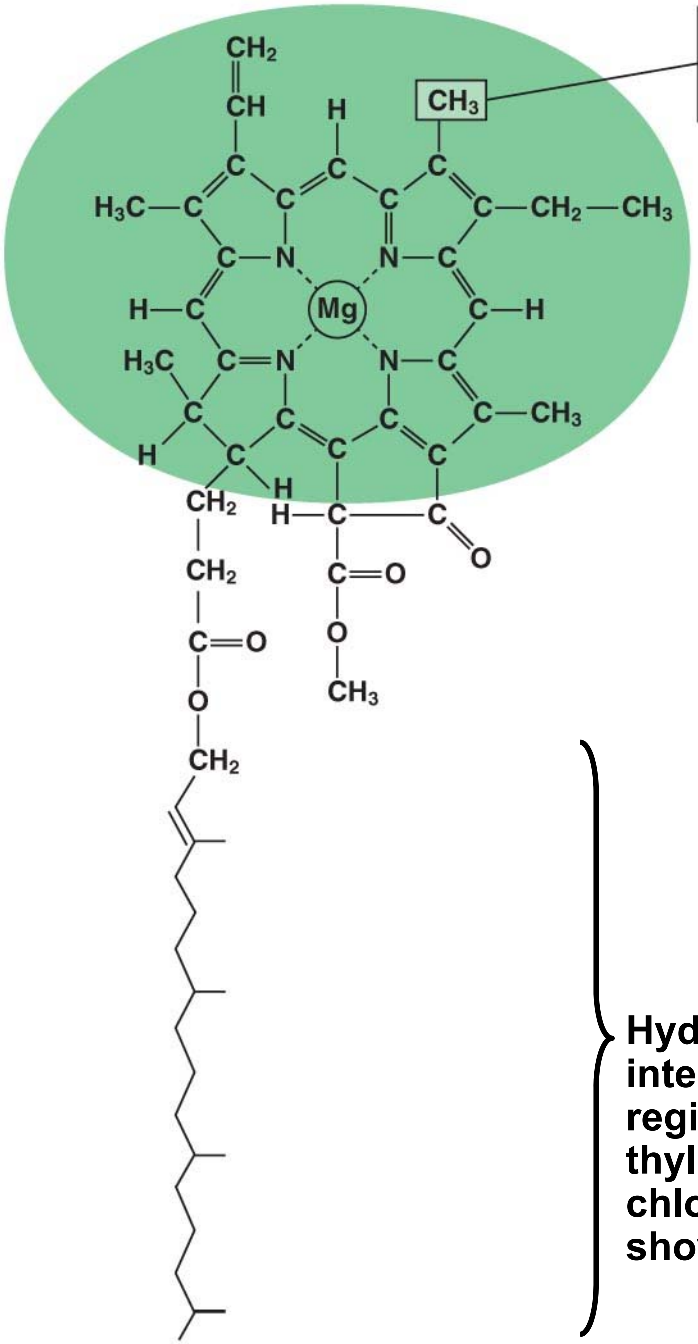
(b) Action spectrum



(c) Engelmann's experiment

- **Chlorophyll *a*** is the main photosynthetic pigment
- Accessory pigments, such as ***chlorophyll b***, broaden the spectrum used for photosynthesis
- Accessory pigments called **carotenoids** absorb excessive light that would damage chlorophyll

Fig. 10-10



CH_3 in chlorophyll *a*

CHO in chlorophyll *b*

Porphyrin ring: light-absorbing "head" of molecule; note magnesium atom at center

Hydrocarbon tail: interacts with hydrophobic regions of proteins inside thylakoid membranes of chloroplasts; H atoms not shown

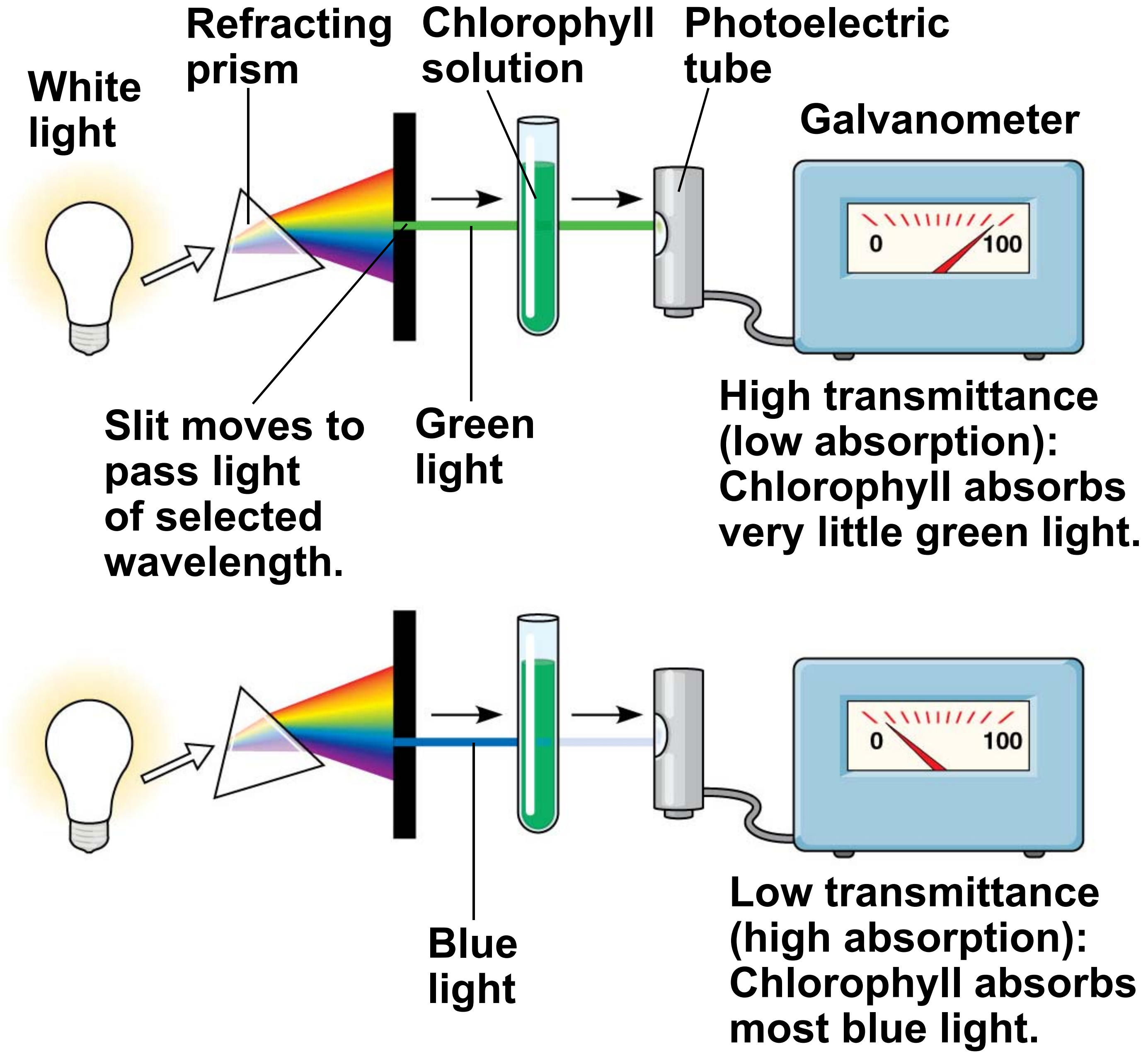
Excitation of Chlorophyll by Light

- When a pigment absorbs light, it goes from a ground state to an excited state, which is unstable
- When excited electrons fall back to the ground state, photons are given off, an afterglow called fluorescence
- If illuminated, an isolated solution of chlorophyll will fluoresce, giving off light and heat

- A **spectrophotometer** measures a pigment's ability to absorb various wavelengths
- This machine sends light through pigments and measures the fraction of light transmitted at each wavelength

Figure 10.9

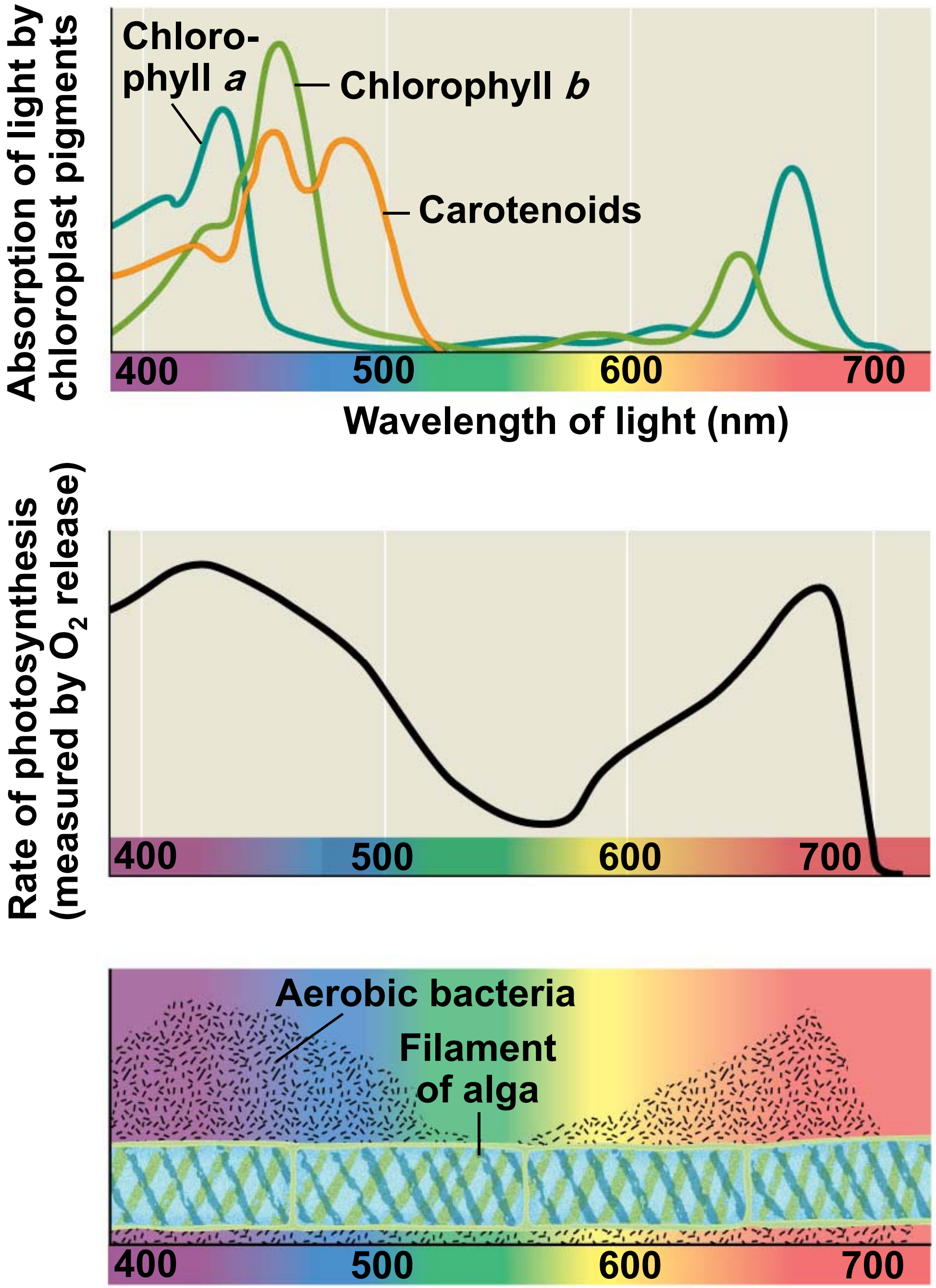
TECHNIQUE



- An **absorption spectrum** is a graph plotting a pigment's light absorption versus wavelength
- The absorption spectrum of **chlorophyll *a*** suggests that violet-blue and red light work best for photosynthesis
- An **action spectrum** profiles the relative effectiveness of different wavelengths of radiation in driving a process

Figure 10.10

RESULTS



(a) Absorption spectra

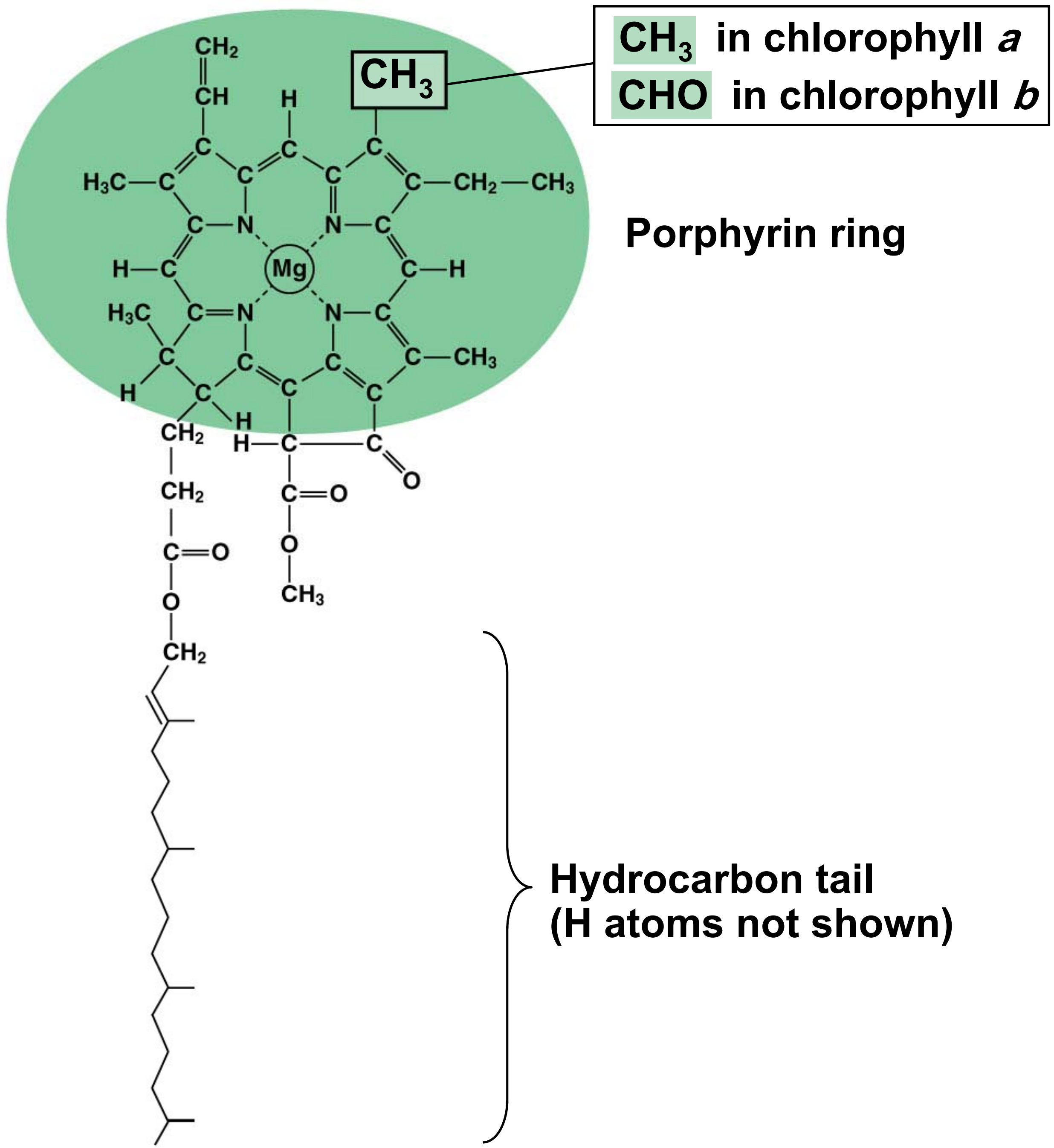
(b) Action spectrum

(c) Engelmann's experiment

- The action spectrum of photosynthesis was first demonstrated in 1883 by Theodor W. Engelmann
- In his experiment, he exposed different segments of a filamentous alga to different wavelengths
- Areas receiving wavelengths favorable to photosynthesis produced excess O_2
- He used the growth of aerobic bacteria clustered along the alga as a measure of O_2 production

- Chlorophyll *a* is the main photosynthetic pigment
- Accessory pigments, such as **chlorophyll *b***, broaden the spectrum used for photosynthesis
- Accessory pigments called **carotenoids** absorb excessive light that would damage chlorophyll

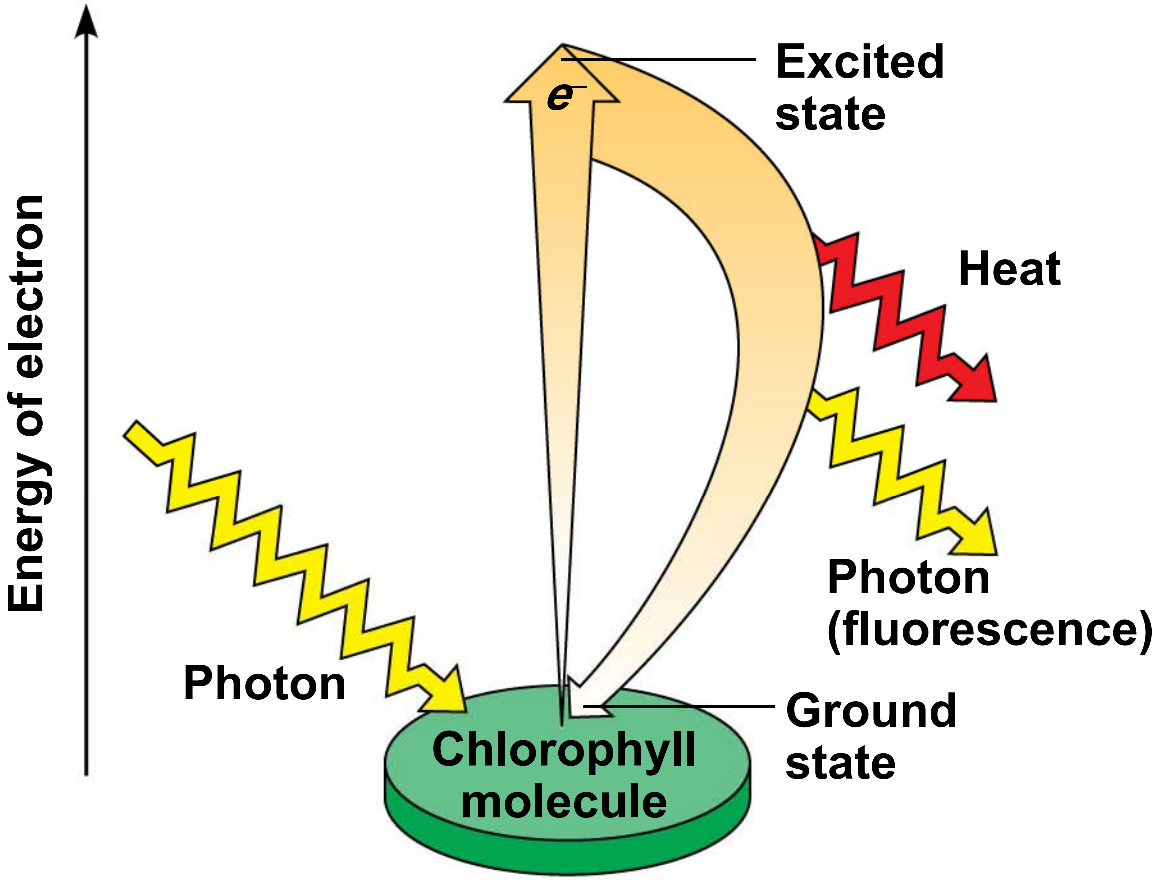
Figure 10.11


CH3 in chlorophyll a
CHO in chlorophyll b
Porphyrin ring
Hydrocarbon tail
(H atoms not shown)

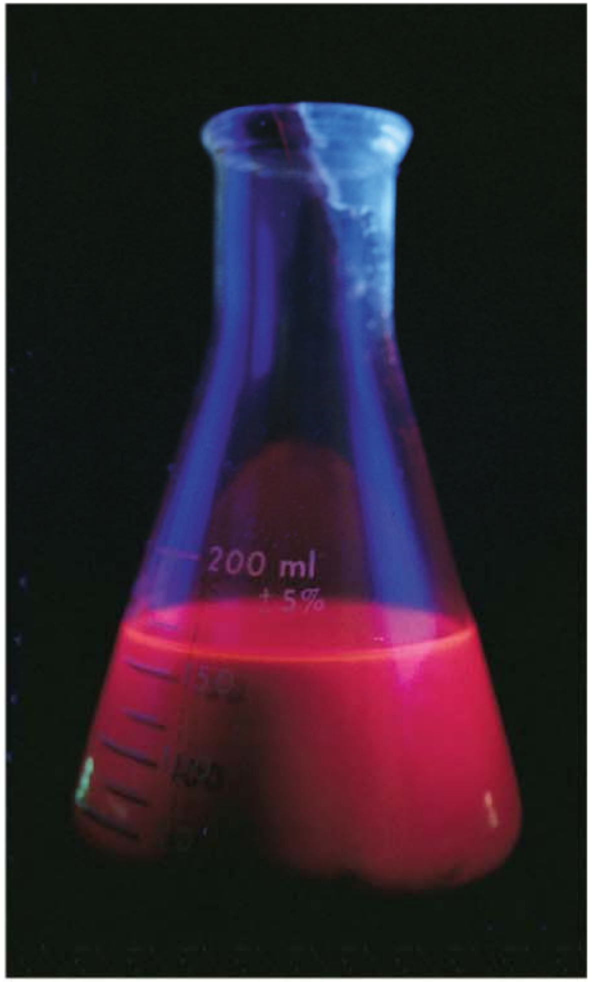
Excitation of Chlorophyll by Light

- When a pigment absorbs light, it goes from a ground state to an excited state, which is unstable
- When excited electrons fall back to the ground state, photons are given off, an afterglow called fluorescence
- If illuminated, an isolated solution of chlorophyll will fluoresce, giving off light and heat

Figure 10.12

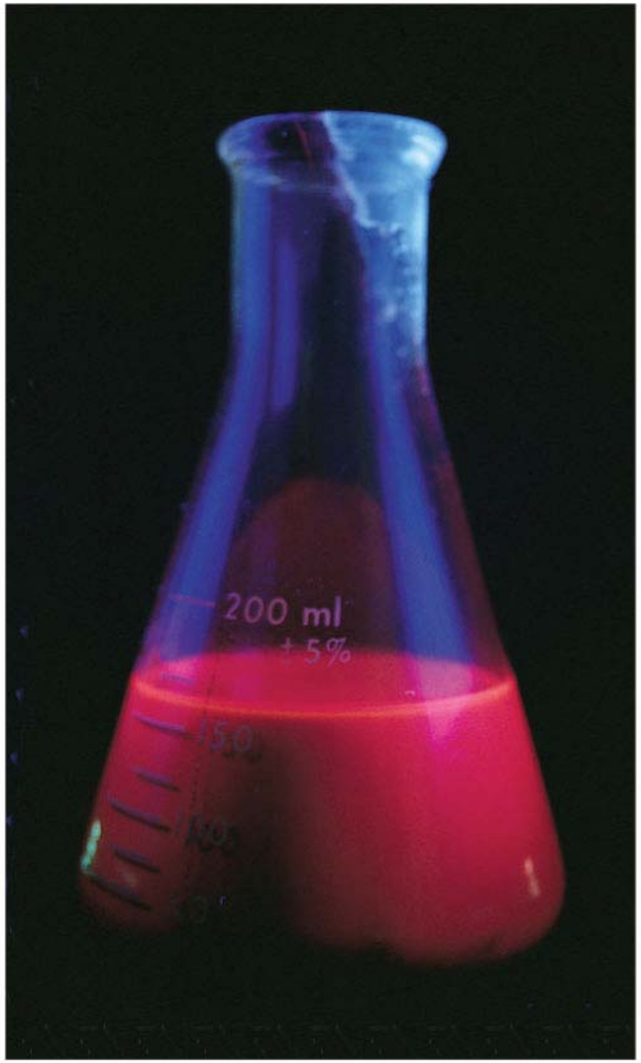


(a) Excitation of isolated chlorophyll molecule



(b) Fluorescence

Figure 10.12a

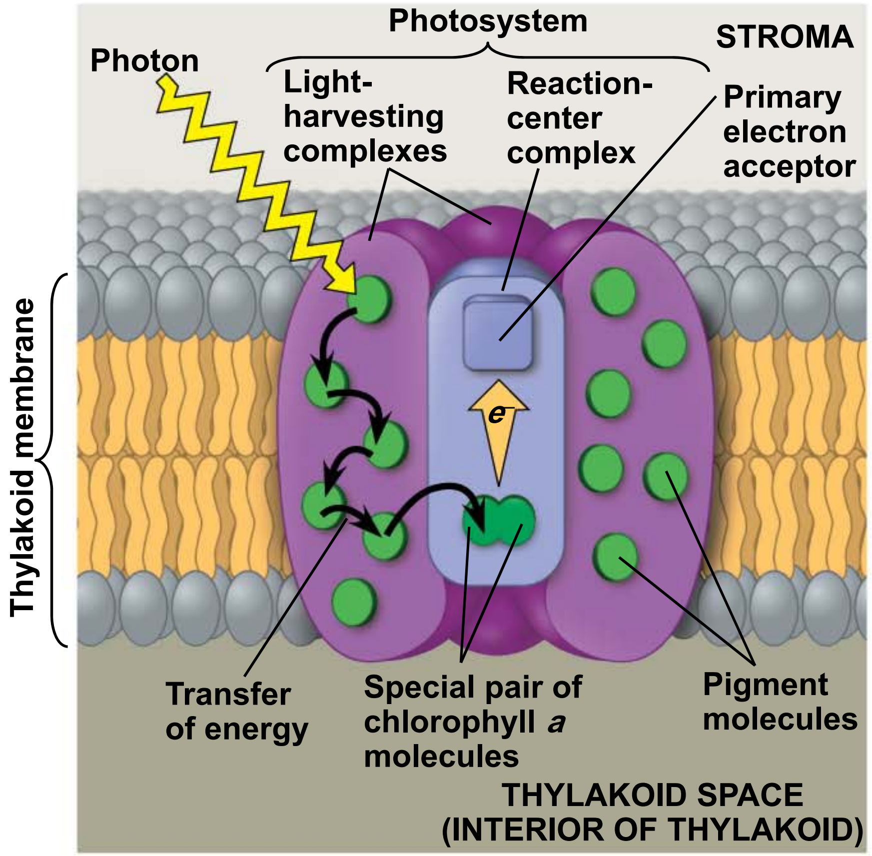


(b) Fluorescence

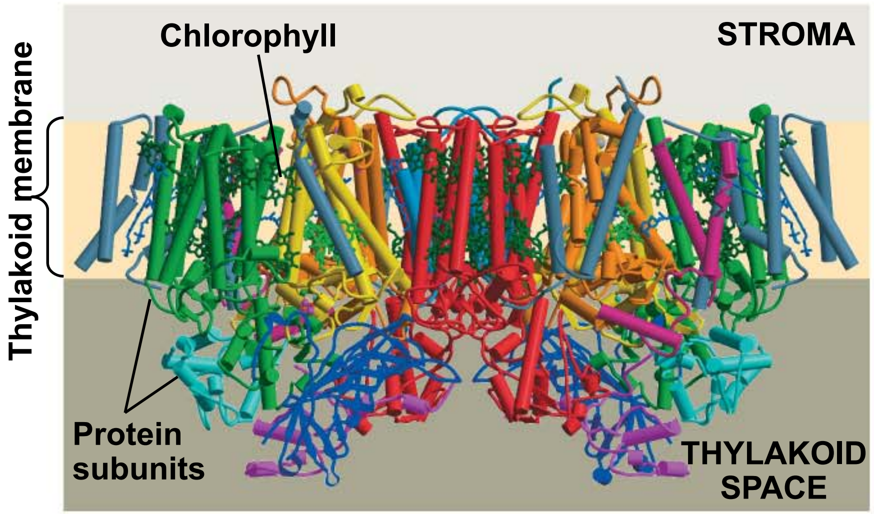
A Photosystem: A Reaction-Center Complex Associated with Light-Harvesting Complexes

- A **photosystem** consists of a **reaction-center complex** (a type of protein complex) surrounded by light-harvesting complexes
- The **light-harvesting complexes** (pigment molecules bound to proteins) transfer the energy of photons to the reaction center

Figure 10.13

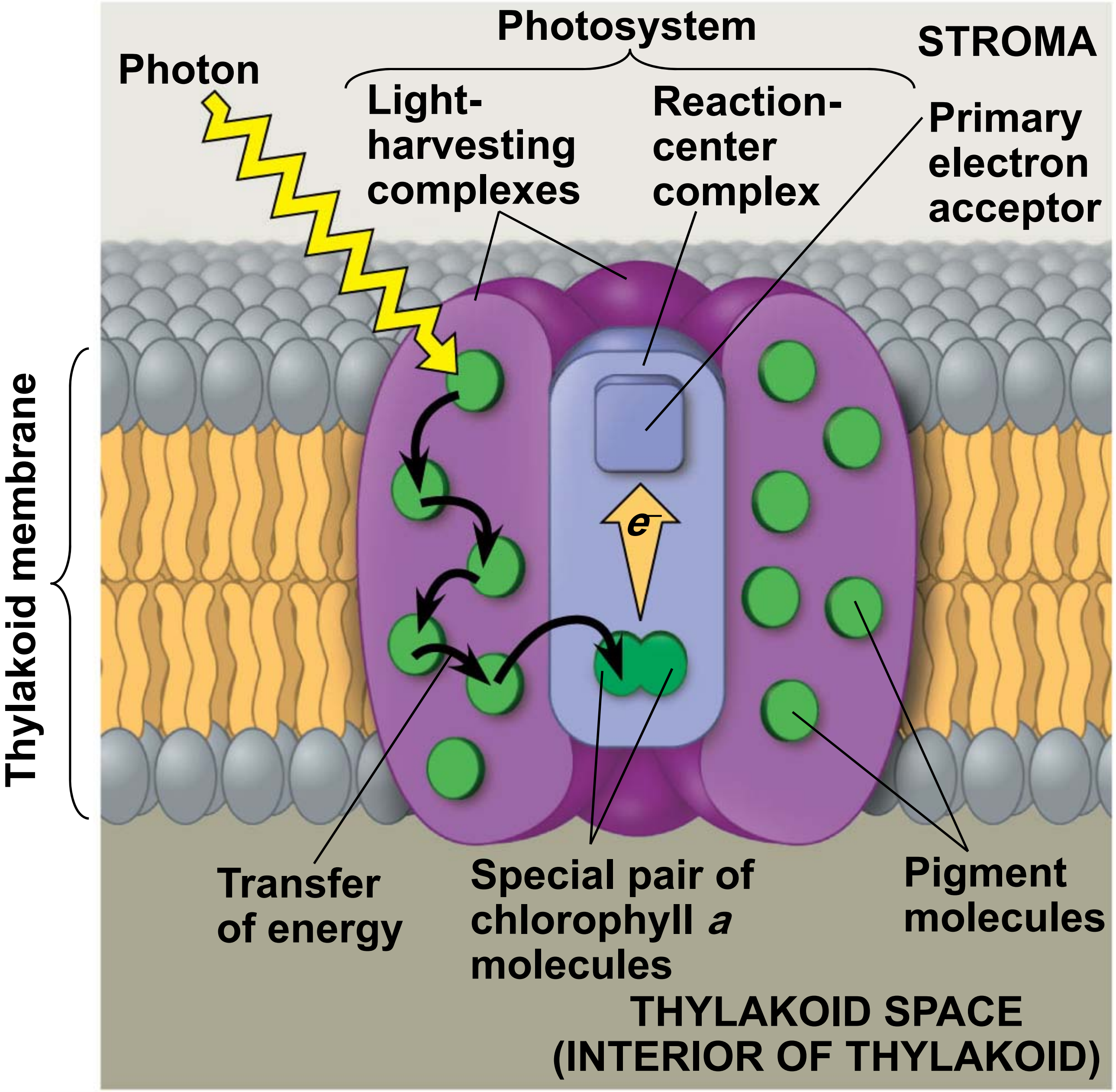


(a) How a photosystem harvests light



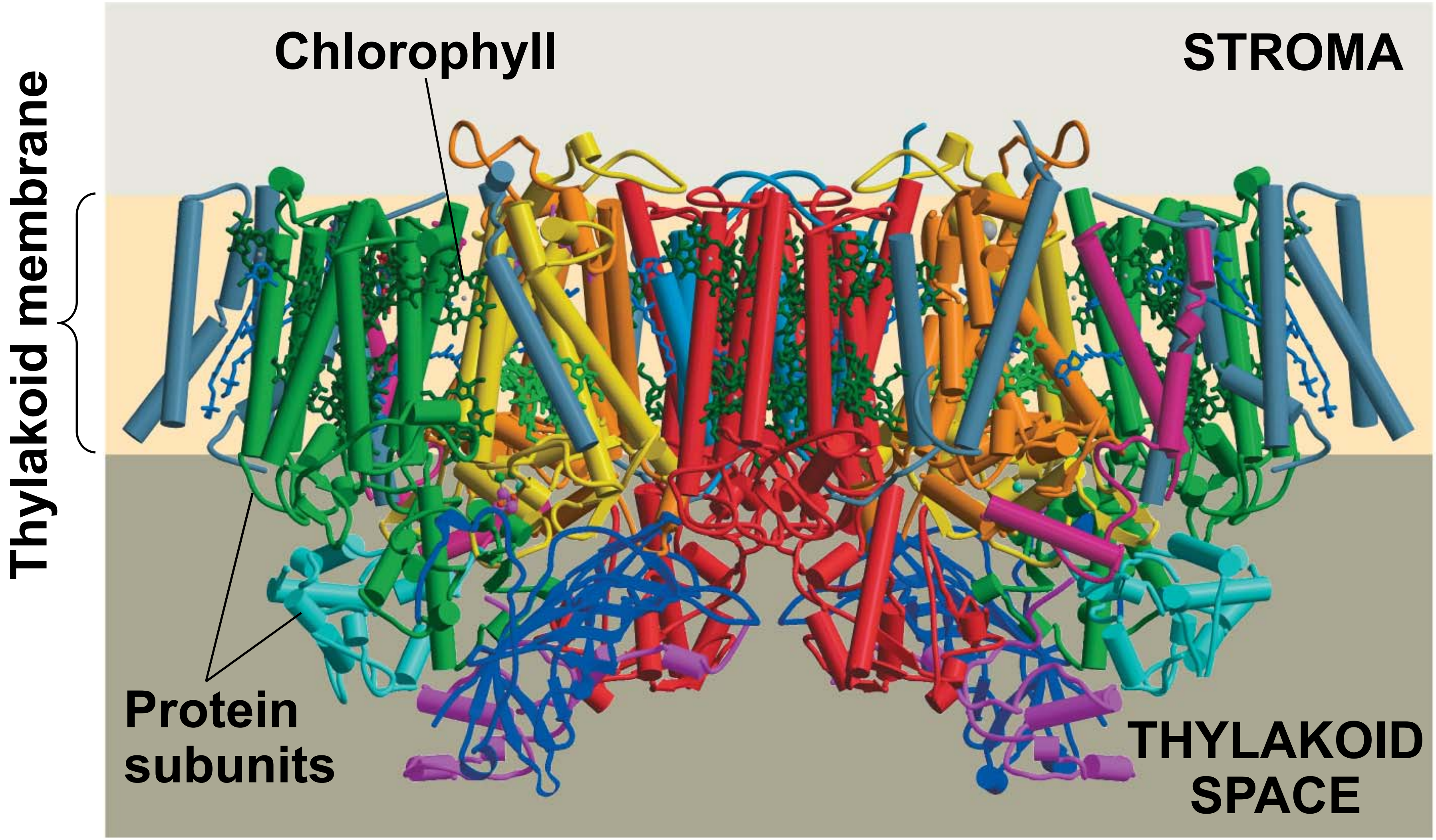
(b) Structure of photosystem II

Figure 10.13a



(a) How a photosystem harvests light

Figure 10.13b



(b) Structure of photosystem II

- A **primary electron acceptor** in the reaction center accepts excited electron and is reduced as a result
- Solar-powered transfer of an electron from a chlorophyll *a* molecule to the primary electron acceptor is the first step of the light reactions

- There are two types of photosystems in the thylakoid membrane
- **Photosystem II (PS II)** functions first (the numbers reflect order of discovery) and is best at absorbing a wavelength of 680 nm
- The reaction-center chlorophyll *a* of PS II is called P680

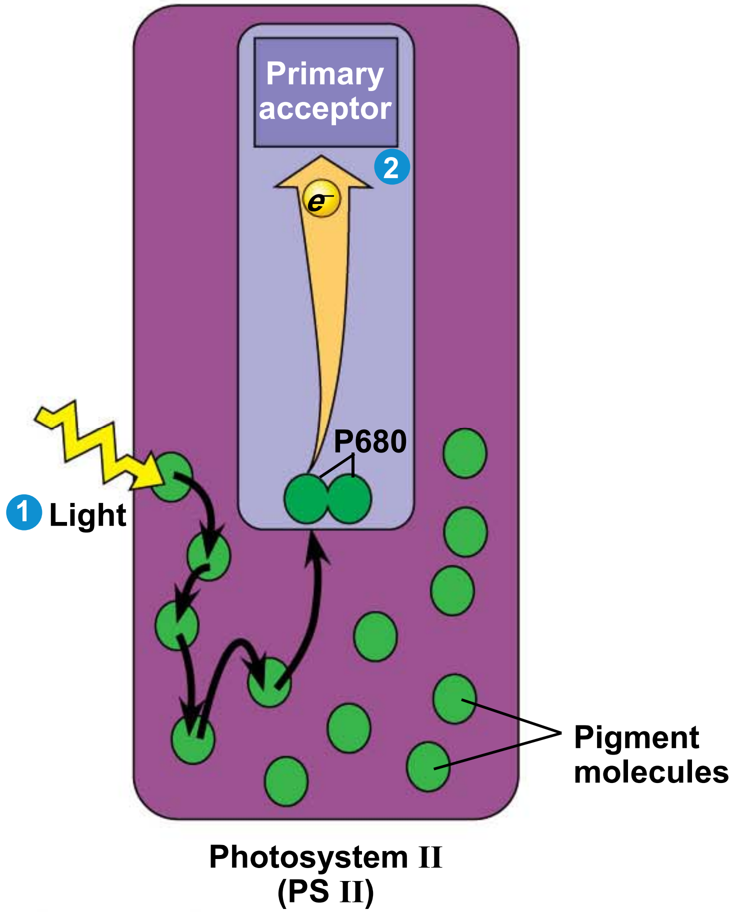
- **Photosystem I (PS I)** is best at absorbing a wavelength of 700 nm
- The reaction-center chlorophyll *a* of PS I is called P700

Linear Electron Flow

- During the light reactions, there are two possible routes for electron flow: cyclic and linear
- **Linear electron flow**, the primary pathway, involves both photosystems and produces ATP and NADPH using light energy

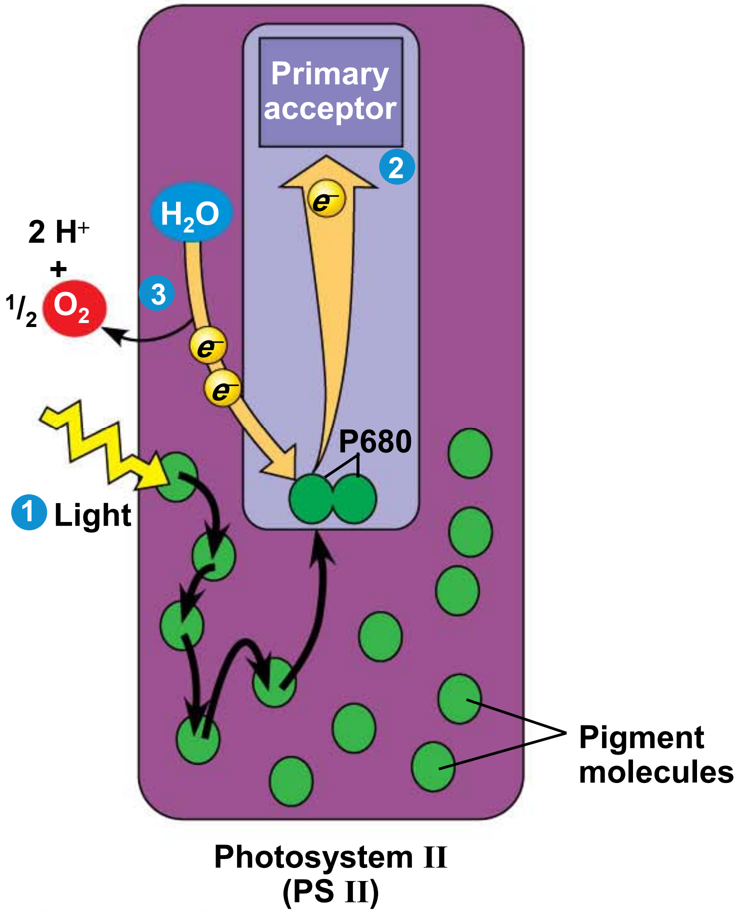
- A photon hits a pigment and its energy is passed among pigment molecules until it excites P680
- An excited electron from P680 is transferred to the primary electron acceptor (we now call it $P680^{+}$)

Figure 10.14-1



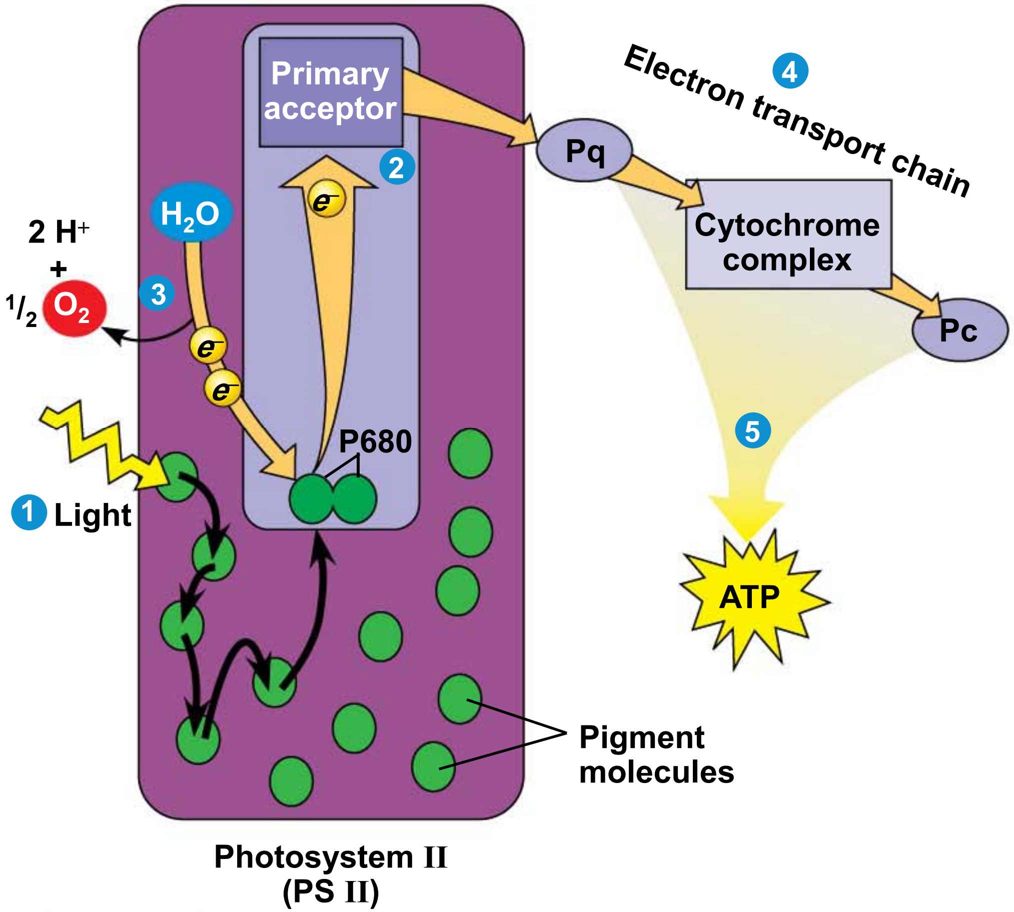
- $P680^+$ is a very strong oxidizing agent
- H_2O is split by enzymes, and the electrons are transferred from the hydrogen atoms to $P680^+$, thus reducing it to P680
- O_2 is released as a by-product of this reaction

Figure 10.14-2



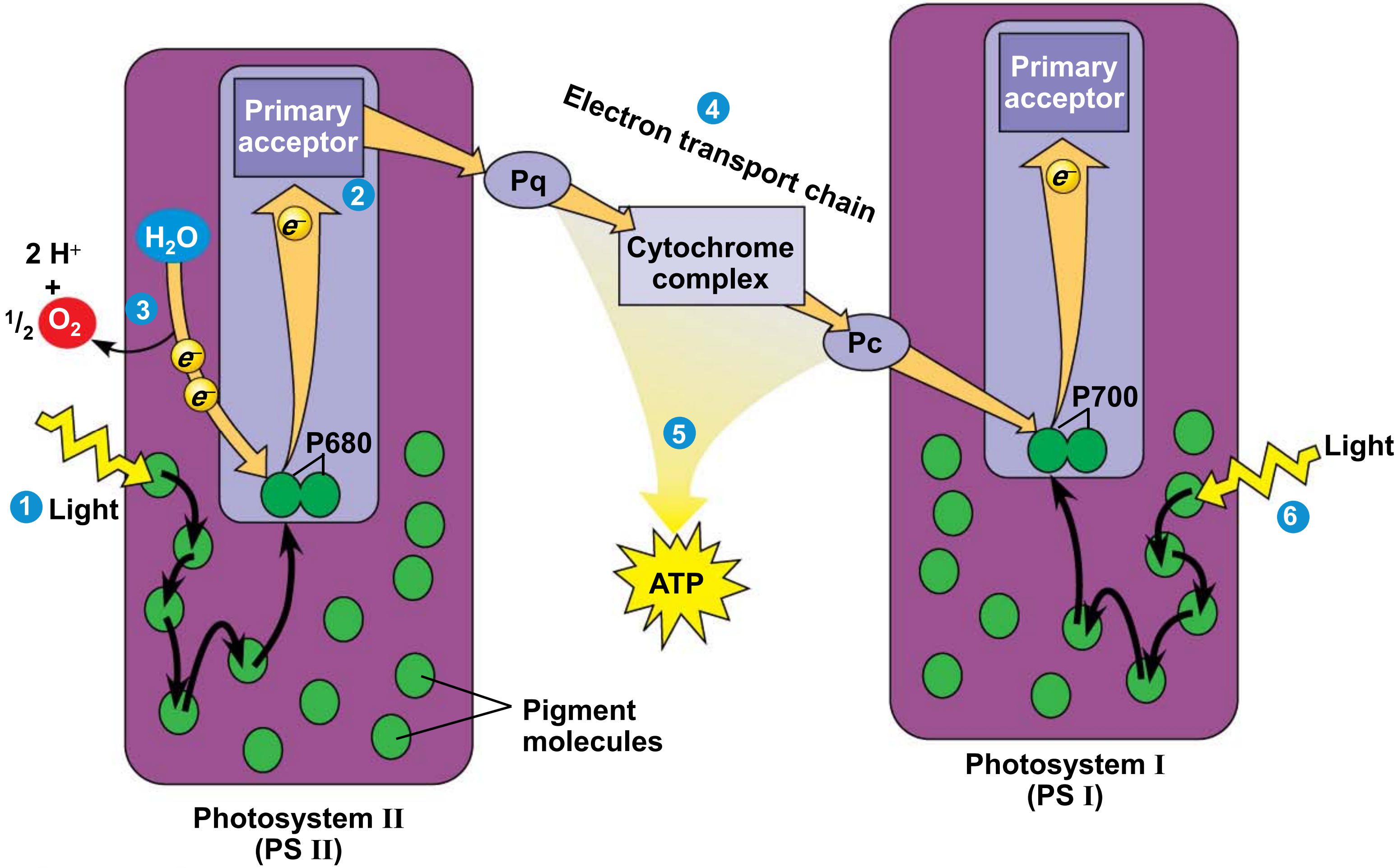
- Each electron “falls” down an electron transport chain from the primary electron acceptor of PS II to PS I
- Energy released by the fall drives the creation of a proton gradient across the thylakoid membrane
- Diffusion of H^+ (protons) across the membrane drives ATP synthesis

Figure 10.14-3



- In PS I (like PS II), transferred light energy excites P700, which loses an electron to an electron acceptor
- $P700^+$ (P700 that is missing an electron) accepts an electron passed down from PS II via the electron transport chain

Figure 10.14-4



- Each electron “falls” down an electron transport chain from the primary electron acceptor of PS I to the protein ferredoxin (Fd)
- The electrons are then transferred to $NADP^+$ and reduce it to NADPH
- The electrons of NADPH are available for the reactions of the Calvin cycle
- This process also removes an H^+ from the stroma

Figure 10.14-5

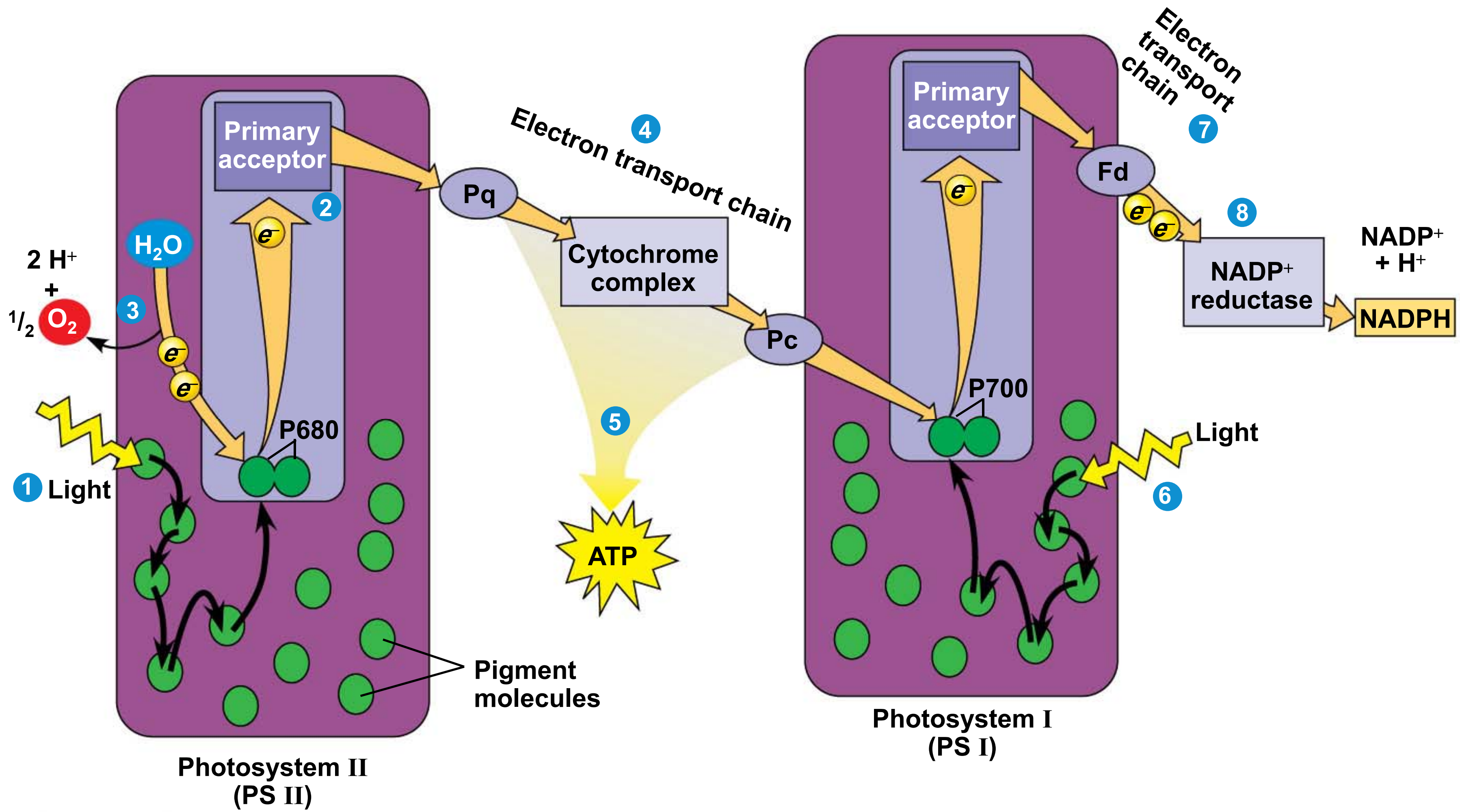
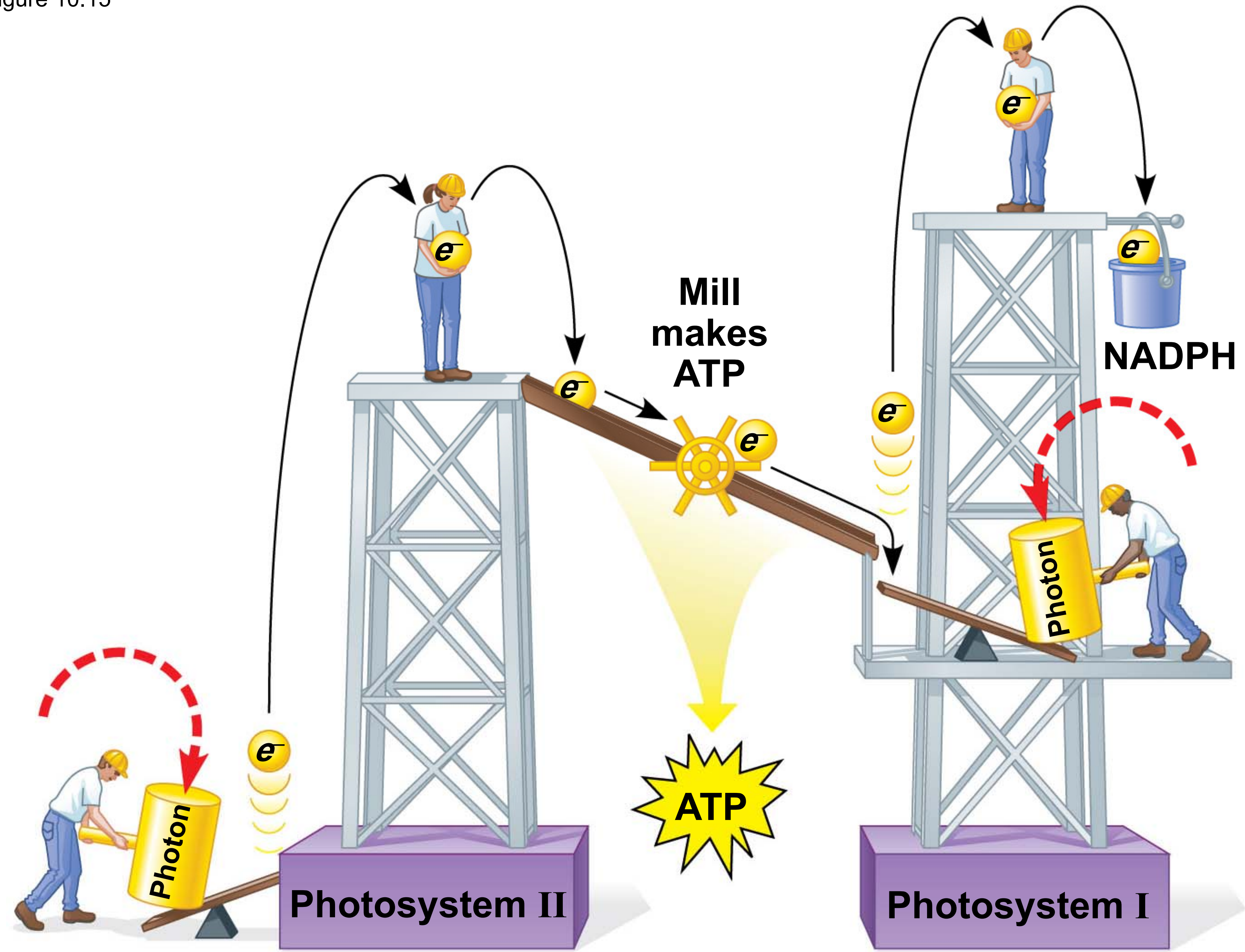


Figure 10.15

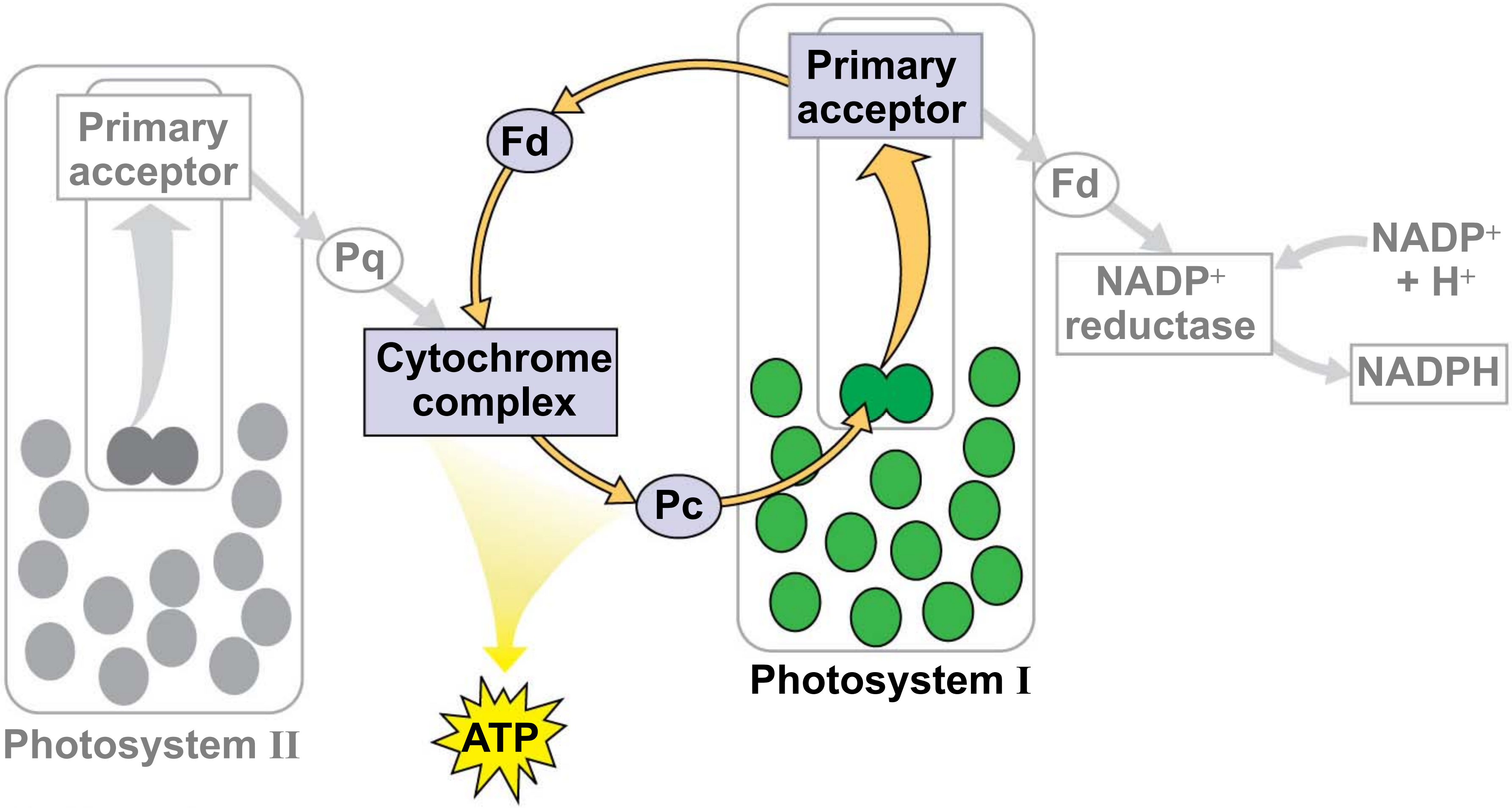


e⁻
Mill makes ATP
NADPH
Photon
ATP
Photosystem II
Photosystem I

Cyclic Electron Flow

- **Cyclic electron flow** uses only photosystem I and produces ATP, but not NADPH
- No oxygen is released
- Cyclic electron flow generates surplus ATP, satisfying the higher demand in the Calvin cycle

Figure 10.16


Primary acceptor
Pq
Fd
Cytochrome complex
Pc
Primary acceptor
Fd
NADP+ + H+
NADP+ reductase
NADPH
Photosystem II
ATP
Photosystem I

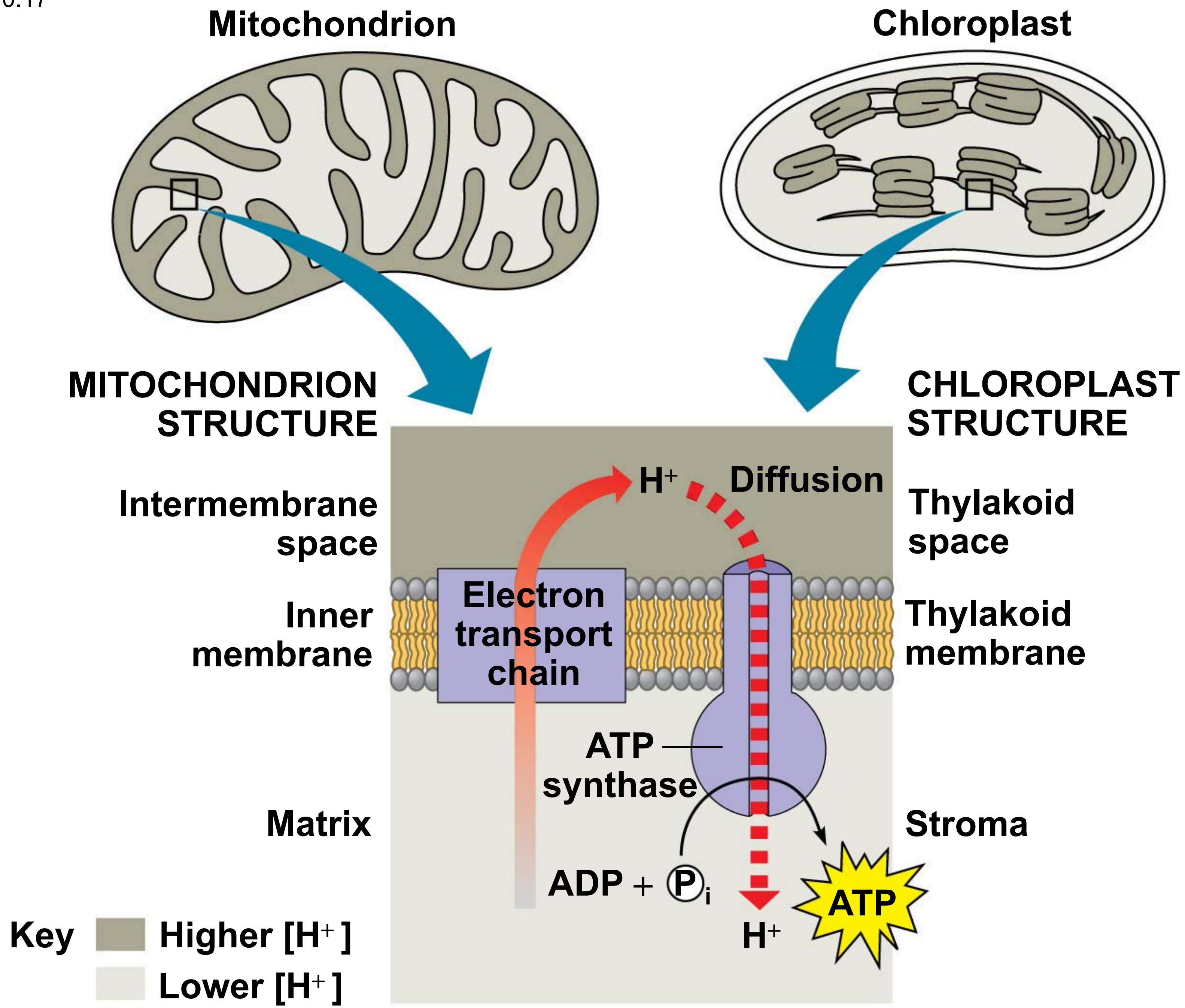
- Some organisms such as purple sulfur bacteria have PS I but not PS II
- Cyclic electron flow is thought to have evolved before linear electron flow
- Cyclic electron flow may protect cells from light-induced damage

A Comparison of Chemiosmosis in Chloroplasts and Mitochondria

- Chloroplasts and mitochondria generate ATP by chemiosmosis, but use different sources of energy
- Mitochondria transfer chemical energy from food to ATP; chloroplasts transform light energy into the chemical energy of ATP
- Spatial organization of chemiosmosis differs between chloroplasts and mitochondria but also shows similarities

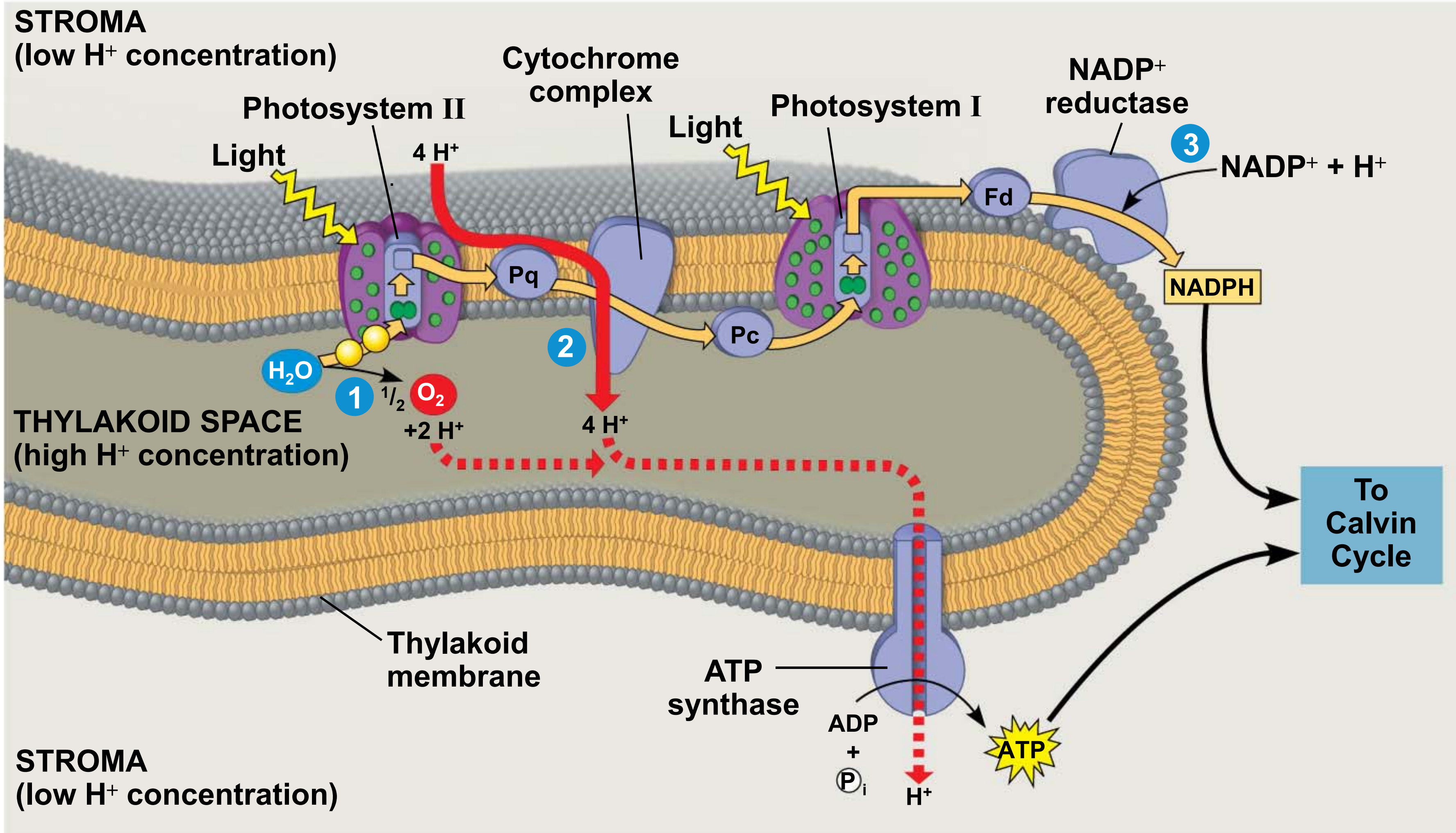
- In mitochondria, protons are pumped to the intermembrane space and drive ATP synthesis as they diffuse back into the mitochondrial matrix
- In chloroplasts, protons are pumped into the thylakoid space and drive ATP synthesis as they diffuse back into the stroma

Figure 10.17


Mitochondrion
Chloroplast
MITOCHONDRION STRUCTURE
CHLOROPLAST STRUCTURE
Intermembrane space
Inner membrane
Matrix
H+
Diffusion
Electron transport chain
ATP synthase
ADP + Pi
H+
ATP
Thylakoid space
Thylakoid membrane
Stroma
Key
Higher [H+]
Lower [H+]

- ATP and NADPH are produced on the side facing the stroma, where the Calvin cycle takes place
- In summary, light reactions generate ATP and increase the potential energy of electrons by moving them from H_2O to NADPH

Figure 10.18



STROMA
(low H+ concentration)
Photosystem II
Light
4 H+
Cytochrome complex
Light
Photosystem I
NADP+ reductase
3
NADP+ + H+
Fd
Pq
NADPH
Pc
2
H2O
1
1/2 O2
+2 H+
4 H+
THYLAKOID SPACE
(high H+ concentration)
To Calvin Cycle
Thylakoid membrane
ATP synthase
ADP
+
Pi
H+
ATP
STROMA
(low H+ concentration)

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

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

- Carbon enters the cycle as CO_2 and leaves as a sugar named **glyceraldehyde 3-phospate (G3P)**
- For net synthesis of 1 G3P, the cycle must take place three times, fixing 3 molecules of CO_2
- The Calvin cycle has three phases
  - **Carbon fixation** (catalyzed by **rubisco**)
  - **Reduction**
  - **Regeneration of the CO_2 acceptor (RuBP)**

Figure 10.19-1

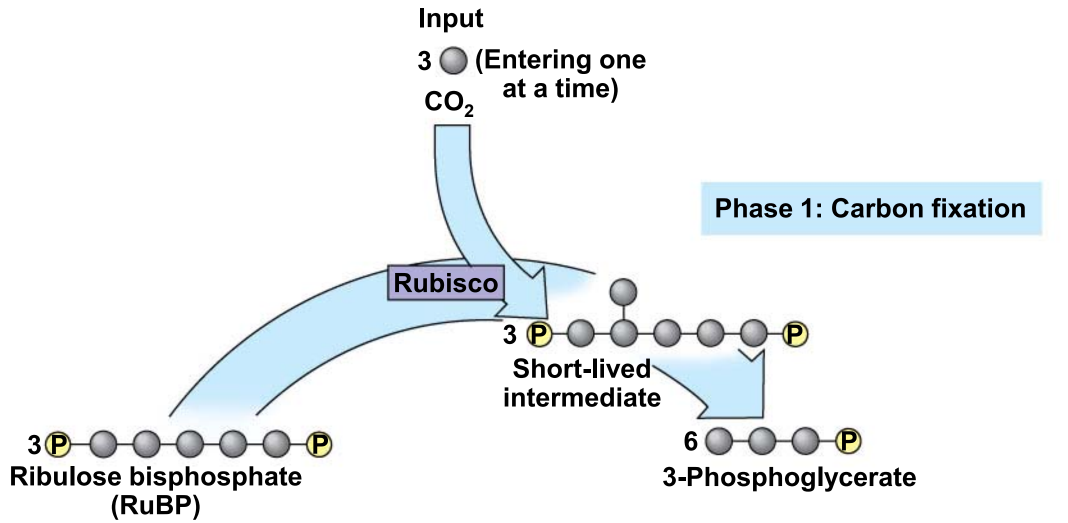


Figure 10.19-2

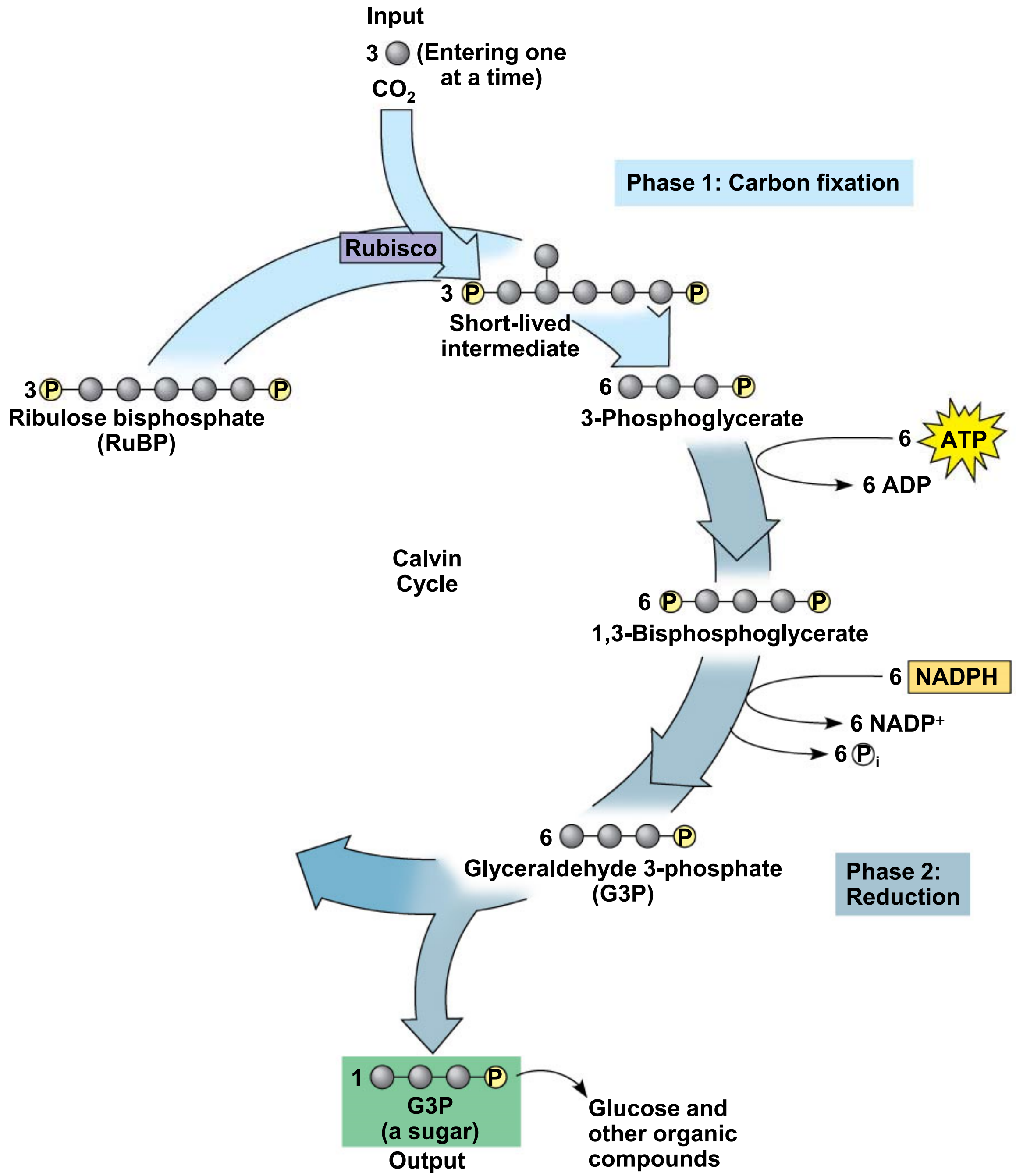
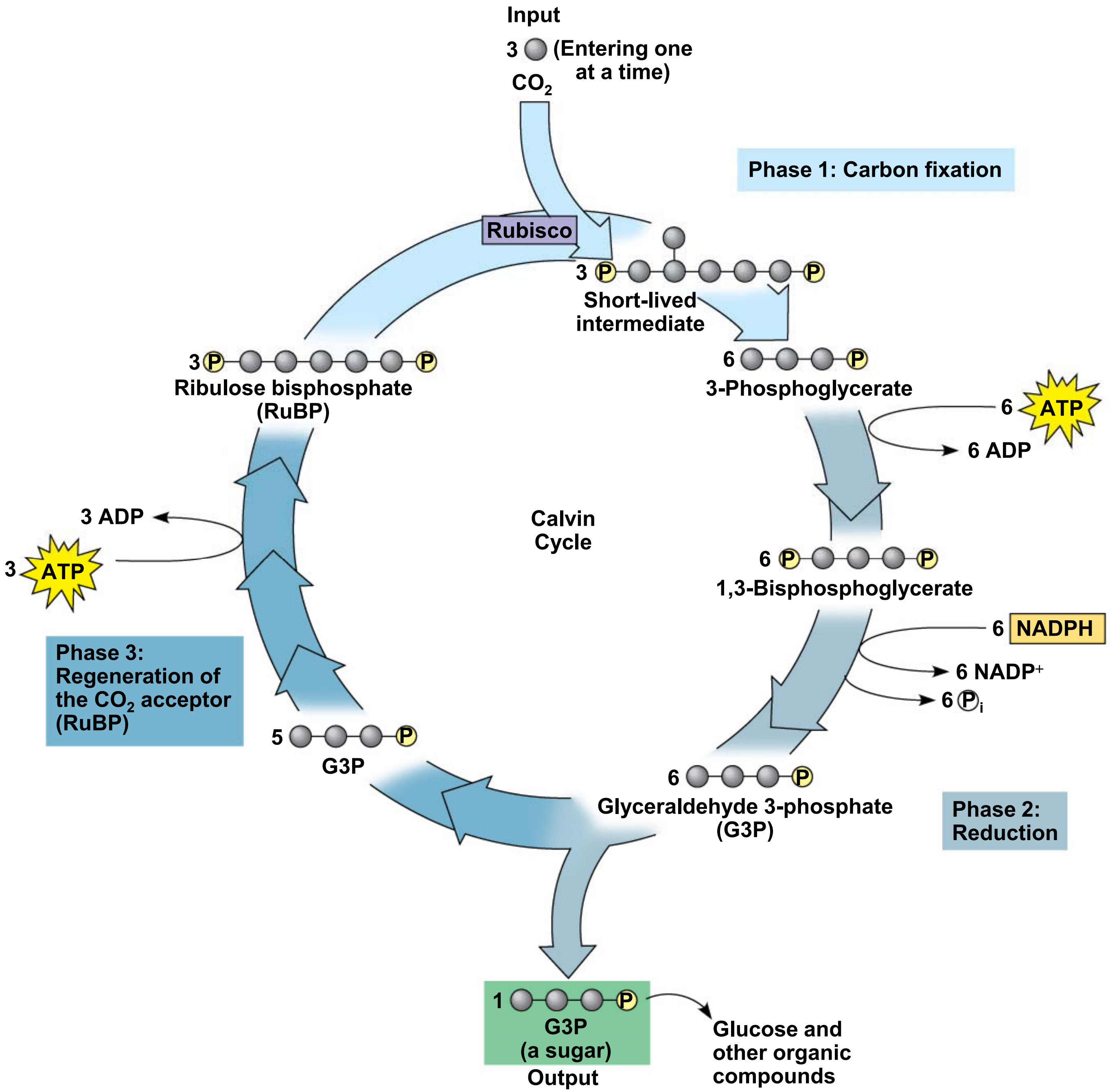


Figure 10.19-3



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

- Dehydration is a problem for plants, sometimes requiring trade-offs with other metabolic processes, especially photosynthesis
- On hot, dry days, plants close stomata, which conserves H_2O but also limits photosynthesis
- The closing of stomata reduces access to CO_2 and causes O_2 to build up
- These conditions favor an apparently wasteful process called **photorespiration**

Photorespiration: An Evolutionary Relic?

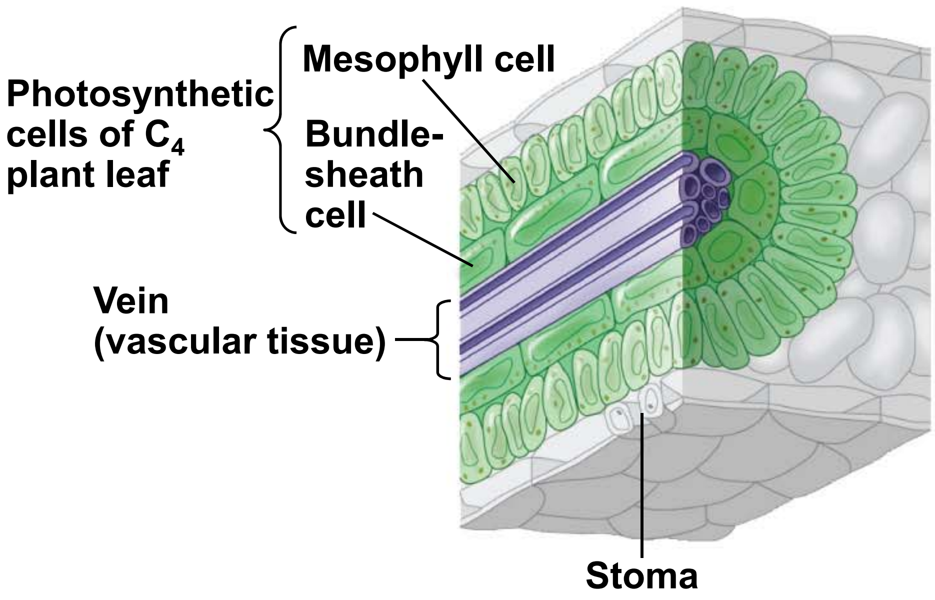
- In most plants (**C_3 plants**), initial fixation of CO_2, via rubisco, forms a three-carbon compound (3-phosphoglycerate)
- In photorespiration, rubisco adds O_2 instead of CO_2 in the Calvin cycle, producing a two-carbon compound
- Photorespiration consumes O_2 and organic fuel and releases CO_2 without producing ATP or sugar

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

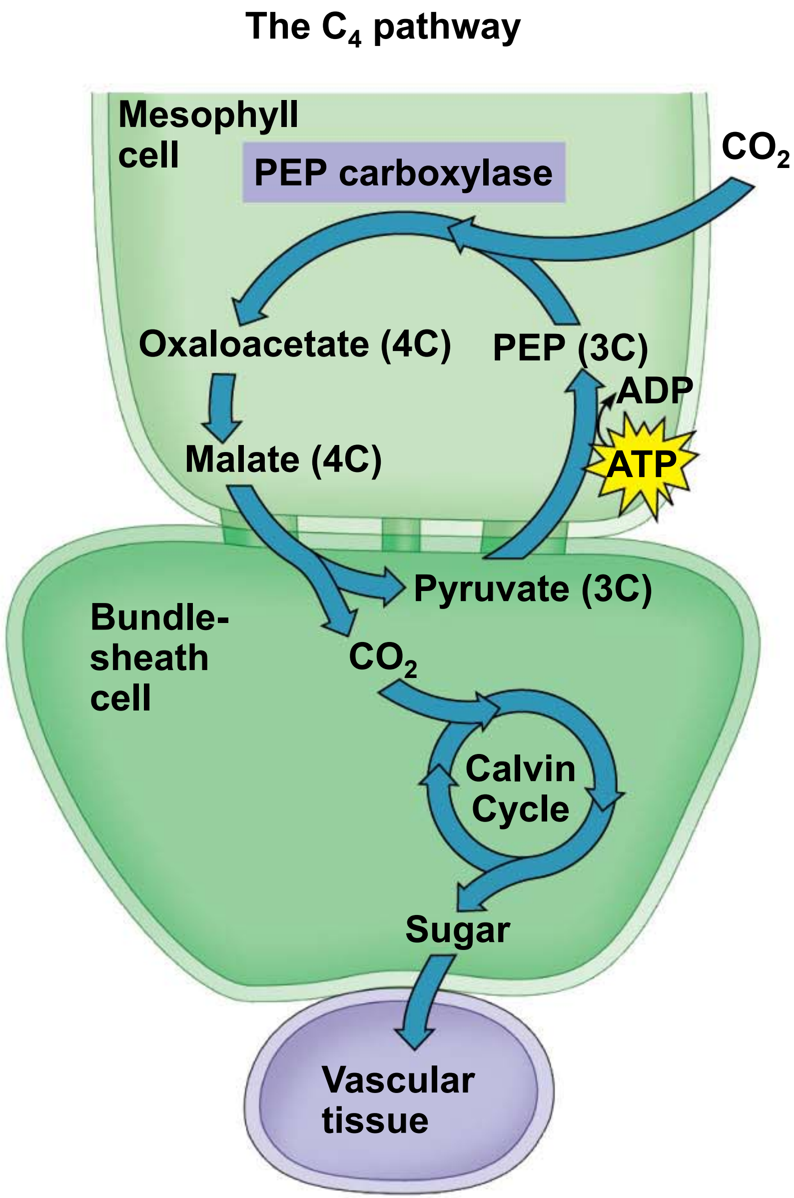
C_4 Plants

- **C_4 plants** minimize the cost of photorespiration by incorporating CO_2 into four-carbon compounds in mesophyll cells
- This step requires the enzyme **PEP carboxylase**
- PEP carboxylase has a higher affinity for CO_2 than rubisco does; it can fix CO_2 even when CO_2 concentrations are low
- These four-carbon compounds are exported to **bundle-sheath cells**, where they release CO_2 that is then used in the Calvin cycle

Figure 10.20



C4 leaf anatomy
Photosynthetic cells of C4 plant leaf
Mesophyll cell
Bundle-sheath cell
Vein (vascular tissue)
Stoma



The C4 pathway
Mesophyll cell
PEP carboxylase
CO2
Oxaloacetate (4C)
PEP (3C)
ADP
ATP
Malate (4C)
Pyruvate (3C)
Bundle-sheath cell
CO2
Calvin Cycle
Sugar
Vascular tissue

Figure 10.20a

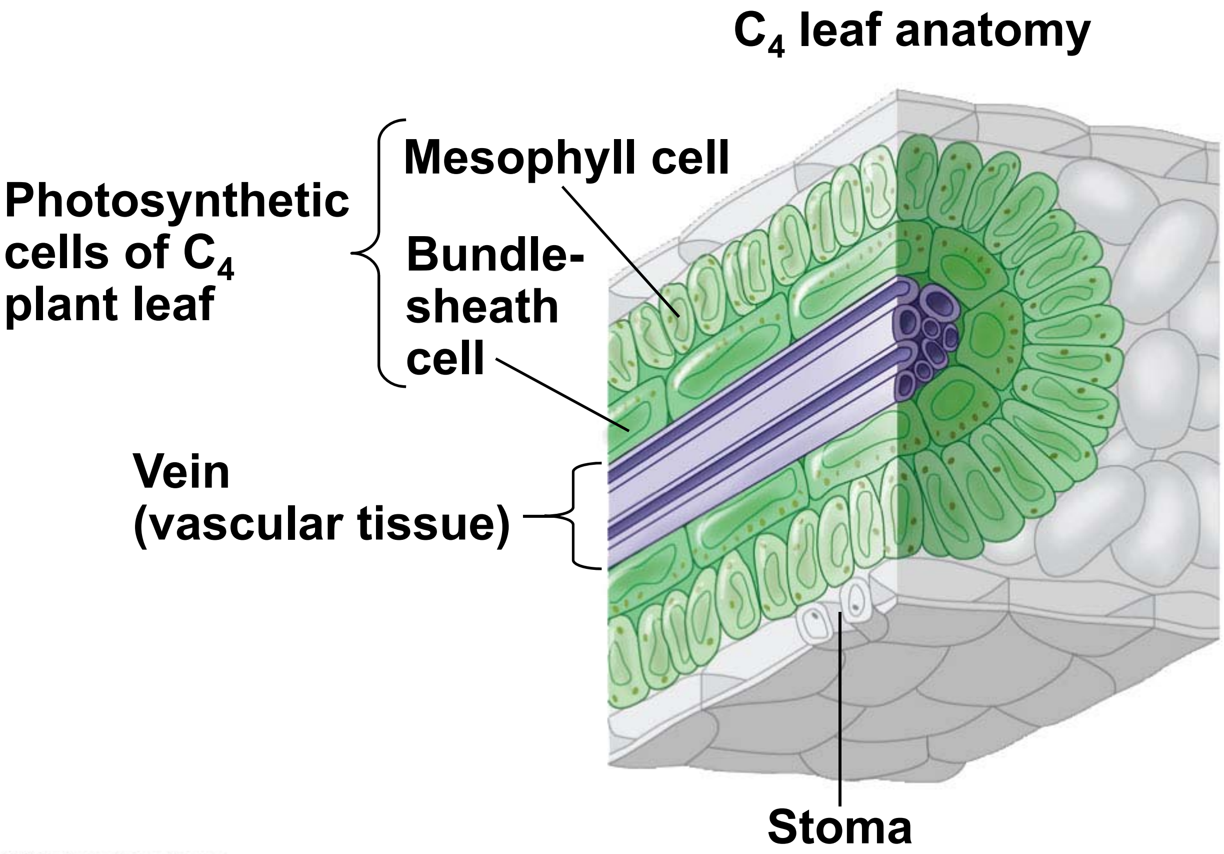
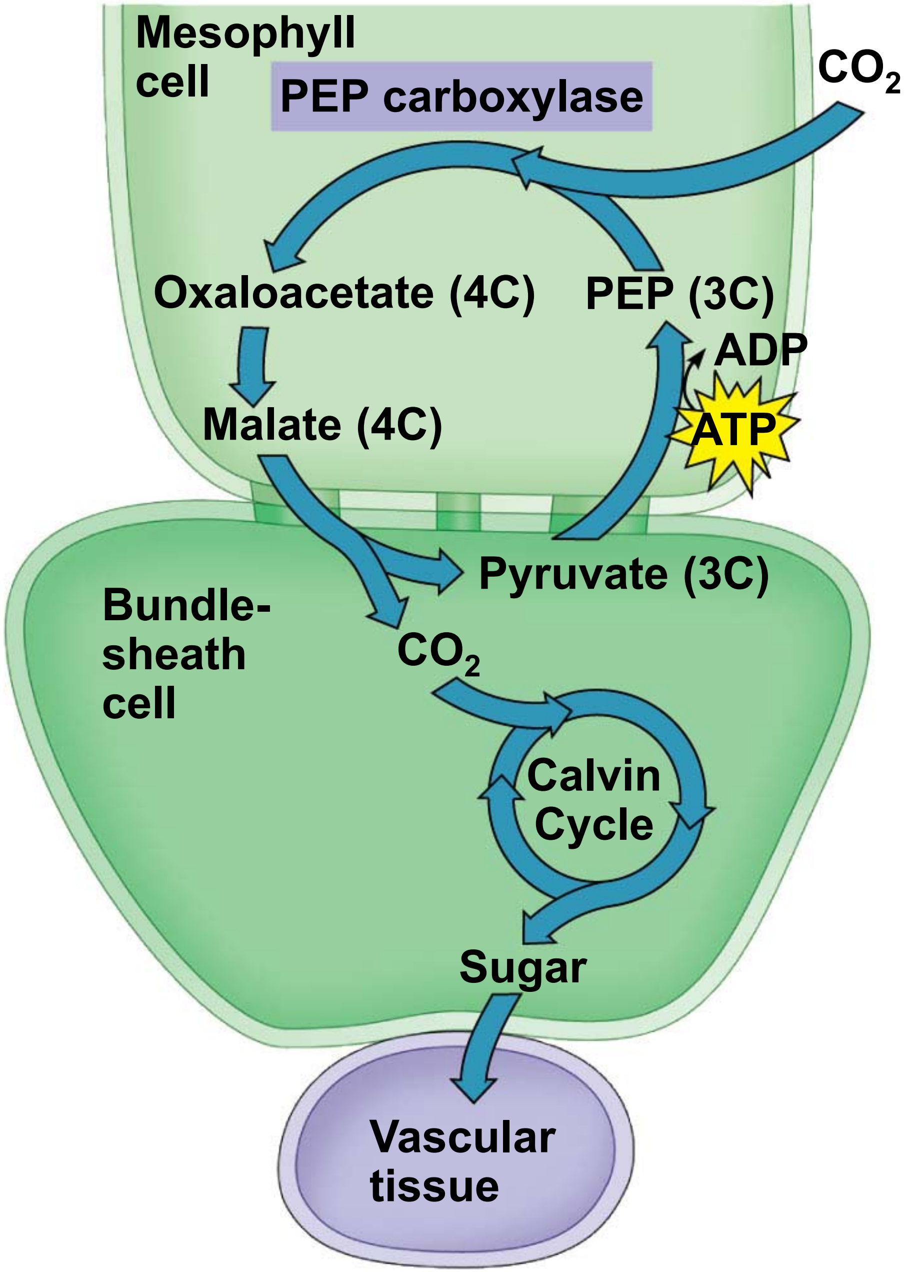


Figure 10.20b

The C_4 pathway

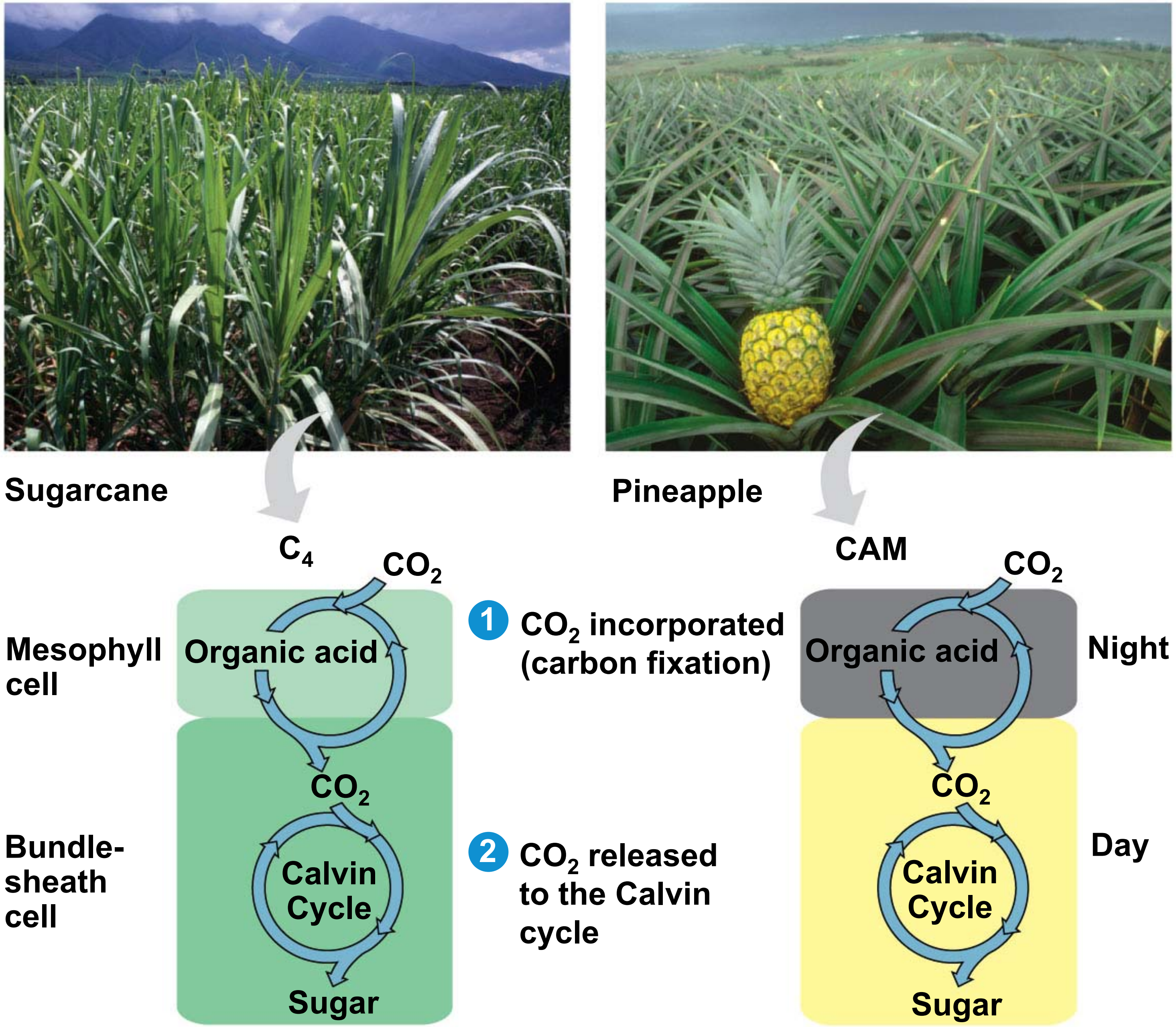


- In the last 150 years since the Industrial Revolution, CO_2 levels have risen gratly
- Increasing levels of CO_2 may affect C_3 and C_4 plants differently, perhaps changing relative abundance of these species
- The effects of such changes are unpredictable and a cause for concern

CAM Plants

- Some plants, including succulents, use **crassulacean acid metabolism (CAM)** to fix carbon
- **CAM plants** open their stomata at night, incorporating CO_2 into organic acids
- Stomata close during the day, and CO_2 is released from organic acids and used in the Calvin cycle

Figure 10.21



(a) Spatial separation of steps

(b) Temporal separation of steps

Figure 10.21a

Sugarcane

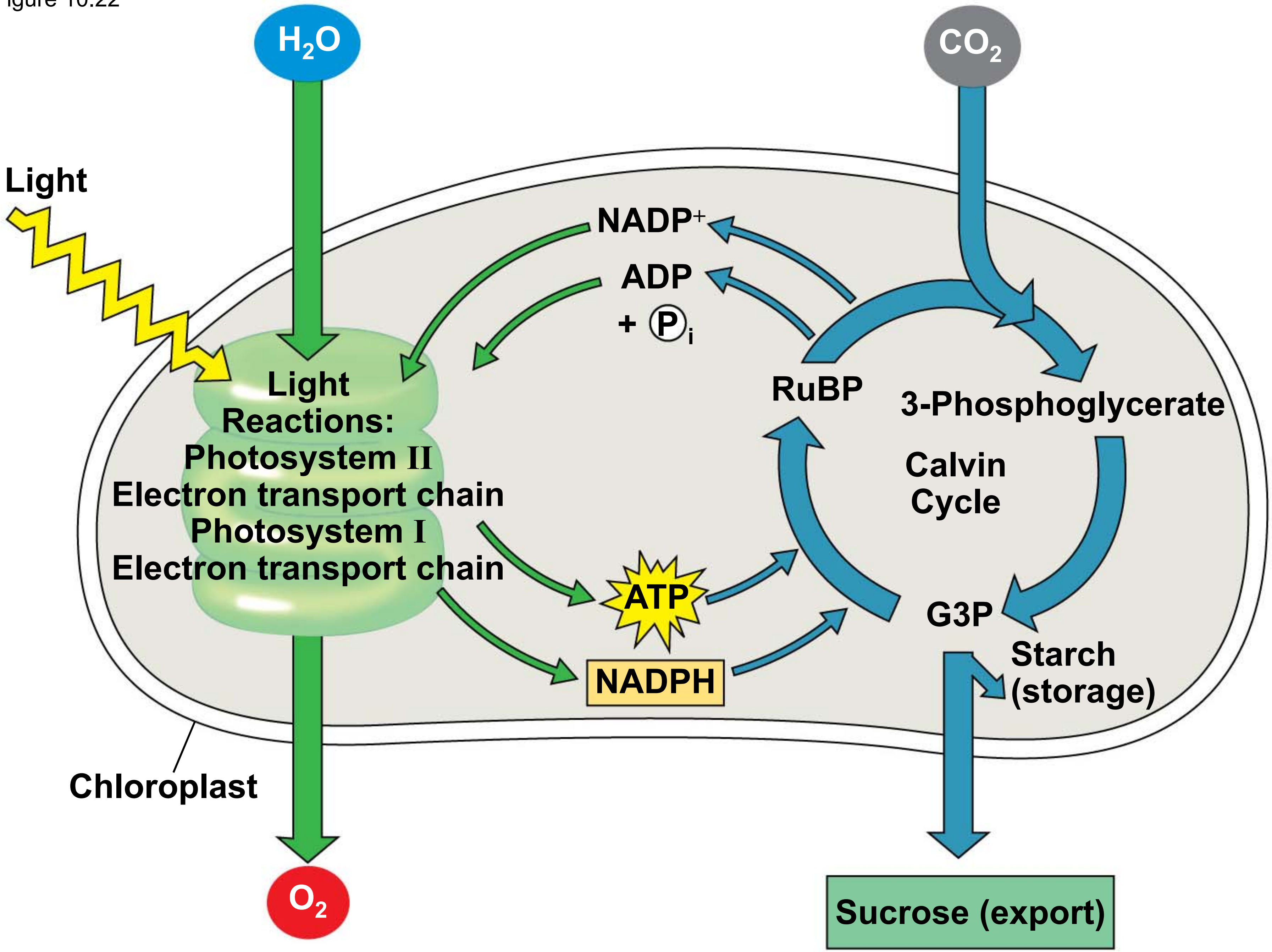
Figure 10.21b

Pineapple

The Importance of Photosynthesis: *A Review*

- The energy entering chloroplasts as sunlight gets stored as chemical energy in organic compounds
- Sugar made in the chloroplasts supplies chemical energy and carbon skeletons to synthesize the organic molecules of cells
- Plants store excess sugar as starch in structures such as roots, tubers, seeds, and fruits
- In addition to food production, photosynthesis produces the O_2 in our atmosphere

Figure 10.22



H_2O
CO_2
Light
NADP+
ADP
+ Ⓟi
Light Reactions:
Photosystem II
Electron transport chain
Photosystem I
Electron transport chain
RuBP
3-Phosphoglycerate
Calvin Cycle
ATP
NADPH
G3P
Starch (storage)
Chloroplast
O_2
Sucrose (export)

Figure 10.UN02

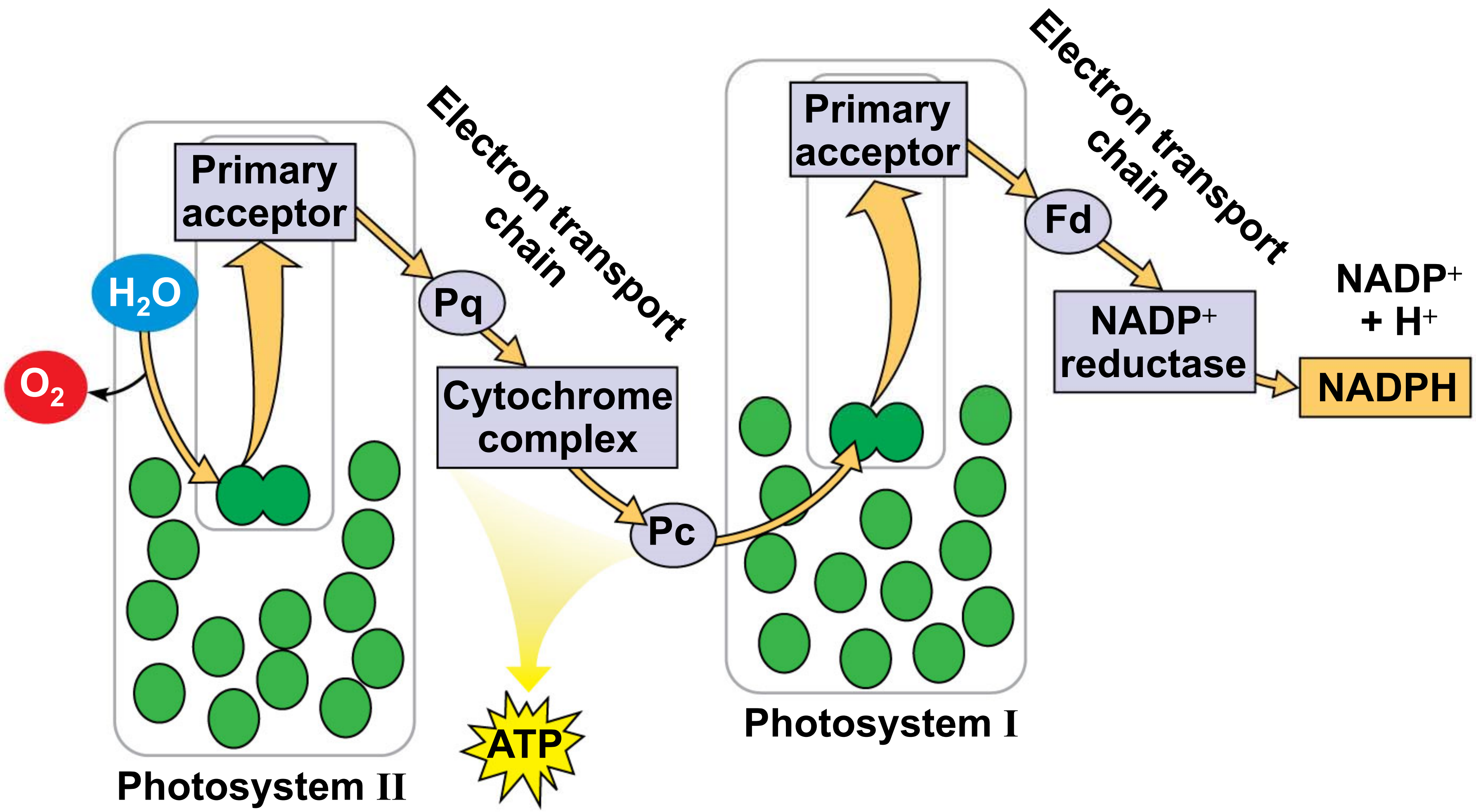


Figure 10.UN03

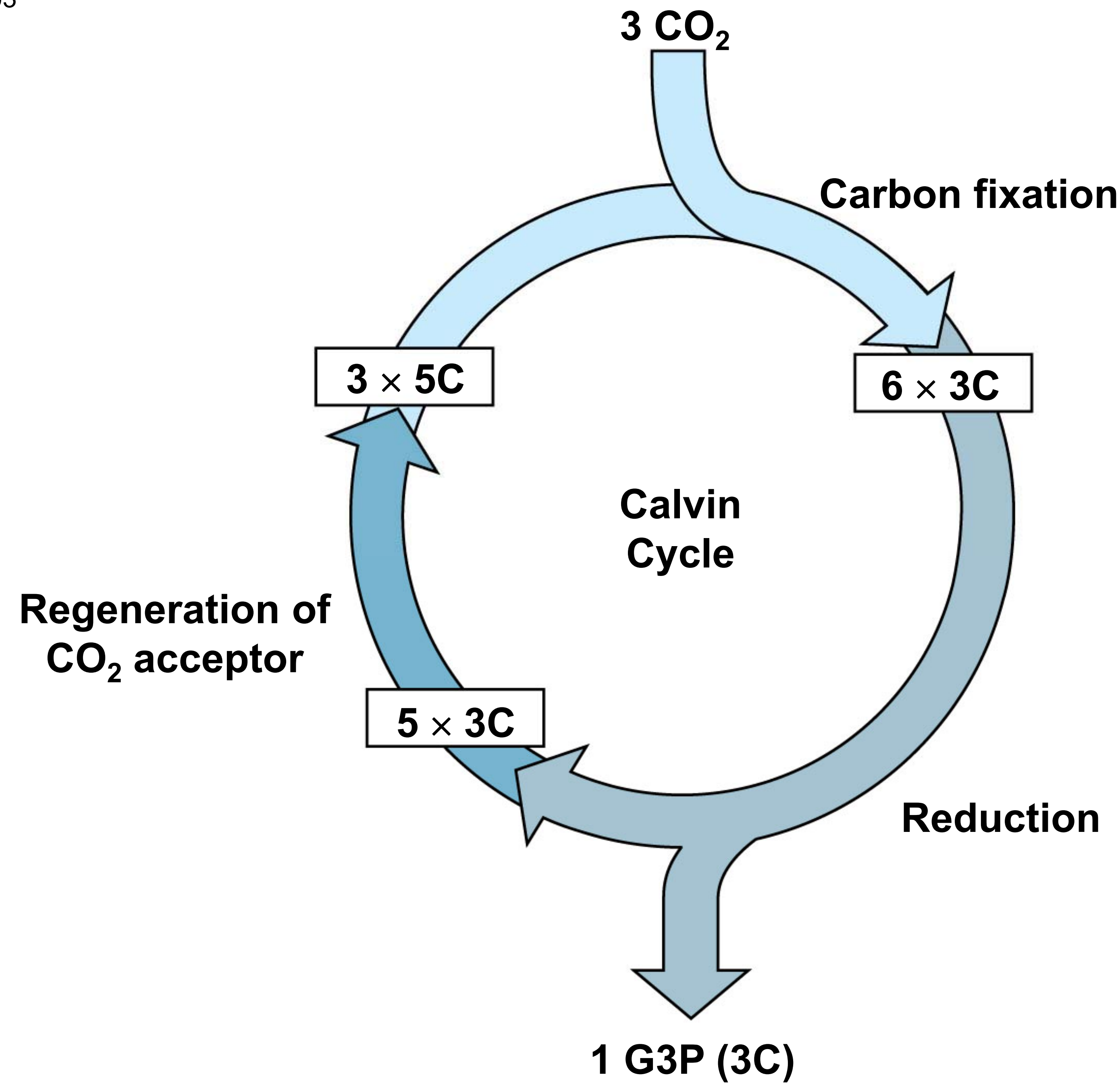


Figure 10.UN04

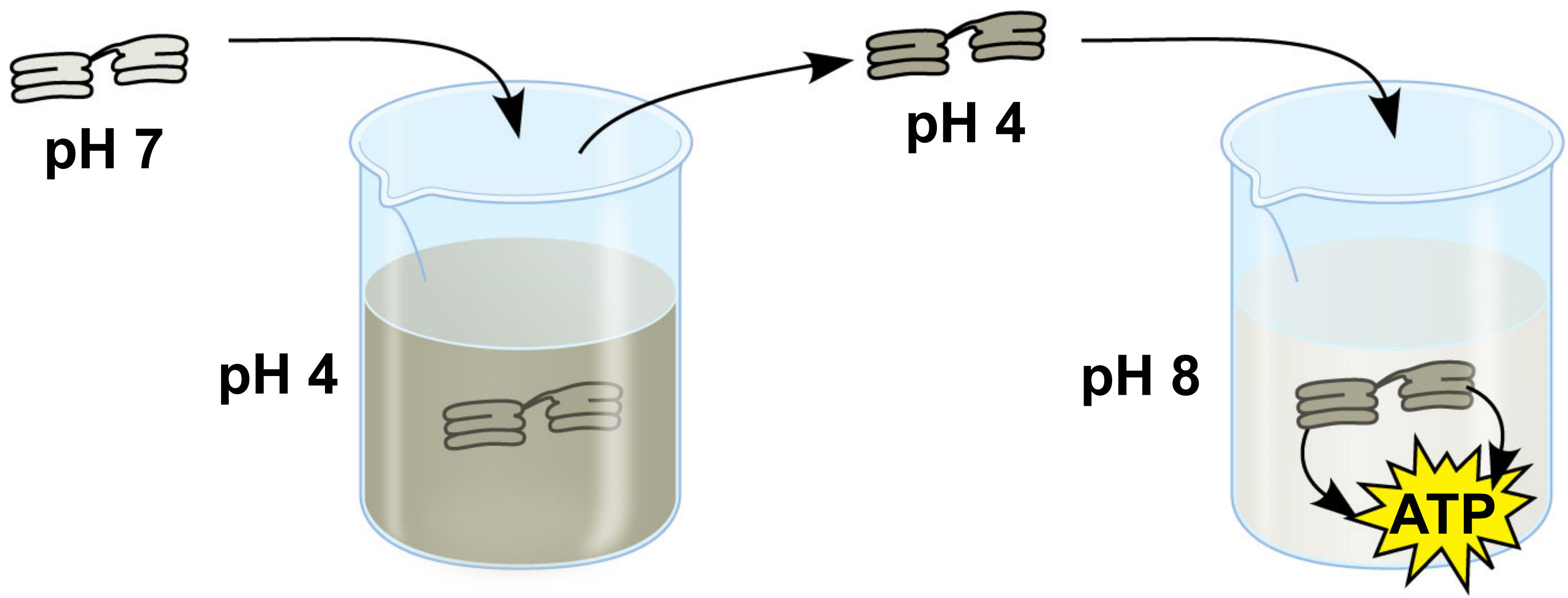


Figure 10.UN05

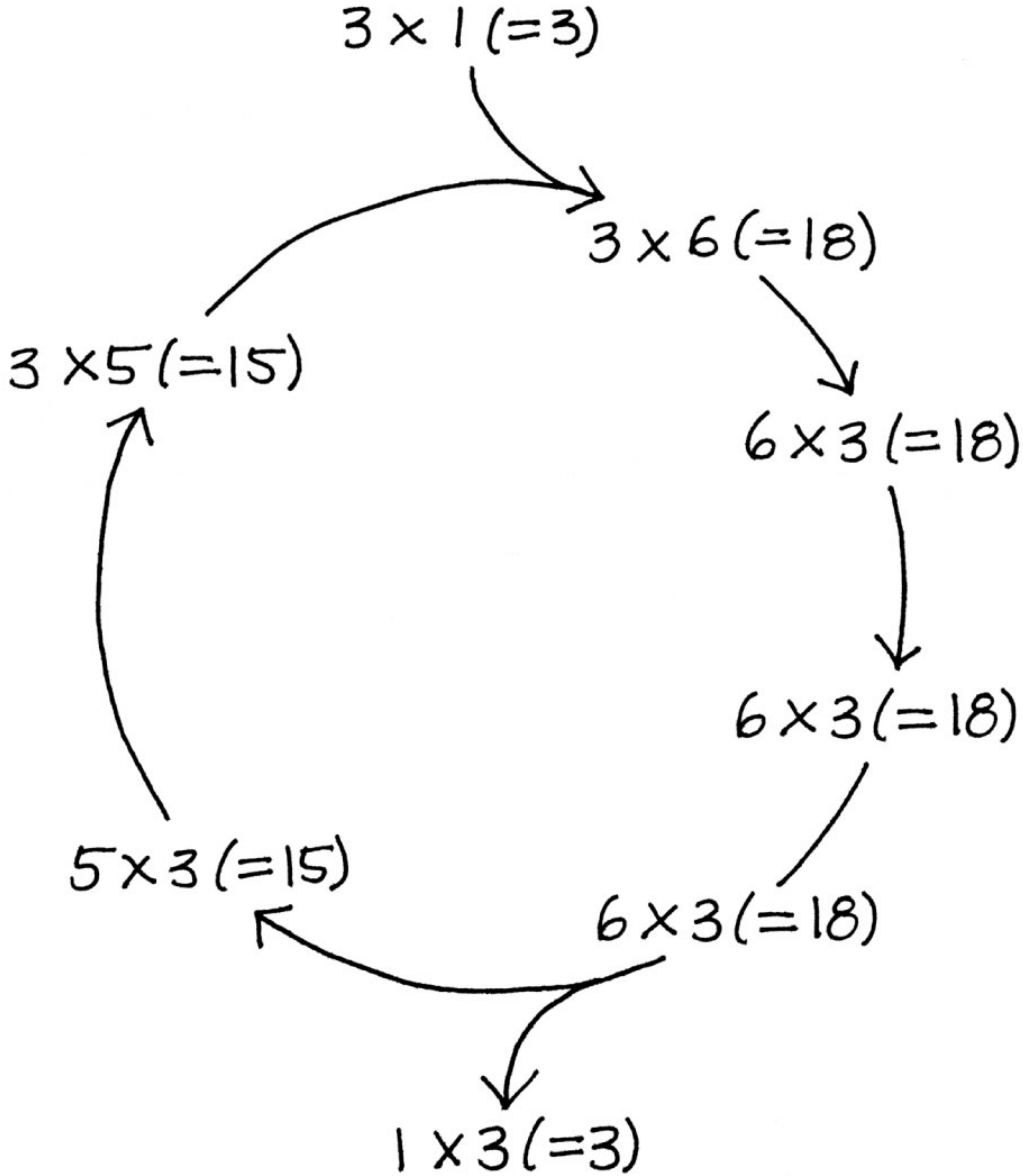


Figure 10.UN06

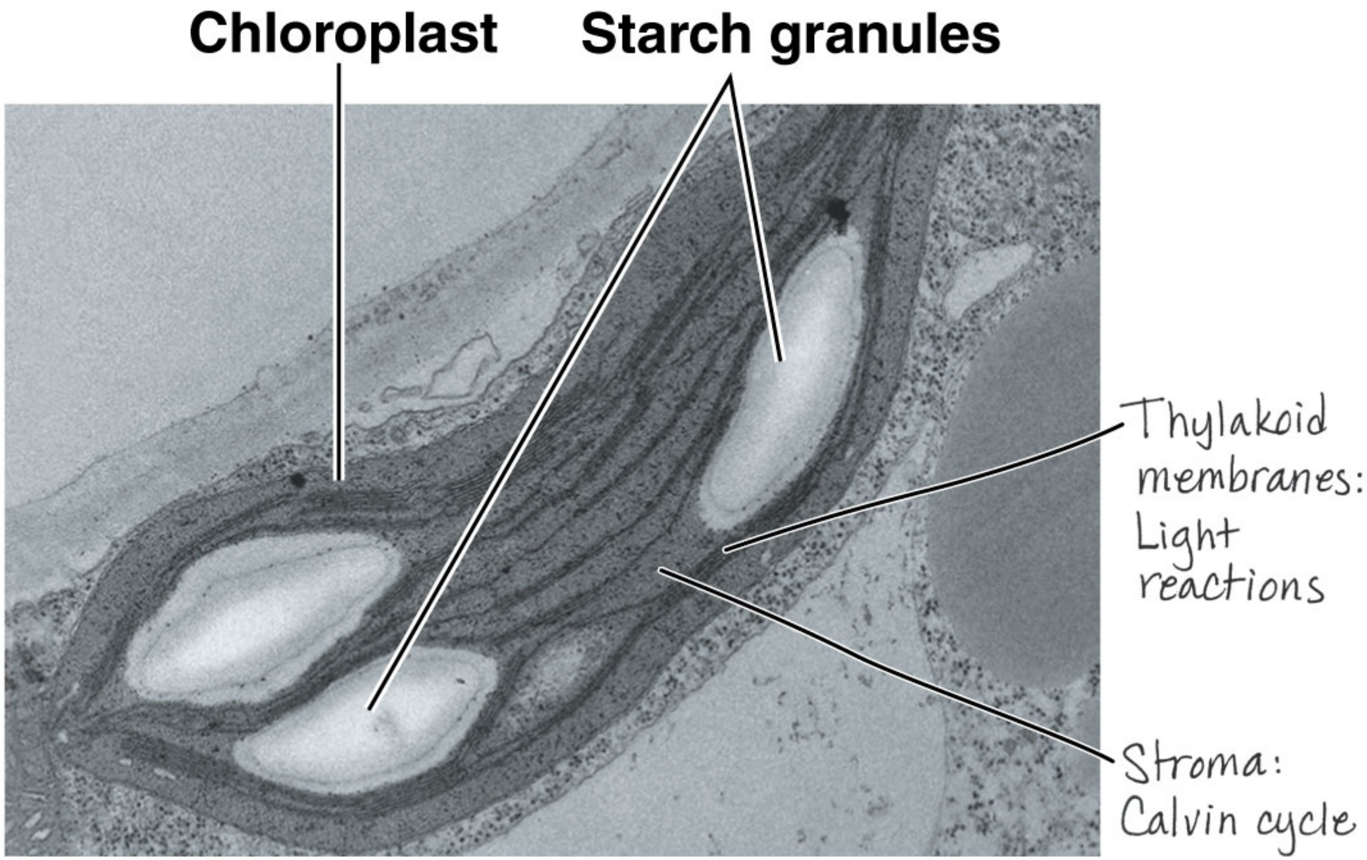


Figure 10.UN07

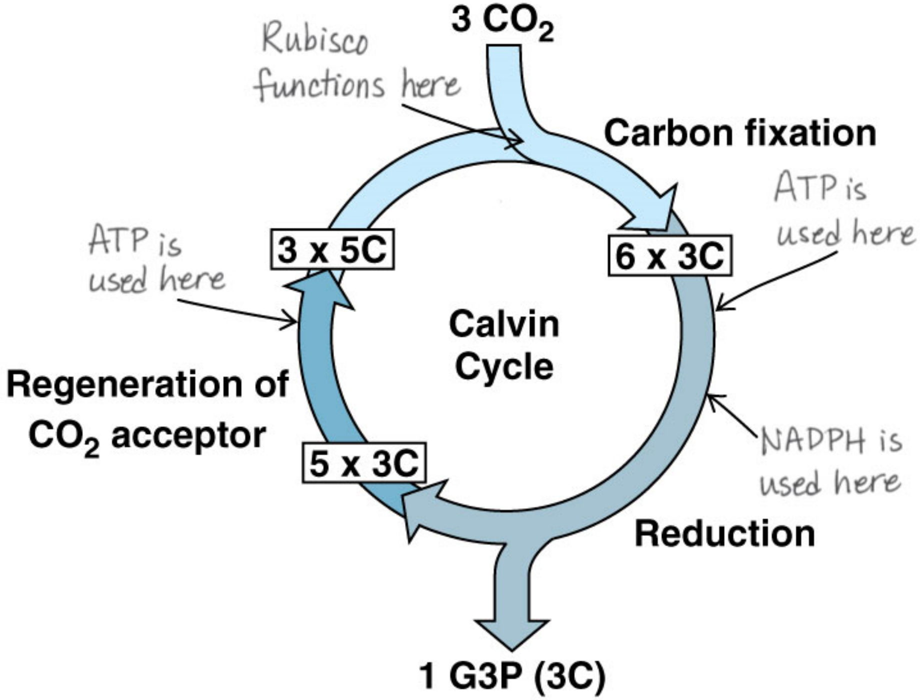
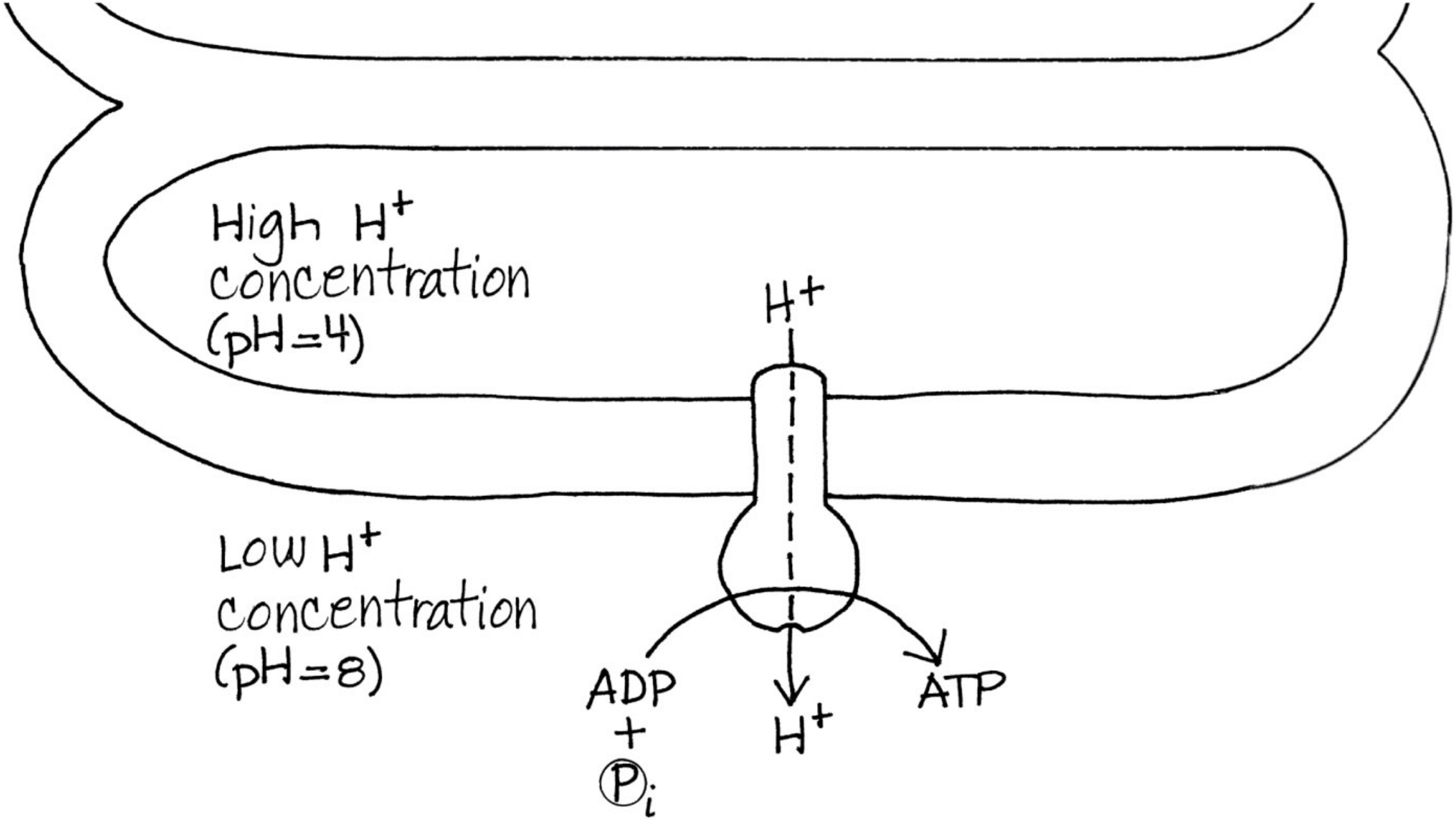


Figure 10.UN08



LECTURE PRESENTATIONS

For CAMPBELL BIOLOGY, NINTH EDITION

Jane B. Reece, Lisa A. Urry, Michael L. Cain, Steven A. Wasserman, Peter V. Minorsky, Robert B. Jackson

Chapter 12

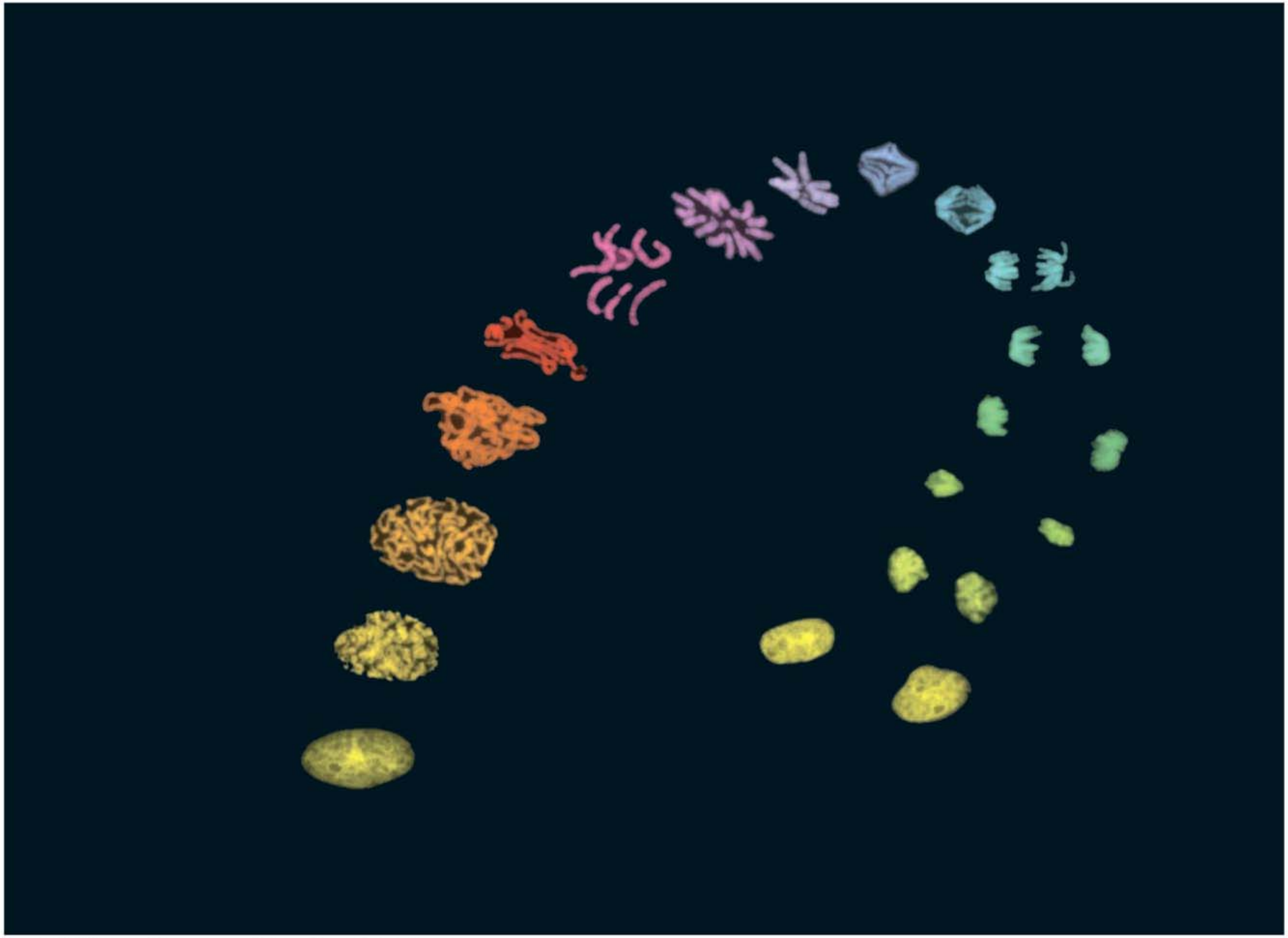
The Cell Cycle

Lectures by
Erin Barley
Kathleen Fitzpatrick

Overview: The Key Roles of Cell Division

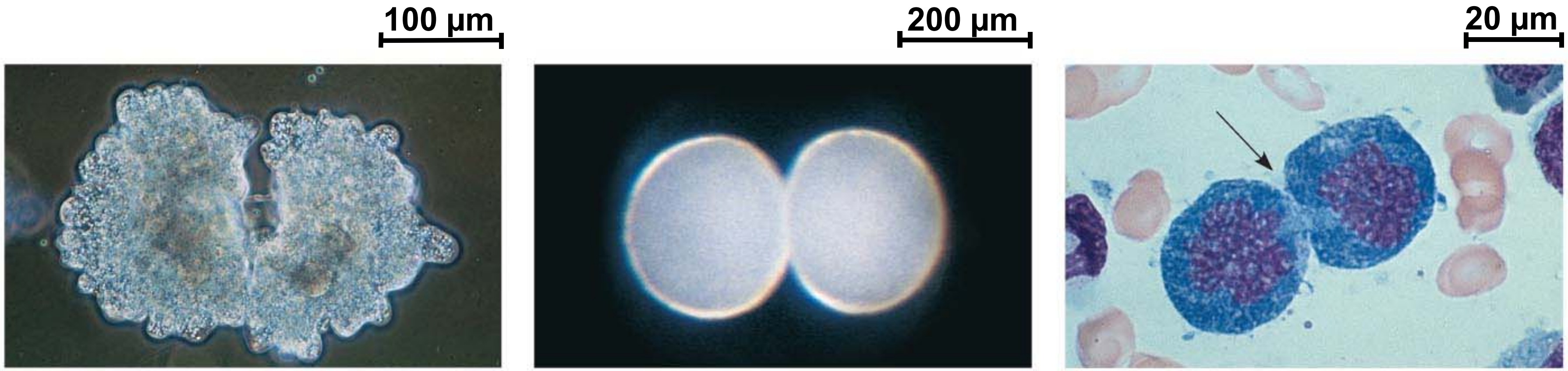
- The ability of organisms to reproduce best distinguishes living things from nonliving matter
- The continuity of life is based on the reproduction of cells, or **cell division**

Fig. 12-1



- In **unicellular organisms**, division of one cell **reproduces** the entire organism
- **Multicellular organisms** depend on cell division for:
  - **Development from a fertilized cell**
  - **Growth**
  - **Repair**
- Cell division is an integral part of the **cell cycle**, the life of a cell from formation to its own division

Fig. 12-2



(a) Reproduction

(b) Growth and development

(c) Tissue renewal

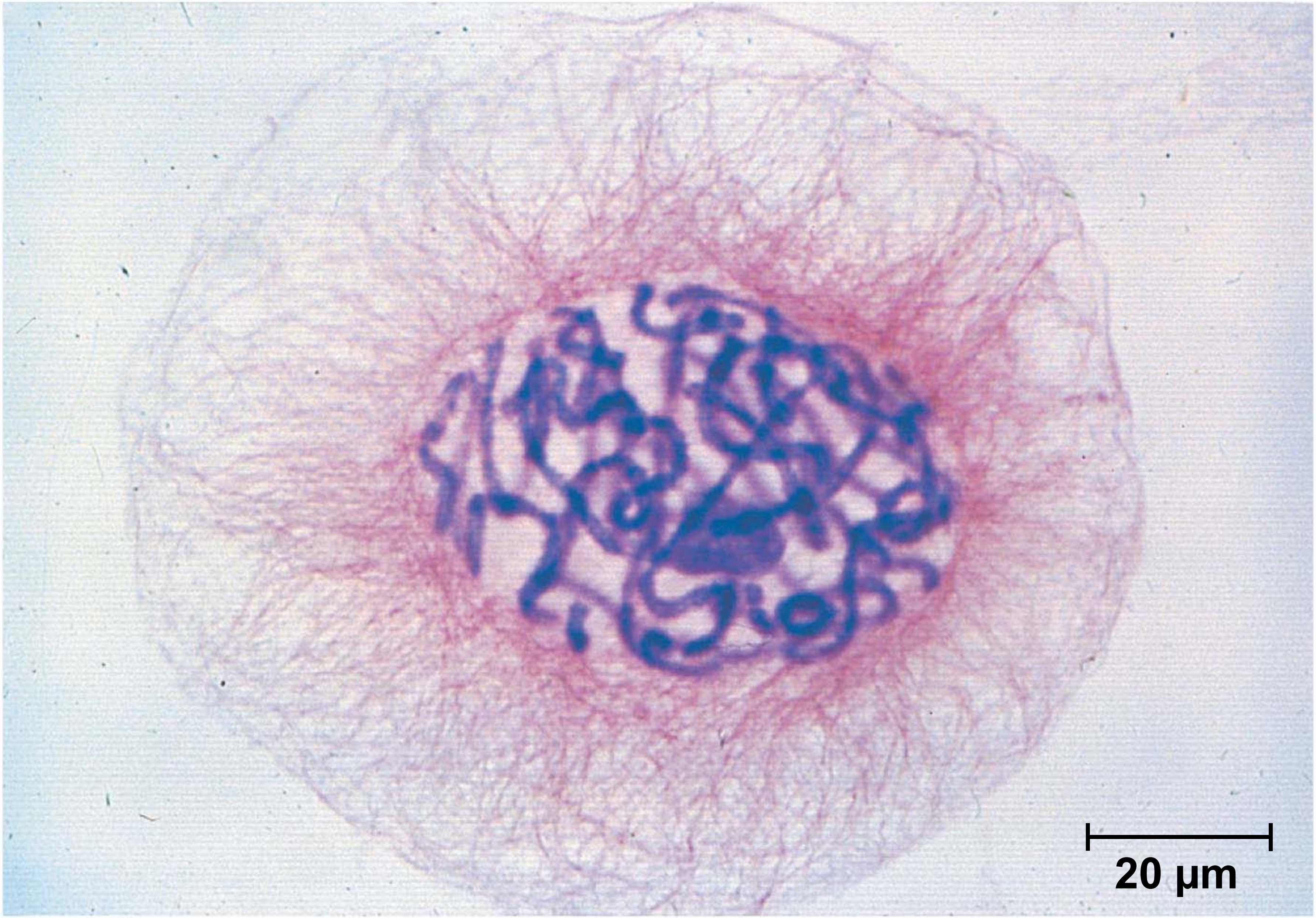
Concept 12.1: Cell division results in genetically identical daughter cells

- Most cell division results in daughter cells with identical genetic information, DNA
- A special type of division produces nonidentical daughter cells (gametes, or sperm and egg cells)

Cellular Organization of the Genetic Material

- *All the DNA in a cell constitutes the cell's* **genome**
- A genome can consist of a single DNA molecule (common in prokaryotic cells) or a number of DNA molecules (common in eukaryotic cells)
- DNA molecules in a cell are packaged into **chromosomes**

Fig. 12-3

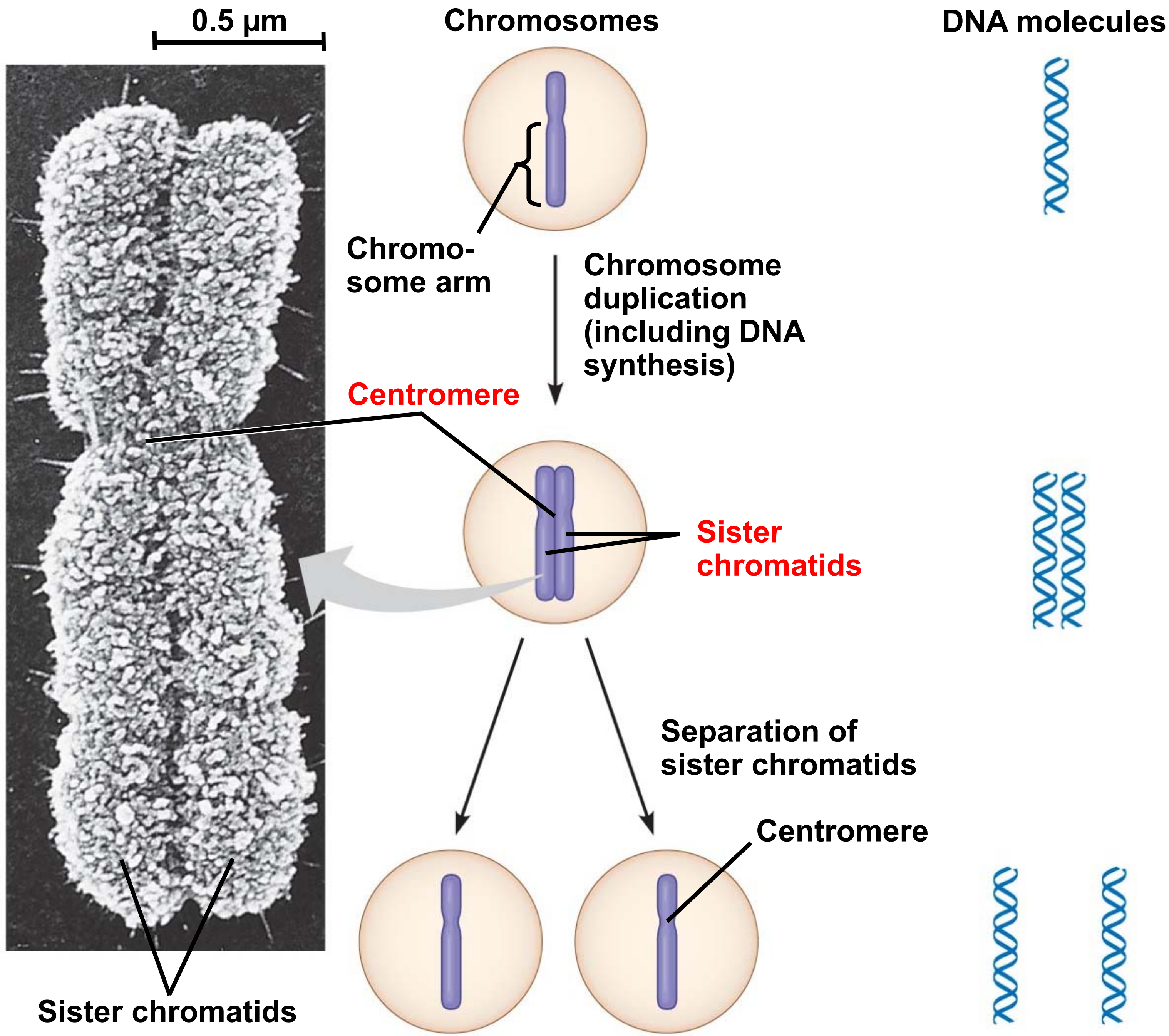


- Every eukaryotic species has a characteristic number of chromosomes in each cell nucleus
- **Somatic cells** (nonreproductive cells) have two sets of chromosomes (2n)
- **Gametes** (reproductive cells: sperm and eggs) have half as many chromosomes as somatic cells (1n).
- Eukaryotic chromosomes consist of **chromatin**, a complex of DNA and protein that condenses during cell division

Distribution of Chromosomes During Eukaryotic Cell Division

- In preparation for cell division, DNA is replicated and the chromosomes condense
- Each duplicated chromosome has two **sister chromatids**, which separate during cell division
- The **centromere** is the narrow "waist" of the duplicated chromosome, where the two chromatids are most closely attached

Fig. 12-4


0.5 µm
Chromosomes
DNA molecules
Chromo-
some arm
Chromosome
duplication
(including DNA
synthesis)
Centromere
Sister
chromatids
Separation of
sister chromatids
Centromere
Sister chromatids

- **Eukaryotic cell division consists of**:
  - **Mitosis**, the division of the nucleus
  - **Cytokinesis**, the division of the cytoplasm
- Gametes are produced by a variation of cell division called **meiosis**
- Meiosis yields nonidentical daughter cells that have only one set of chromosomes, half as many as the parent cell

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

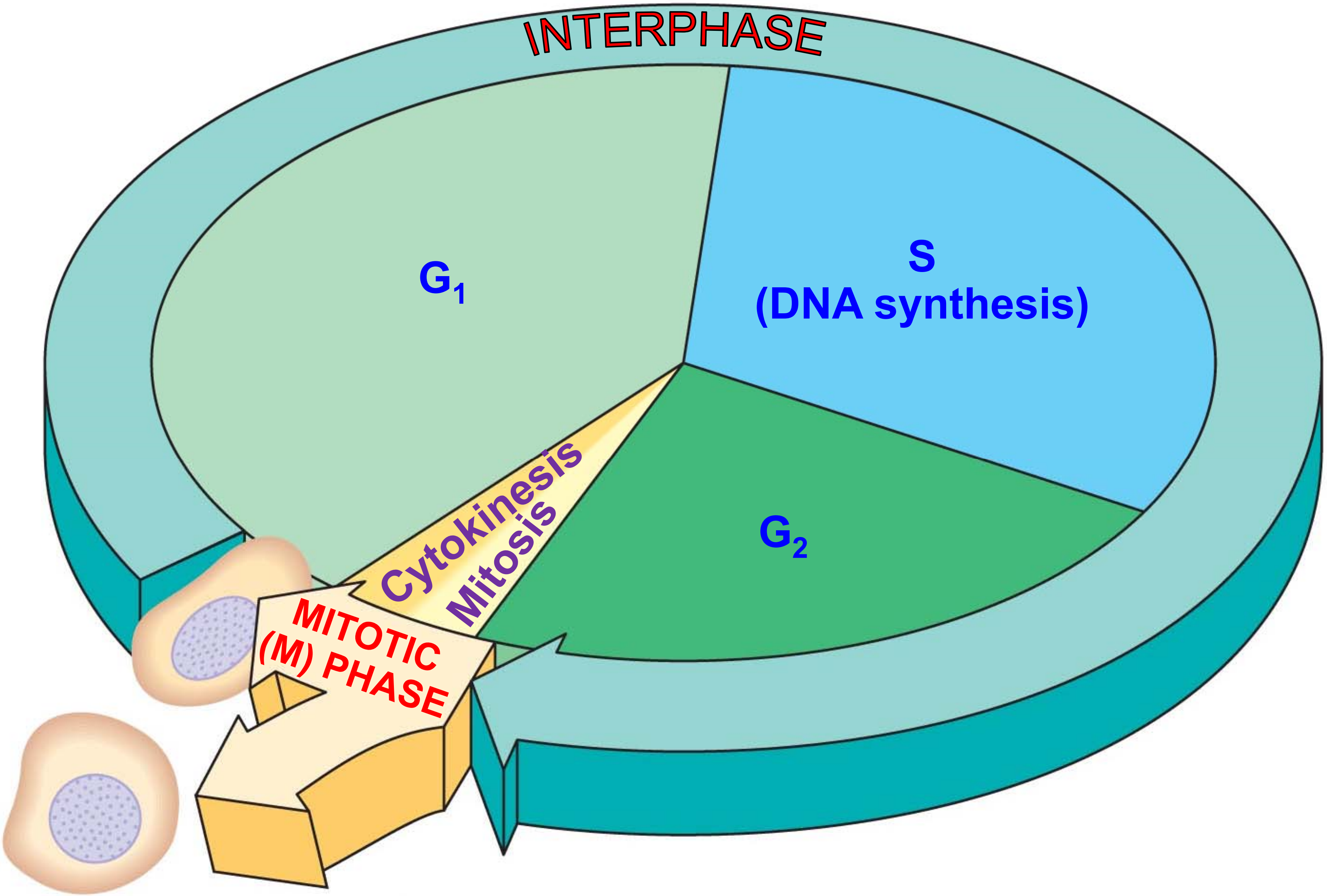
- In 1882, the German anatomist **Walther Flemming** developed dyes to observe chromosomes during mitosis and cytokinesis

Phases of the Cell Cycle

- The cell cycle consists of
  - **Mitotic (M) phase** (mitosis and cytokinesis)
  - **Interphase** (cell growth and copying of chromosomes in preparation for cell division)

- Interphase (about 90% of the cell cycle) can be divided into **subphases**:
  - **G_1 phase** ("first gap")
  - **S phase** ("synthesis")
  - **G_2 phase** ("second gap")
- The cell grows during all three phases, but chromosomes are duplicated only during the S phase

Fig. 12-5

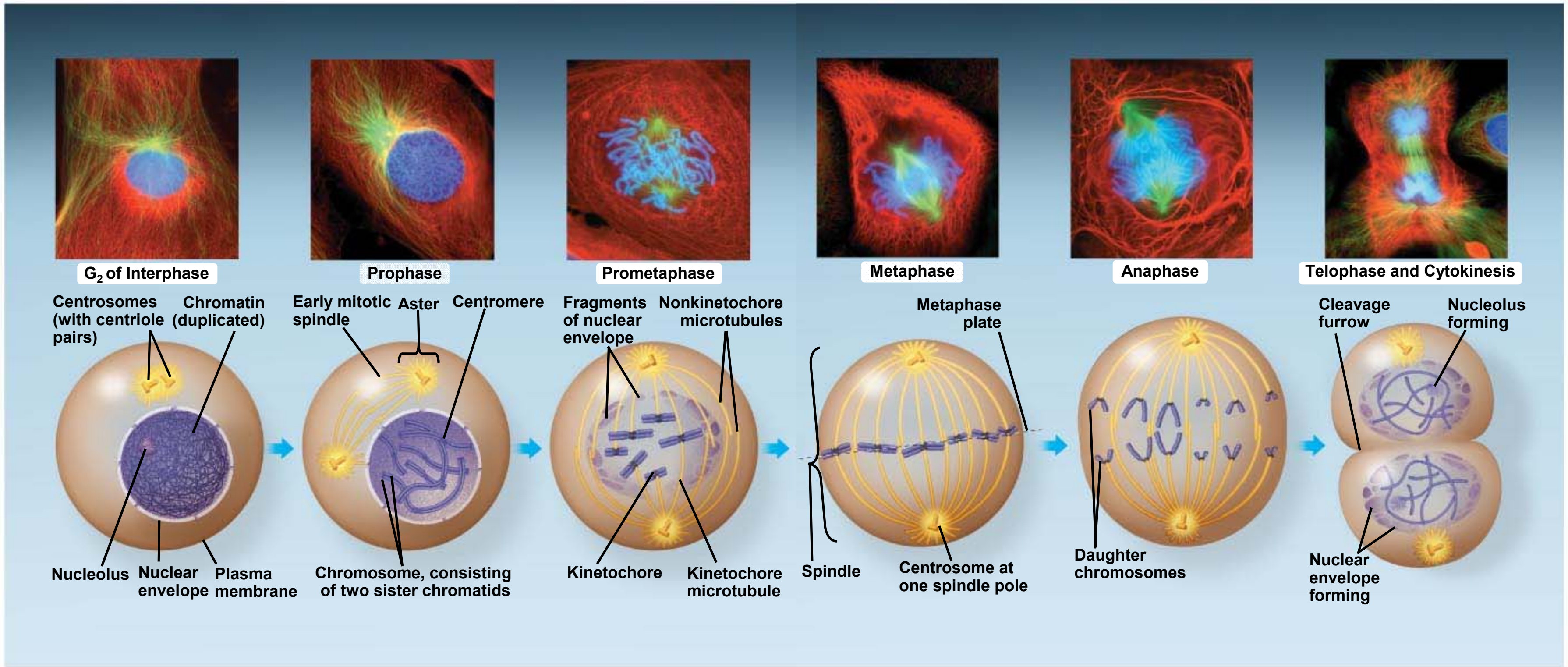


INTERPHASE
G1
S
(DNA synthesis)
G2
Cytokinesis
Mitosis
MITOTIC
(M) PHASE

- Mitosis is conventionally divided into five phases:
  - **Prophase**
  - **Prometaphase**
  - **Metaphase**
  - **Anaphase**
  - **Telophase**
- Cytokinesis is well underway by late telophase

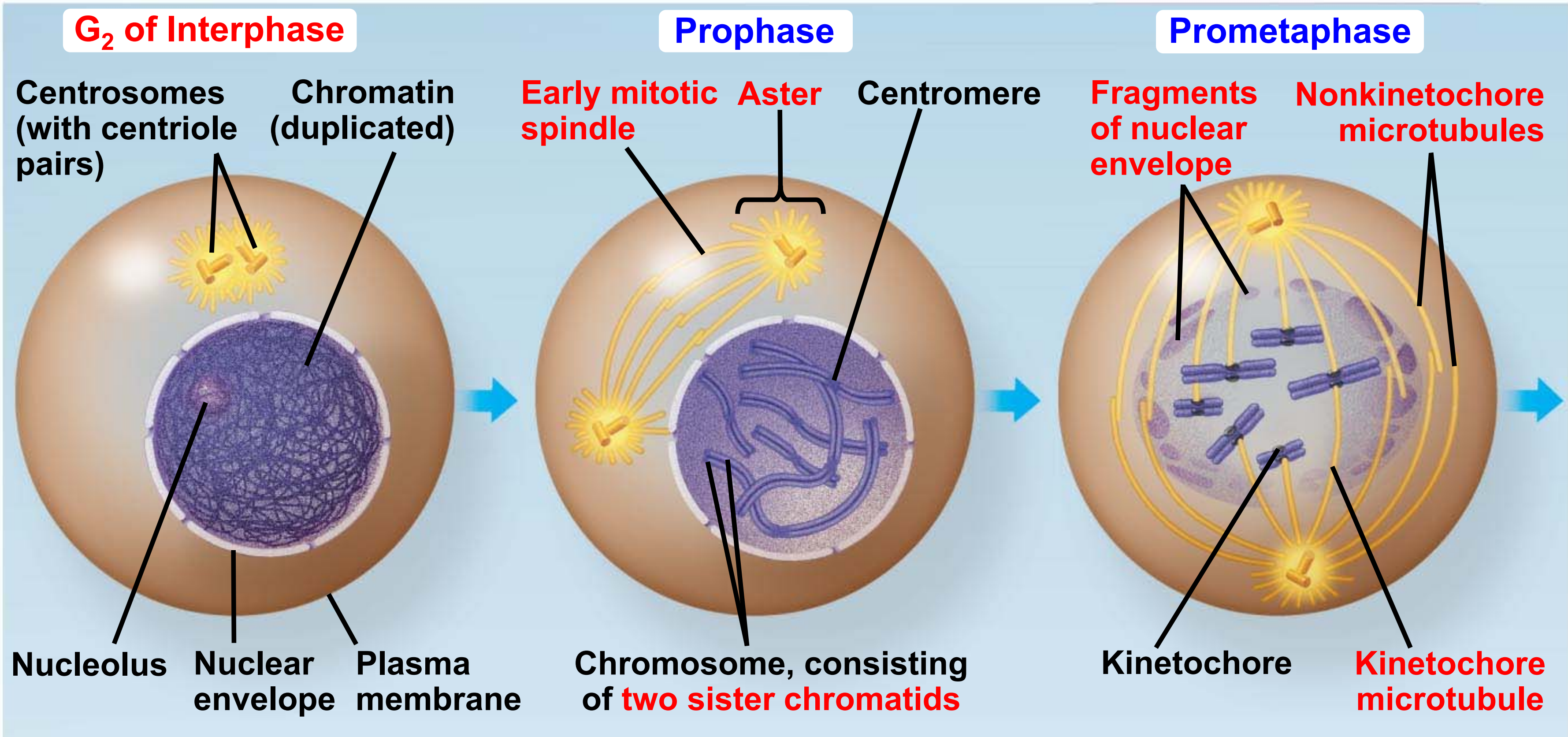
PLAY **BioFlix: Mitosis**

Fig. 12-6



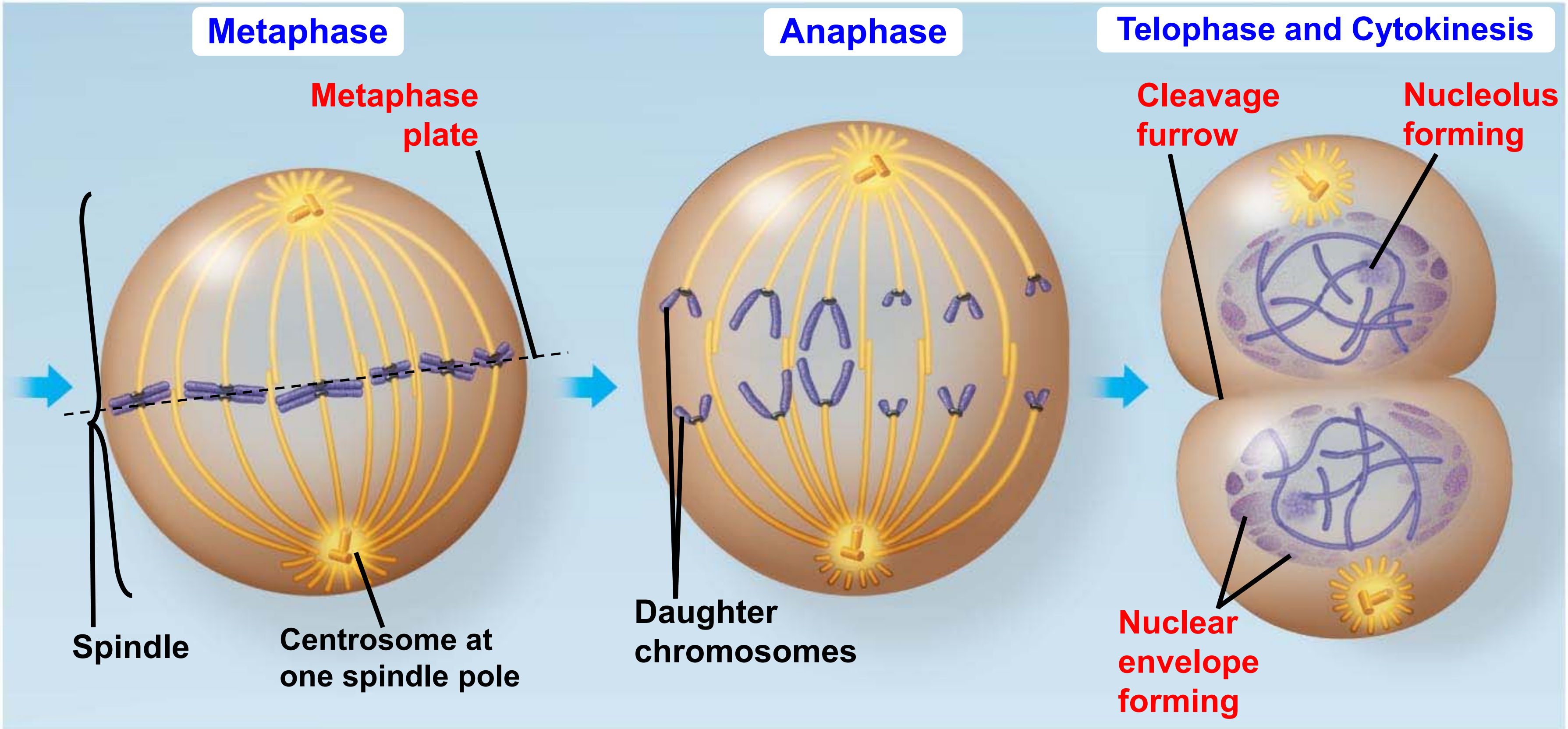
G2 of Interphase
Prophase
Prometaphase
Metaphase
Anaphase
Telophase and Cytokinesis
Centrosomes (with centriole pairs)
Chromatin (duplicated)
Early mitotic spindle
Aster
Centromere
Fragments of nuclear envelope
Nonkinetochore microtubules
Metaphase plate
Cleavage furrow
Nucleolus forming
Nucleolus
Nuclear envelope
Plasma membrane
Chromosome, consisting of two sister chromatids
Kinetochore
Kinetochore microtubule
Spindle
Centrosome at one spindle pole
Daughter chromosomes
Nuclear envelope forming

Fig. 12-6b



G_2 of Interphase
Prophase
Prometaphase
Centrosomes (with centriole pairs)
Chromatin (duplicated)
Early mitotic spindle
Aster
Centromere
Fragments of nuclear envelope
Nonkinetochore microtubules
Nucleolus
Nuclear envelope
Plasma membrane
Chromosome, consisting of two sister chromatids
Kinetochore
Kinetochore microtubule

Fig. 12-6d



Metaphase
Anaphase
Telophase and Cytokinesis
Metaphase plate
Cleavage furrow
Nucleolus forming
Spindle
Centrosome at one spindle pole
Daughter chromosomes
Nuclear envelope forming

Fig. 12-6a

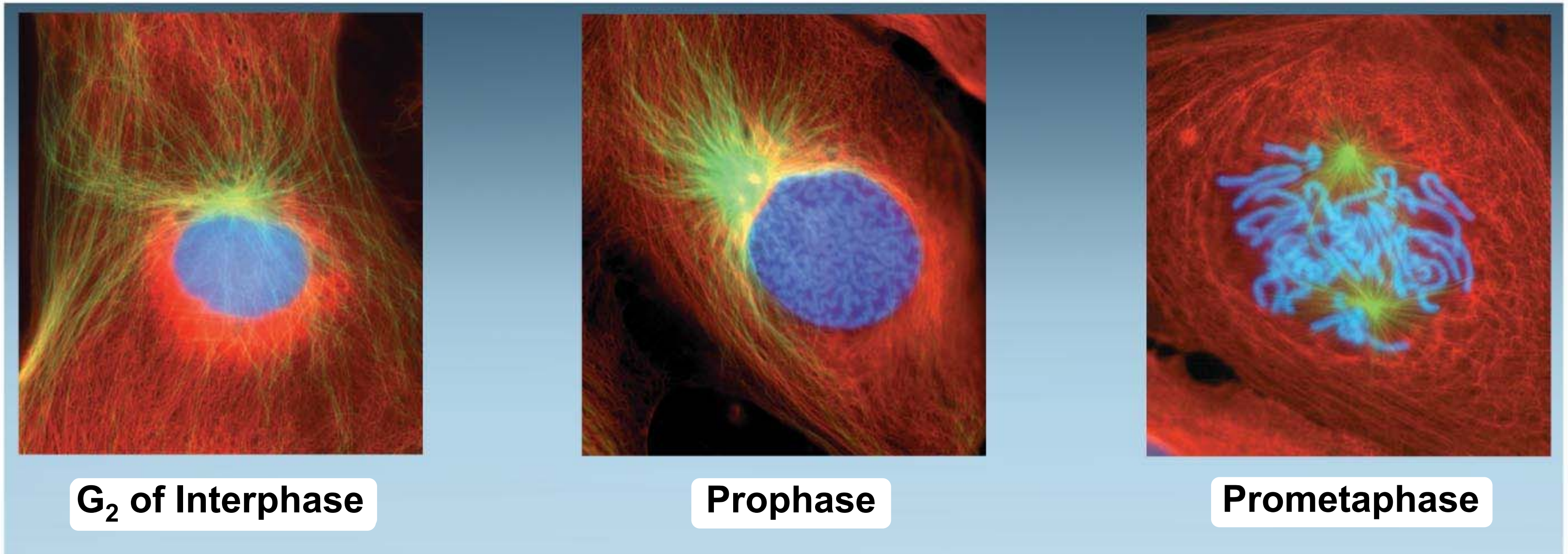
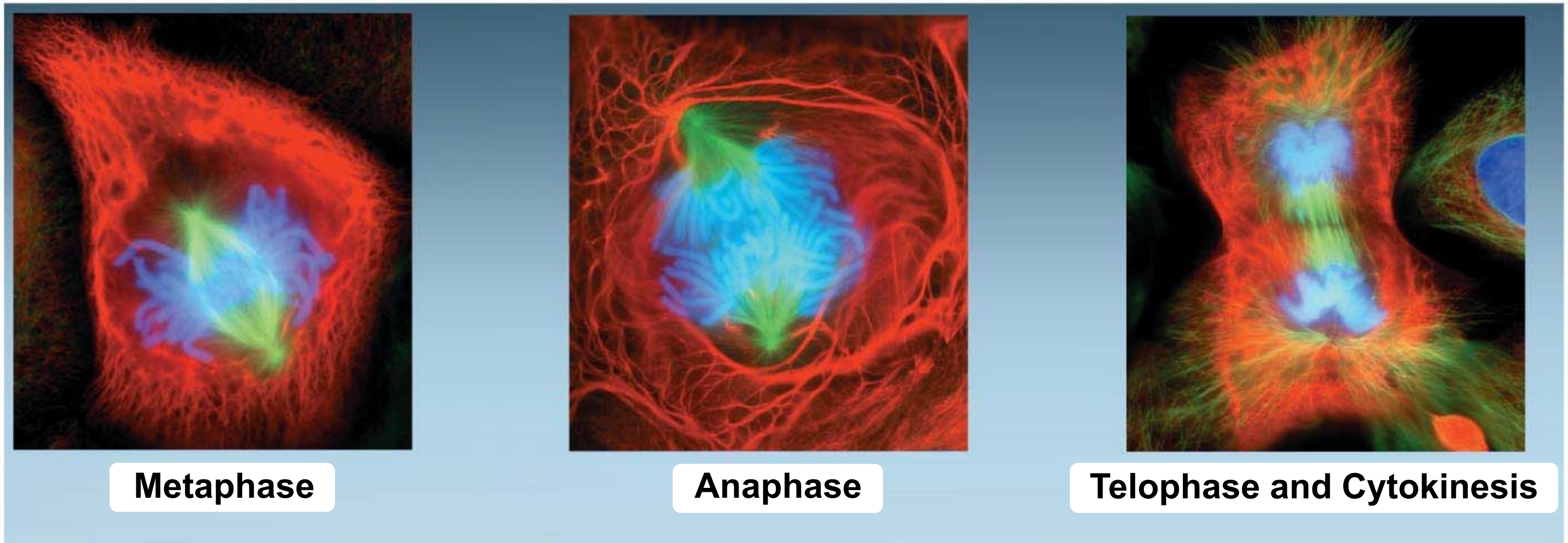


Fig. 12-6c

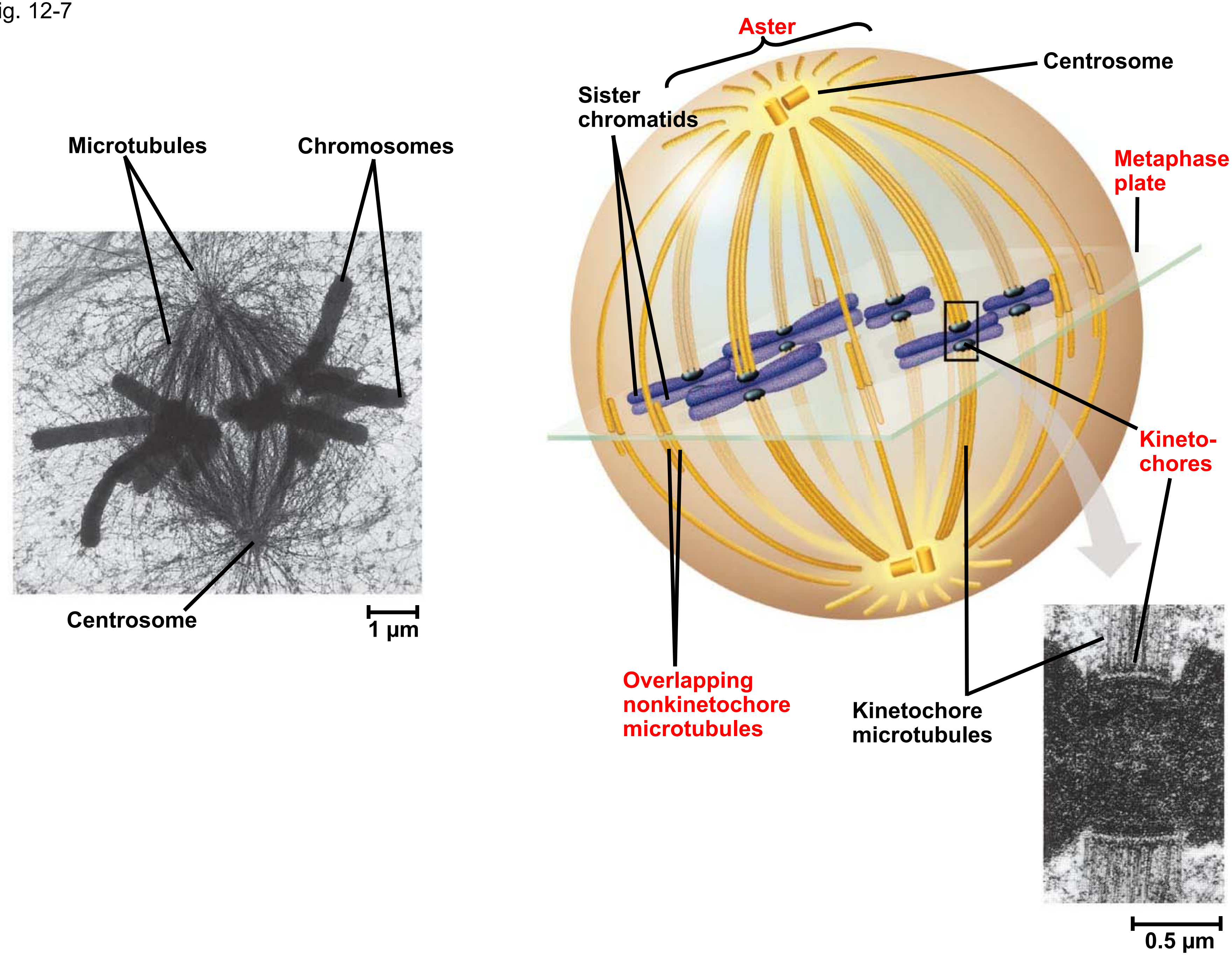


The Mitotic Spindle: *A Closer Look*

- The **mitotic spindle** is an apparatus of microtubules that controls chromosome movement during mitosis
- An **aster** (a radial array of short microtubules) extends from each centrosome

- During **prometaphase**, some spindle microtubules attach to the **kinetochores** of chromosomes and begin to move the chromosomes
- At **metaphase**, the chromosomes are all lined up at the **metaphase plate**, the midway point between the spindle's two poles

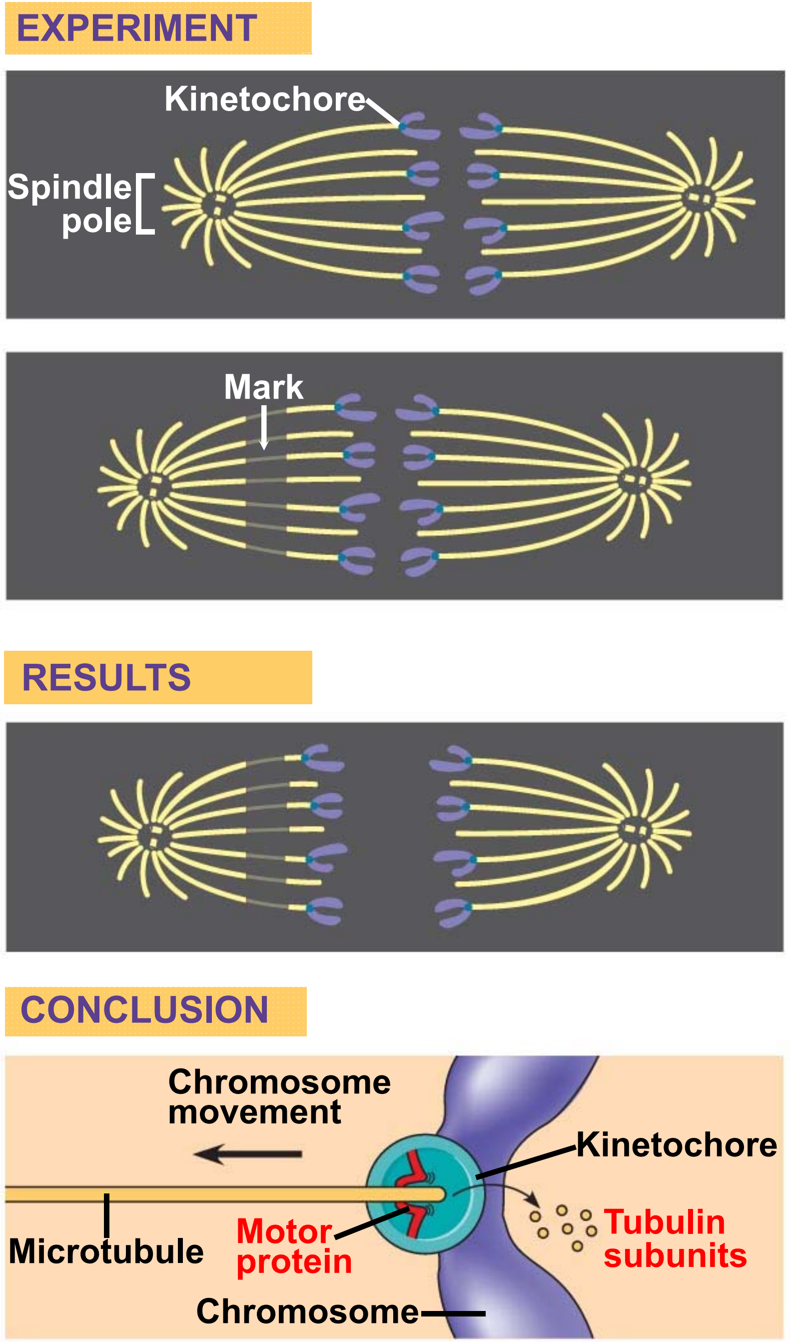
Fig. 12-7



Microtubules
Chromosomes
Centrosome
1 µm
Aster
Centrosome
Sister chromatids
Metaphase plate
Kineto-chores
Overlapping nonkinetochore microtubules
Kinetochore microtubules
0.5 µm

- In **anaphase**, **sister chromatids separate** and move along the kinetochore microtubules toward opposite ends of the cell
- The microtubules shorten by depolymerizing at their kinetochore ends

Fig. 12-8



EXPERIMENT
Kinetochore
Spindle pole
Mark
RESULTS
CONCLUSION
Chromosome movement
Kinetochore
Microtubule
Motor protein
Tubulin subunits
Chromosome

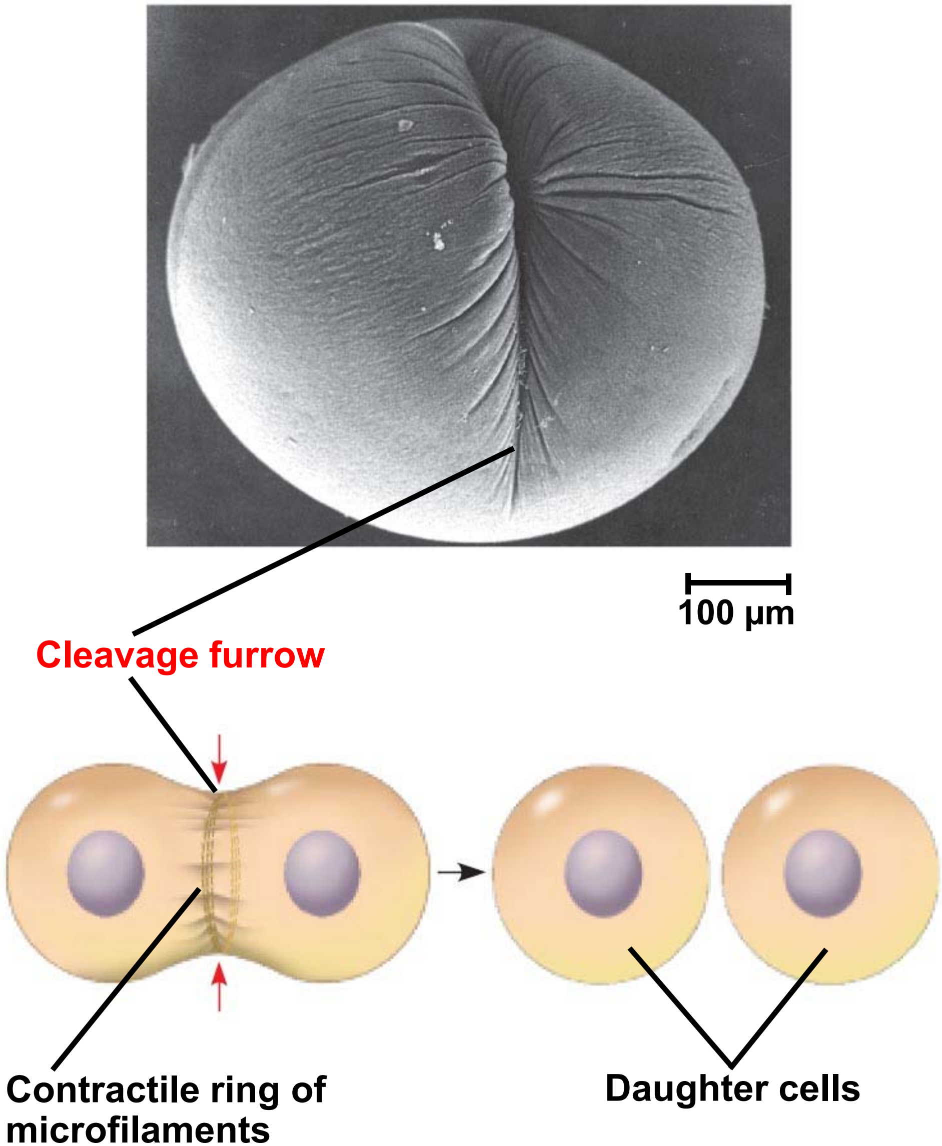
- Nonkinetochore microtubules from opposite poles overlap and push against each other, elongating the cell
- In **telophase**, genetically identical daughter nuclei form at opposite ends of the cell

Cytokinesis: *A Closer Look*

- In animal cells, **cytokinesis** occurs by a process known as **cleavage**, forming a **cleavage furrow**
- In plant cells, a **cell plate** forms during cytokinesis

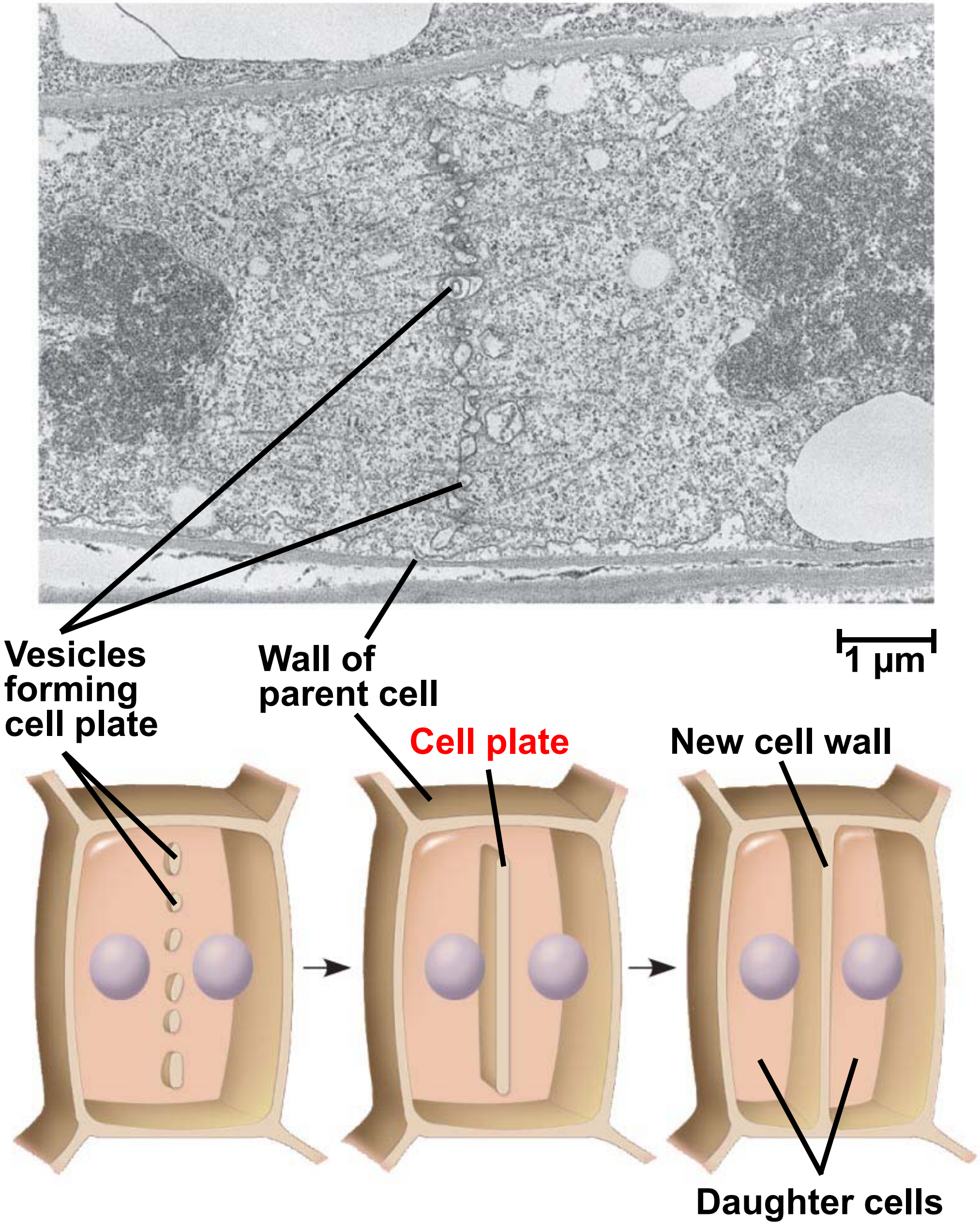
PLAY **Animation: Cytokinesis**

Fig. 12-9a



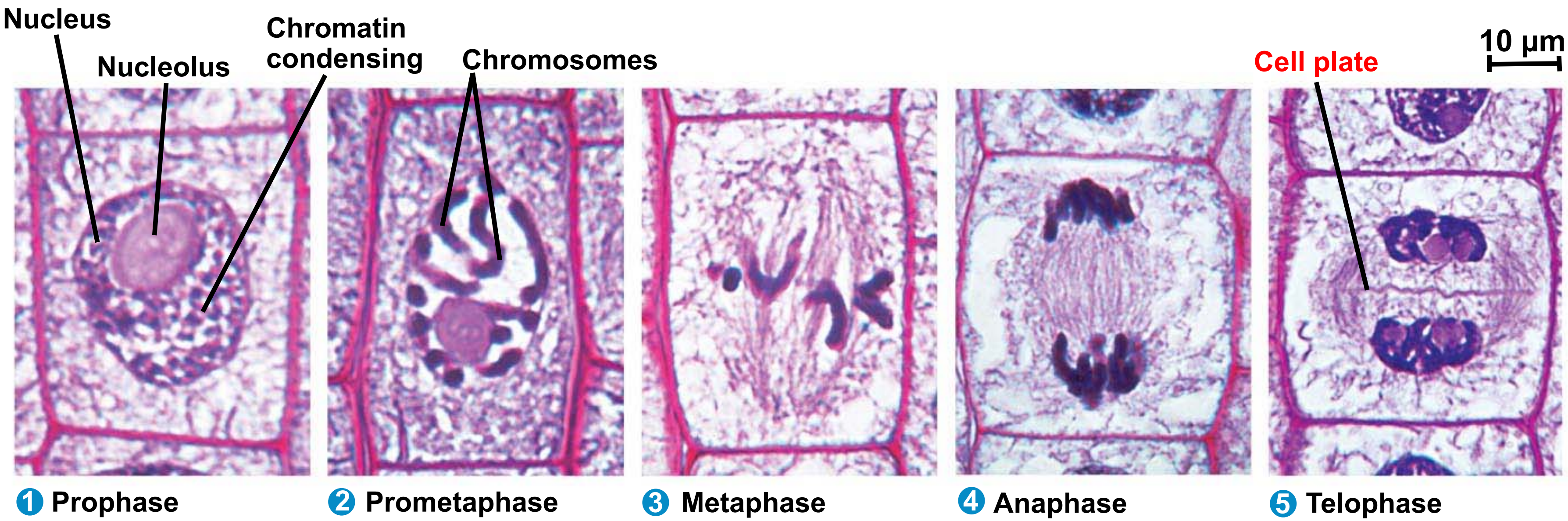
(a) Cleavage of an animal cell (SEM)

Fig. 12-9b



(b) Cell plate formation in a plant cell (TEM)

Fig. 12-10


Nucleus
Nucleolus
Chromatin condensing
Chromosomes
Cell plate
10 µm
1 Prophase
2 Prometaphase
3 Metaphase
4 Anaphase
5 Telophase

Binary Fission

- Prokaryotes (bacteria and archaea) reproduce by a type of cell division called **binary fission**
- In binary fission, the **chromosome replicates** (beginning at the **origin of replication**), and the two daughter chromosomes actively move apart

Fig. 12-11-1

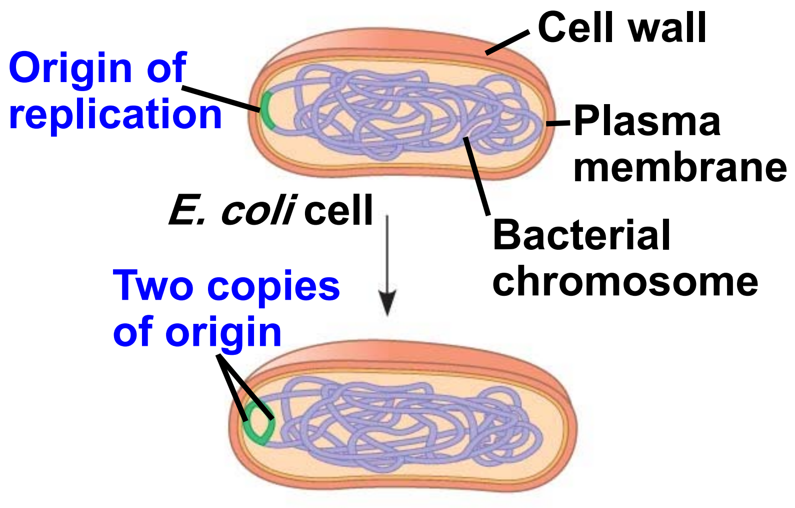
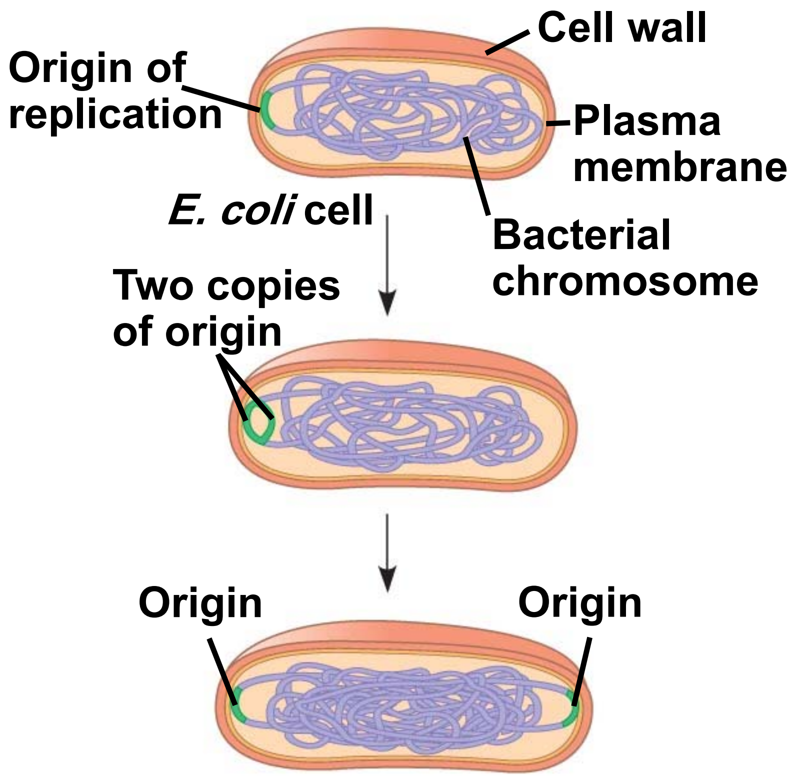

Origin of replication
Cell wall
Plasma membrane
E. coli cell
Bacterial chromosome
Two copies of origin

Fig. 12-11-2



Origin of replication
Cell wall
Plasma membrane
E. coli cell
Bacterial chromosome
Two copies of origin
Origin
Origin

Fig. 12-11-3

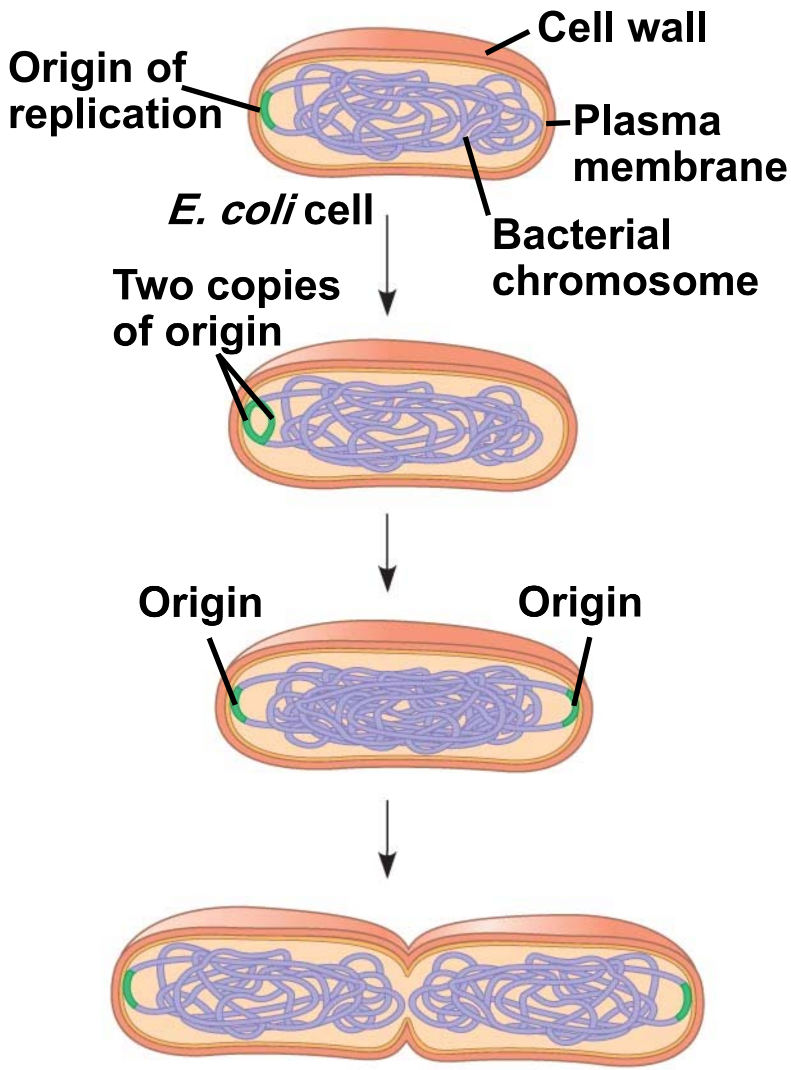
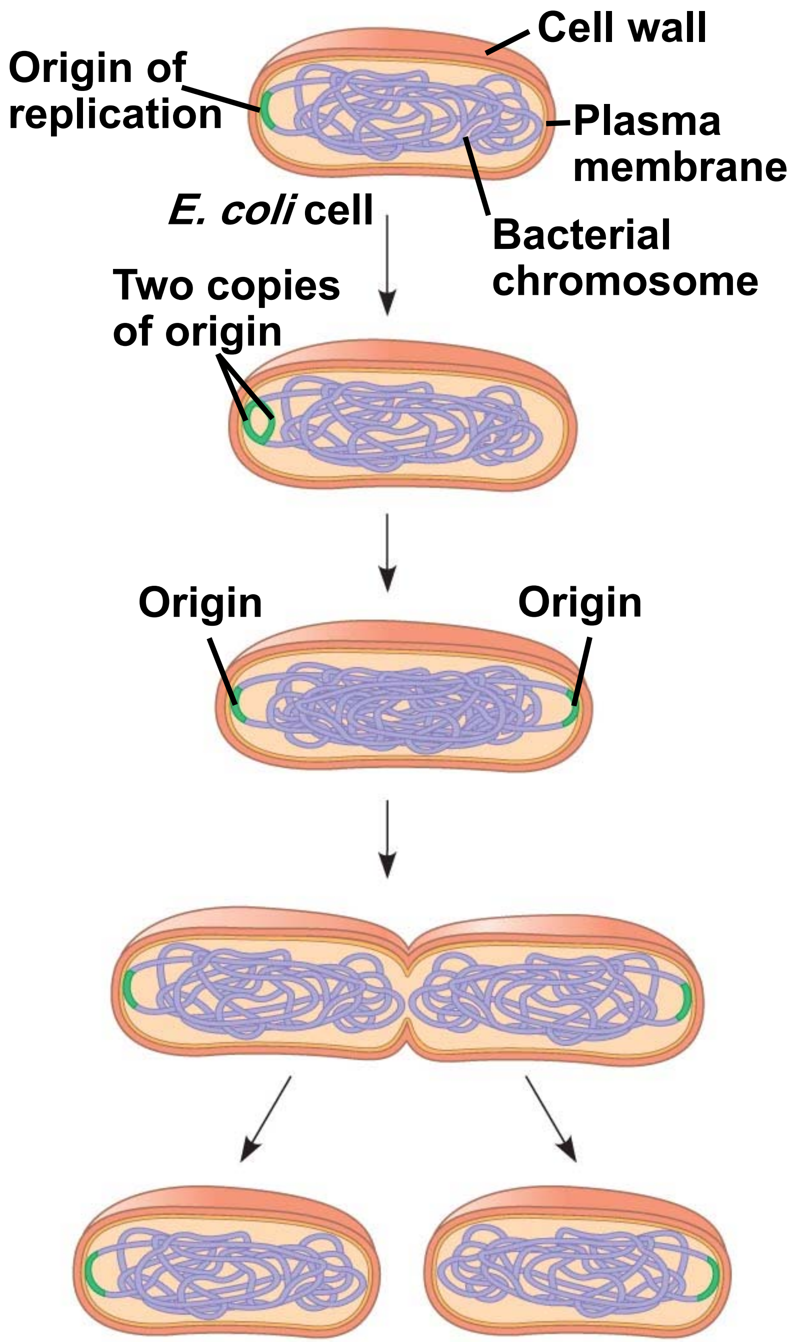

Origin of replication
Cell wall
Plasma membrane
E. coli cell
Bacterial chromosome
Two copies of origin
Origin
Origin

Fig. 12-11-4


Cell wall
Origin of replication
Plasma membrane
E. coli cell
Bacterial chromosome
Two copies of origin
Origin
Origin

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Chapter 13

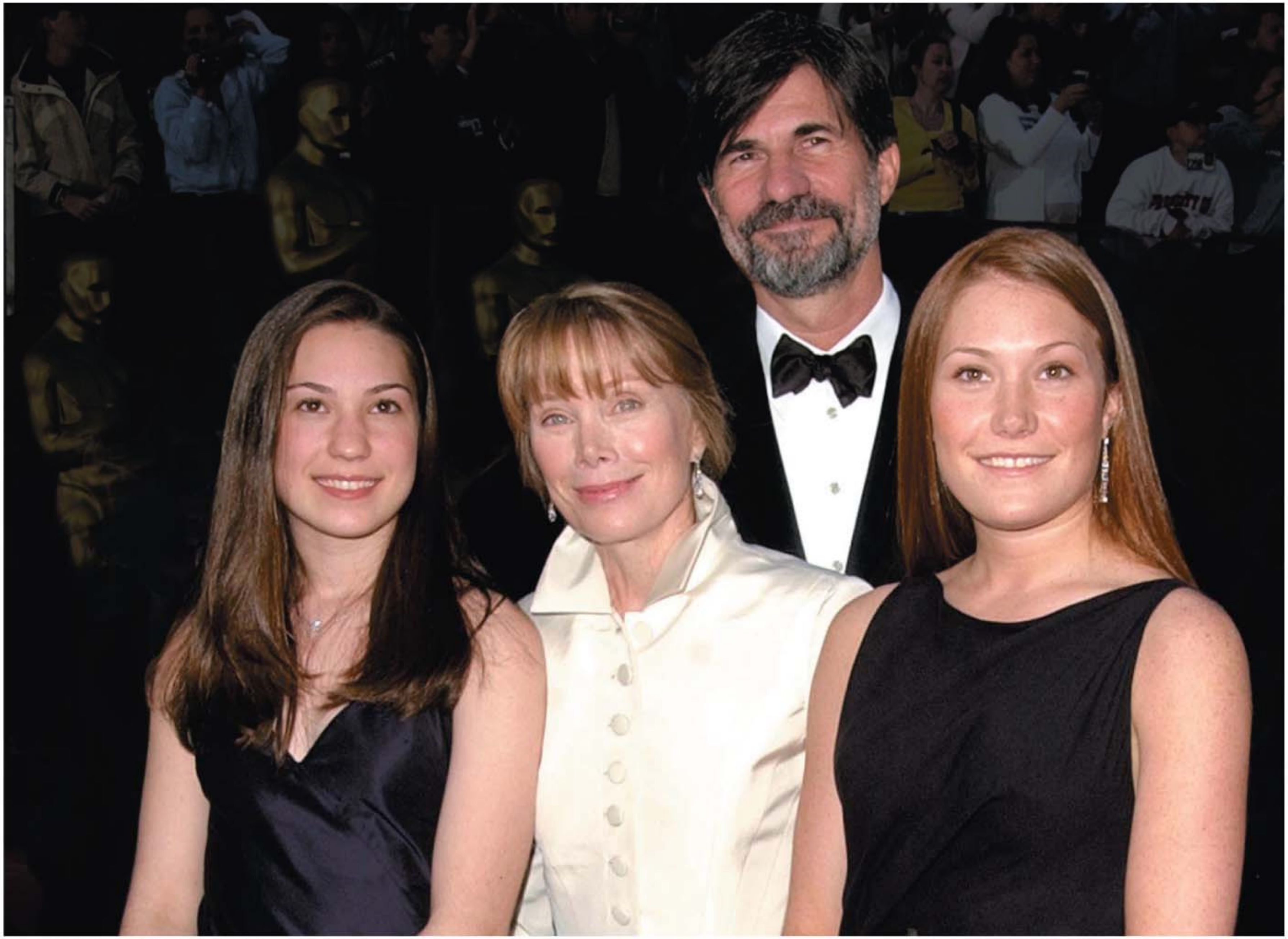
Meiosis and Sexual Life Cycles

Lectures by
Erin Barley
Kathleen Fitzpatrick

Overview: Variations on a Theme

- Living organisms are distinguished by their ability to reproduce their own kind
- **Genetics** is the scientific study of heredity and variation
- **Heredity** is the transmission of traits from one generation to the next
- **Variation** is demonstrated by the differences in appearance that offspring show from parents and siblings

Fig. 13-1



Concept 13.1: Offspring acquire genes from parents by inheriting chromosomes

- In a literal sense, children do not inherit particular physical traits from their parents
- It is genes that are actually inherited

Inheritance of Genes

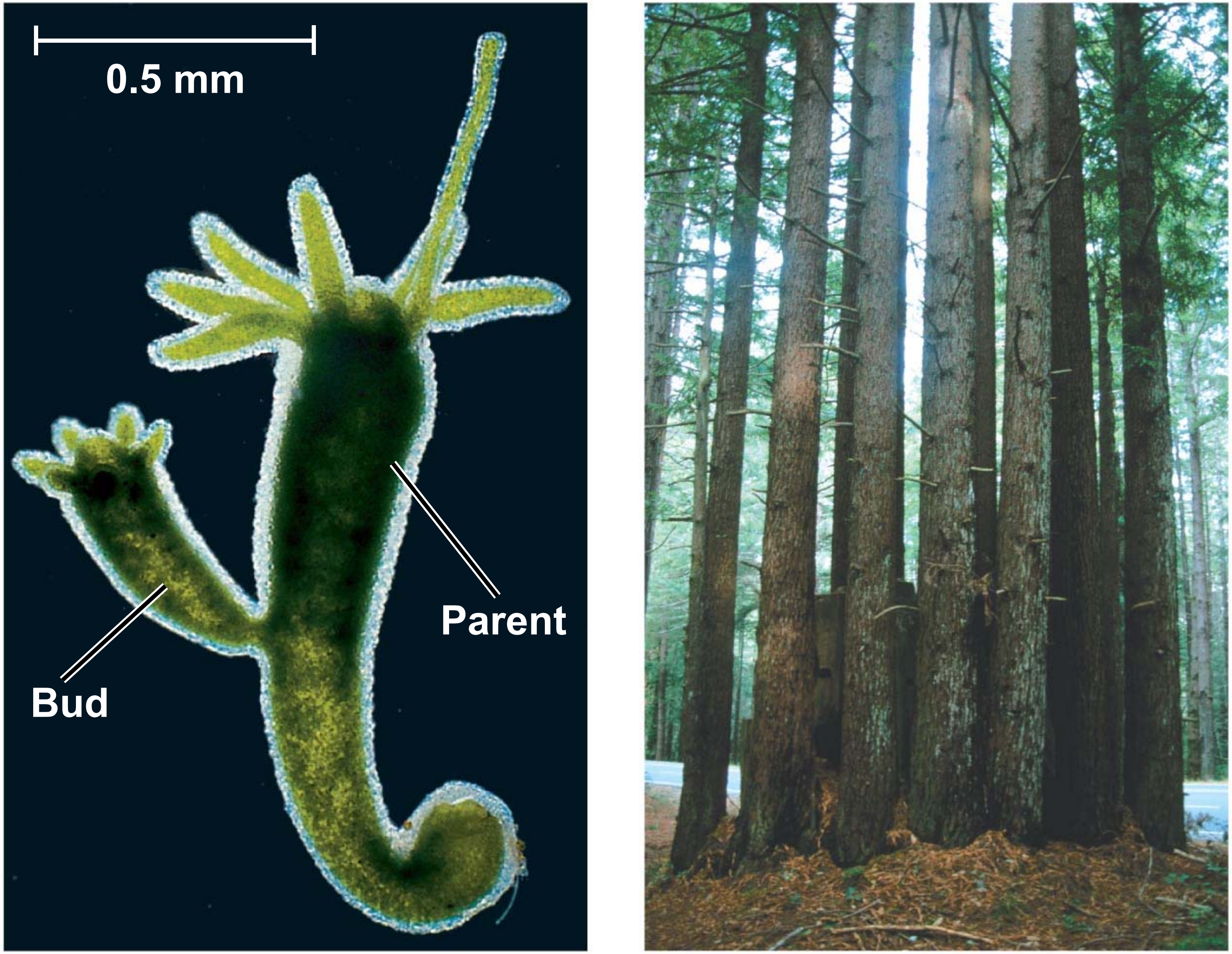
- **Genes** are the units of heredity, and are made up of segments of DNA
- Genes are passed to the next generation through reproductive cells called **gametes** (sperm and eggs)
- Each gene has a specific location called a **locus** on a certain chromosome
- One set of chromosomes is inherited from each parent

Comparison of Asexual and Sexual Reproduction

- In **asexual reproduction**, one parent produces genetically identical offspring by mitosis
- A **clone** is a group of genetically identical individuals from the same parent
- In **sexual reproduction**, two parents give rise to offspring that have unique combinations of genes inherited from the two parents

PLAY Video: Hydra Budding

Fig. 13-2



(a) Hydra

(b) Redwoods

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

Sets of Chromosomes in Human Cells

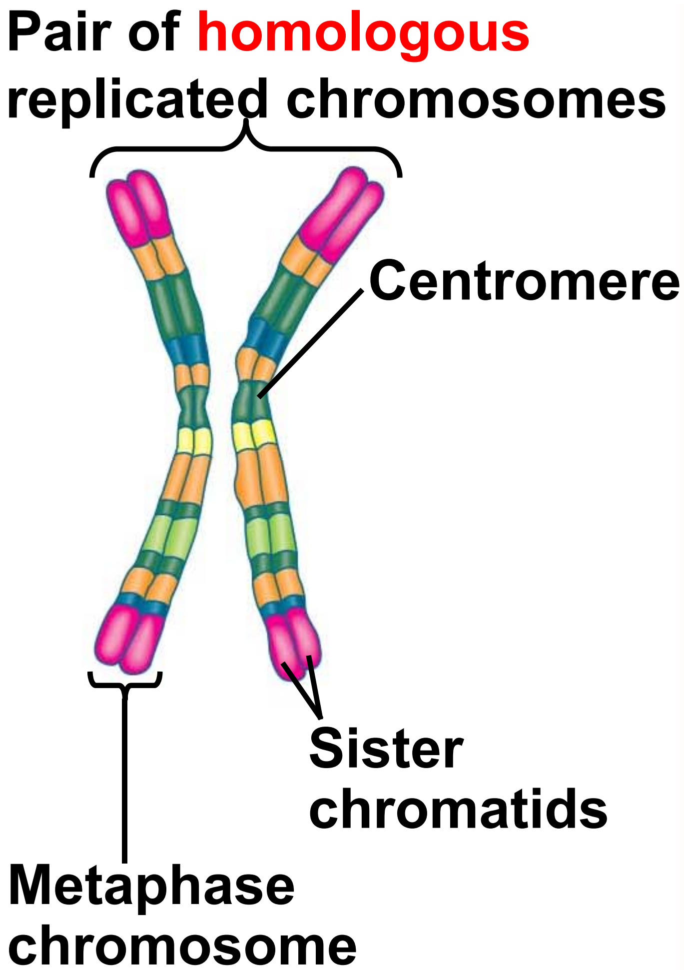
- Human **somatic cells** (any cell other than a gamete) have 23 pairs of chromosomes
- A **karyotype** is an ordered display of the pairs of chromosomes from a cell
- The two chromosomes in each pair are called **homologous chromosomes**, or homologs
- Chromosomes in a homologous pair are the same length and carry genes controlling the same inherited characters

Fig. 13-3a

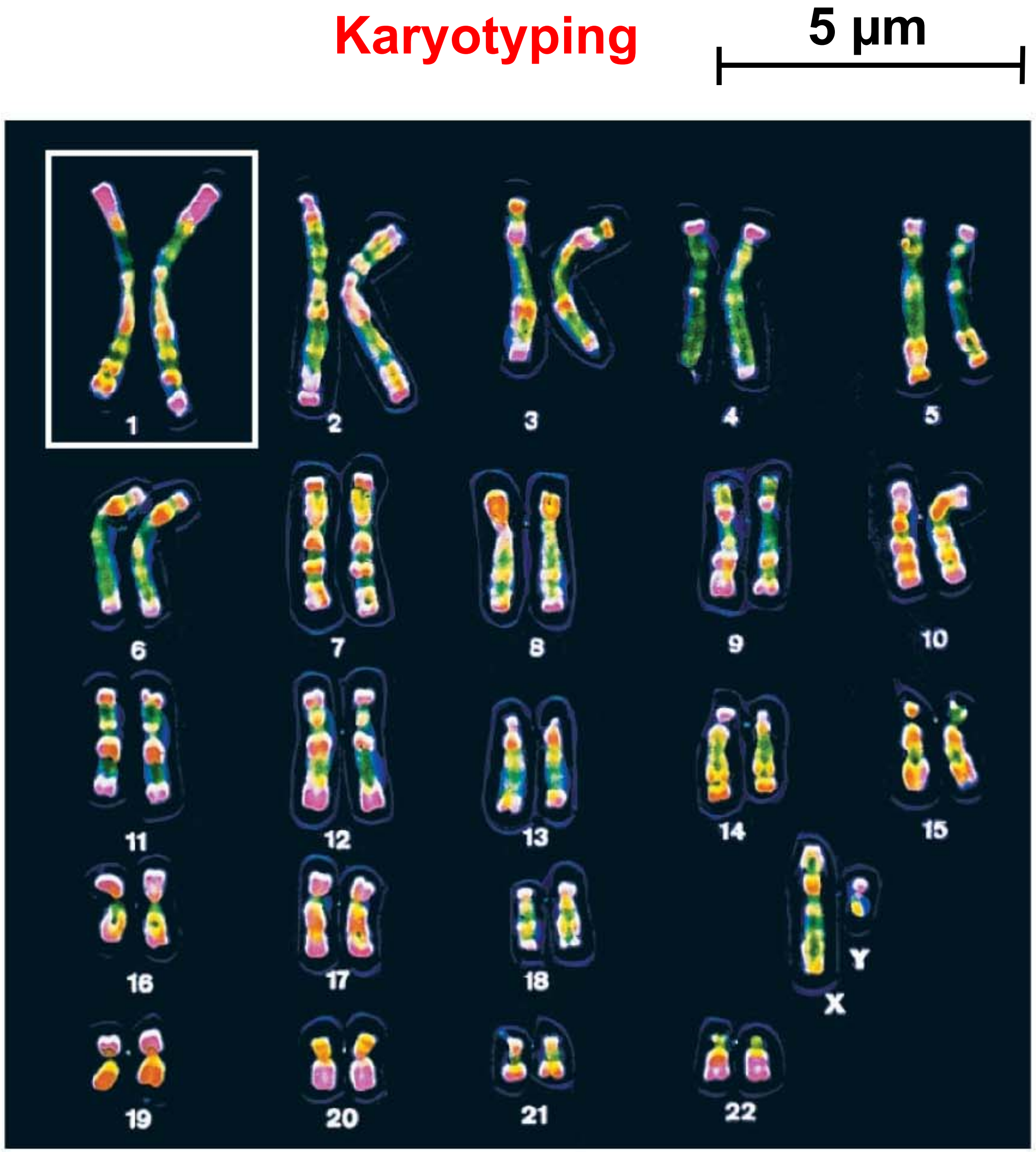
APPLICATION

Fig. 13-3b

TECHNIQUE



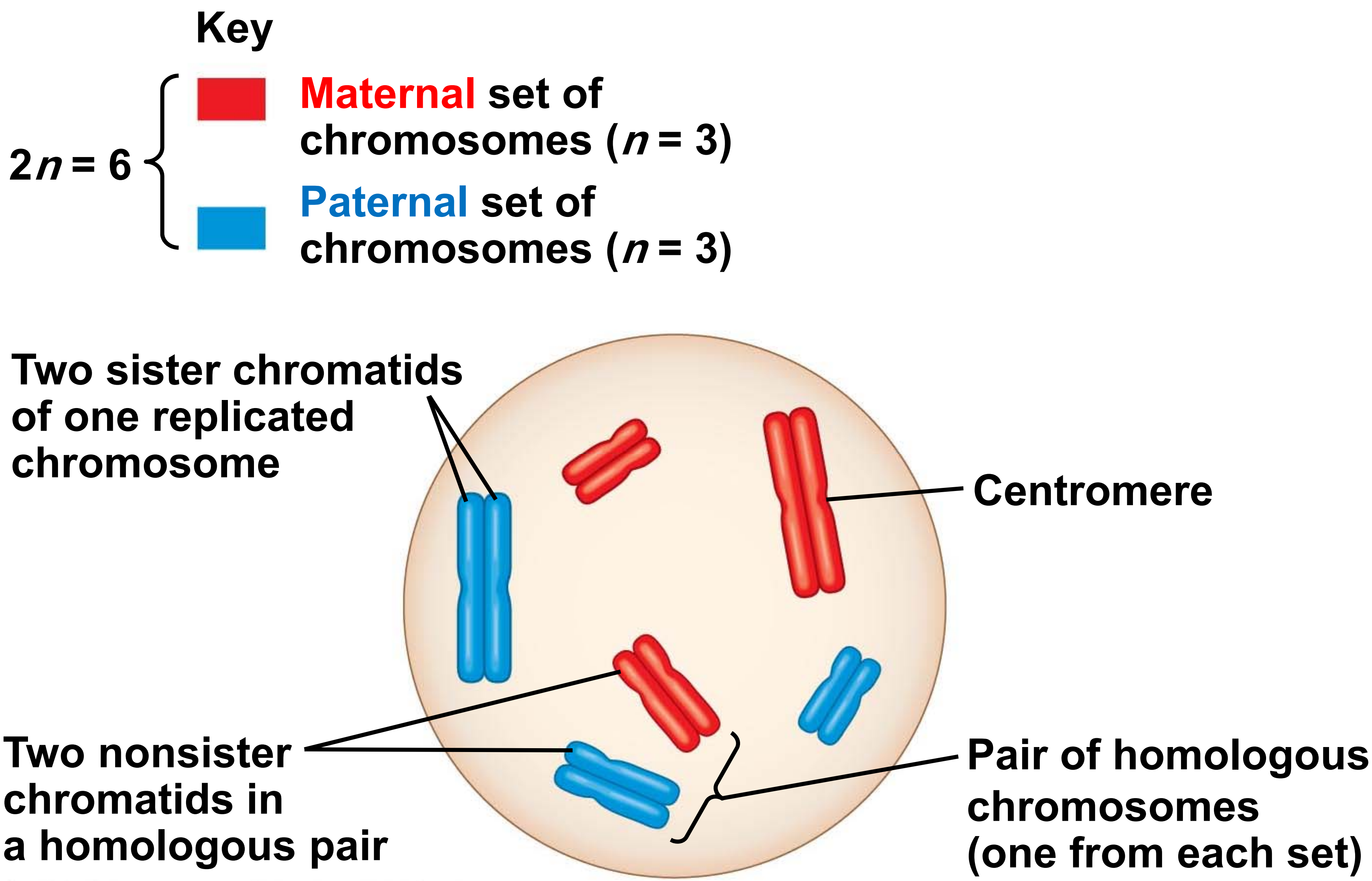
Karyotyping



- The **sex chromosomes** are called X and Y
- Human **females** have a homologous pair of X chromosomes (**XX**)
- Human **males** have one X and one Y chromosome (**XY**)
- The **22 pairs** of chromosomes that do not determine sex are called **autosomes**

- Each pair of homologous chromosomes includes one chromosome from each parent
- The 46 chromosomes in a human somatic cell are two sets of 23: one from the mother and one from the father
- A **diploid cell** (2*n*) has two sets of chromosomes
- For humans, the diploid number is 46 (2*n* = 46)

Fig. 13-4


Key
2n = 6
Maternal set of chromosomes (n = 3)
Paternal set of chromosomes (n = 3)
Two sister chromatids of one replicated chromosome
Centromere
Two nonsister chromatids in a homologous pair
Pair of homologous chromosomes (one from each set)

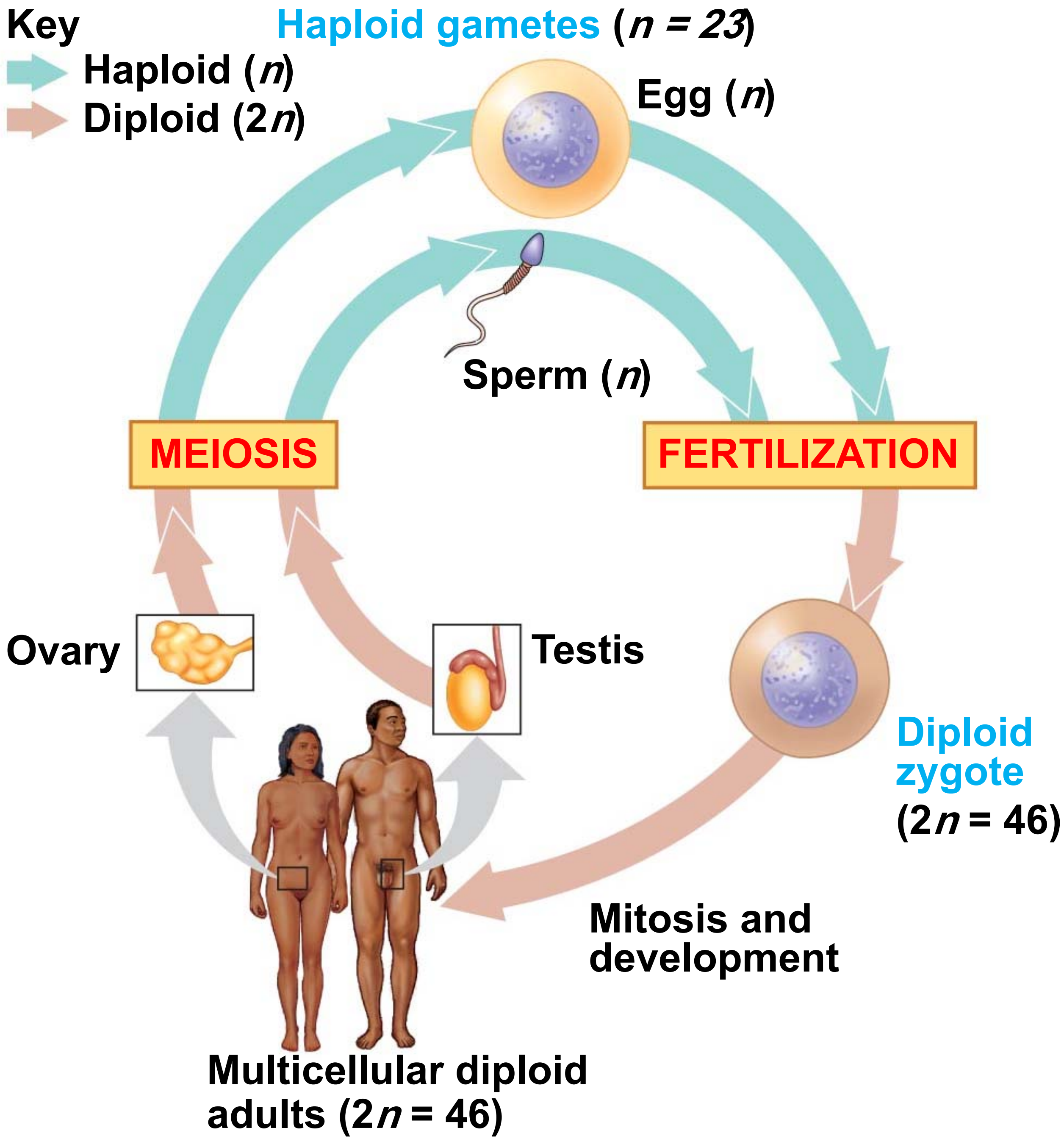
- A **gamete** (sperm or egg) contains a single set of chromosomes, and is **haploid** (n)
- For humans, the haploid number is 23 ($n = 23$)
- Each set of 23 chromosomes consists of 22 autosomes and a single sex chromosome

Behavior of Chromosome Sets in the Human Life Cycle

- **Fertilization** *is the union of gametes (the sperm and the egg)*
- The fertilized egg is called a **zygote** and has one set of chromosomes from each parent
- The zygote produces somatic cells by mitosis and develops into an adult

- At sexual maturity, the ovaries and testes produce haploid gametes
- Gametes are the only types of human cells produced by **meiosis**, rather than mitosis
- Meiosis results in one set of chromosomes in each gamete

Fig. 13-5


Key
Haploid (n)
Diploid (2n)
Haploid gametes (n = 23)
Egg (n)
Sperm (n)
MEIOSIS
FERTILIZATION
Ovary
Testis
Diploid zygote (2n = 46)
Mitosis and development
Multicellular diploid adults (2n = 46)

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

- Like mitosis, meiosis is preceded by the replication of chromosomes
- Meiosis takes place in **two sets of cell divisions**, called **meiosis I** and **meiosis II**
- The two cell divisions result in four daughter cells, rather than the two daughter cells in mitosis
- Each daughter cell has only half as many chromosomes as the parent cell

The Stages of Meiosis

- In the first cell division (meiosis I), homologous chromosomes separate
- Meiosis I results in two haploid daughter cells with replicated chromosomes; it is called the reductional division
- In the second cell division (meiosis II), sister chromatids separate
- Meiosis II results in four haploid daughter cells with unreplicated chromosomes; it is called the equational division

Fig. 13-7-1

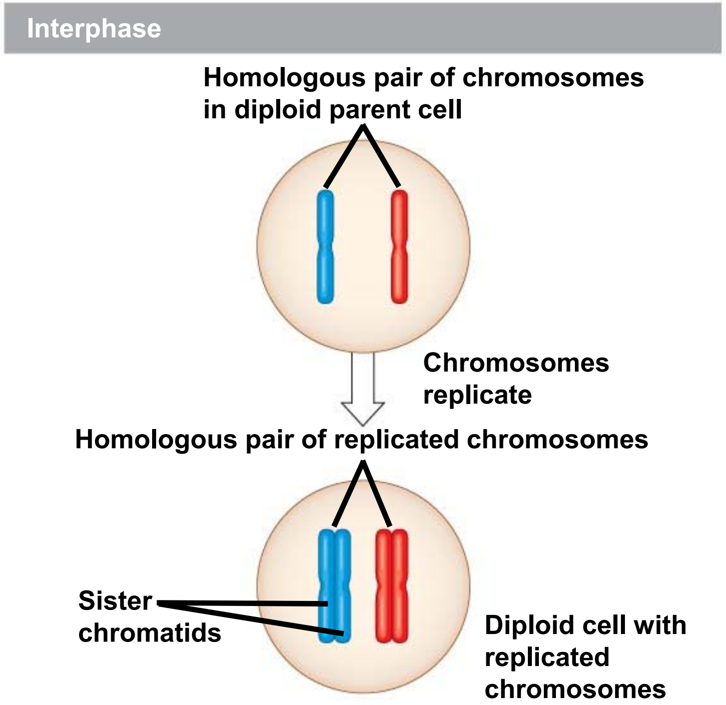
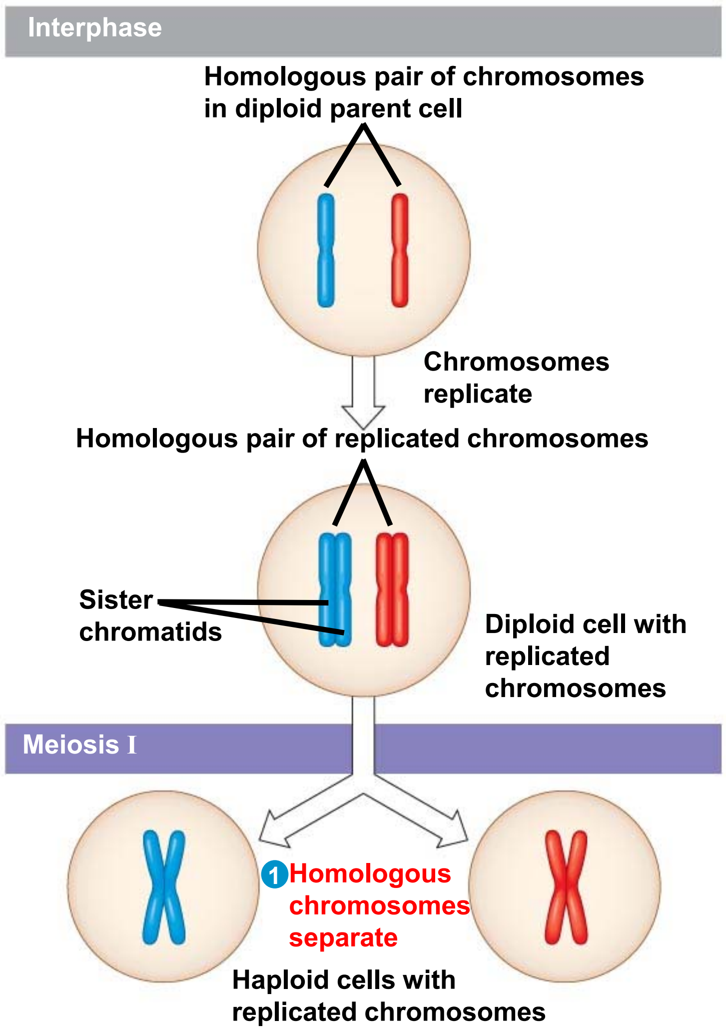
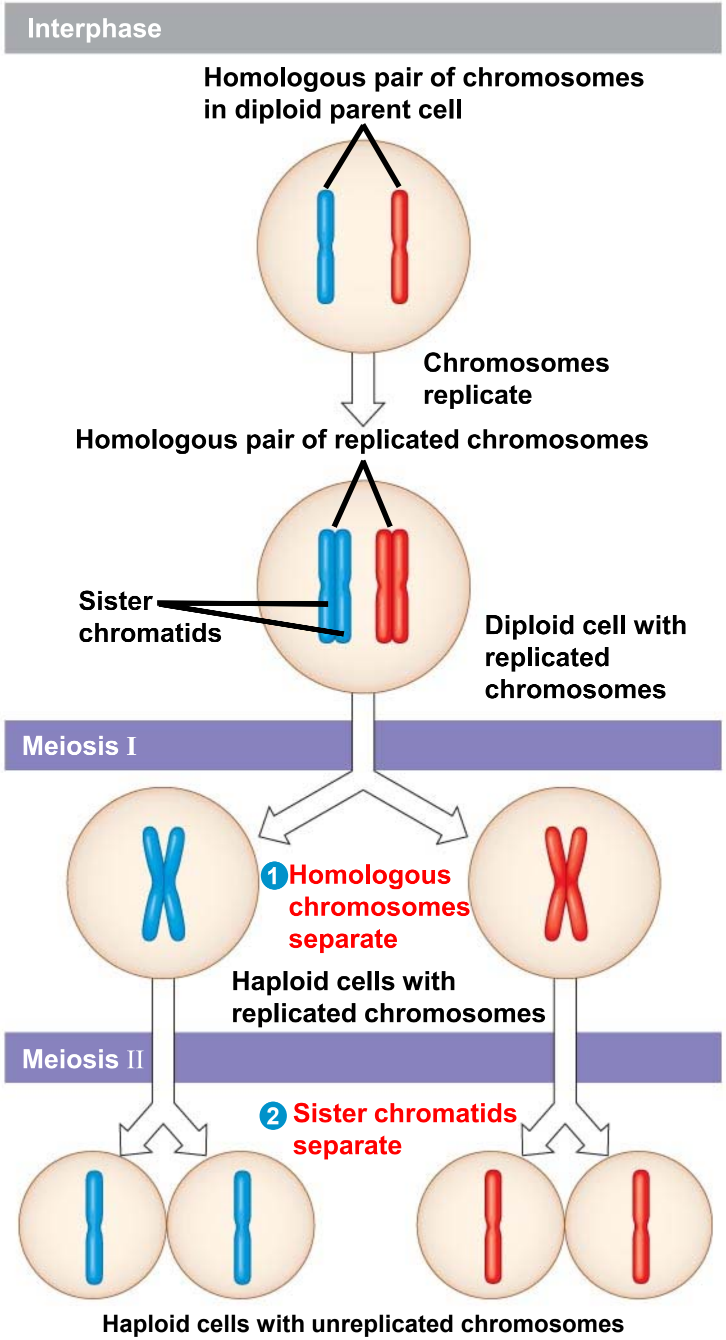

Interphase
Homologous pair of chromosomes in diploid parent cell
Chromosomes replicate
Homologous pair of replicated chromosomes
Sister chromatids
Diploid cell with replicated chromosomes

Fig. 13-7-2



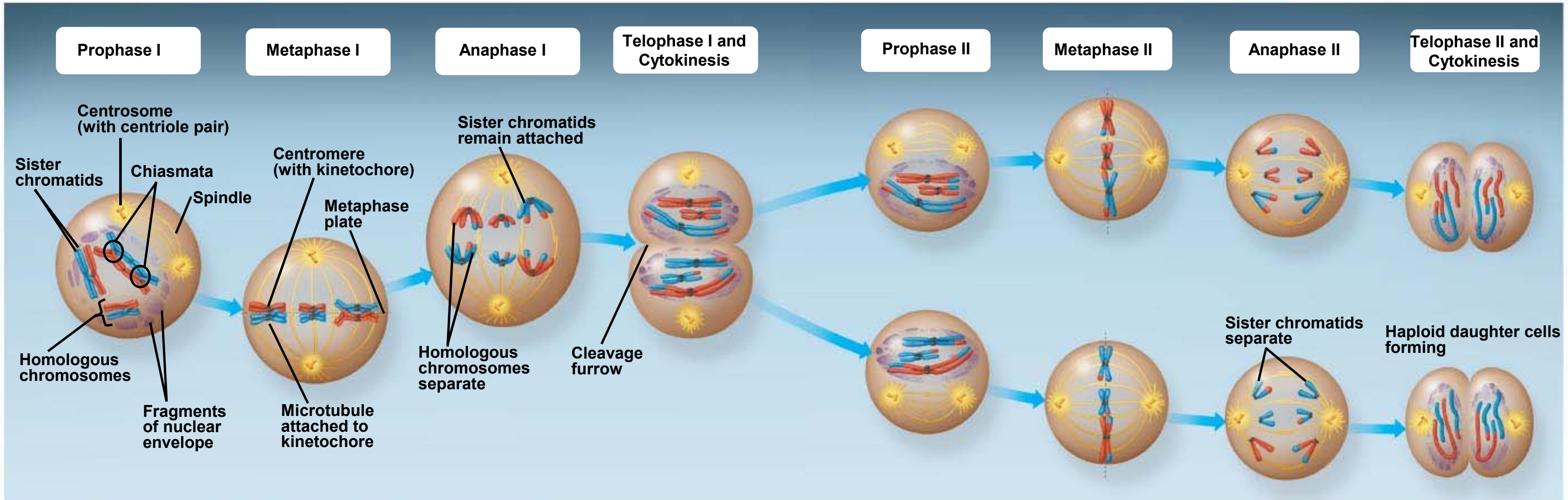
Interphase
Homologous pair of chromosomes in diploid parent cell
Chromosomes replicate
Homologous pair of replicated chromosomes
Sister chromatids
Diploid cell with replicated chromosomes
Meiosis I
1 Homologous chromosomes separate
Haploid cells with replicated chromosomes

Fig. 13-7-3



Interphase
Homologous pair of chromosomes in diploid parent cell
Chromosomes replicate
Homologous pair of replicated chromosomes
Sister chromatids
Diploid cell with replicated chromosomes
Meiosis I
1 Homologous chromosomes separate
Haploid cells with replicated chromosomes
Meiosis II
2 Sister chromatids separate
Haploid cells with unreplicated chromosomes

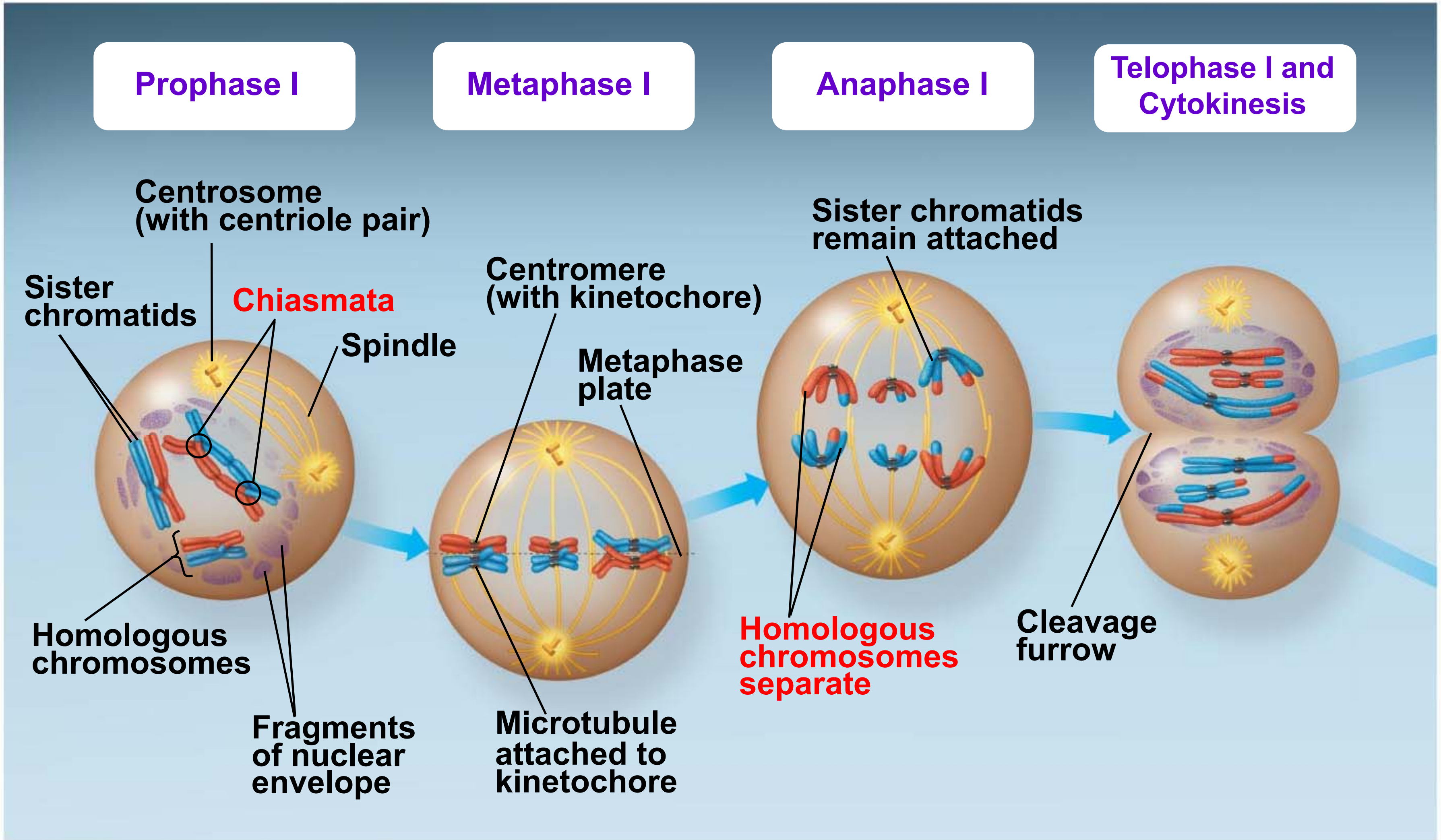
Fig. 13-8



Prophase I
Metaphase I
Anaphase I
Telophase I and Cytokinesis
Prophase II
Metaphase II
Anaphase II
Telophase II and Cytokinesis
Centrosome (with centriole pair)
Sister chromatids
Chiasmata
Spindle
Homologous chromosomes
Fragments of nuclear envelope
Centromere (with kinetochore)
Metaphase plate
Microtubule attached to kinetochore
Sister chromatids remain attached
Homologous chromosomes separate
Cleavage furrow
Sister chromatids separate
Haploid daughter cells forming

- Division in meiosis I occurs in four phases:
  - **Prophase I**
  - **Metaphase I**
  - **Anaphase I**
  - **Telophase I and cytokinesis**

Fig. 13-8a



Prophase I
Metaphase I
Anaphase I
Telophase I and Cytokinesis
Centrosome (with centriole pair)
Sister chromatids
Chiasmata
Spindle
Homologous chromosomes
Fragments of nuclear envelope
Centromere (with kinetochore)
Metaphase plate
Microtubule attached to kinetochore
Sister chromatids remain attached
Homologous chromosomes separate
Cleavage furrow

Prophase I

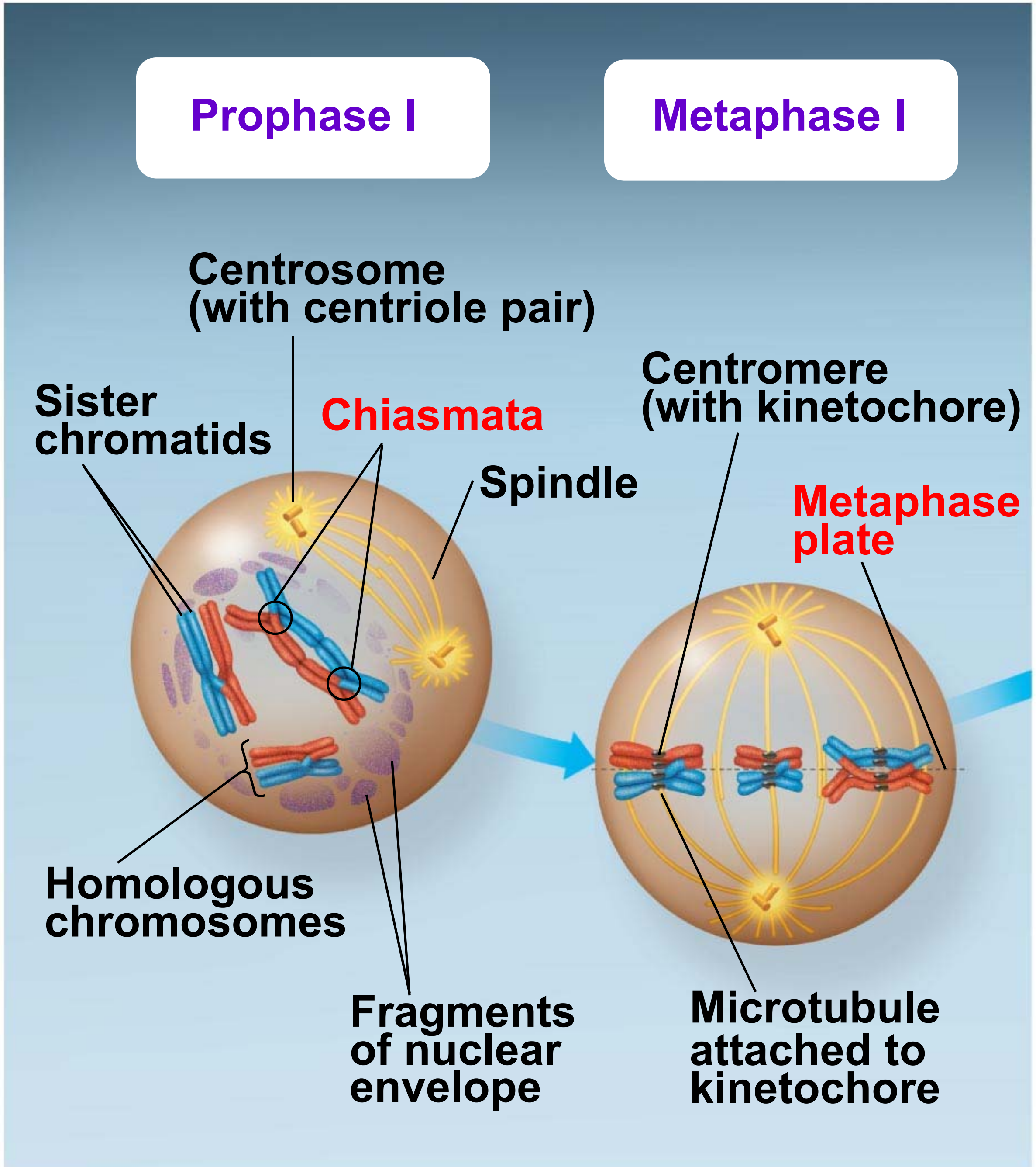
- Prophase I typically occupies more than 90% of the time required for meiosis
- Chromosomes begin to condense
- In **synapsis**, homologous chromosomes loosely pair up, aligned gene by gene

- In **crossing over**, nonsister chromatids exchange DNA segments
- Each pair of chromosomes forms a **tetrad**, a group of **four chromatids**
- Each tetrad usually has one or more **chiasmata**, *X-shaped regions where crossing over occurred*

Metaphase I

- In metaphase I, tetrads line up at the metaphase plate, with one chromosome facing each pole
- Microtubules from one pole are attached to the kinetochore of one chromosome of each tetrad
- Microtubules from the other pole are attached to the kinetochore of the other chromosome

Fig. 13-8b



Prophase I
Metaphase I
Centrosome (with centriole pair)
Sister chromatids
Chiasmata
Spindle
Centromere (with kinetochore)
Metaphase plate
Homologous chromosomes
Fragments of nuclear envelope
Microtubule attached to kinetochore

Anaphase I

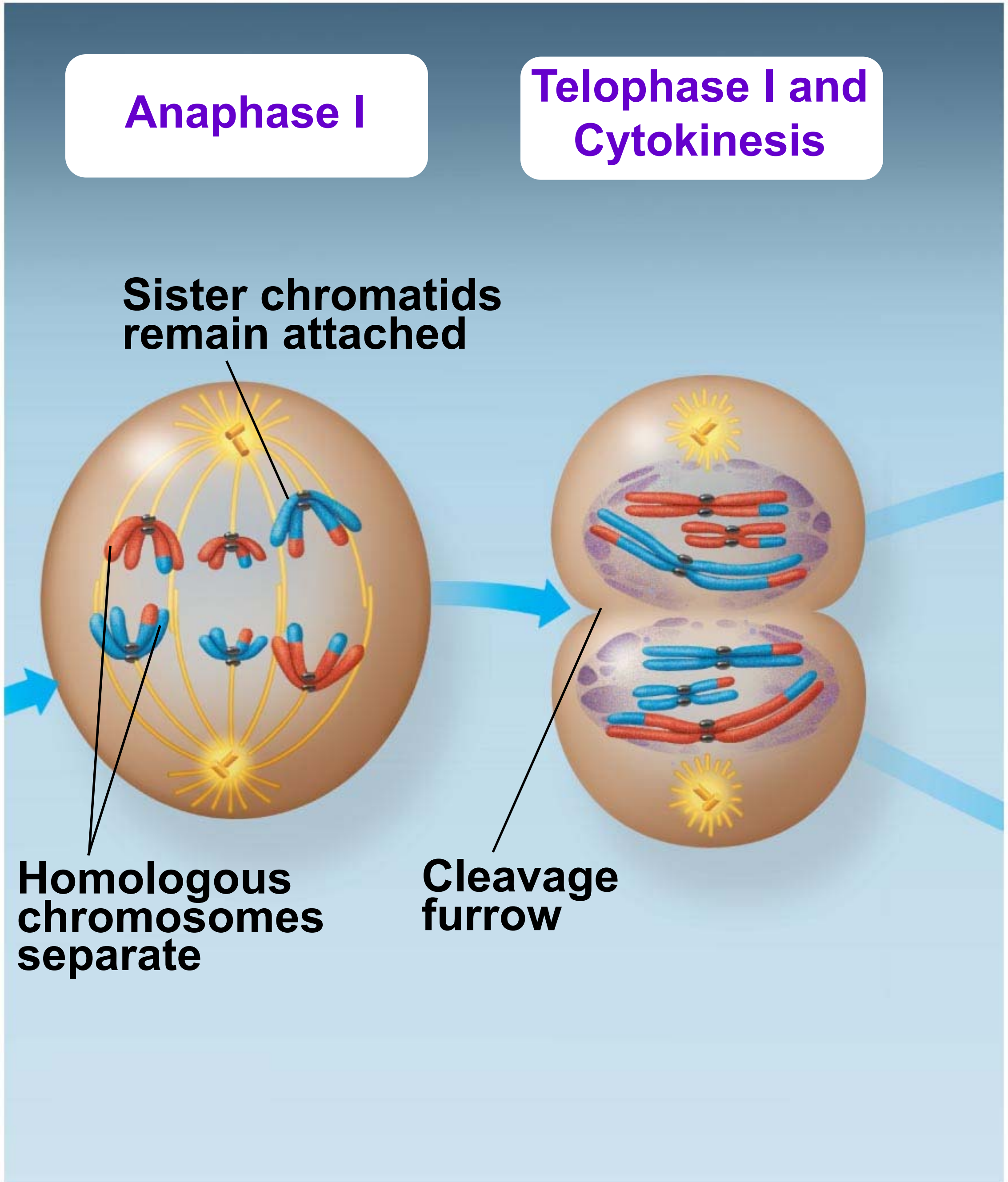
- In anaphase I, **pairs of homologous chromosomes separate**
- One chromosome moves toward each pole, guided by the spindle apparatus
- Sister chromatids remain attached at the centromere and move as one unit toward the pole

Telophase I and Cytokinesis

- In the beginning of telophase I, each half of the cell has a haploid set of chromosomes; each chromosome still consists of two sister chromatids
- **Cytokinesis** usually occurs simultaneously, forming **two haploid daughter cells**

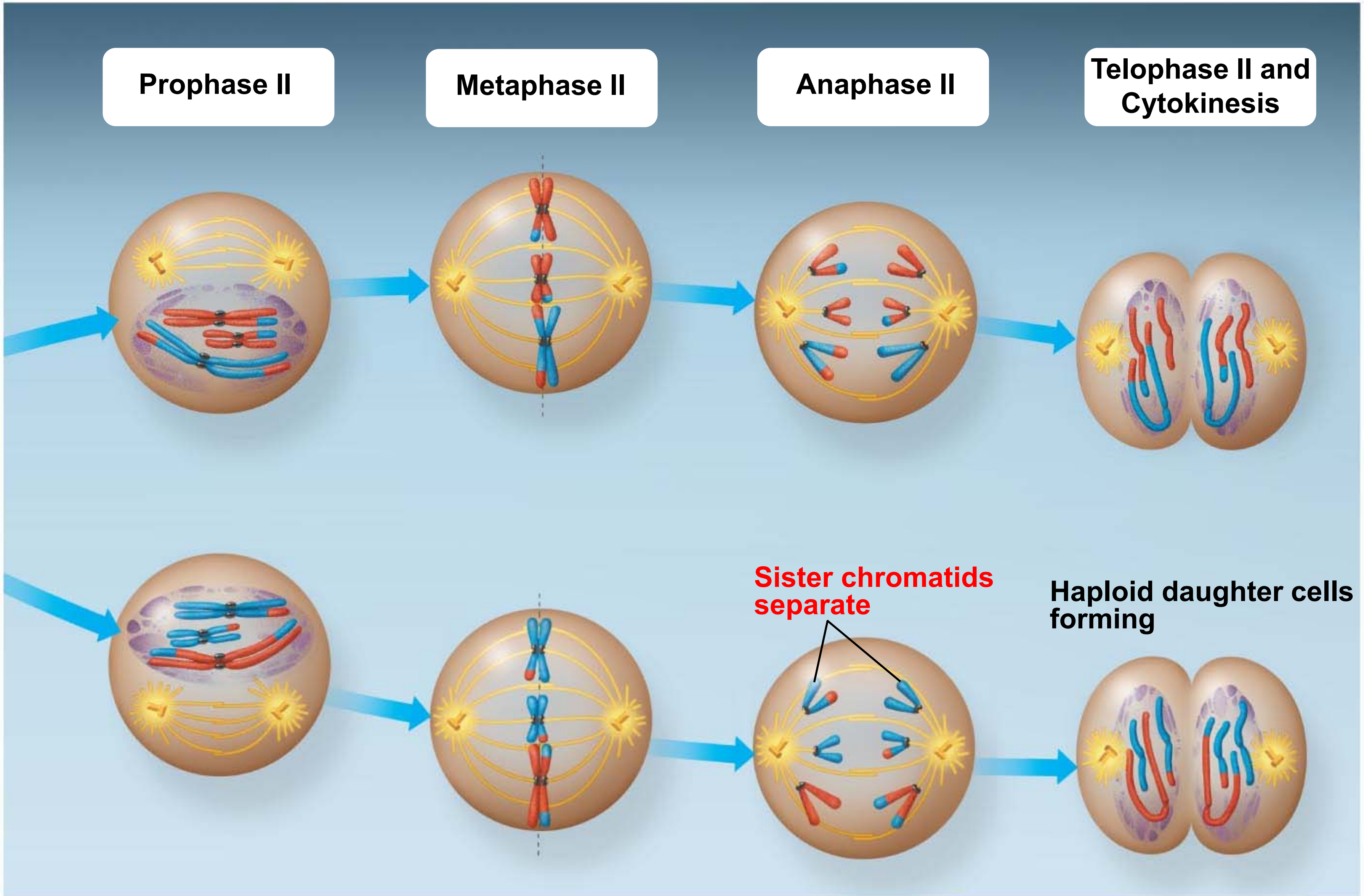
- In animal cells, a cleavage furrow forms; in plant cells, a cell plate forms
- *No chromosome replication occurs between the end of meiosis I and the beginning of meiosis II* because the chromosomes are already replicated

Fig. 13-8c


Anaphase I
Telophase I and Cytokinesis
Sister chromatids remain attached
Homologous chromosomes separate
Cleavage furrow

- **Division in meiosis II** also occurs in four phases:
  - **Prophase II**
  - **Metaphase II**
  - **Anaphase II**
  - **Telophase II and cytokinesis**
- Meiosis II is **very similar to mitosis**

Fig. 13-8d


Prophase II
Metaphase II
Anaphase II
Telophase II and Cytokinesis
Sister chromatids separate
Haploid daughter cells forming

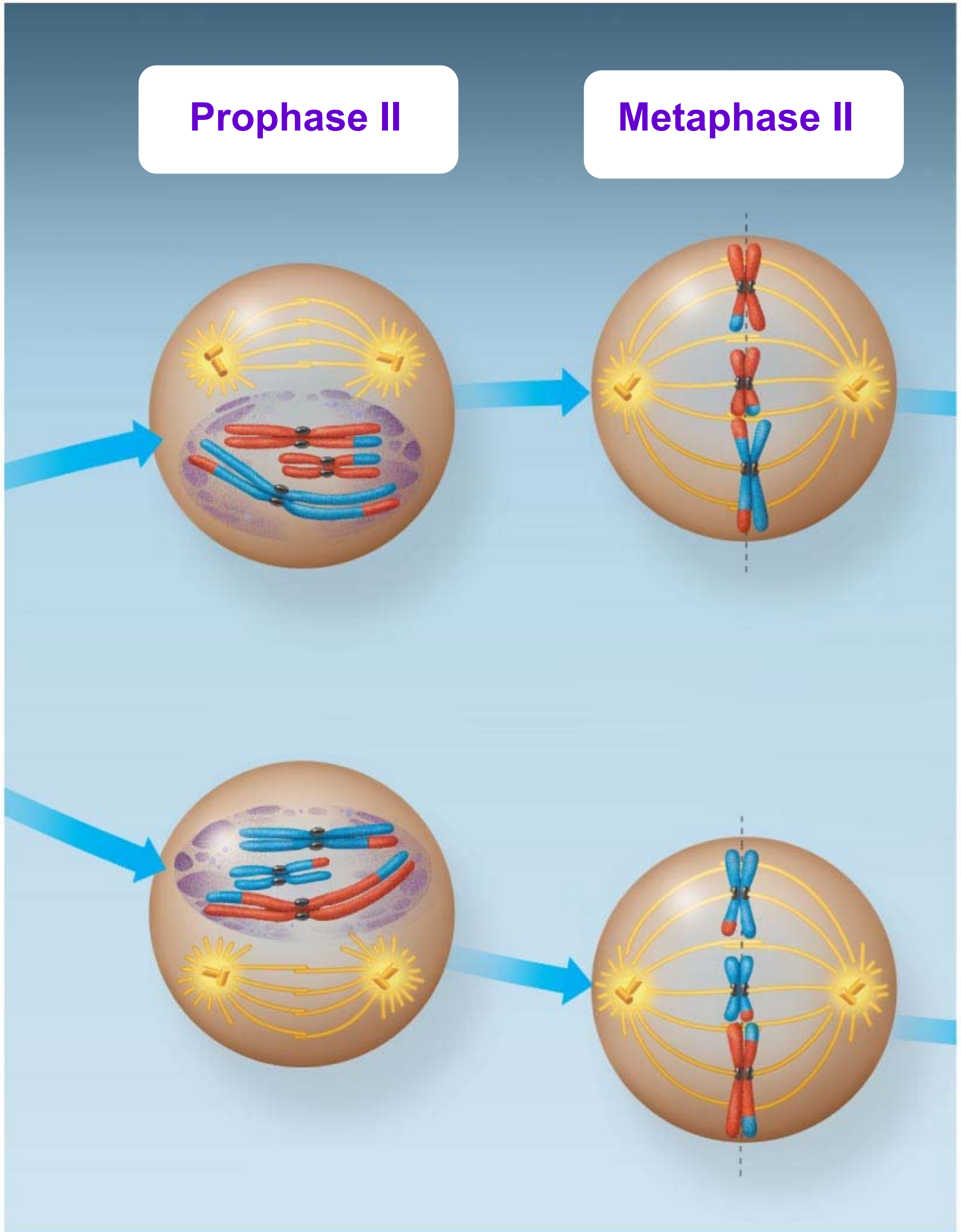
Prophase II

- In prophase II, a spindle apparatus forms
- In late prophase II, chromosomes (each still composed of two chromatids) move toward the metaphase plate

Metaphase II

- In metaphase II, the sister chromatids are arranged at the metaphase plate
- Because of crossing over in meiosis I, the two sister chromatids of each chromosome are no longer genetically identical
- The kinetochores of sister chromatids attach to microtubules extending from opposite poles

Fig. 13-8e



Anaphase II

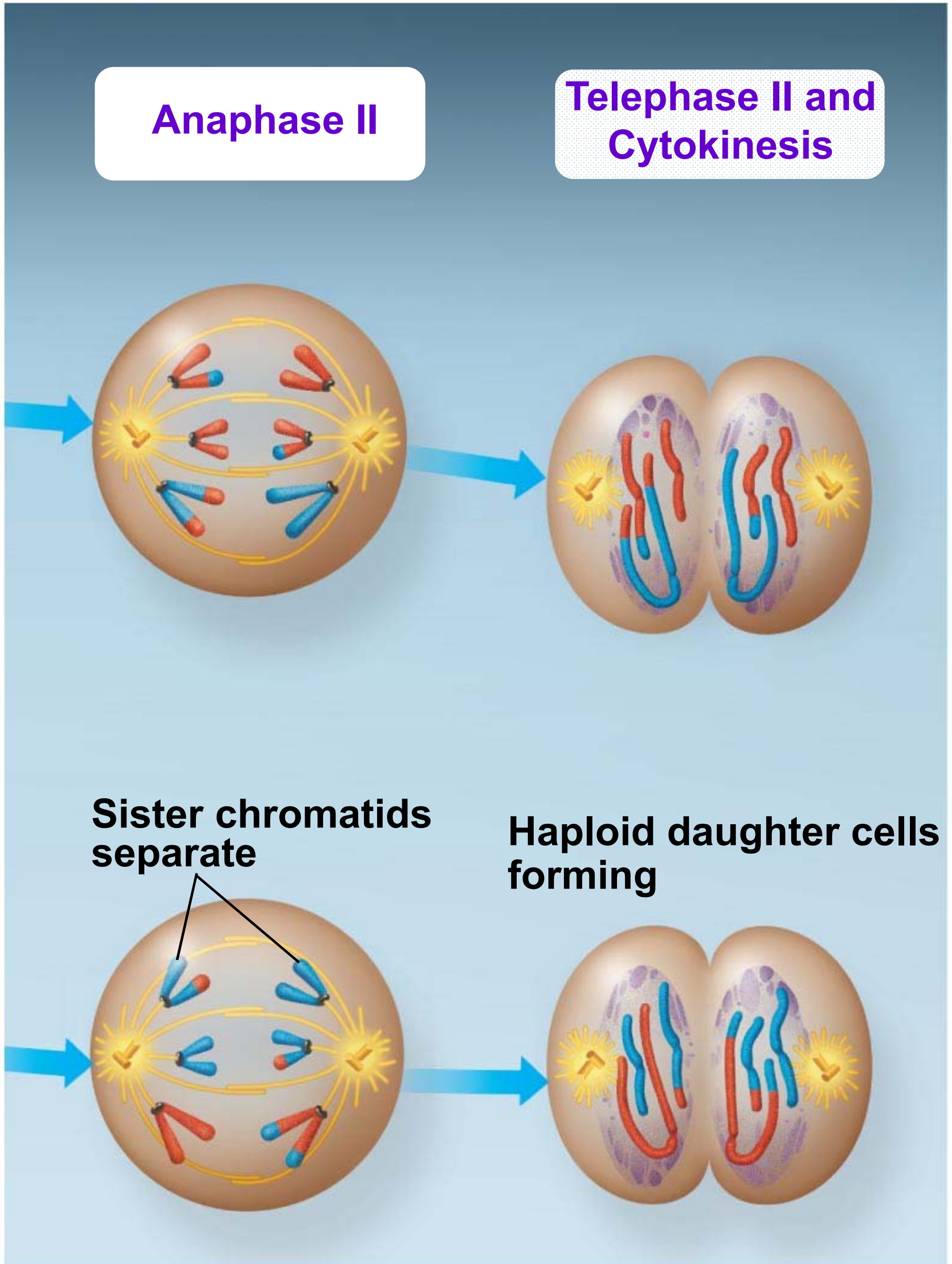
- In anaphase II, **the sister chromatids separate**
- The sister chromatids of each chromosome now move as two newly individual chromosomes toward opposite poles

Telophase II and Cytokinesis

- In telophase II, the chromosomes arrive at opposite poles
- Nuclei form, and the chromosomes begin decondensing

- Cytokinesis separates the cytoplasm
- At the end of meiosis, there are four daughter cells, each with a haploid set of unreplicated chromosomes
- Each daughter cell is genetically distinct from the others and from the parent cell

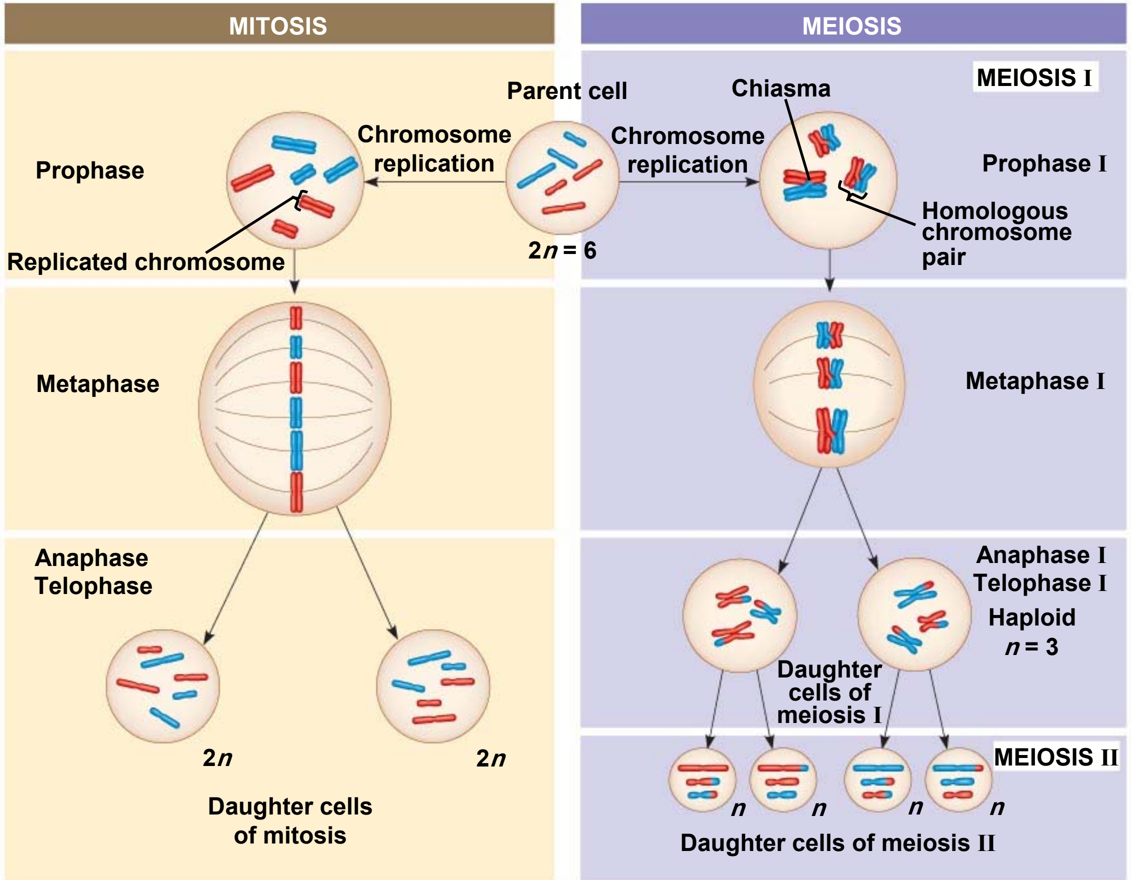
Fig. 13-8f


Anaphase II
Telephase II and Cytokinesis
Sister chromatids separate
Haploid daughter cells forming

A Comparison of Mitosis and Meiosis

- Mitosis conserves the number of chromosome sets, producing cells that are genetically identical to the parent cell
- Meiosis reduces the number of chromosomes sets from two (diploid) to one (haploid), producing cells that differ genetically from each other and from the parent cell
- The mechanism for separating sister chromatids is virtually identical in meiosis II and mitosis

Fig. 13-9



SUMMARY

Property	Mitosis	Meiosis
DNA replication	Occurs during interphase before mitosis begins	Occurs during interphase before meiosis I begins
Number of divisions	One, including prophase, metaphase, anahase, and telophase	Two, each including prophase, metaphase, anaphase, and telophase
Synapsis of homologous chromosomes	Does not occur	Occurs during prophase I along with crossing over between nonsister chromatids; resulting chiasmata hold pairs together due to sister chromatid cohesion
Number of daughter cells and genetic composition	Two, each diploid (2*n*) and genetically identical to the parent cell	Four, each haploid (*n*), containing half as many chromosomes as the parent cell; genetically different from the parent cell and from each other
Role in the animal body	Enables multicellular adult to arise from zygote; produces cells for growth, repair, and, in some species, asexual reproduction	Produces gametes; reduces number of chromosomes by half and introduces genetic variability amoung the gametes

Fig. 13-9a

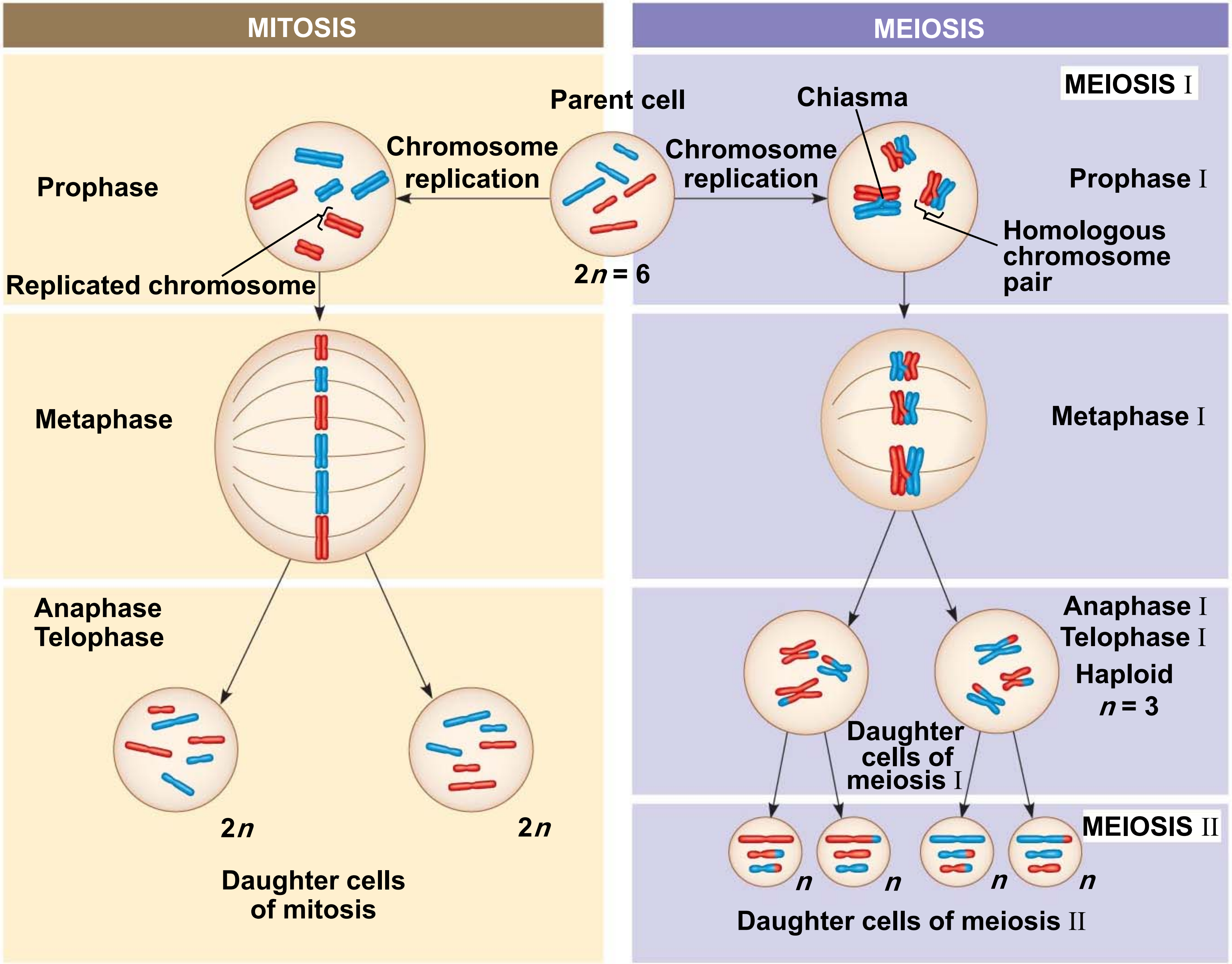

MITOSIS
MEIOSIS
MEIOSIS I
Parent cell
Chiasma
Chromosome replication
Chromosome replication
Prophase
Prophase I
Homologous chromosome pair
Replicated chromosome
2n = 6
Metaphase
Metaphase I
Anaphase
Telophase
Anaphase I
Telophase I
Haploid
n = 3
Daughter cells of meiosis I
MEIOSIS II
2n
2n
n
n
n
n
Daughter cells of mitosis
Daughter cells of meiosis II

Fig. 13-9b

SUMMARY		
Property	**Mitosis**	**Meiosis**
DNA replication	Occurs during interphase before mitosis begins	Occurs during interphase before meiosis I begins
Number of divisions	One, including prophase, metaphase, anaphase, and telophase	Two, each including prophase, metaphase, anaphase, and telophase
Synapsis of homologous chromosomes	Does not occur	Occurs during prophase I along with crossing over between nonsister chromatids; resulting chiasmata hold pairs together due to sister chromatid cohesion
Number of daughter cells and genetic composition	Two, each diploid ($2n$) and genetically identical to the parent cell	Four, each haploid (n), containing half as many chromosomes as the parent cell; genetically different from the parent cell and from each other
Role in the animal body	Enables multicellular adult to arise from zygote; produces cells for growth, repair, and, in some species, asexual reproduction	Produces gametes; reduces number of chromosomes by half and introduces genetic variability among the gametes

- Three events are unique to meiosis, and all three occur in meiosis I:
  - **Synapsis** and **crossing over** in prophase I: Homologous chromosomes physically connect and exchange genetic information
  - At the metaphase plate, there are **paired homologous chromosomes (tetrads),** instead of individual replicated chromosomes
  - At **anaphase I**, it is **homologous chromosomes**, instead of sister chromatids, that separate

- Sister chromatid cohesion allows sister chromatids of a single chromosome to stay together through meiosis I
- Protein complexes **called cohesins** are responsible for this cohesion

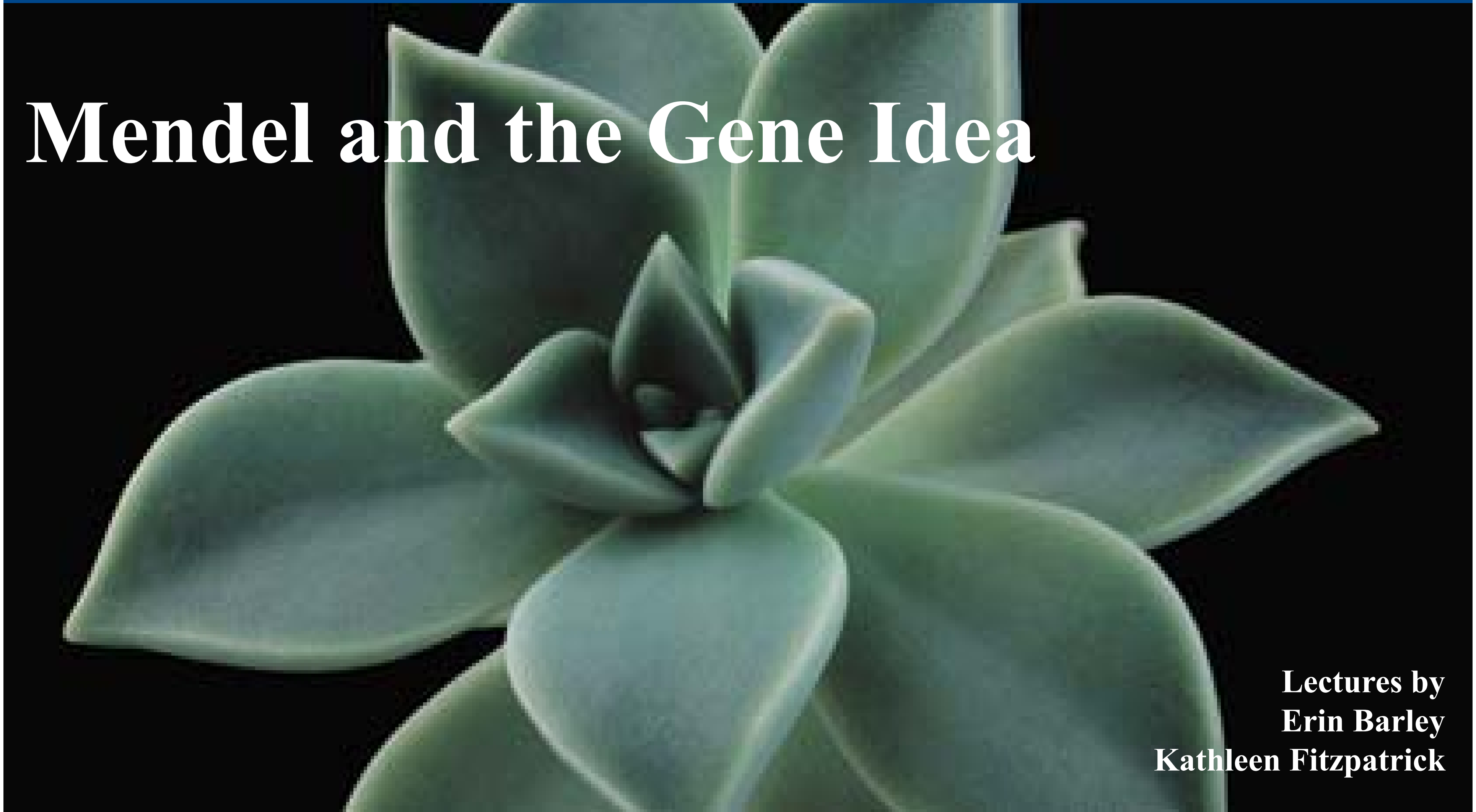
LECTURE PRESENTATIONS

For CAMPBELL BIOLOGY, NINTH EDITION

Jane B. Reece, Lisa A. Urry, Michael L. Cain, Steven A. Wasserman, Peter V. Minorsky, Robert B. Jackson

Chapter 14

Mendel and the Gene Idea



Lectures by
Erin Barley
Kathleen Fitzpatrick

Overview:

- What genetic principles account for the passing of traits from parents to offspring?
- The "**blending**" **hypothesis** is the idea that genetic material from the two parents blends together (like blue and yellow paint blend to make green)

- The “**particulate**” **hypothesis** is the idea that parents pass on **discrete heritable units (genes)**
- **Mendel documented a particulate mechanism** through his experiments with garden peas

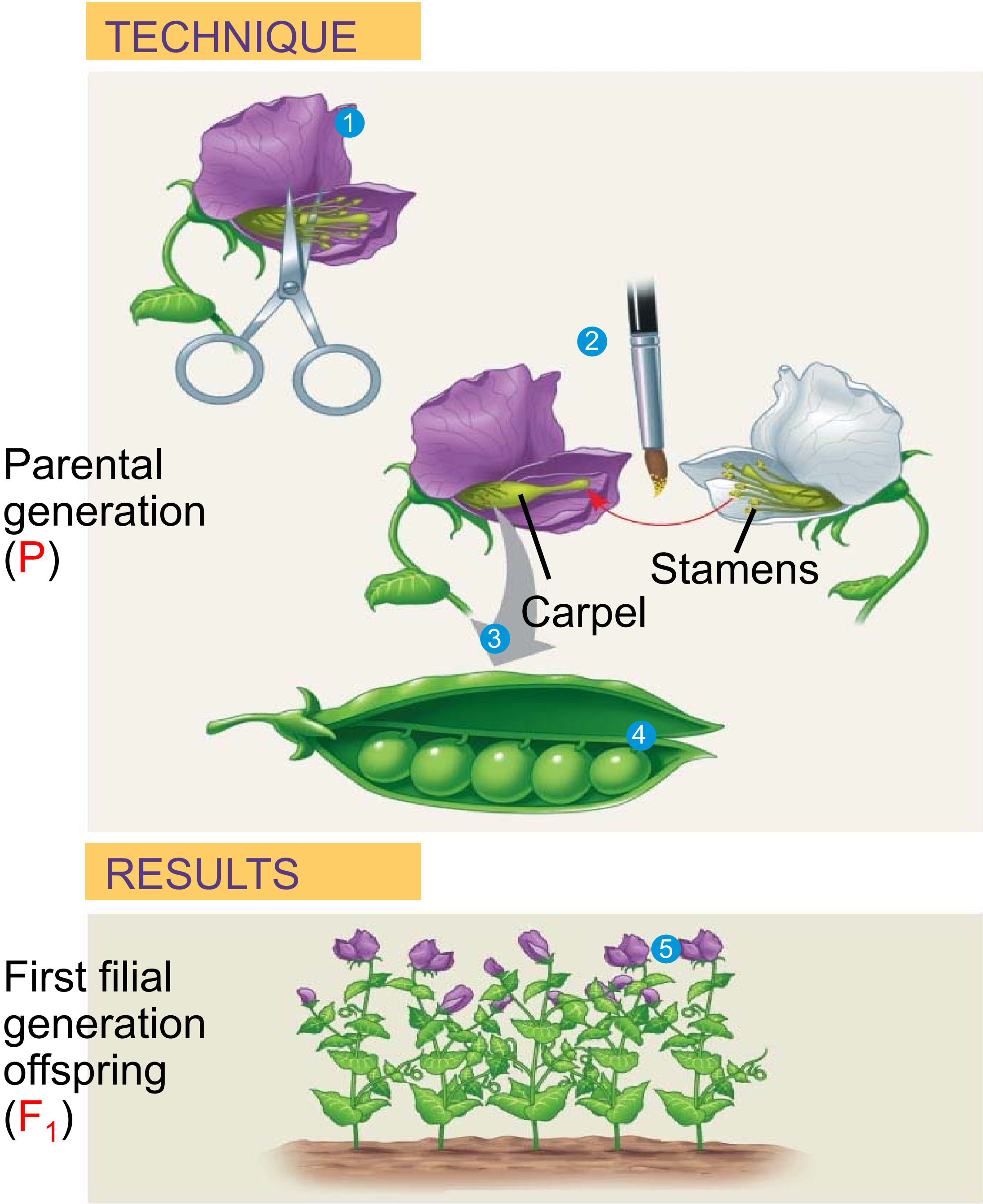
Concept 14.1: Mendel used the scientific approach to identify two laws of inheritance

- Mendel discovered the basic principles of heredity by breeding garden peas in carefully planned experiments

Mendel's Experimental, Quantitative Approach

- **Advantages of pea plants** for genetic study:
  - There are **many varieties** with distinct heritable features, or **characters** (such as flower color); character variants (such as purple or white flowers) are called **traits**
  - Mating of plants can be controlled
  - Each pea plant has sperm-producing organs (stamens) and egg-producing organs (carpels)
  - **Cross-pollination** (fertilization between different plants) can be achieved by dusting one plant with pollen from another

Fig. 14-2


TECHNIQUE
1
2
Parental
generation
(P)
Stamens
Carpel
3
4
RESULTS
5
First filial
generation
offspring
(F_1)

- Mendel chose to track only those **characters that varied** in an **either-or** manner
- He also used varieties that were **true-breeding** (*plants that produce offspring of the same variety when they self-pollinate*)

- In a typical experiment, Mendel mated two contrasting, true-breeding varieties, a process called **hybridization**
- The true-breeding parents are the **P generation**
- The hybrid offspring of the P generation are called the **F_1 generation**
- When F_1 individuals self-pollinate, the **F_2 generation** is produced

The Law of Segregation

- When Mendel crossed contrasting, true-breeding **white** and **purple** flowered pea plants, all of the F_1 hybrids were purple
- When Mendel crossed the F_1 hybrids, many of the F_2 plants had purple flowers, but some had white
- Mendel discovered a ratio of about **three to one**, purple to white flowers, in the F_2 generation

Fig. 14-3-1

EXPERIMENT

P Generation
(true-breeding
parents)

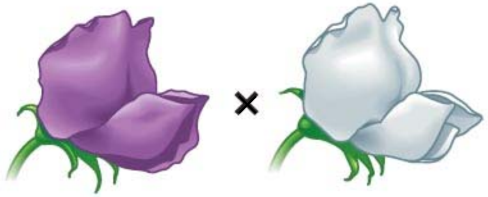


Fig. 14-3-2

EXPERIMENT

P Generation

(true-breeding parents)

F$_1$ Generation

(hybrids)

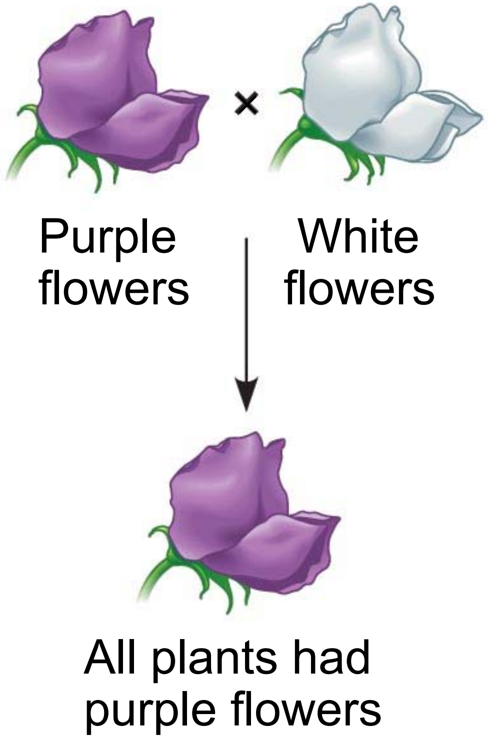
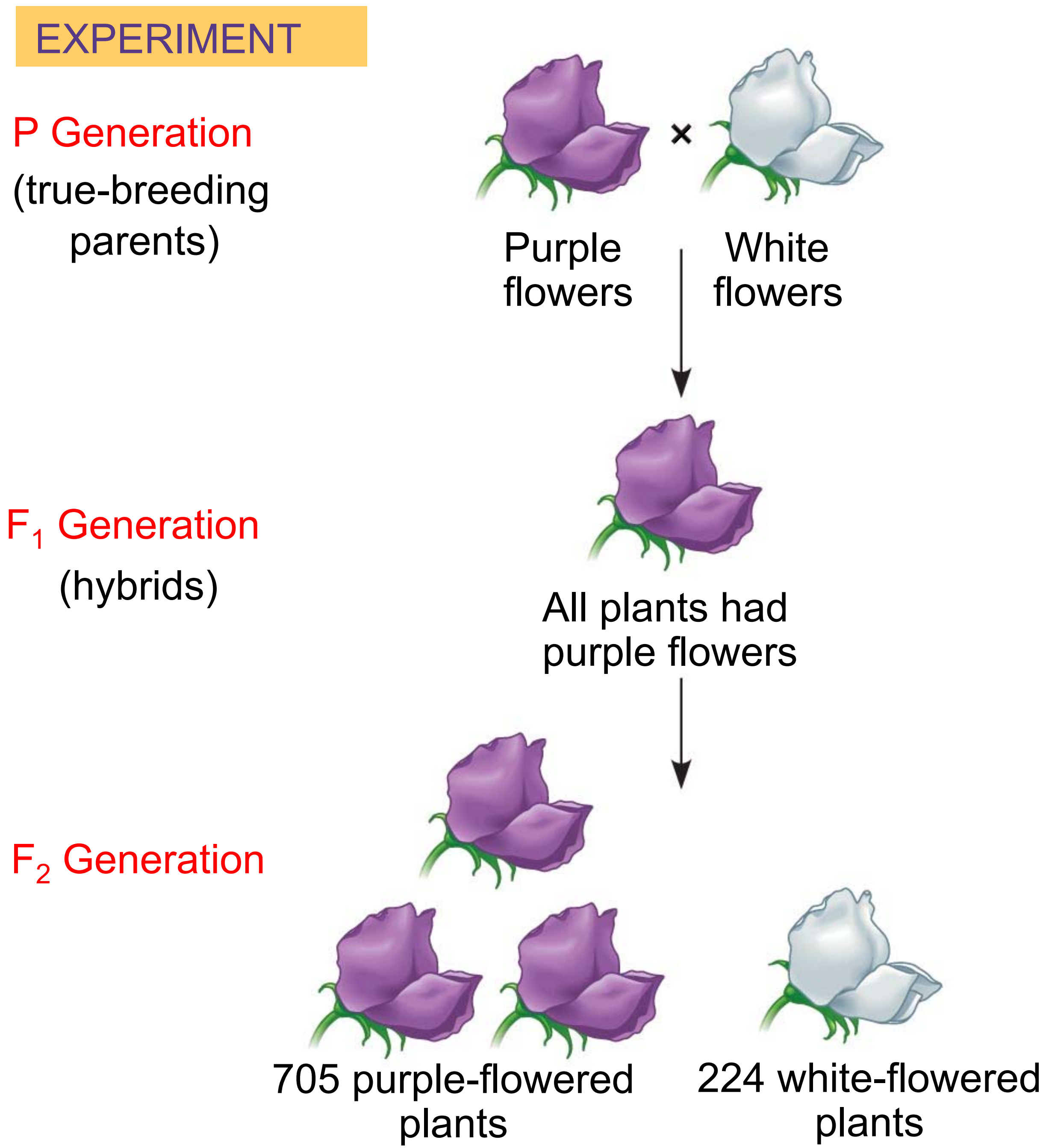


Fig. 14-3-3


EXPERIMENT
P Generation
(true-breeding parents)
×
Purple flowers
White flowers
F_1 Generation
(hybrids)
All plants had purple flowers
F_2 Generation
705 purple-flowered plants
224 white-flowered plants

- Mendel reasoned that *only the purple flower factor was affecting flower color in the F_1 hybrids*
- Mendel called the **purple flower** color a **dominant trait** and the **white flower** color a **recessive trait**
- Mendel observed the same pattern of inheritance in six other pea plant characters, each represented by two traits
- What Mendel called a “heritable factor” is what we now call a gene

Table 14-1

Table 14.1 The Results of Mendel's F_1 Crosses for Seven Characters in Pea Plants

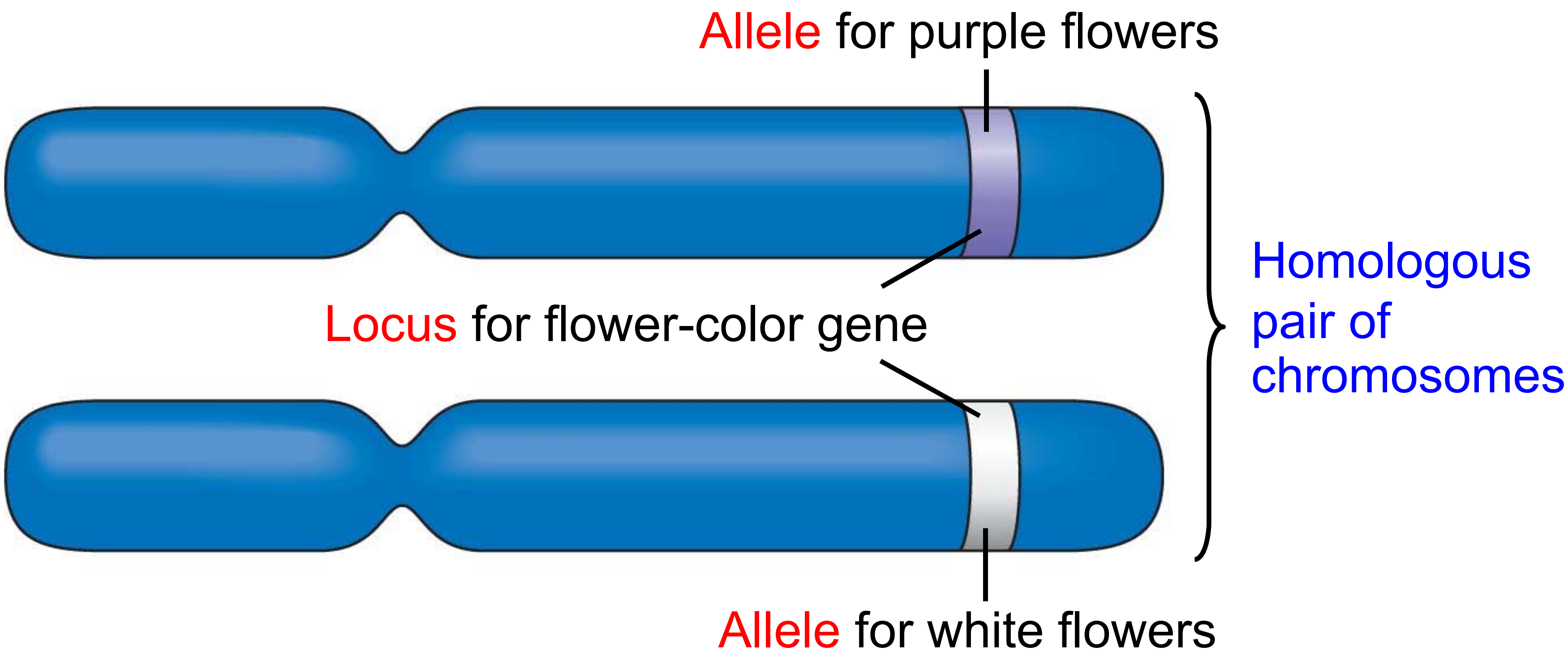
Character	Dominant Trait	x	Recessive Trait	F_2 Generation Dominant:Recessive	Ratio
Flower color	Purple 	×	White 	705:224	3.15:1
Flower position	Axial 	×	Terminal 	651:207	3.14:1
Seed color	Yellow 	×	Green 	6,022:2,001	3.01:1
Seed shape	Round 	×	Wrinkled 	5,474:1,850	2.96:1
Pod shape	Inflated 	×	Constricted 	882:299	2.95:1
Pod color	Green 	×	Yellow 	428:152	2.82:1
Stem length	Tall 	×	Dwarf 	787:277	2.84:1

Mendel's Model

- Mendel developed a hypothesis to explain the **3:1 inheritance pattern** he observed in F_2 offspring
- **Four related concepts** make up this model
- These concepts can be related to what we now know about genes and chromosomes

- The **first concept** *is that alternative versions of genes account for variations in inherited characters*
- For example, the gene for flower color in pea plants exists in two versions, one for purple flowers and the other for white flowers
- *These alternative versions of a gene are now called* **alleles**
- Each gene resides at a **specific locus** on a specific chromosome

Fig. 14-4


Allele for purple flowers
Locus for flower-color gene
Homologous
pair of
chromosomes
Allele for white flowers

- The second concept is that *for each character an organism inherits two alleles, one from each parent*
- Mendel made this deduction without knowing about the role of chromosomes
- The two alleles at a locus on a chromosome **may be identical**, *as in the true-breeding plants of Mendel's P generation*
- Alternatively, *the two alleles at a locus may differ*, as in the F_1 hybrids

- The **third concept** *is that if the two alleles at a locus differ, then one (the **dominant allele**) determines the organism's appearance, and the other (the **recessive allele**) has no noticeable effect on appearance*
- In the flower-color example, the F_1 plants had purple flowers because the allele for that trait is dominant

- **The fourth concept**, now known as the **law of segregation**, states that *the two alleles for a heritable character separate (segregate) during gamete formation and end up in different gametes*
- Thus, an egg or a sperm gets only one of the two alleles that are present in the somatic cells of an organism
- This segregation of alleles corresponds to the distribution of homologous chromosomes to different gametes in meiosis

- Mendel's segregation model accounts for the 3:1 ratio he observed in the F_2 generation of his numerous crosses
- The possible combinations of sperm and egg can be shown using a **Punnett square**, a diagram for predicting the results of a genetic cross between individuals of known genetic makeup
- A capital letter represents a dominant allele, and a lowercase letter represents a recessive allele

Fig. 14-5-1

P Generation

Appearance: Purple flowers White flowers

Genetic makeup: *PP* *pp*

Gametes: *P* *p*

Fig. 14-5-2

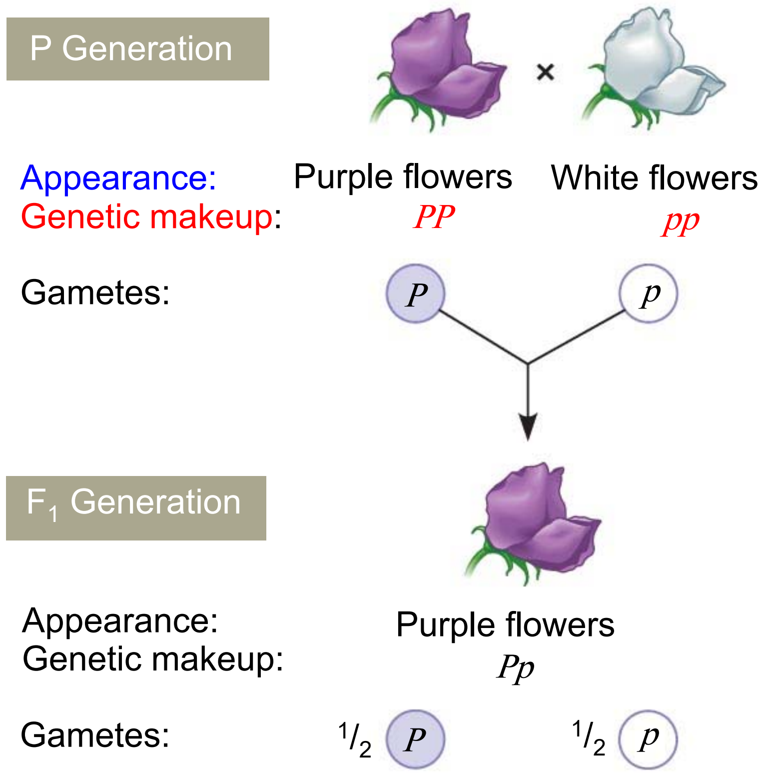
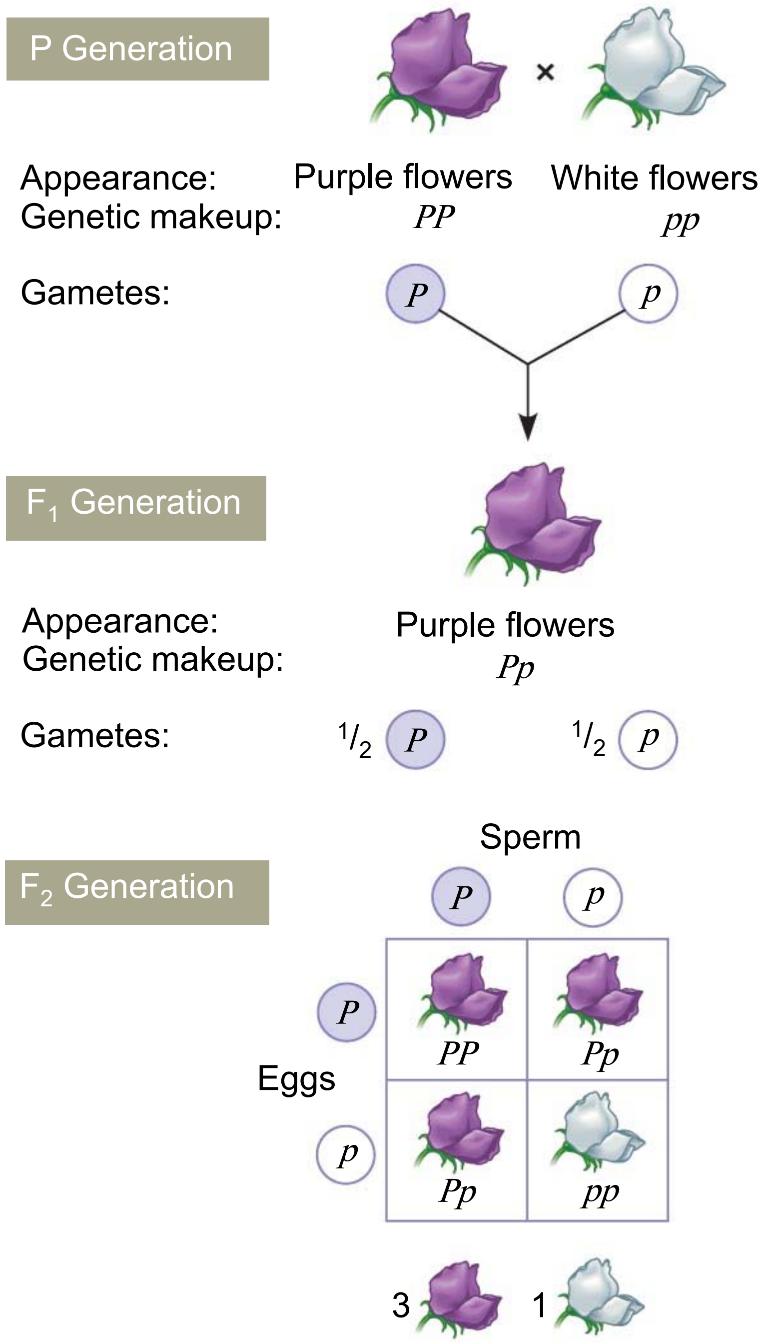

P Generation
×
Appearance:
Purple flowers
White flowers
Genetic makeup:
PP
pp
Gametes:
P
p
F1 Generation
Appearance:
Purple flowers
Genetic makeup:
Pp
Gametes:
1/2 P
1/2 p

Fig. 14-5-3

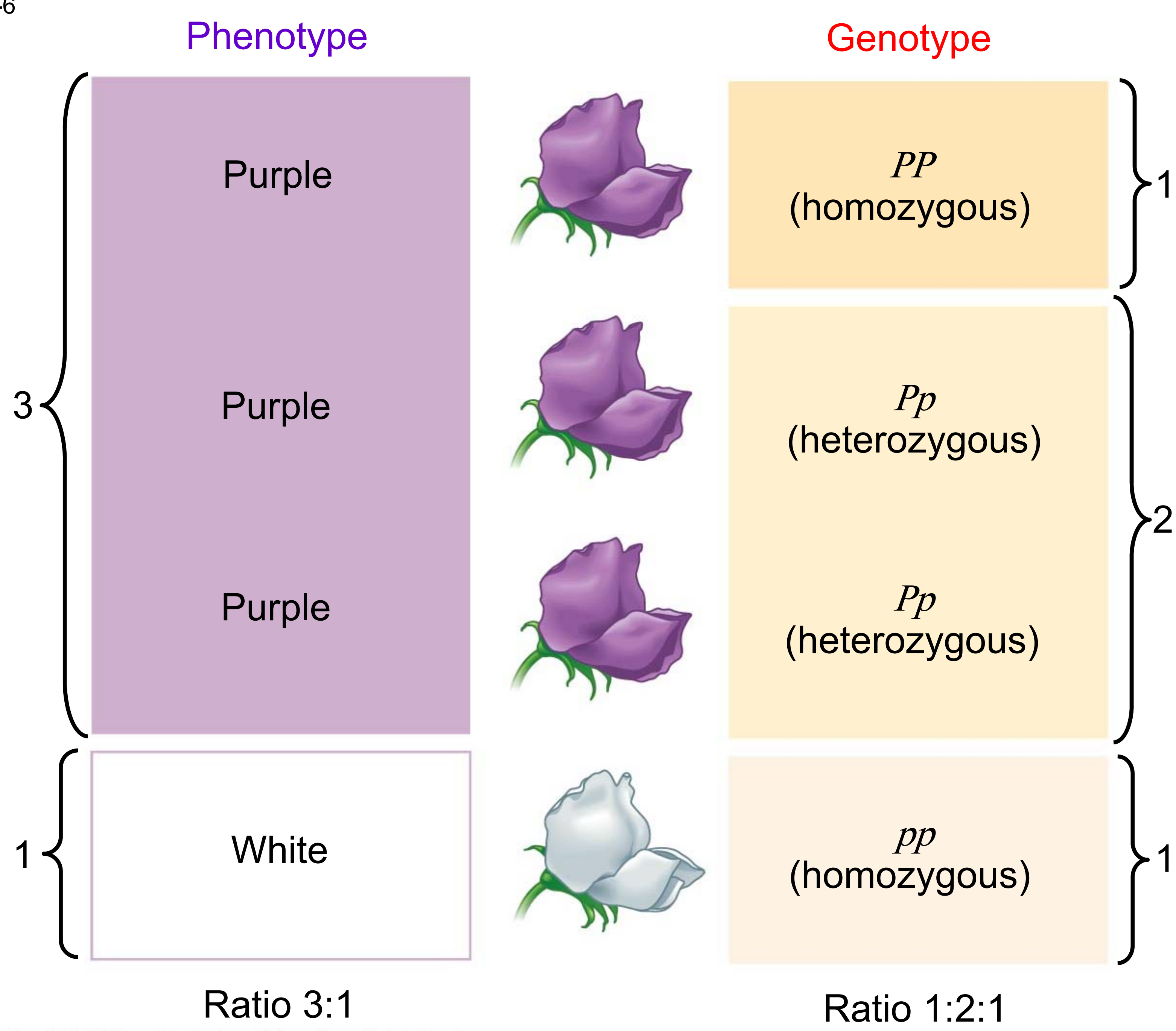

P Generation
Appearance:
Genetic makeup:
Purple flowers
PP
White flowers
pp
Gametes:
P
p
F1 Generation
Appearance:
Genetic makeup:
Purple flowers
Pp
Gametes:
1/2 P
1/2 p
Sperm
F2 Generation
P
p
Eggs
P
p
PP
Pp
Pp
pp
3
1

Useful Genetic Vocabulary

- An organism with **two identical alleles** for a character is said to be **homozygous** for the gene controlling that character
- An organism that has **two different alleles** for a gene is said to be **heterozygous** for the gene controlling that character
- Unlike homozygotes, heterozygotes are not true-breeding

- Because of the different effects of dominant and recessive alleles, an organism’s traits do not always reveal its genetic composition
- Therefore, we distinguish between an organism’s **phenotype**, or physical appearance, and its **genotype**, or genetic makeup
- In the example of flower color in pea plants, ***PP*** and ***Pp*** plants have the same phenotype (purple) but different genotypes

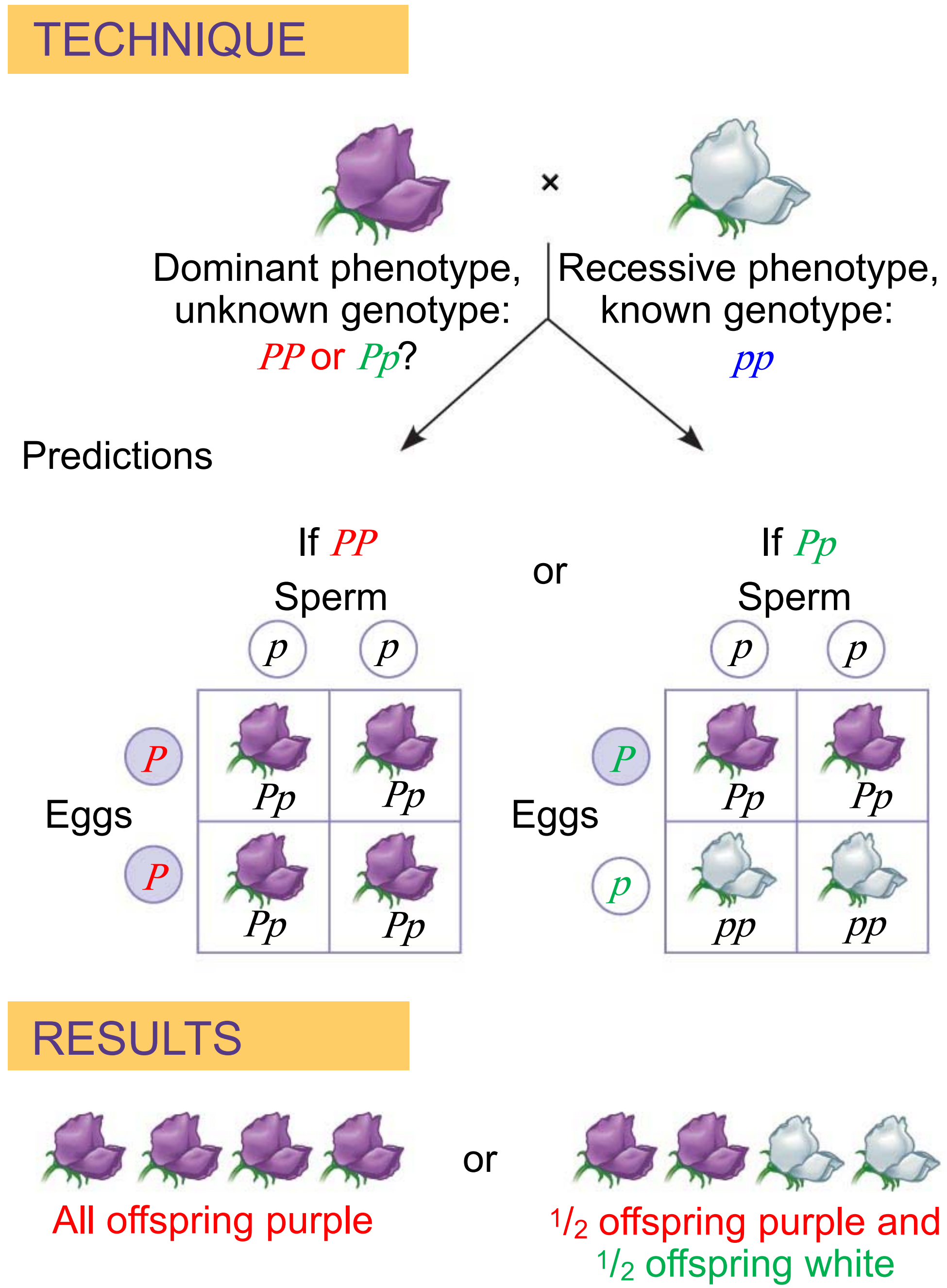
Fig. 14-6


Phenotype
Genotype
Purple
PP
(homozygous)
1
Purple
Pp
(heterozygous)
3
2
Purple
Pp
(heterozygous)
White
pp
(homozygous)
1
1
Ratio 3:1
Ratio 1:2:1

The Testcross

- How can we tell the genotype of an individual with the dominant phenotype?
- Such an individual must have one dominant allele, but the individual could be either homozygous dominant or heterozygous
- The answer is to carry out a **testcross**: *breeding the mystery individual with a homozygous recessive individual*
- If any offspring display the recessive phenotype, the mystery parent must be heterozygous

Fig. 14-7



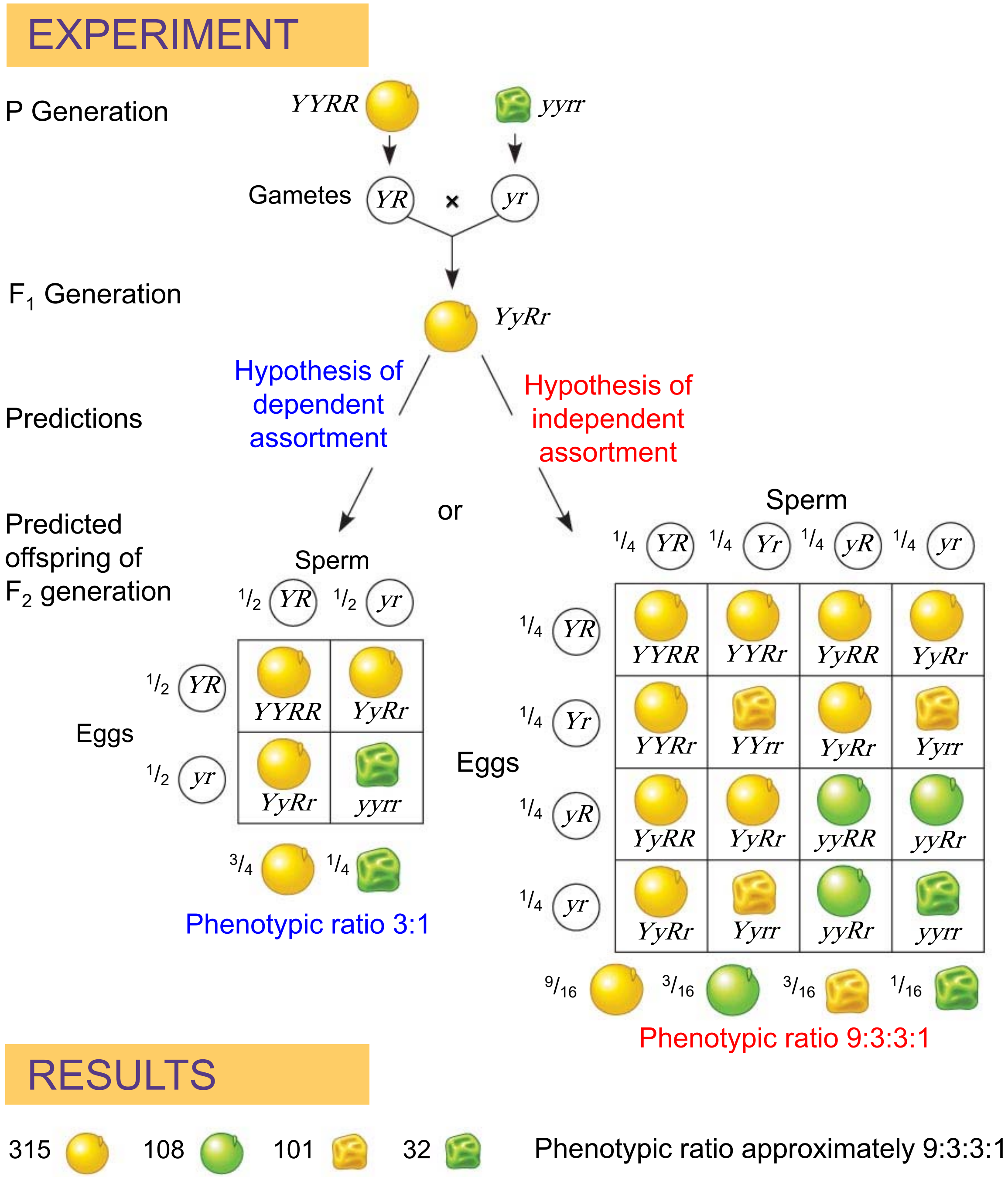
TECHNIQUE
×
Dominant phenotype, unknown genotype: PP or Pp?
Recessive phenotype, known genotype: pp
Predictions
If PP
Sperm
p
p
Eggs
P
P
Pp
Pp
Pp
Pp
or
If Pp
Sperm
p
p
Eggs
P
p
Pp
Pp
pp
pp
RESULTS
All offspring purple
or
1/2 offspring purple and 1/2 offspring white

The Law of Independent Assortment

- Mendel derived the law of segregation by following a single character
- The F_1 offspring produced in this cross were **monohybrids**, *individuals that are heterozygous for one character*
- A cross between such heterozygotes is called a *monohybrid cross*

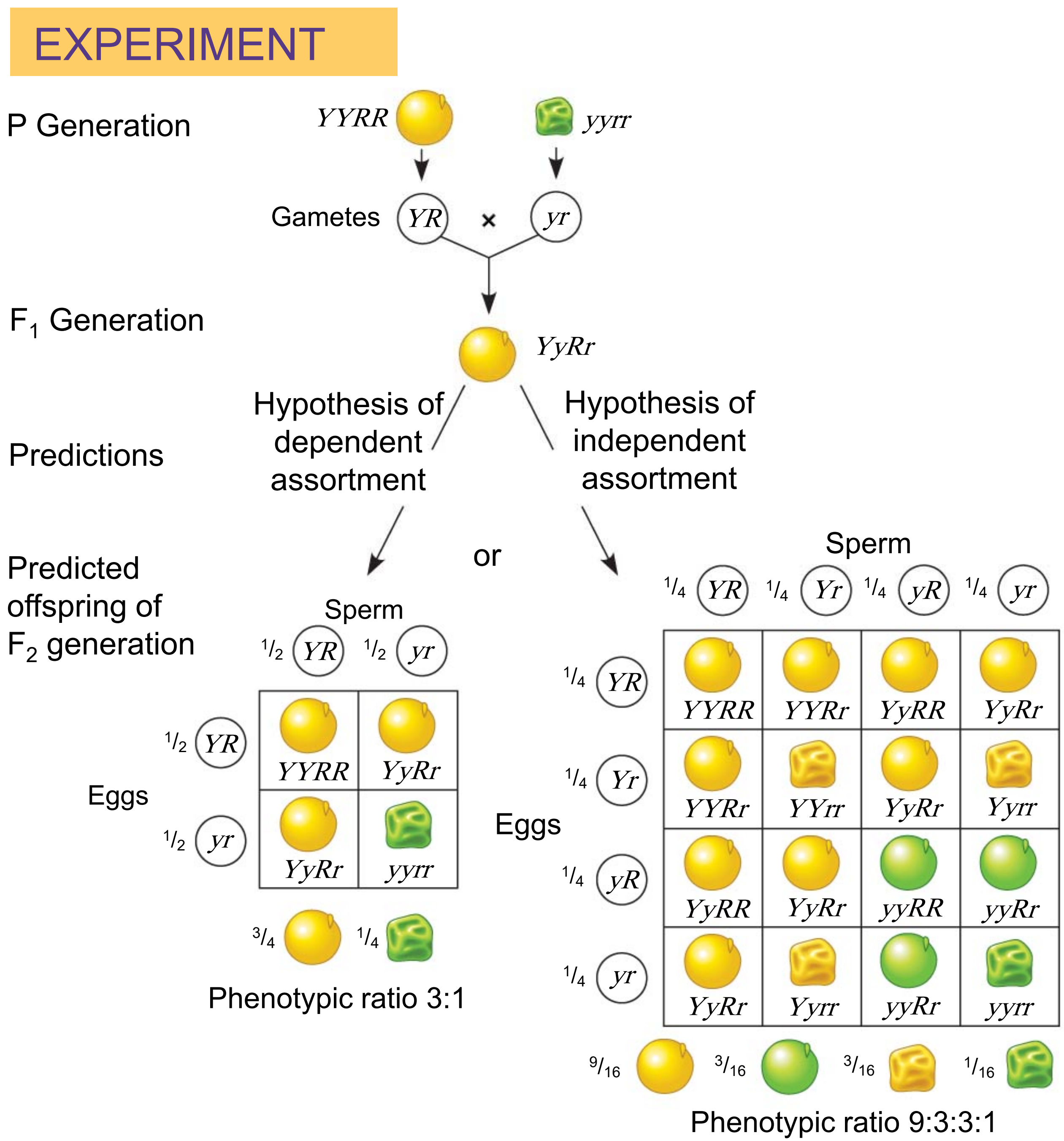
- Mendel identified his **second law of inheritance** by following two characters at the same time
- Crossing two true-breeding parents differing in two characters produces **dihybrids** in the F_1 generation, heterozygous for both characters
- A dihybrid cross, a cross between F_1 dihybrids, *can determine whether two characters are transmitted to offspring as a package or independently*

Fig. 14-8



EXPERIMENT
P Generation
YYRR
yyrr
Gametes
YR
×
yr
F1 Generation
YyRr
Predictions
Hypothesis of dependent assortment
Hypothesis of independent assortment
or
Predicted offspring of F2 generation
Sperm
1/2 YR
1/2 yr
Eggs
1/2 YR
1/2 yr
YYRR
YyRr
YyRr
yyrr
3/4
1/4
Phenotypic ratio 3:1
Sperm
1/4 YR
1/4 Yr
1/4 yR
1/4 yr
Eggs
1/4 YR
1/4 Yr
1/4 yR
1/4 yr
YYRR
YYRr
YyRR
YyRr
YYRr
YYrr
YyRr
Yyrr
YyRR
YyRr
yyRR
yyRr
YyRr
Yyrr
yyRr
yyrr
9/16
3/16
3/16
1/16
Phenotypic ratio 9:3:3:1
RESULTS
315
108
101
32
Phenotypic ratio approximately 9:3:3:1

Fig. 14-8a


EXPERIMENT
P Generation
YYRR
yyrr
Gametes
YR
×
yr
F1 Generation
YyRr
Predictions
Hypothesis of dependent assortment
Hypothesis of independent assortment
or
Predicted offspring of F2 generation
Sperm
1/2 YR
1/2 yr
Eggs
1/2 YR
1/2 yr
YYRR
YyRr
YyRr
yyrr
3/4
1/4
Phenotypic ratio 3:1
Sperm
1/4 YR
1/4 Yr
1/4 yR
1/4 yr
Eggs
1/4 YR
1/4 Yr
1/4 yR
1/4 yr
YYRR
YYRr
YyRR
YyRr
YYRr
YYrr
YyRr
Yyrr
YyRR
YyRr
yyRR
yyRr
YyRr
Yyrr
yyRr
yyrr
9/16
3/16
3/16
1/16
Phenotypic ratio 9:3:3:1

- Using a dihybrid cross, Mendel developed the **law of independent assortment**
- The **law of independent assortment** states that each pair of alleles segregates independently of each other pair of alleles during gamete formation
- Strictly speaking, this law applies only to genes on different, nonhomologous chromosomes
- Genes located near each other on the same chromosome tend to be inherited together

Concept 14.2: The laws of probability govern Mendelian inheritance

- Mendel's laws of segregation and independent assortment reflect the rules of probability
- When tossing a coin, *the outcome of one toss has no impact on the outcome of the next toss*
- In the same way, the alleles of one gene segregate into gametes independently of another gene's alleles

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

- The relationship between genotype and phenotype is rarely as simple as in the pea plant characters Mendel studied
- Many heritable characters are not determined by only one gene with two alleles
- However, the basic principles of segregation and independent assortment apply even to more complex patterns of inheritance

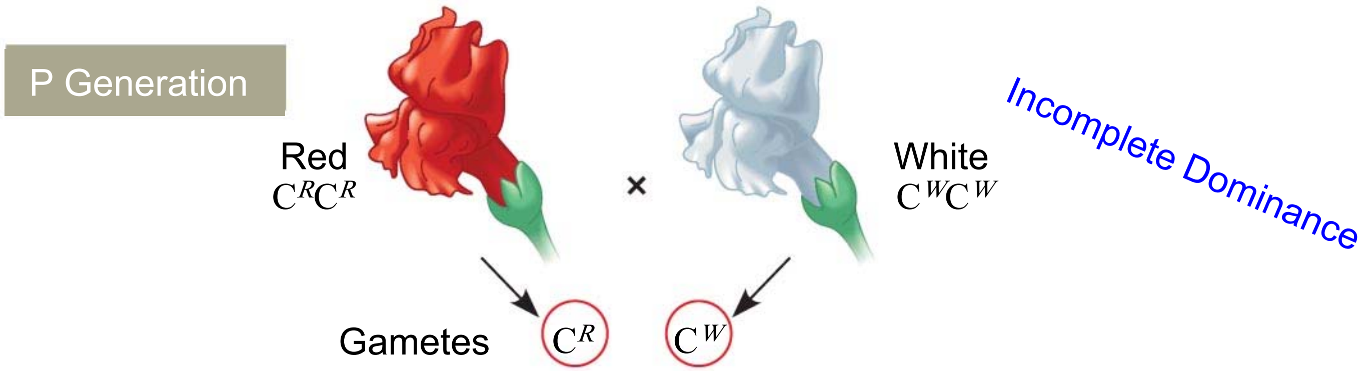
Extending Mendelian Genetics for a Single Gene

- Inheritance of characters by a single gene may deviate from simple Mendelian patterns in the following situations:
  - **When alleles are not completely dominant or recessive**
  - **When a gene has more than two alleles**
  - **When a gene produces multiple phenotypes**

Degrees of Dominance

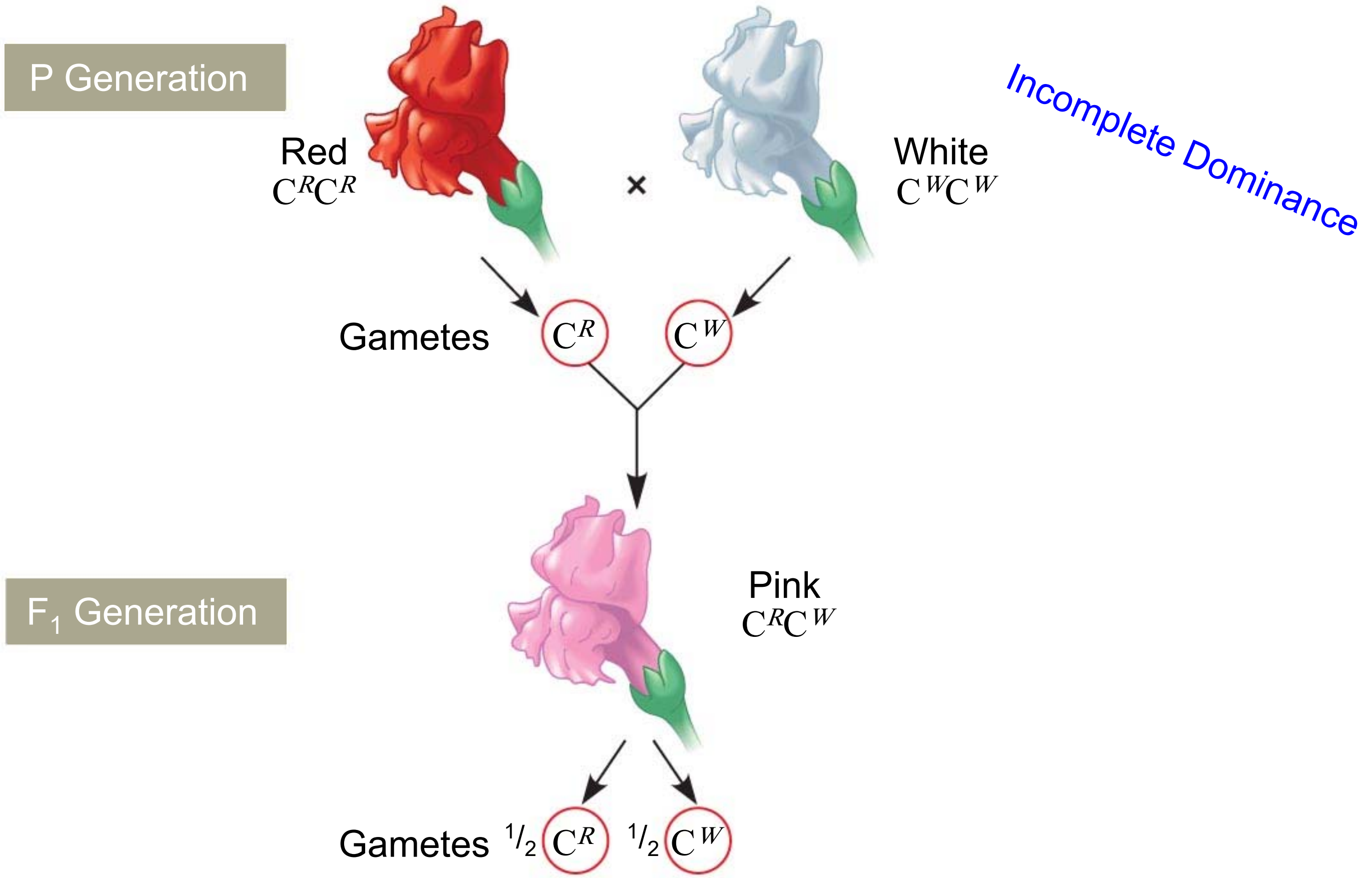
- **Complete dominance** occurs when phenotypes of the heterozygote and dominant homozygote are identical
- In **incomplete dominance**, the phenotype of F_1 hybrids is somewhere between the phenotypes of the two parental varieties
- In **codominance**, two dominant alleles affect the phenotype in separate, distinguishable ways

Fig. 14-10-1



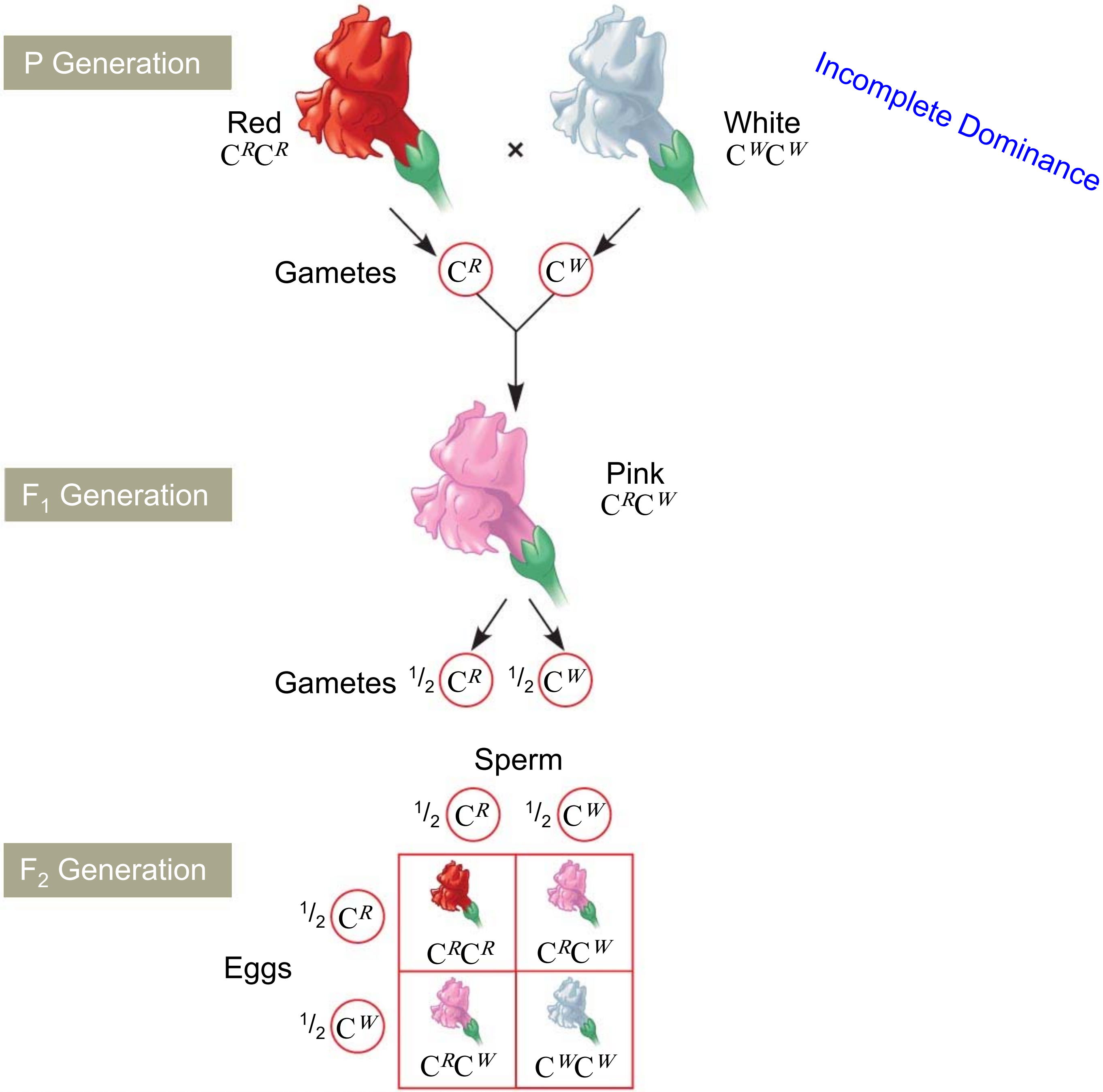
P Generation
Red
C^RC^R
×
White
C^WC^W
Incomplete Dominance
Gametes
C^R
C^W

Fig. 14-10-2



P Generation
Red
C^RC^R
×
White
C^WC^W
Incomplete Dominance
Gametes
C^R
C^W
F_1 Generation
Pink
C^RC^W
Gametes
$^1/_2$ C^R
$^1/_2$ C^W

Fig. 14-10-3



P Generation
Red
C^RC^R
×
White
C^WC^W
Incomplete Dominance
Gametes
C^R
C^W
F_1 Generation
Pink
C^RC^W
Gametes
$^1/_2$ C^R
$^1/_2$ C^W
Sperm
$^1/_2$ C^R
$^1/_2$ C^W
F_2 Generation
Eggs
$^1/_2$ C^R
$^1/_2$ C^W
C^RC^R
C^RC^W
C^RC^W
C^WC^W

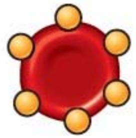
Multiple Alleles

- Most genes exist in populations in more than two allelic forms
- For example, the **four phenotypes** of the ABO blood group in humans are determined by **three alleles** for the enzyme (I) that attaches A or B carbohydrates to red blood cells: I^A, I^B, and i.
- The enzyme encoded by the I^A allele adds the **A** carbohydrate, whereas the enzyme encoded by the I^B allele adds the **B** carbohydrate; the enzyme encoded by the i allele **adds neither**

Fig. 14-11

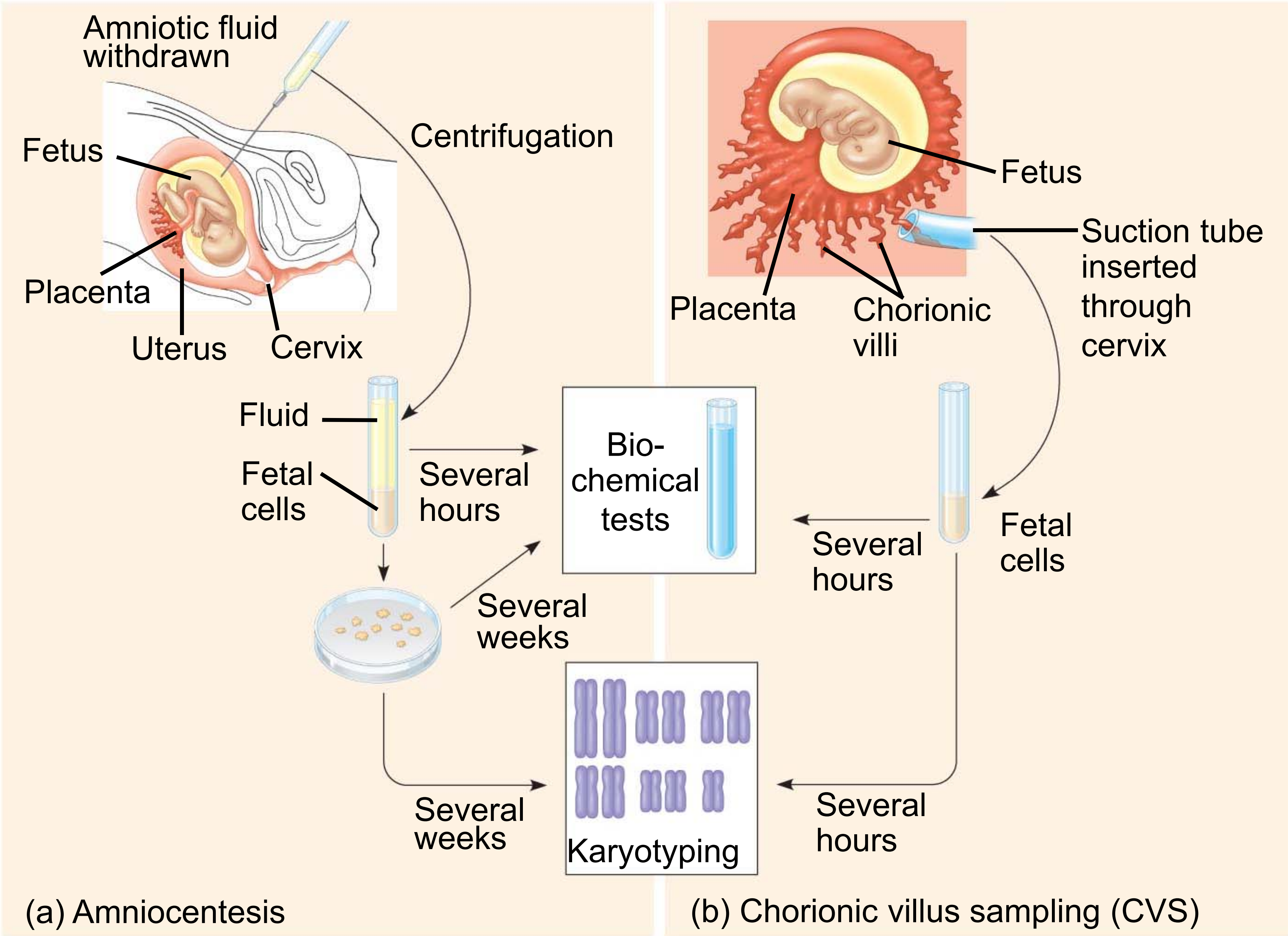
Allele	Carbohydrate
I^A	A
I^B	B
i	none

(a) The three alleles for the ABO blood groups and their associated carbohydrates

Genotype	Red blood cell appearance	Phenotype (blood group)
I^AI^A or I^Ai		A
I^BI^B or I^Bi		B
I^AI^B		AB
ii		O

(b) Blood group genotypes and phenotypes

Fig. 14-18



Amniotic fluid withdrawn
Fetus
Placenta
Uterus
Cervix
Centrifugation
Fluid
Fetal cells
Several hours
Several weeks
Bio-chemical tests
Several weeks
Karyotyping
(a) Amniocentesis
Fetus
Suction tube inserted through cervix
Placenta
Chorionic villi
Fetal cells
Several hours
Several hours
(b) Chorionic villus sampling (CVS)

Fig. 14-UN2

Degree of dominance	Description	Example
Complete dominance of one allele	Heterozygous phenotype same as that of homozygous dominant	PP  Pp 
Incomplete dominance of either allele	Heterozygous phenotype intermediate between the two homozygous phenotypes	 C^RC^R C^RC^W C^WC^W
Codominance	Heterozygotes: Both phenotypes expressed	I^AI^B 
Multiple alleles	In the whole population, some genes have more than two alleles	ABO blood group alleles I^A, I^B, i

Chapter 41

Animal Nutrition

PowerPoint® Lecture Presentations for

Biology

Eighth Edition

Neil Campbell and Jane Reece

Lectures by Chris Romero, updated by Erin Barley with contributions from Joan Sharp

Overview: The Need to Feed

- Food is taken in, taken apart, and taken up in the process of animal **nutrition**
- In general, animals fall into three categories:
  - **Herbivores** eat mainly autotrophs (plants and algae)
  - **Carnivores** eat other animals
  - **Omnivores** regularly consume animals as well as plants or algal matter

Fig. 41-1

Concept 41.1: An animal's diet must supply chemical energy, organic molecules, and essential nutrients

- An animal's diet provides chemical energy, which is converted into ATP and powers processes in the body
- Animals need a source of organic carbon and organic nitrogen in order to construct organic molecules
- Essential nutrients are required by cells and must be obtained from dietary sources

Essential Nutrients

- There are four classes of essential nutrients:
  - **Essential amino acids**
  - **Essential fatty acids**
  - **Vitamins**
  - **Minerals**

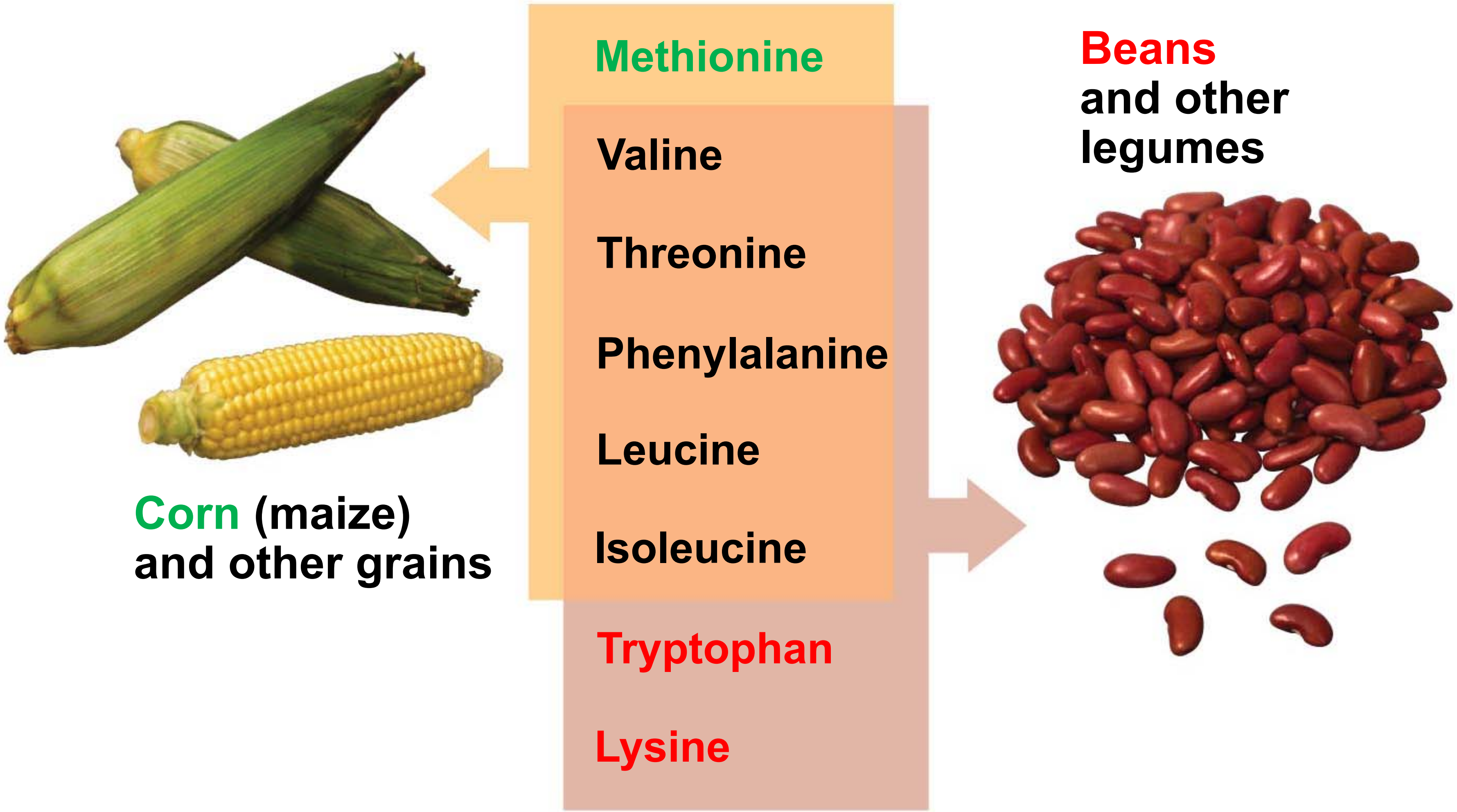
Essential Amino Acids

- Animals require 20 amino acids and can synthesize about half from molecules in their diet
- The remaining amino acids, the **essential amino acids**, *must be obtained from food in preassembled form*
- A diet that provides insufficient essential amino acids causes **malnutrition** called protein deficiency

- **Meat**, **eggs**, and **cheese** provide all the essential amino acids and are thus “complete” proteins
- Most plant proteins are incomplete in amino acid makeup
- Individuals who eat only plant proteins (**vegetarians**) need to eat **specific plant combinations** to get all essential amino acids

Fig. 41-2

Essential amino acids for adults



Essential Fatty Acids

- Animals can synthesize most of the fatty acids they need
- The **essential fatty acids** are certain unsaturated fatty acids that must be obtained from the diet
- Example: linoleic acid (to synthesize some membrane phospholipids).
- Deficiencies in fatty acids are rare

Vitamins

- **Vitamins** are organic molecules required in the diet in small amounts
- 13 vitamins essential to humans have been identified
- Vitamins are grouped into two categories: fat-soluble and water-soluble

Table 41-1a

Table 41.1 Vitamin Requirements of Humans

Vitamin	Major Dietary Sources	Major Functions in the Body	Symptoms of Deficiency or Extreme Excess
Water-Soluble Vitamins			
Vitamin B_1 (thiamine)	Pork, legumes, peanuts, whole grains	Coenzyme used in removing CO_2 from organic compounds	Beriberi (nerve disorders, emaciation, anemia)
Vitamin B_2 (riboflavin)	Dairy products, meats, enriched grains, vegetables	Component of coenzymes FAD and FMN	Skin lesions such as cracks at corners of mouth
Niacin (B_3)	Nuts, meats, grains	Component of coenzymes NAD^+ and $NADP^+$	Skin and gastrointestinal lesions, nervous disorders **Liver damage**
Vitamin B_6 (pyridoxine)	Meats, vegetables, whole grains	Coenzyme used in amino acid metabolism	Irritability, convulsions, muscular twitching, anemia **Unstable gait, numb feet, poor coordination**
Pantothenic acid (B_5)	Most foods: meats, dairy products, whole grains, etc.	Component of coenzyme A	Fatigue, numbness, tingling of hands and feet
Folic acid (folacin) (B_9)	Green vegetables, oranges, nuts, legumes, whole grains	Coenzyme in nucleic acid and amino acid metabolism	Anemia, birth defects **May mask deficiency of vitamin B_{12}**
Vitamin B_{12}	Meats, eggs, dairy products	Coenzyme in nucleic acid metabolism; maturation of red blood cells	Anemia, nervous system disorders
Biotin	Legumes, other vegetables, meats	Coenzyme in synthesis of fat, glycogen, and amino acids	Scaly skin inflammation, neuromuscular disorders
Vitamin C (ascorbic acid)	Fruits and vegetables, especially citrus fruits, broccoli, cabbage, tomatoes, green peppers	Used in collagen synthesis (such as for bone, cartilage, gums); antioxidant; aids in detoxification; improves iron absorption	Scurvy (degeneration of skin, teeth, blood vessels), weakness, delayed wound healing, impaired immunity **Gastrointestinal upset**

Table 41-1b

Table 41.1 Vitamin Requirements of Humans

Vitamin	Major Dietary Sources	Major Functions in the Body	Symptoms of Deficiency or Extreme Excess
Fat-Soluble Vitamins			
Vitamin A (retinol)	Provitamin A (beta-carotene) in deep green and orange vegetables and fruits; retinal in dairy products	Component of visual pigments; maintenance of epithelial tissues; antioxidant; helps prevent damage to cell membranes	Blindness and increased death rate **Headache, irritability, vomiting, hair loss, blurred vision, liver and bone damage**
Vitamin D	Dairy products, egg yolk; also made in human skin in presence of sunlight	Aids in absorption and use of calcium and phosphorus; promotes bone growth	Rickets (bone deformities) in children, bone softening in adults **Brain, cardiovascular, and kidney damage**
Vitamin E (tocopherol)	Vegetable oils, nuts, seeds	Antioxidant; helps prevent damage to cell membranes	Degeneration of the nervous system
Vitamin K (phylloquinone)	Green vegetables, tea; also made by colon bacteria	Important in blood clotting	Defective blood clotting **Liver damage and anemia**

Minerals

- **Minerals** are simple inorganic nutrients, usually required in small amounts

Table 41-2a

Table 41.2 Mineral Requirements of Humans

	Mineral	Major Dietary Sources	Major Functions in the Body	Symptoms of Deficiency*
Greater than 200 mg per day required	Calcium (Ca)	Dairy products, dark green vegetables, legumes	Bone and tooth formation, blood clotting, nerve and muscle function	Retarded growth, possibly loss of bone mass
	Phosphorus (P)	Dairy products, meats, grains	Bone and tooth formation, acid-base balance, nucleotide synthesis	Weakness, loss of minerals from bone, calcium loss
	Sulfur (S)	Proteins from many sources	Component of certain amino acids	Symptoms of protein deficiency
	Potassium (K)	Meats, dairy products, many fruits and vegetables, grains	Acid-base balance, water balance, nerve function	Muscular weakness, paralysis, nausea, heart failure
	Chlorine (Cl)	Table salt	Acid-base balance, formation of gastric juice, nerve function, osmotic balance	Muscle cramps, reduced appetite
	Sodium (Na)	Table salt	Acid-base balance, water balance, nerve function	Muscle cramps, reduced appetite
	Magnesium (Mg)	Whole grains, green leafy vegetables	Cofactor; ATP bioenergetics	Nervous system disturbances
	Iron (Fe)	Meats, eggs, legumes, whole grains, green leafy vegetables	Component of hemoglobin and of electron carriers in energy metabolism; enzyme cofactor	Iron-deficiency anemia, weakness, impaired immunity

*All of these minerals are also harmful when consumed in excess.

Table 41-2b

Table 41.2 Mineral Requirements of Humans

Mineral	Major Dietary Sources	Major Functions in the Body	Symptoms of Deficiency*
Fluorine (F)	Drinking water, tea, seafood	Maintenance of tooth (and probably bone) structure	Higher frequency of tooth decay
Zinc (Zn)	Meats, seafood, grains	Component of certain digestive enzymes and other proteins	Growth failure, skin abnormalities, reproductive failure, impaired immunity
Copper (Cu)	Seafood, nuts, legumes, organ meats	Enzyme cofactor in iron metabolism, melanin synthesis, electron transport	Anemia, cardiovascular abnormalities
Manganese (Mn)	Nuts, grains, vegetables, fruits, tea	Enzyme cofactor	Abnormal bone and cartilage
Iodine (I)	Seafood, dairy products, iodized salt	Component of thyroid hormones	Goiter (enlarged thyroid)
Cobalt (Co)	Meats and dairy products	Component of vitamin B_{12}	None, except as B_{12} deficiency
Selenium (Se)	Seafood, meats, whole grains	Enzyme cofactor; antioxidant functioning in close association with vitamin E	Muscle pain, possibly heart muscle deterioration
Chromium (Cr)	Brewer's yeast, liver, seafood, meats, some vegetables	Involved in glucose and energy metabolism	Impaired glucose metabolism
Molybdenum (Mo)	Legumes, grains, some vegetables	Enzyme cofactor	Disorder in excretion of nitrogen-containing compounds

*All of these minerals are also harmful when consumed in excess.

Dietary Deficiencies

- **Undernourishment** is the result of a diet that consistently supplies less chemical energy than the body requires
- **Malnourishment** is the long-term absence from the diet of one or more essential nutrients

Undernourishment

- An undernourished individual will
  - **Use up stored fat and carbohydrates**
  - **Break down its own proteins**
  - **Lose muscle mass**
  - **Suffer protein deficiency of the brain**
  - **Die or suffer irreversible damage**

Malnourishment

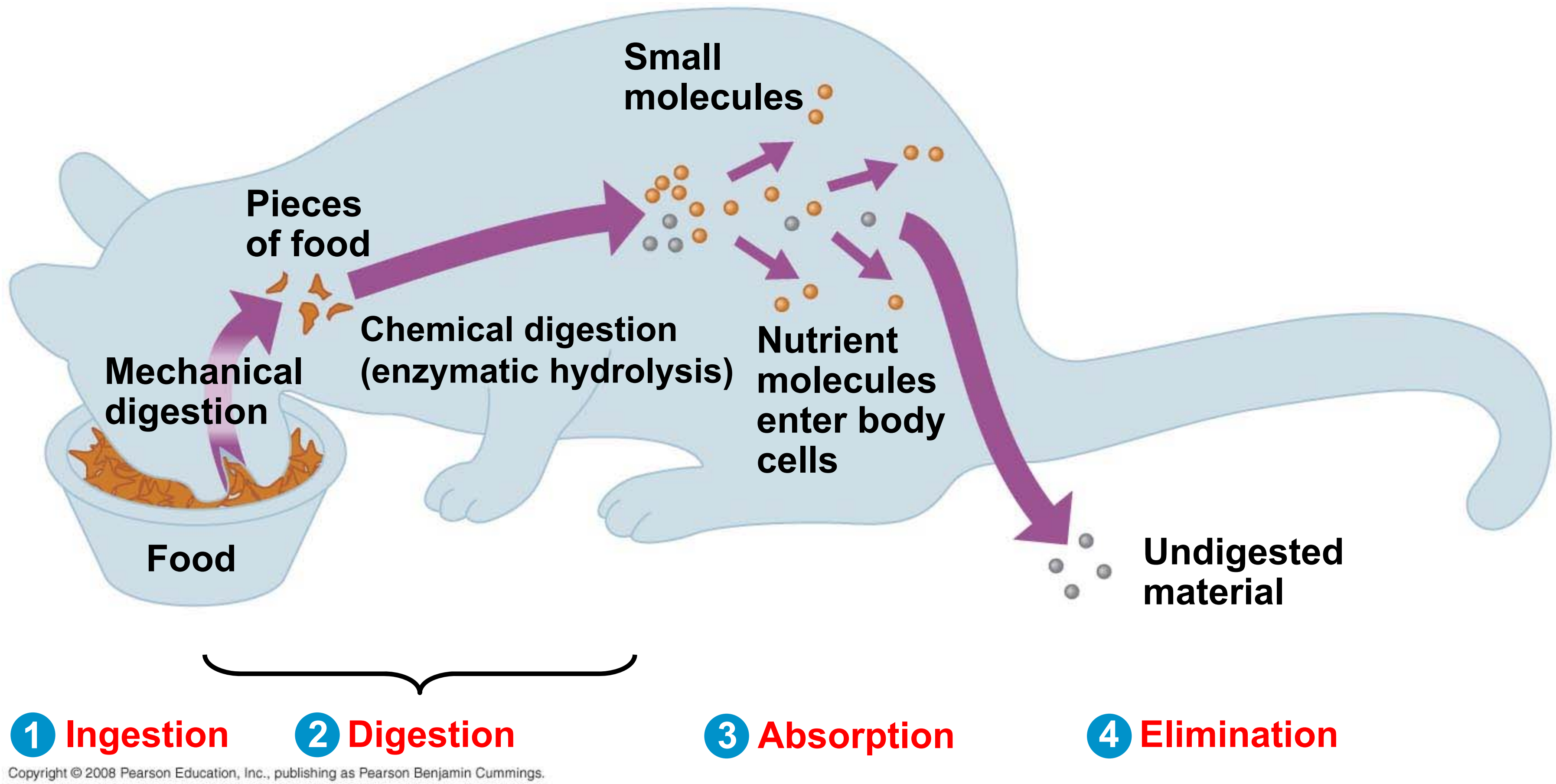
- Malnourishment can cause deformities, disease, and death
- Malnourishment can be corrected by changes to a diet

Fig. 41-4

Concept 41.2: The main stages of food processing

- Ingestion
- Digestion
- Absorption
- Elimination

Fig. 41-7


Small molecules
Pieces of food
Chemical digestion (enzymatic hydrolysis)
Nutrient molecules enter body cells
Mechanical digestion
Food
Undigested material
1 Ingestion
2 Digestion
3 Absorption
4 Elimination
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Ingestion:

- Ingestion *is the act of eating*
- Ingestion could be in many ways (feeding habits):
  - **Suspension feeder**
  - **Substrate Feeders**
  - **Fluid Feeders**
  - **Bulk Feeders**

Suspension Feeders

- Many **aquatic** animals are **suspension feeders**, which sift small food particles from the water

Fig. 41-6a

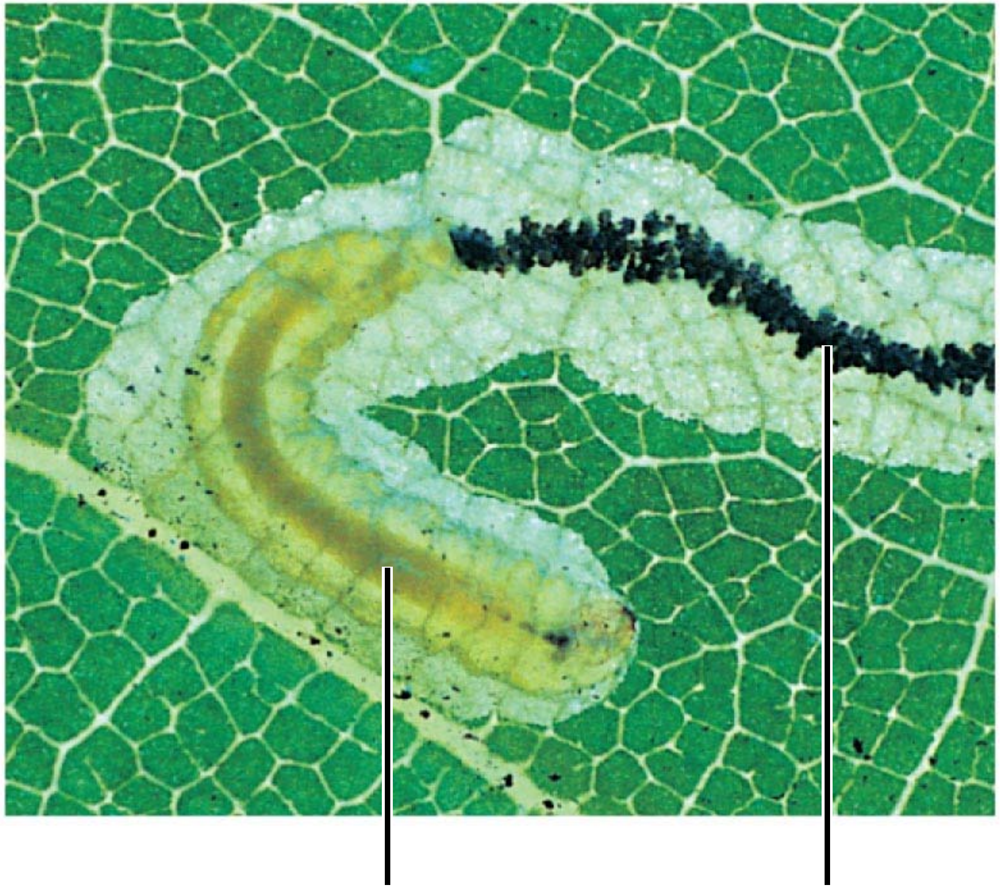
Humpback whale, a suspension feeder

Substrate Feeders

- **Substrate feeders** *are animals that live in or on their food source*

Fig. 41-6b

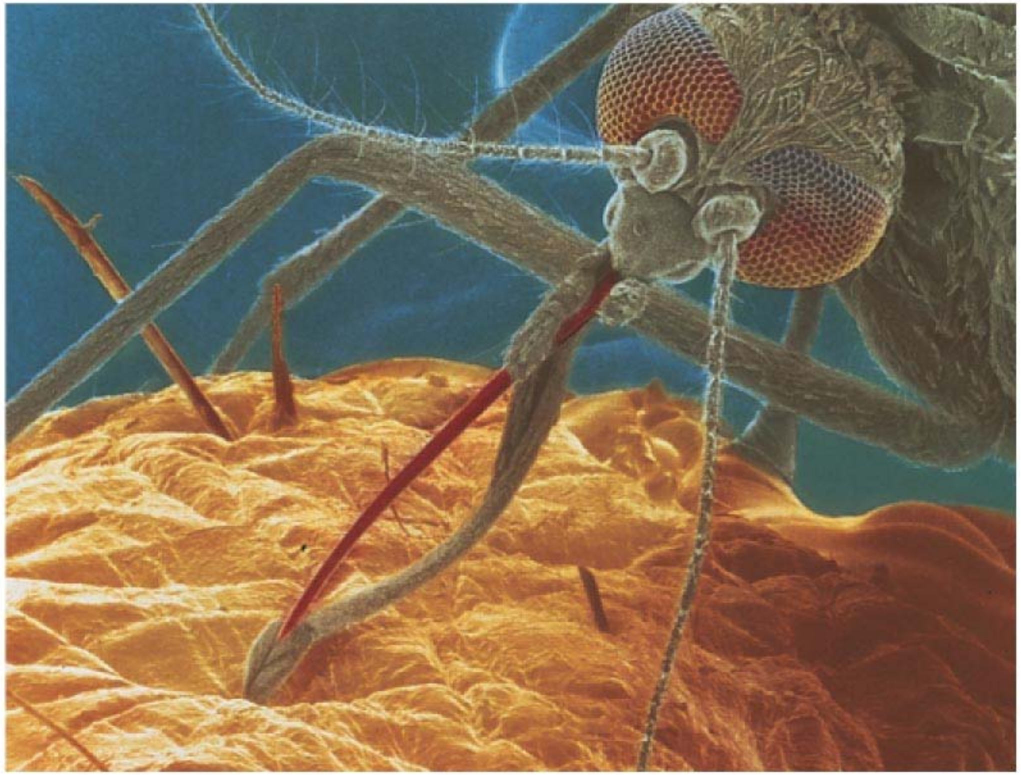
Leaf miner caterpillar, a substrate feeder



Fluid Feeders

- **Fluid feeders** *suck nutrient-rich fluid from a living host*

Fig. 41-6c



Mosquito, a fluid feeder

Bulk Feeders

- **Bulk feeders** *eat relatively large pieces of food*

Fig. 41-6d

Rock python, a bulk feeder

- **Digestion:**

- **Digestion** is *the process of breaking food down into molecules small enough to absorb*
  - In **chemical digestion**, the process of **enzymatic hydrolysis** splits bonds in molecules with the addition of water
- **Absorption** *is uptake of nutrients by body cells*
- **Elimination** *is the passage of undigested material out of the digestive compartment*

Digestive Compartments

- Most animals process food in specialized compartments
- These compartments reduce the risk of an animal digesting its own cells and tissues

Intracellular Digestion

- In **intracellular digestion (within cells)**, *food particles are engulfed by endocytosis and digested within food vacuoles*

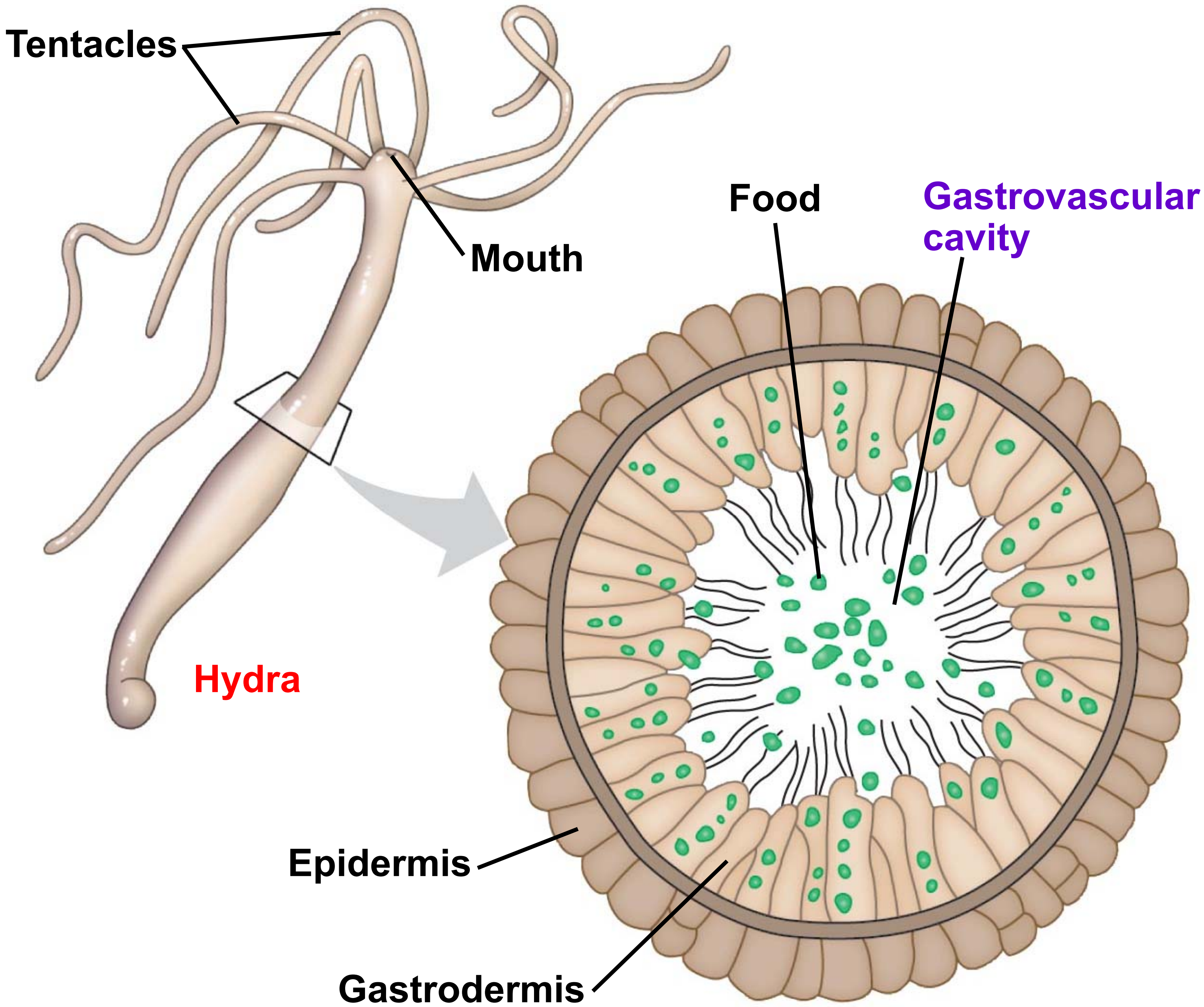
Extracellular Digestion

- **Extracellular digestion** *is the breakdown of food particles outside of cells*
- It occurs in compartments that are continuous with the outside of the animal's body

- Animals with simple body plans have a **gastrovascular cavity** that *functions in both digestion and distribution of nutrients*

PLAY **Video: Hydra Eating Daphnia**

Fig. 41-8


Tentacles
Mouth
Food
Gastrovascular cavity
Hydra
Epidermis
Gastrodermis

- **More complex animals** have a *digestive tube with two openings*, a **mouth** and an **anus**
- This digestive tube is called a **complete digestive tract** or an **alimentary canal**
- It can have specialized regions that carry out digestion and absorption in a stepwise fashion

Fig. 41-9

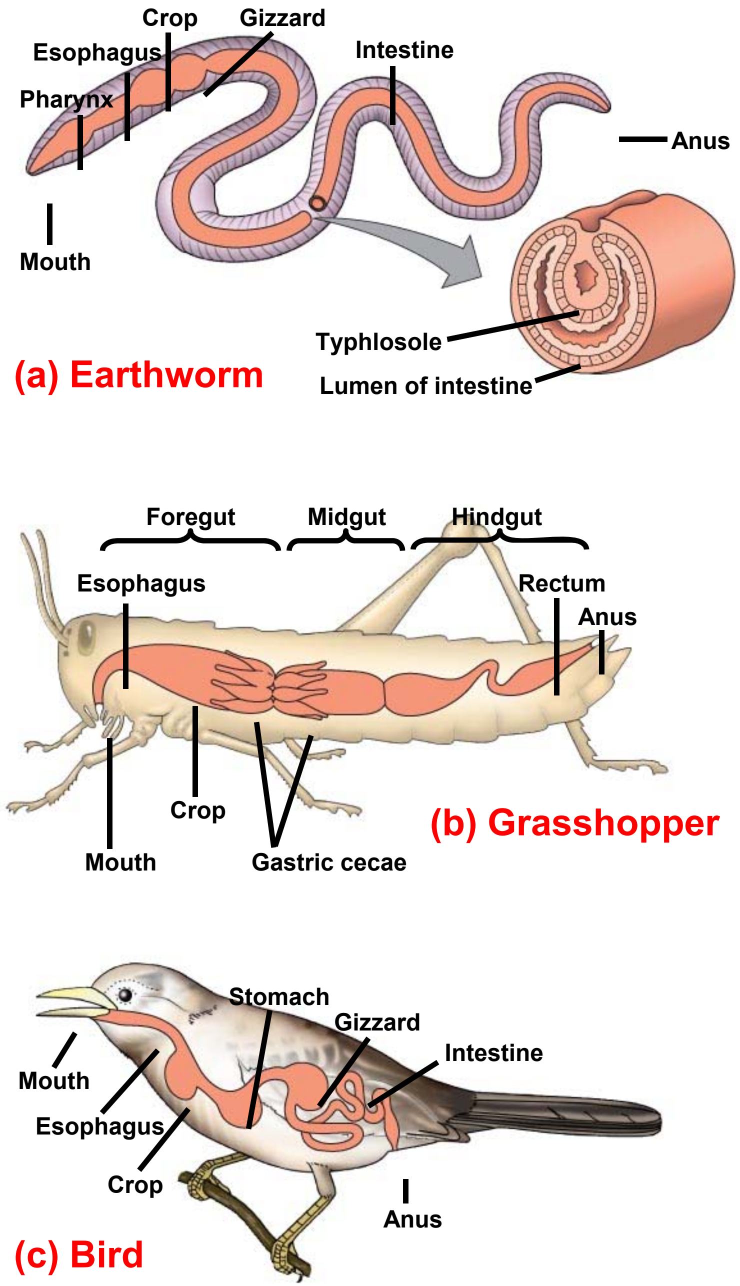
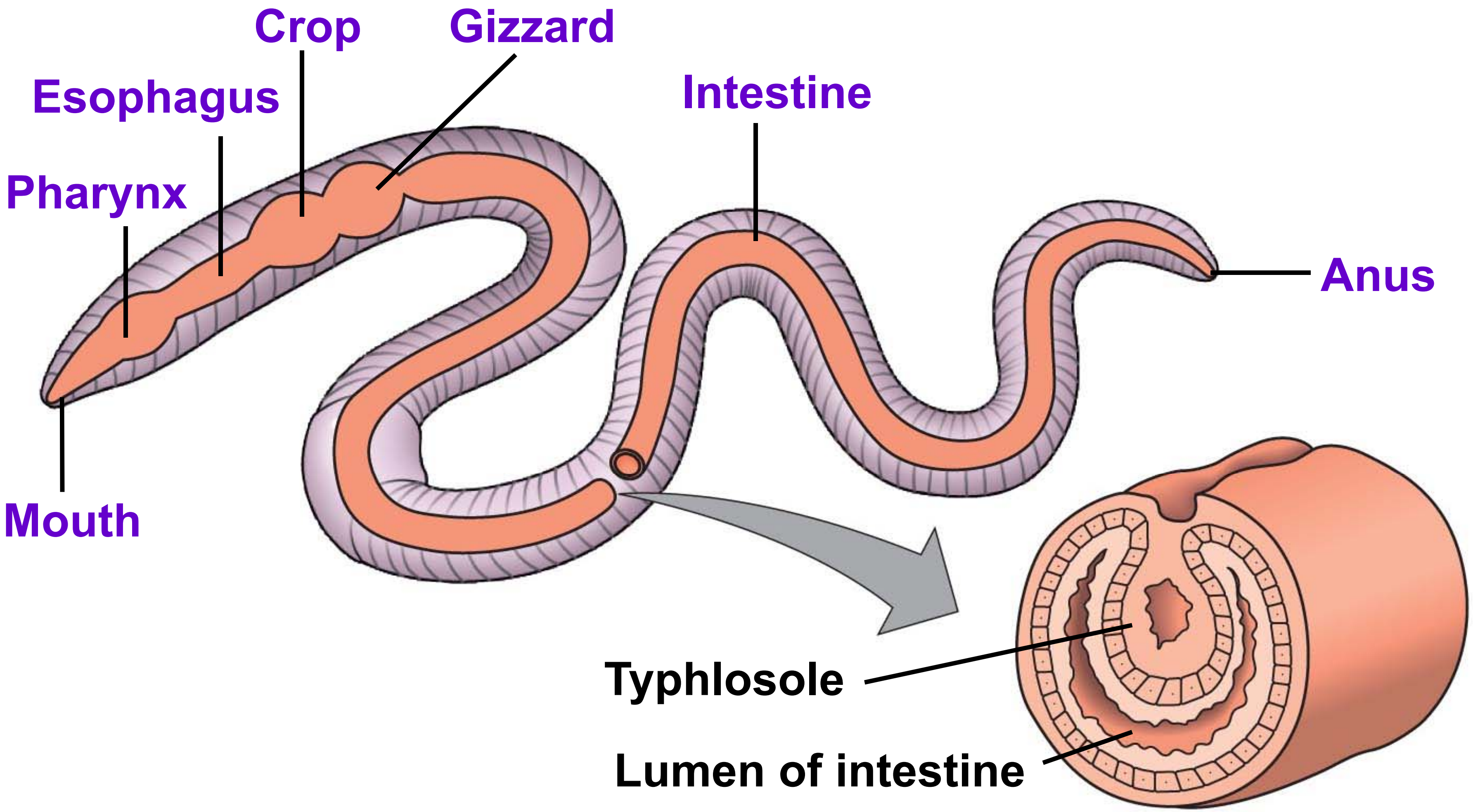
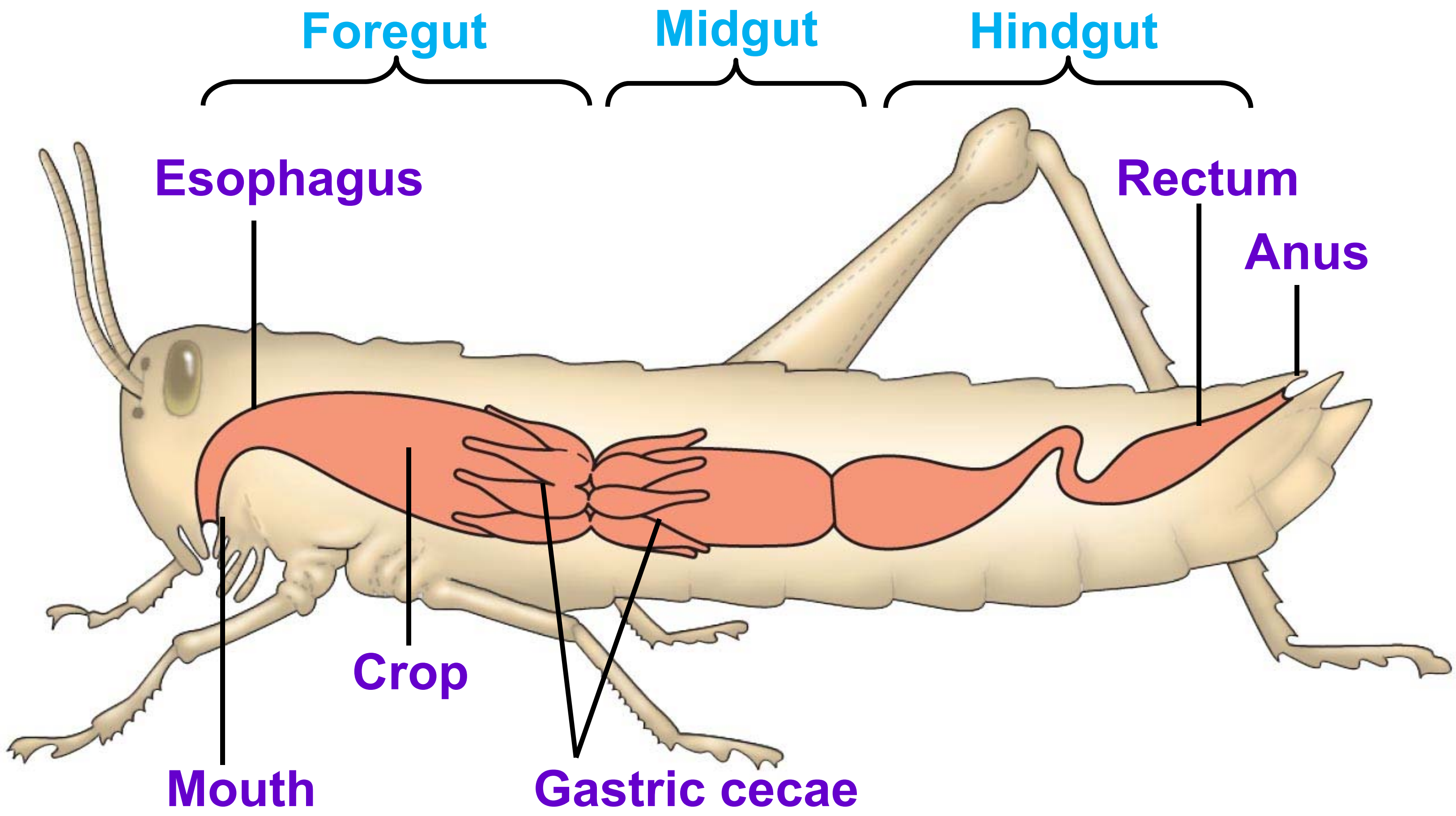

Crop
Gizzard
Esophagus
Intestine
Pharynx
Anus
Mouth
Typhlosole
Lumen of intestine
(a) Earthworm
Foregut
Midgut
Hindgut
Esophagus
Rectum
Anus
Crop
Mouth
Gastric cecae
(b) Grasshopper
Stomach
Gizzard
Intestine
Mouth
Esophagus
Crop
Anus
(c) Bird

Fig. 41-9a



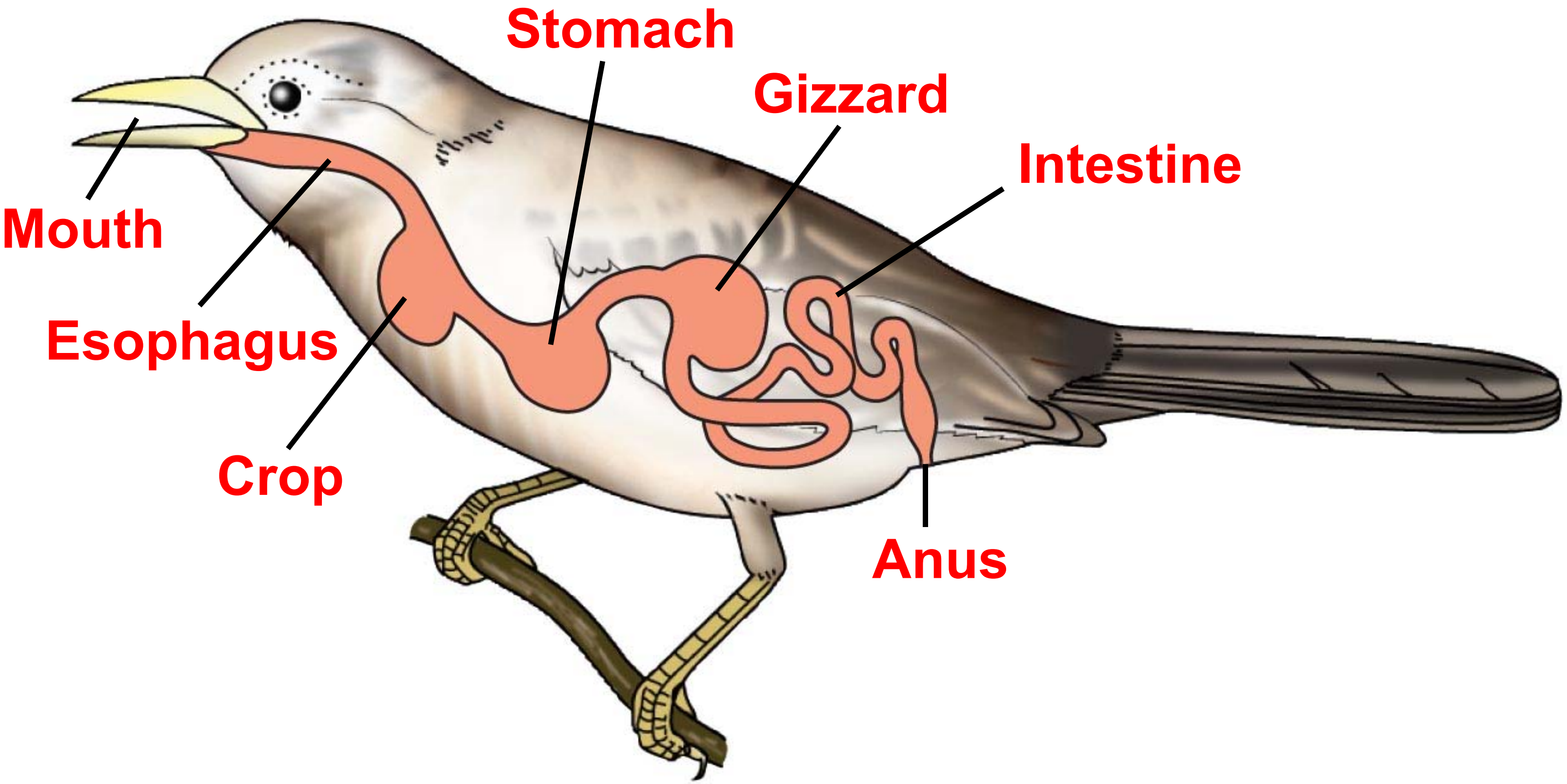
(a) Earthworm

Fig. 41-9b



(b) Grasshopper

Fig. 41-9c



(c) Bird

Concept 41.3: Organs specialized for sequential stages of food processing form the mammalian digestive system

- The mammalian digestive system **consists of an** alimentary canal and accessory glands that secrete digestive juices through ducts
- Mammalian **accessory glands** are the salivary glands, the pancreas, the liver, and the gallbladder

- Food is pushed along by **peristalsis**, *rhythmic contractions of muscles in the wall of the canal*
- Valves called **sphincters** regulate the movement of material between compartments

Fig. 41-10a

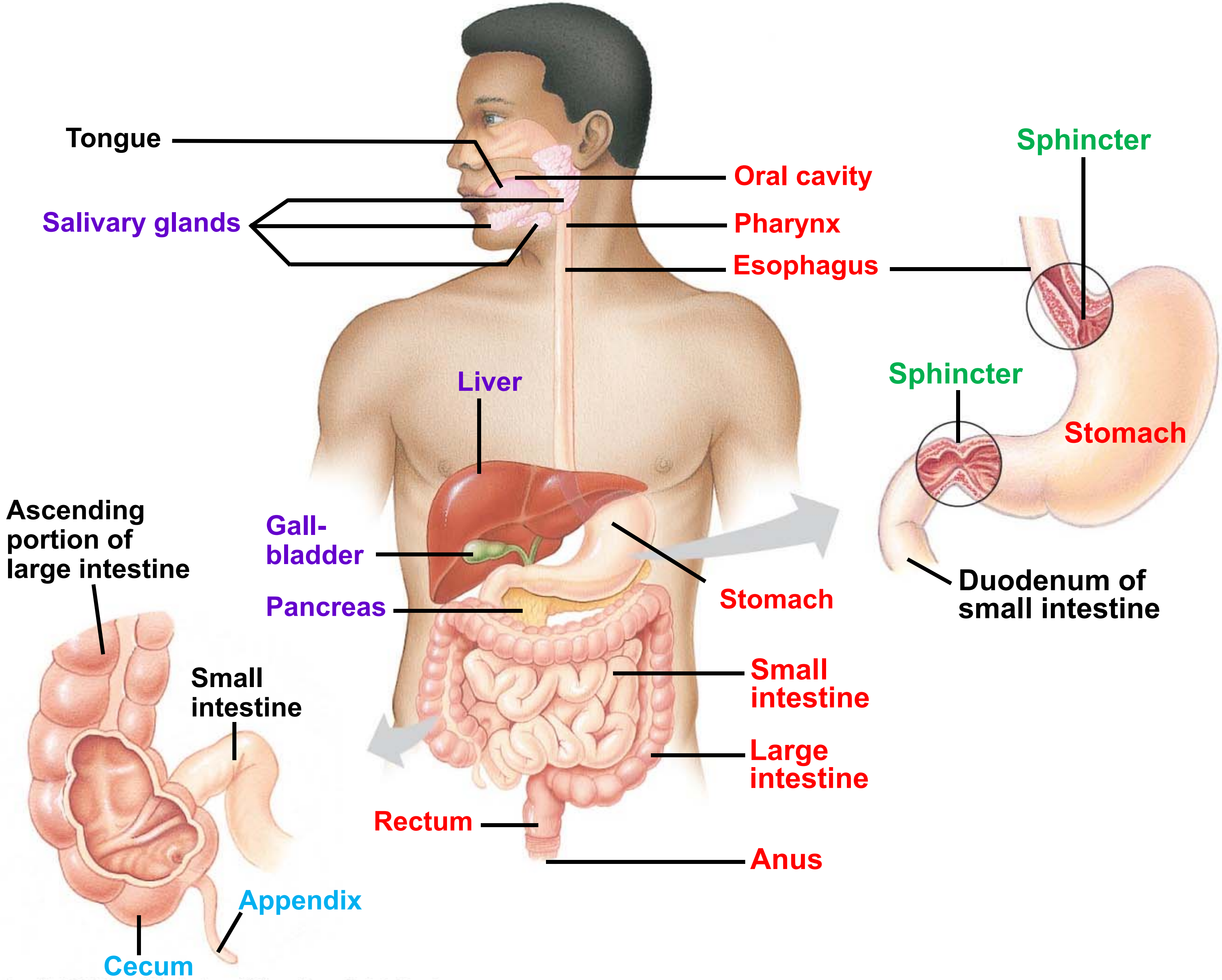
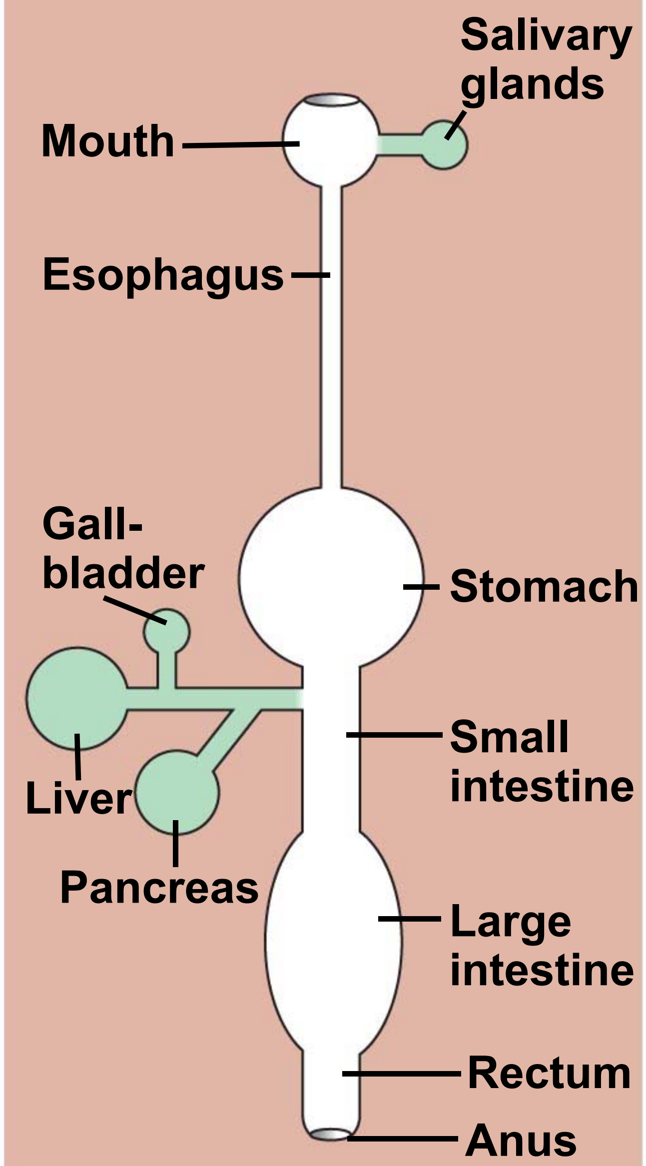

Tongue
Salivary glands
Oral cavity
Pharynx
Esophagus
Sphincter
Sphincter
Stomach
Duodenum of
small intestine
Liver
Gall-
bladder
Pancreas
Stomach
Small
intestine
Large
intestine
Rectum
Anus
Ascending
portion of
large intestine
Small
intestine
Appendix
Cecum

Fig. 41-10b



A schematic diagram of the human digestive system

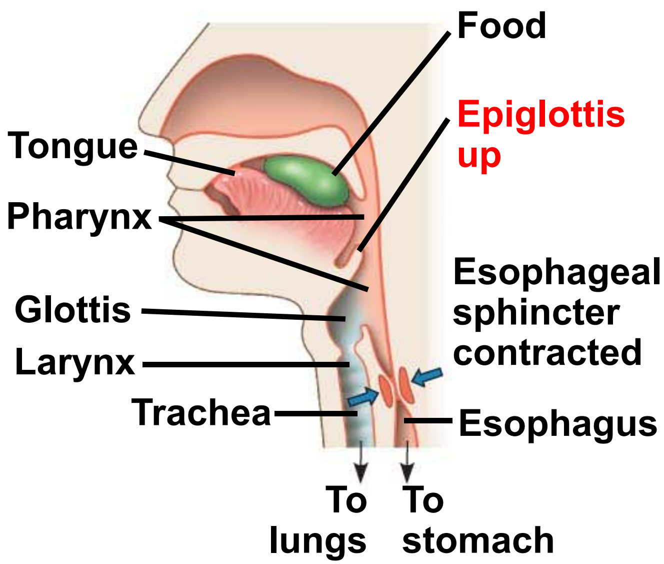
The Oral Cavity, Pharynx, and Esophagus

- The first stage of digestion is **mechanical** and takes place in the **oral cavity**
- **Salivary glands** deliver **saliva** to lubricate food
- **Teeth chew food** into smaller particles that are exposed to salivary **amylase**, initiating breakdown of glucose polymers

- The **tongue** shapes food into a **bolus** and provides help with swallowing
- The region we call our throat is the **pharynx**, a junction that opens to both the esophagus and the trachea (windpipe)
- The trachea leads to the lungs

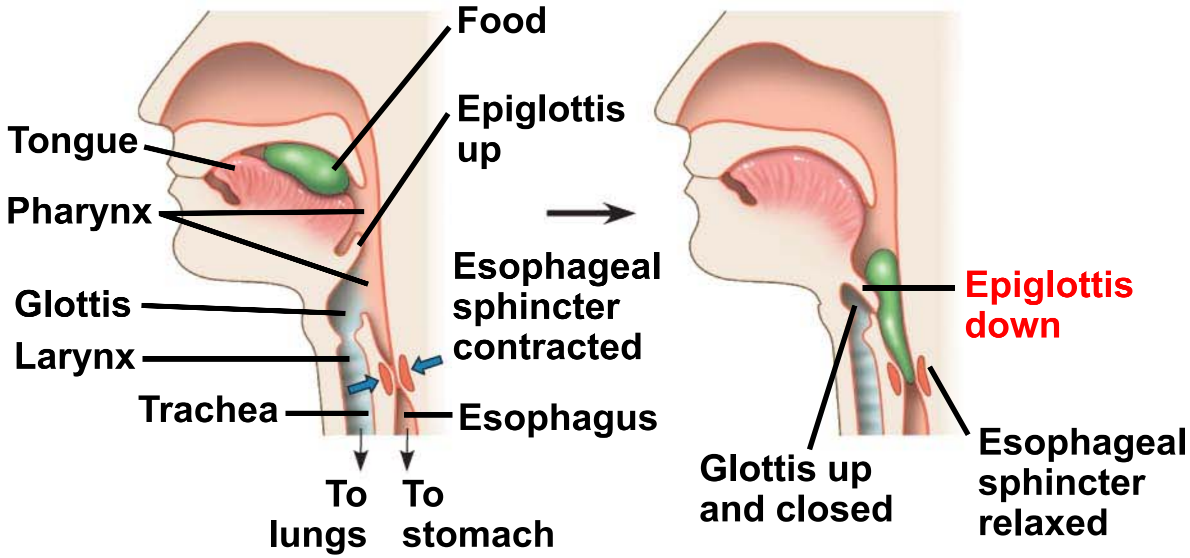
- The **esophagus** conducts food from the pharynx down to the stomach by peristalsis
- Swallowing causes the epiglottis to block entry to the trachea.
- **Coughing** occurs when the swallowing reflex fails and food or liquids reach the windpipe

Fig. 41-11-1



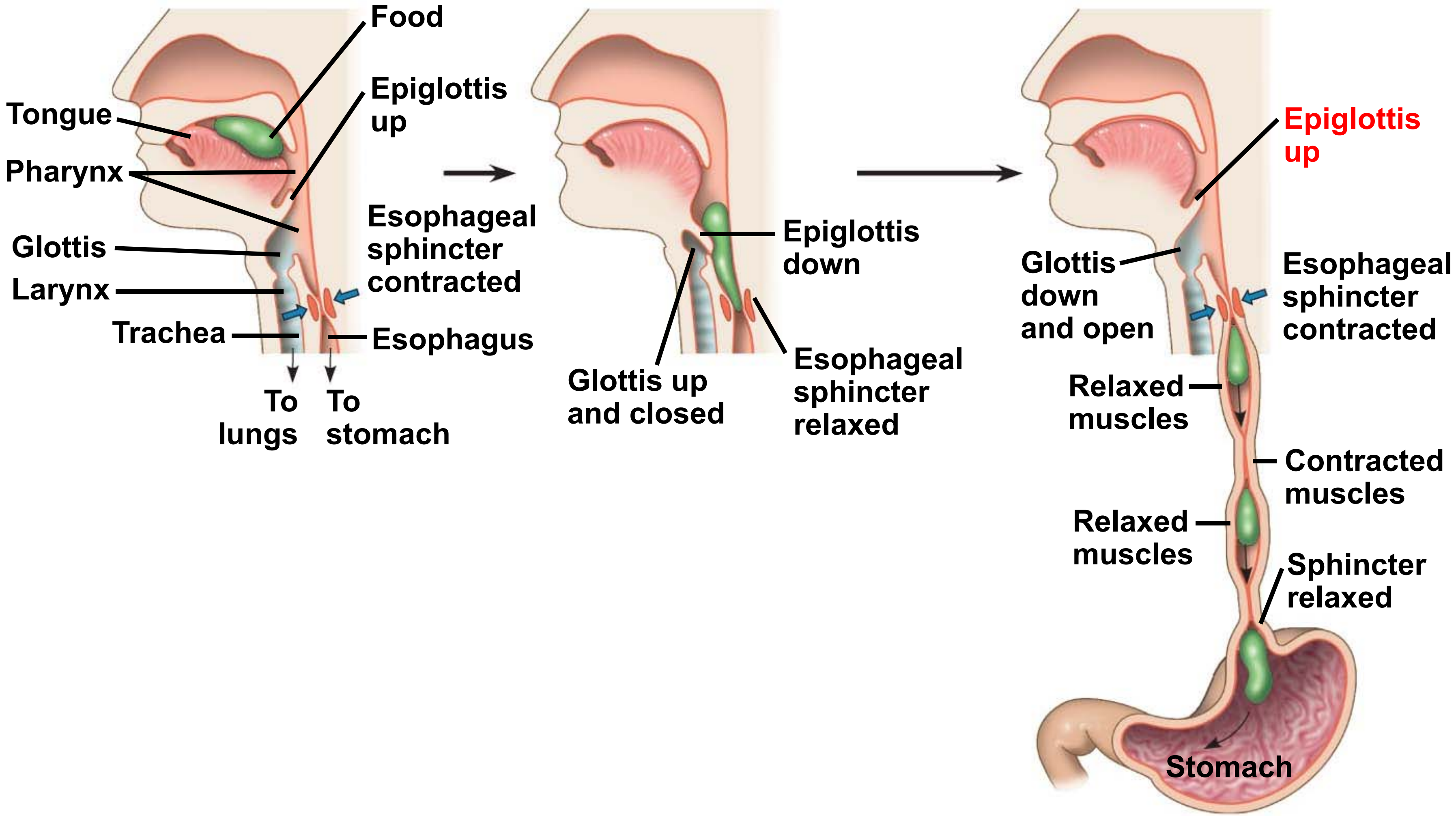
Food
Epiglottis up
Tongue
Pharynx
Esophageal sphincter contracted
Glottis
Larynx
Trachea
Esophagus
To lungs
To stomach

Fig. 41-11-2



Food
Tongue
Epiglottis up
Pharynx
Esophageal sphincter contracted
Glottis
Larynx
Trachea
Esophagus
To lungs
To stomach
Epiglottis down
Glottis up and closed
Esophageal sphincter relaxed

Fig. 41-11-3


Food
Tongue
Epiglottis up
Pharynx
Esophageal sphincter contracted
Glottis
Larynx
Trachea
Esophagus
To lungs
To stomach
Epiglottis down
Glottis up and closed
Esophageal sphincter relaxed
Epiglottis up
Glottis down and open
Esophageal sphincter contracted
Relaxed muscles
Contracted muscles
Relaxed muscles
Sphincter relaxed
Stomach

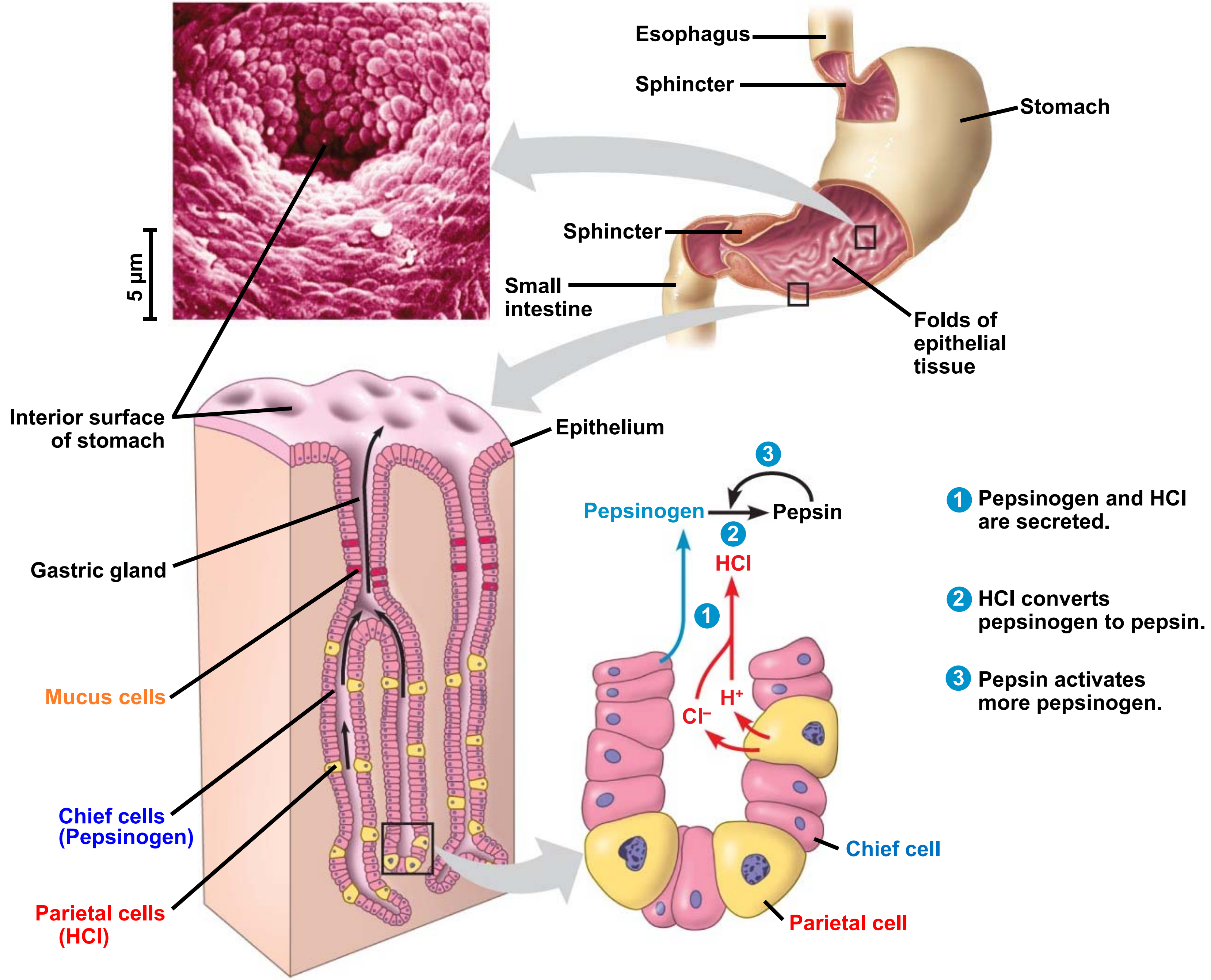
Digestion in the Stomach

- The **stomach** stores food and secretes **gastric juice**, which converts a meal to acid **chyme**

Chemical Digestion in the Stomach

- **Gastric juice** is made up of **hydrochloric acid** and the **enzyme pepsin**
- ***Parietal cells*** secrete hydrogen and chloride ions separately
- ***Chief cells*** secrete inactive **pepsinogen**, which is **activated to pepsin** when mixed with hydrochloric acid in the stomach
- **Mucus** protects the stomach lining from gastric juice

Fig. 41-12



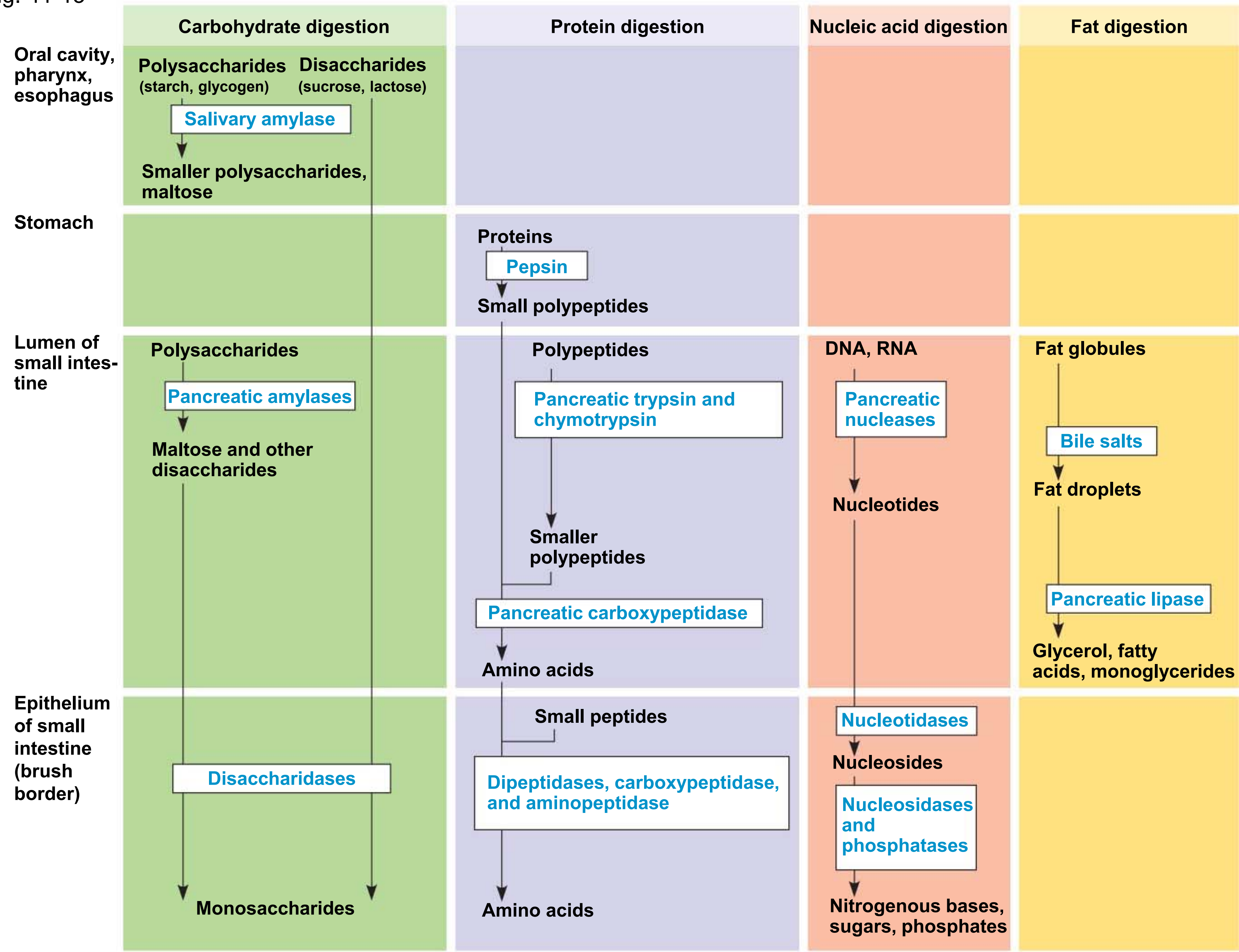
5 µm
Esophagus
Sphincter
Stomach
Sphincter
Small intestine
Folds of epithelial tissue
Interior surface of stomach
Epithelium
Gastric gland
Mucus cells
Chief cells (Pepsinogen)
Parietal cells (HCl)
3
Pepsinogen
Pepsin
2
HCl
1
H+
Cl–
Chief cell
Parietal cell
1 Pepsinogen and HCl are secreted.
2 HCl converts pepsinogen to pepsin.
3 Pepsin activates more pepsinogen.

- **Gastric ulcers**, lesions in the lining, are *caused mainly by the bacterium Helicobacter pylori*

Digestion in the Small Intestine

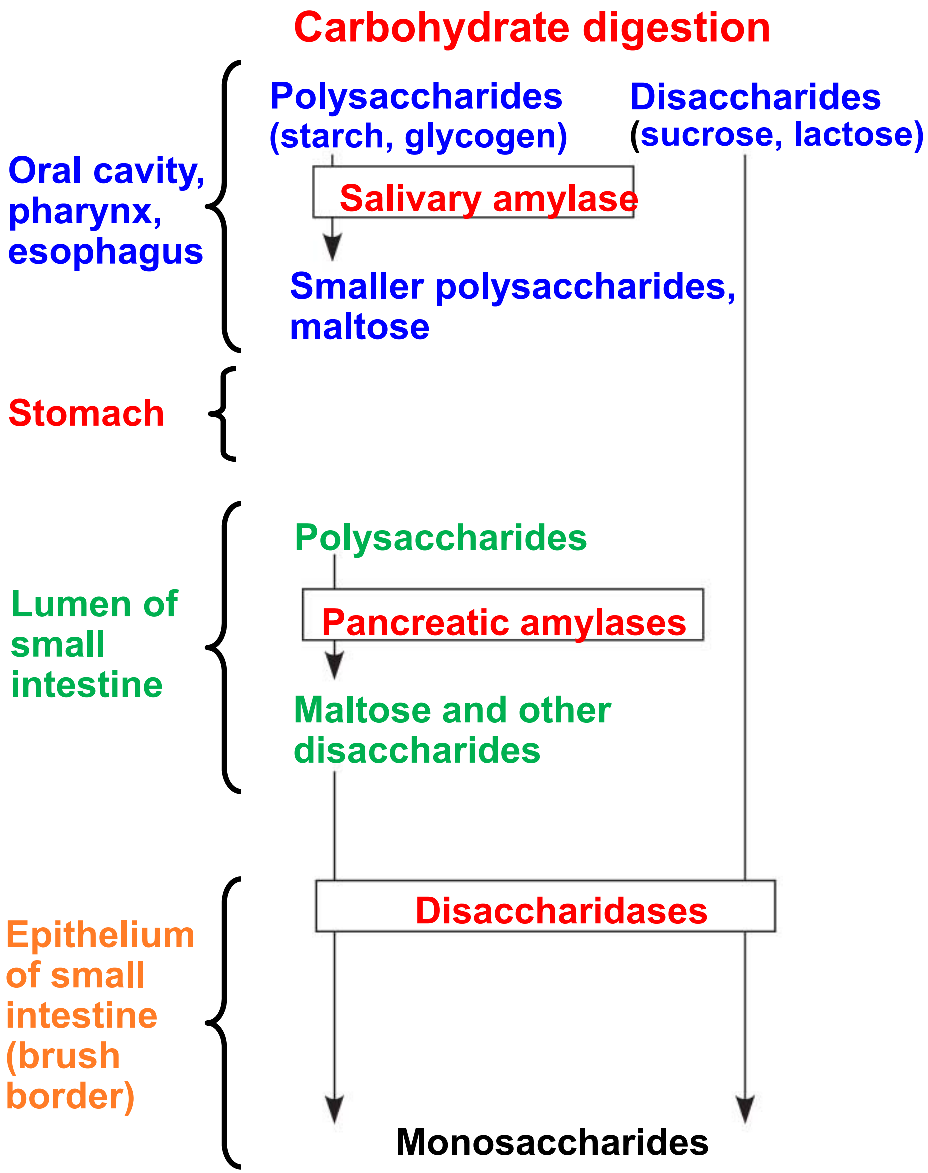
- The **small intestine** is the longest section of the alimentary canal
- It is the major organ of digestion and absorption

Fig. 41-13



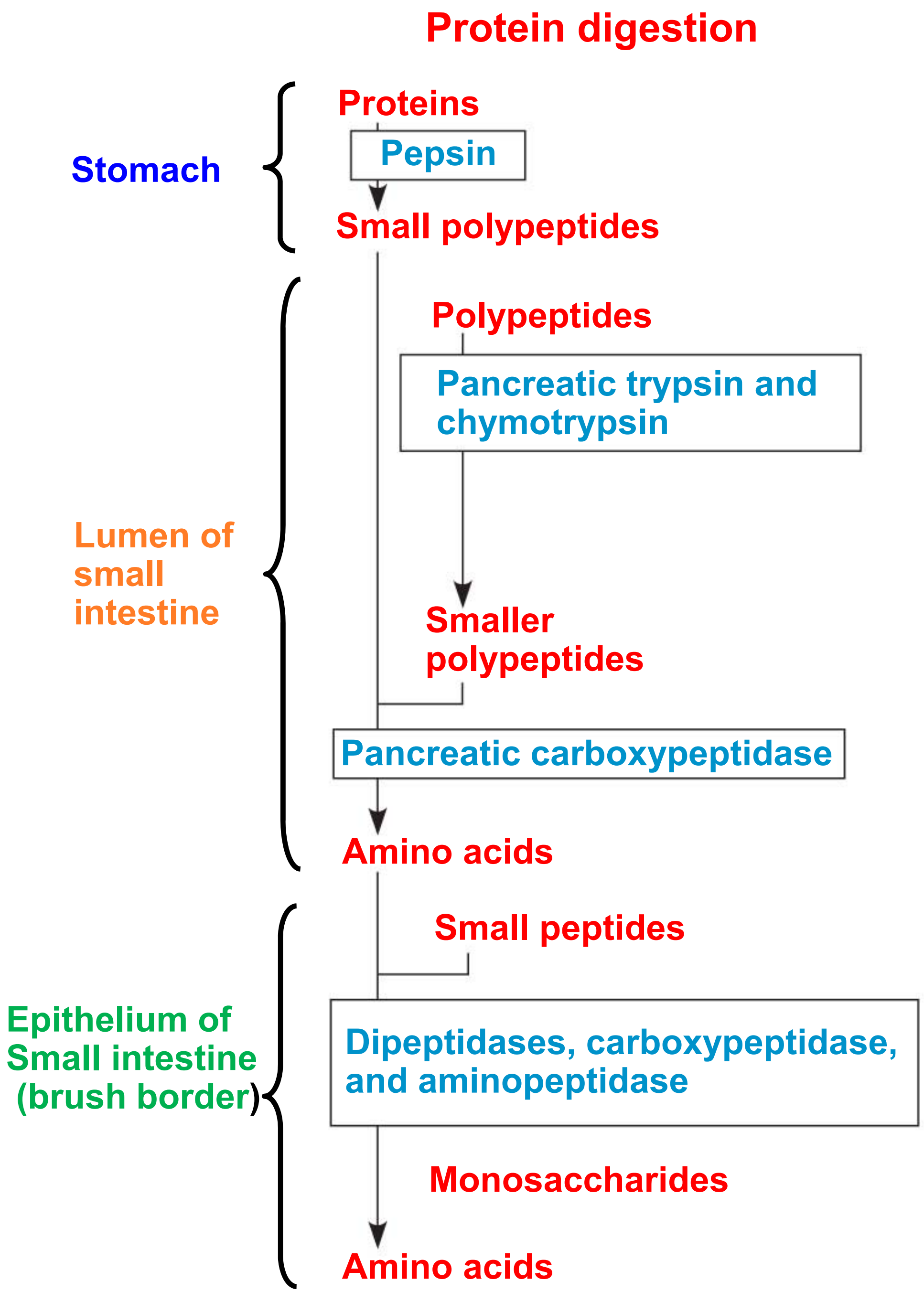
Carbohydrate digestion
Protein digestion
Nucleic acid digestion
Fat digestion
Oral cavity, pharynx, esophagus
Polysaccharides (starch, glycogen)
Disaccharides (sucrose, lactose)
Salivary amylase
Smaller polysaccharides, maltose
Stomach
Proteins
Pepsin
Small polypeptides
Lumen of small intestine
Polysaccharides
Pancreatic amylases
Maltose and other disaccharides
Polypeptides
Pancreatic trypsin and chymotrypsin
Smaller polypeptides
Pancreatic carboxypeptidase
Amino acids
DNA, RNA
Pancreatic nucleases
Nucleotides
Fat globules
Bile salts
Fat droplets
Pancreatic lipase
Glycerol, fatty acids, monoglycerides
Epithelium of small intestine (brush border)
Disaccharidases
Monosaccharides
Small peptides
Dipeptidases, carboxypeptidase, and aminopeptidase
Amino acids
Nucleotidases
Nucleosides
Nucleosidases and phosphatases
Nitrogenous bases, sugars, phosphates

Fig. 41-13a



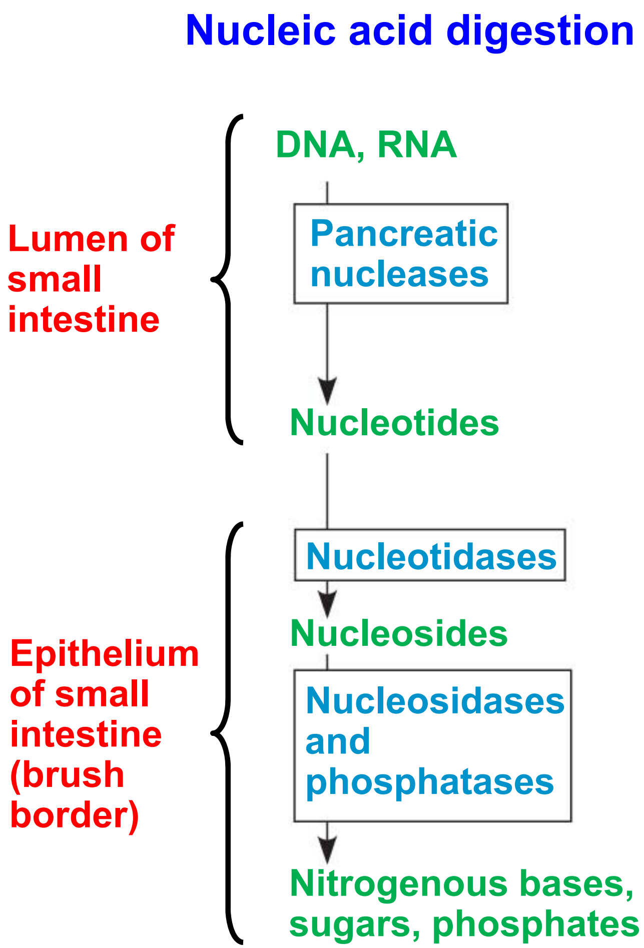
Carbohydrate digestion
Oral cavity, pharynx, esophagus
Polysaccharides (starch, glycogen)
Disaccharides (sucrose, lactose)
Salivary amylase
Smaller polysaccharides, maltose
Stomach
Lumen of small intestine
Polysaccharides
Pancreatic amylases
Maltose and other disaccharides
Epithelium of small intestine (brush border)
Disaccharidases
Monosaccharides

Fig. 41-13b



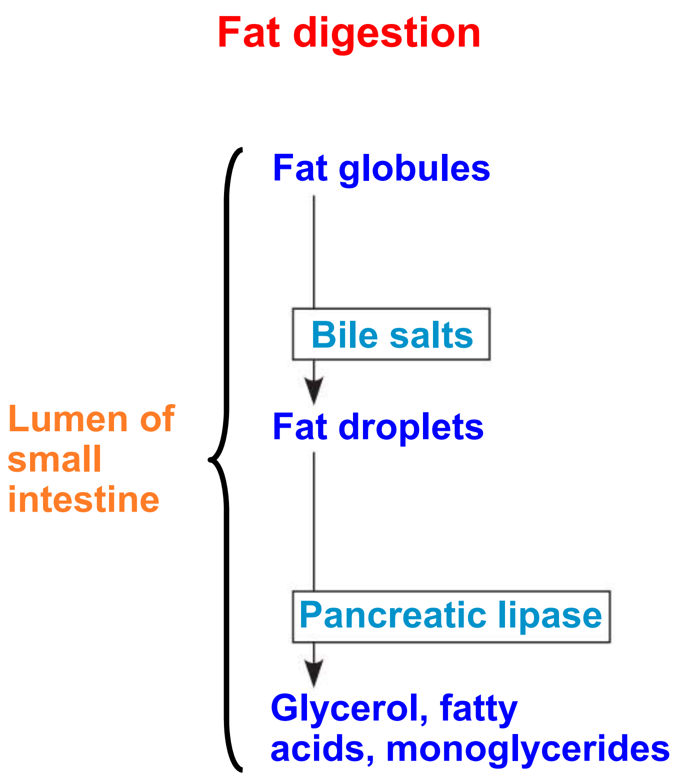
Protein digestion
Stomach
Proteins
Pepsin
Small polypeptides
Lumen of small intestine
Polypeptides
Pancreatic trypsin and chymotrypsin
Smaller polypeptides
Pancreatic carboxypeptidase
Amino acids
Epithelium of Small intestine (brush border)
Small peptides
Dipeptidases, carboxypeptidase, and aminopeptidase
Monosaccharides
Amino acids

Fig. 41-13c



Nucleic acid digestion
Lumen of small intestine
DNA, RNA
Pancreatic nucleases
Nucleotides
Epithelium of small intestine (brush border)
Nucleotidases
Nucleosides
Nucleosidases and phosphatases
Nitrogenous bases, sugars, phosphates

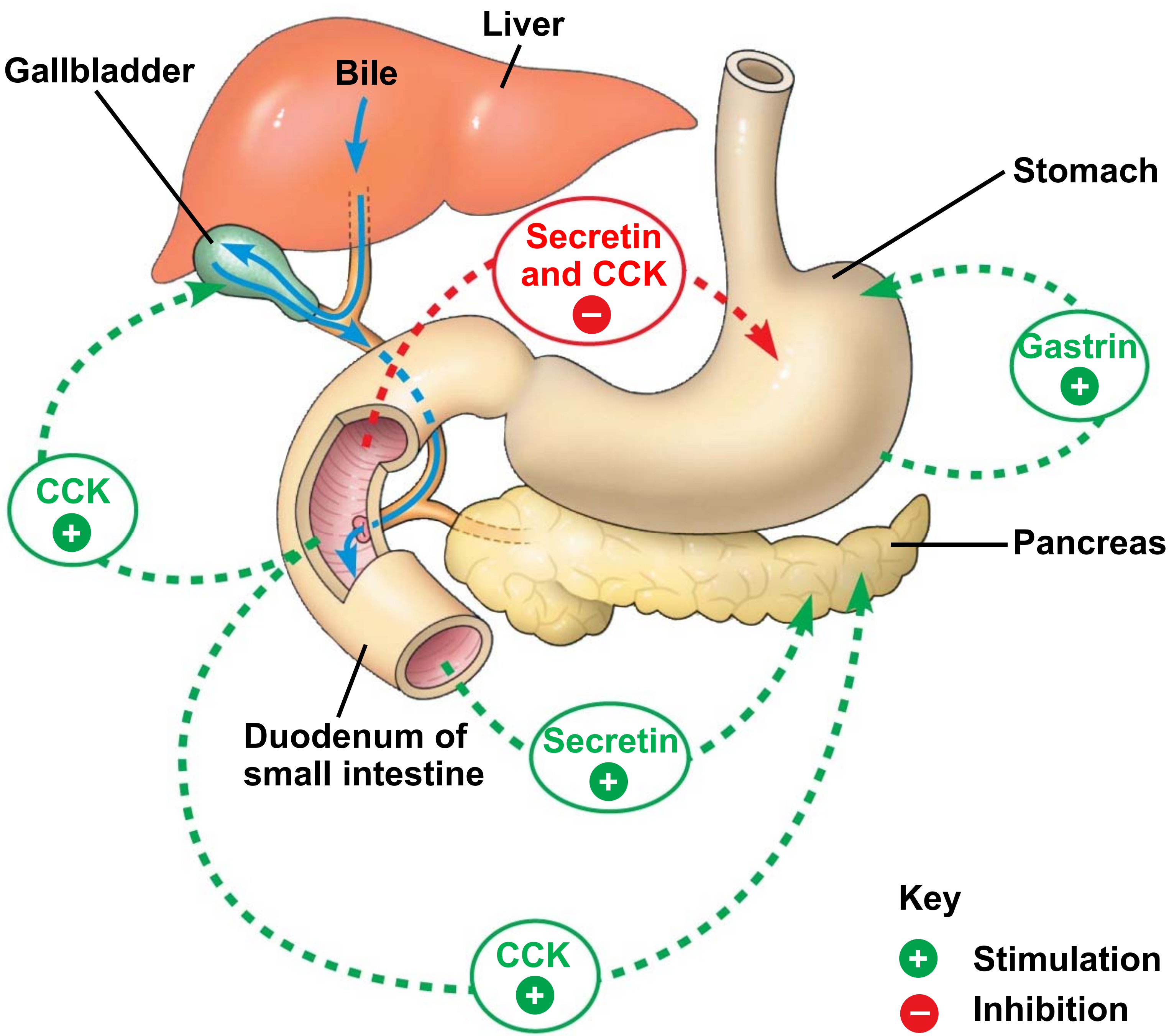
Fig. 41-13d



Fat digestion
Lumen of small intestine
Fat globules
Bile salts
Fat droplets
Pancreatic lipase
Glycerol, fatty acids, monoglycerides

- The first portion of the small intestine is the **duodenum**, where acid chyme from the stomach mixes with digestive juices from the: pancreas, liver, gallbladder, and the small intestine itself

Fig. 41-14


Liver
Gallbladder
Bile
Stomach
Secretin and CCK
Gastrin
CCK
Pancreas
Duodenum of small intestine
Secretin
CCK
Key
Stimulation
Inhibition

Pancreatic Secretions

- The **pancreas** produces proteases **trypsin** and **chymotrypsin**, protein-digesting enzymes that are activated after entering the duodenum
- Its solution is alkaline and neutralizes the acidic chyme

Bile Production by the Liver

- In the small intestine, **bile** aids in digestion and absorption of fats
- Bile is made in the **liver** and stored in the **gallbladder**

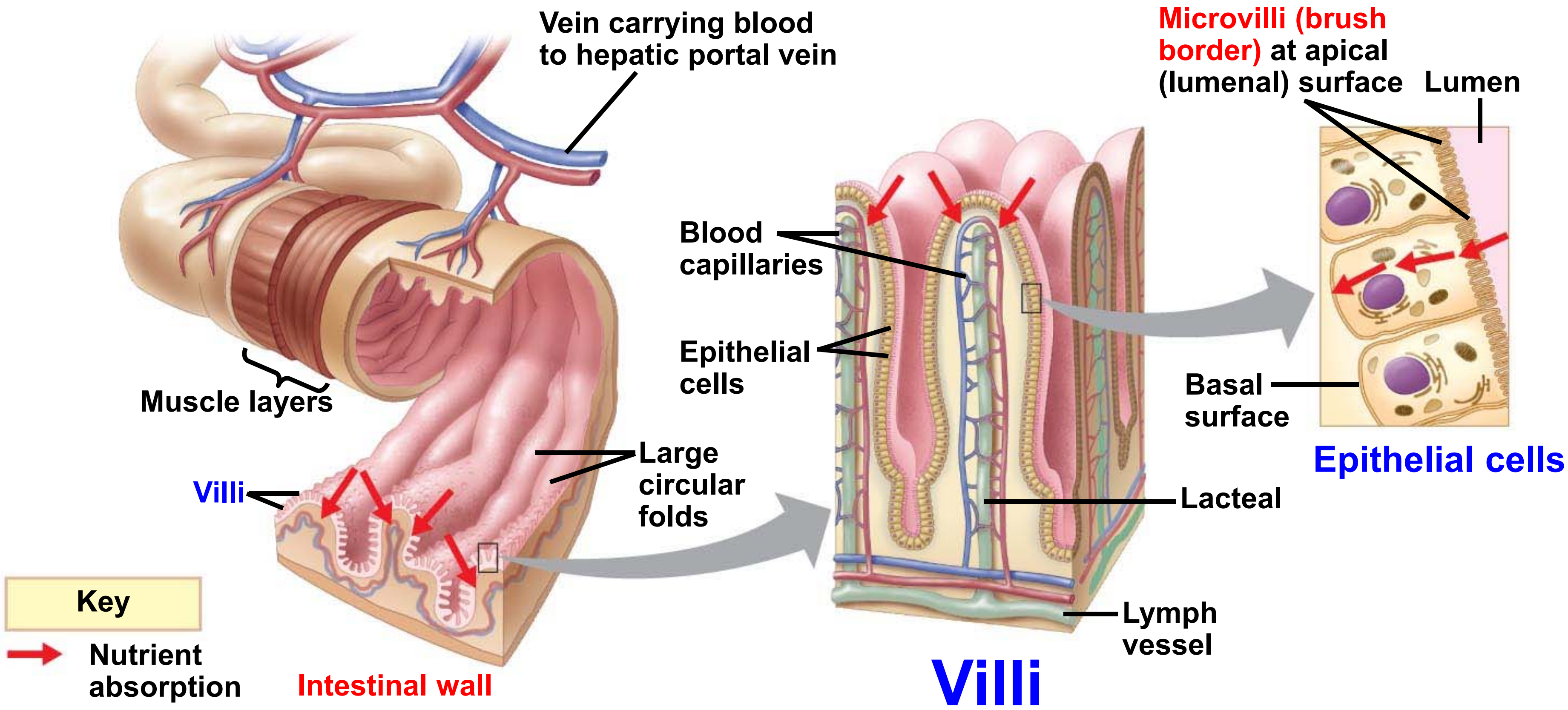
Secrections of the Small Intestine

- The epithelial lining of the duodenum, called the brush border, produces several digestive enzymes
- Enzymatic digestion is completed as peristalsis moves the chyme and digestive juices along the small intestine
- Most digestion occurs in the **duodenum**; the **jejunum** and **ileum** function mainly in absorption of nutrients and water

Absorption in the Small Intestine

- The small intestine has a huge surface area, due to **villi** and **microvilli** that are exposed to the intestinal lumen
- The enormous microvillar surface greatly increases the rate of nutrient absorption

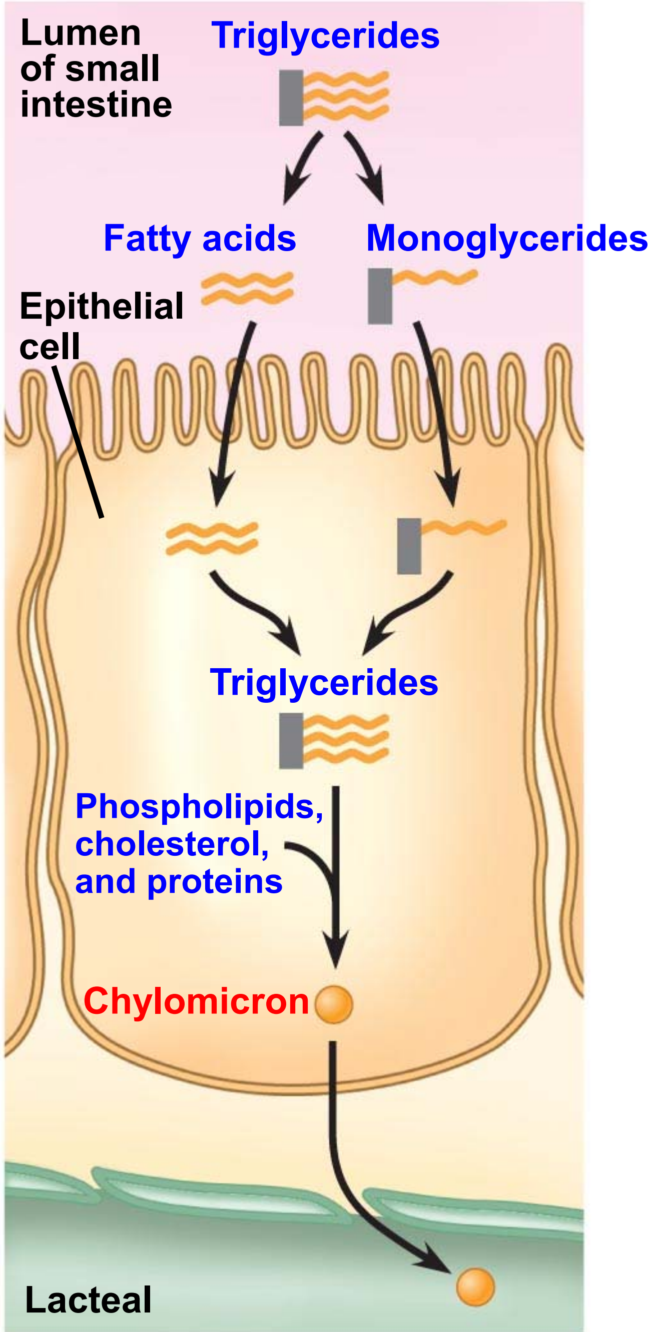
Fig. 41-15



Vein carrying blood to hepatic portal vein
Muscle layers
Villi
Large circular folds
Key
Nutrient absorption
Intestinal wall
Blood capillaries
Epithelial cells
Lacteal
Lymph vessel
Villi
Microvilli (brush border) at apical (lumenal) surface
Lumen
Basal surface
Epithelial cells

- Each villus contains a network of blood vessels and a small lymphatic vessel called a **lacteal**
- After glycerol and fatty acids are absorbed by epithelial cells, they are recombined into fats within these cells
- These fats are mixed with cholesterol and coated with protein, forming molecules called **chylomicrons**, which are transported into lacteals

Fig. 41-16


Lumen of small intestine
Triglycerides
Fatty acids
Monoglycerides
Epithelial cell
Triglycerides
Phospholipids, cholesterol, and proteins
Chylomicron
Lacteal

- Amino acids and sugars pass through the epithelium of the small intestine and enter the bloodstream
- Capillaries and veins from the lacteals converge in the **hepatic portal vein** and deliver blood to the liver and then on to the heart

Absorption in the Large Intestine

- The **colon** of the **large intestine** is connected to the small intestine
- The **cecum** aids in the fermentation of plant material and connects where the small and large intestines meet
- The human cecum has an extension called the **appendix**, which plays a very minor role in immunity

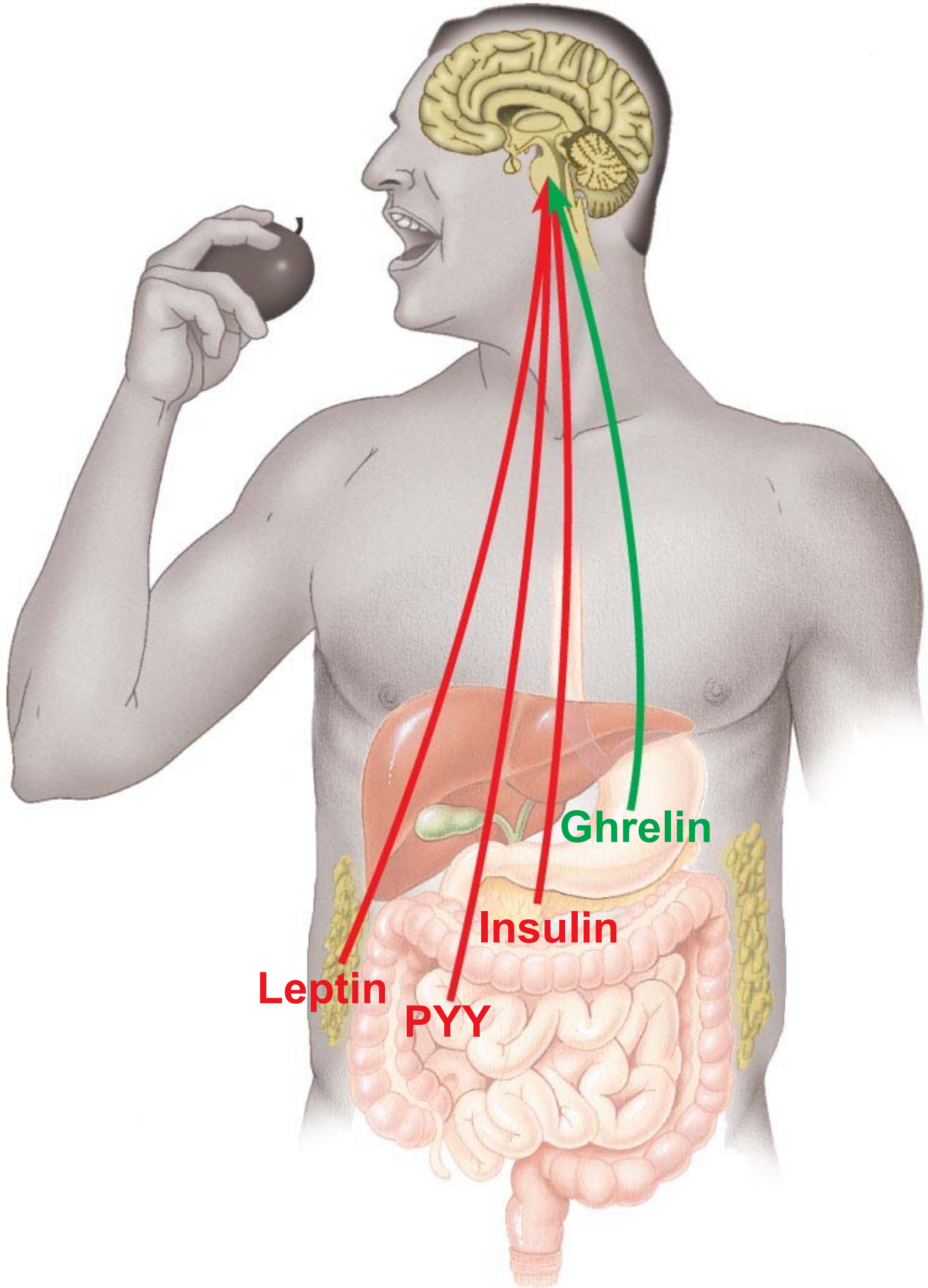
- A major function of the colon is *to recover water that has entered the alimentary canal*
- Wastes of the digestive tract, the **feces**, become more solid as they move through the colon
- Feces pass through the rectum and exit via the anus

- The colon houses strains of the bacterium ***Escherichia coli***, some of which produce vitamins
- Feces are stored in the **rectum** until they can be eliminated
- Two sphincters between the rectum and anus control bowel movements

Overnourishment and Obesity

- **Overnourishment** causes obesity, which results from excessive intake of food energy with the excess stored as fat
- Obesity contributes to *diabetes (type 2), cancer of the colon and breasts*, heart attacks, and strokes

Fig. 41-23



- The complexity of weight control in humans is evident from studies of the hormone leptin
- Mice that inherit a defect in the gene for leptin become very obese

Fig. 41-24a

EXPERIMENT

Obese mouse with mutant *ob* gene (left) next to wild-type mouse.

Chapter 42

Circulation and Gas Exchange

PowerPoint® Lecture Presentations for

Biology

Eighth Edition

Neil Campbell and Jane Reece

Lectures by Chris Romero, updated by Erin Barley with contributions from Joan Sharp

Overview: Trading Places

- Every organism must exchange materials with its environment
- Exchanges ultimately occur at the cellular level
- In unicellular organisms, these exchanges occur directly with the environment

- For most cells making up multicellular organisms, direct exchange with the environment is not possible
- Gills are an example of a specialized exchange system in animals
- Internal transport and gas exchange are functionally related in most animals

Fig. 42-1

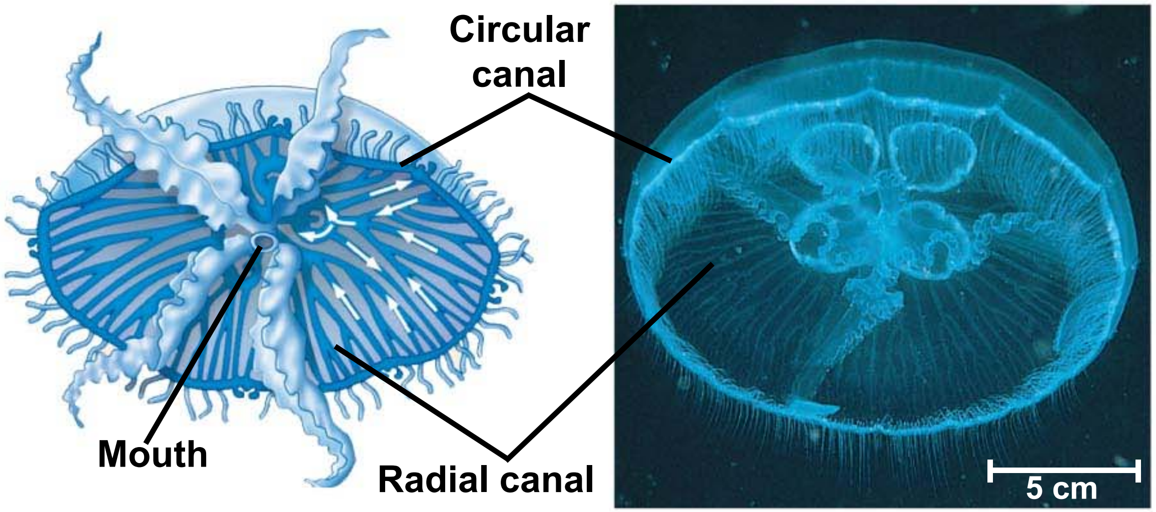
Concept 42.1: Circulatory systems link exchange surfaces with cells throughout the body

- In small and/or thin animals, cells can exchange materials directly with the surrounding medium
- In most animals, transport systems connect the organs of exchange with the body cells
- Most complex animals have internal transport systems that circulate fluid

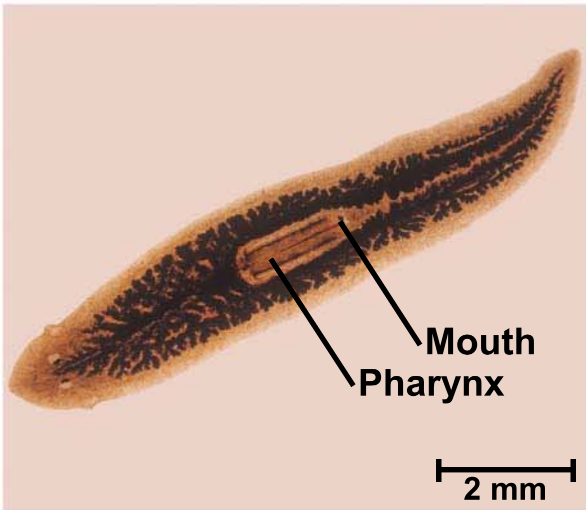
Gastrovascular Cavities

- Simple animals, such as cnidarians, have a body wall that is only two cells thick and that encloses a gastrovascular cavity
- This cavity functions in both digestion and distribution of substances throughout the body
- Examples: Jelly fish and flatworms

Fig. 42-2



(a) **The moon jelly *Aurelia*, a cnidarian**



(b) **The planarian *Dugesia*, a flatworm**

Open and Closed Circulatory Systems

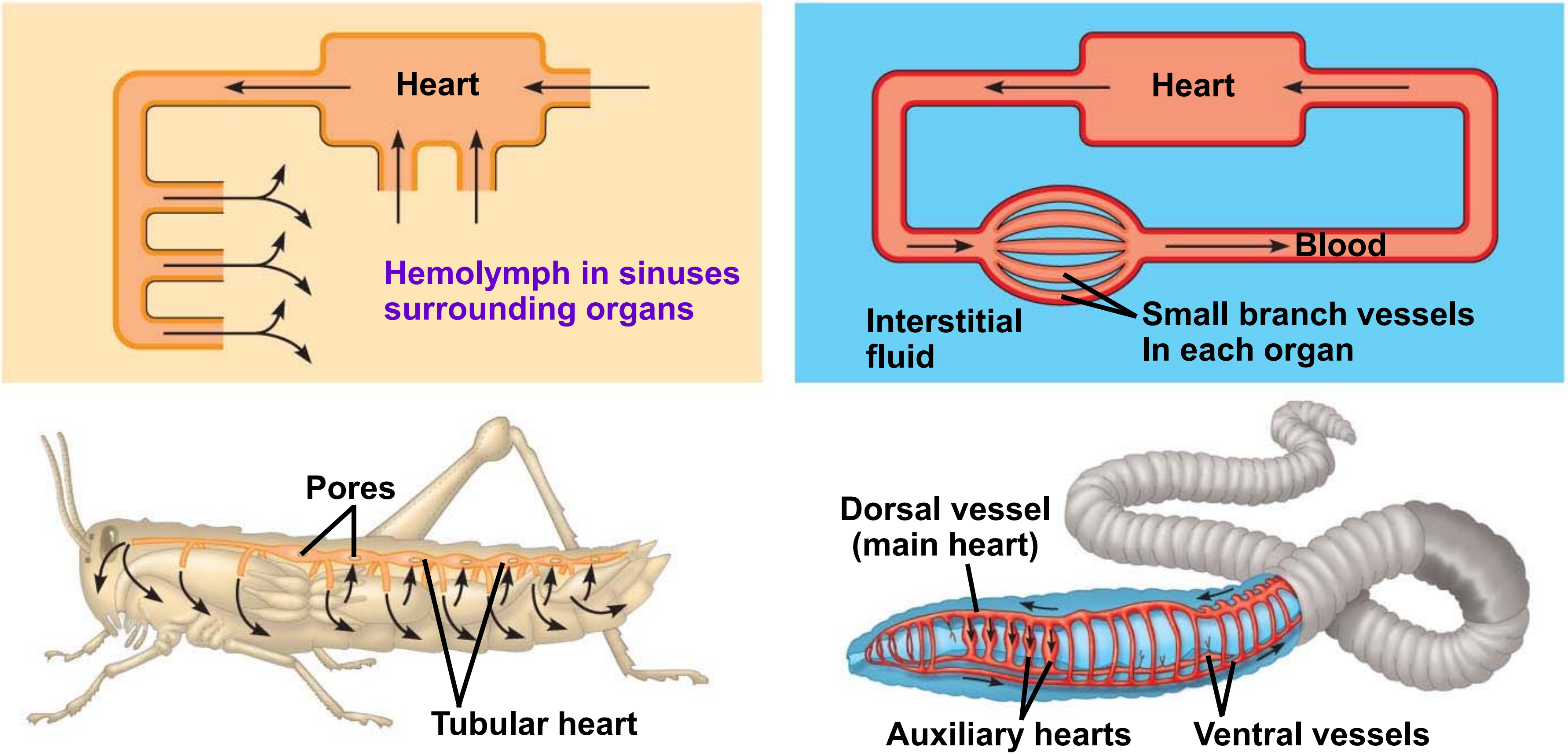
- More complex animals have either open or closed circulatory systems
- Both systems have three basic components:
  - A circulatory fluid (blood or hemolymph)
  - A set of tubes (blood vessels)
  - A muscular pump (the **heart**)

- In insects, other arthropods, and most molluscs, blood bathes the organs directly in an **open circulatory system**
- In an open circulatory system, there is no distinction between blood and interstitial fluid, and this general body fluid is more correctly called **hemolymph**

- In a **closed circulatory system**, *blood is confined to vessels and is distinct from the interstitial fluid*

- Closed systems are more efficient at transporting circulatory fluids to tissues and cells

Fig. 42-3



(a) An open circulatory system

(b) A closed circulatory system

Organization of Vertebrate Circulatory Systems

- Humans and other vertebrates have a closed circulatory system, often called the **cardiovascular system**
- The three main types of blood vessels are arteries, veins, and capillaries

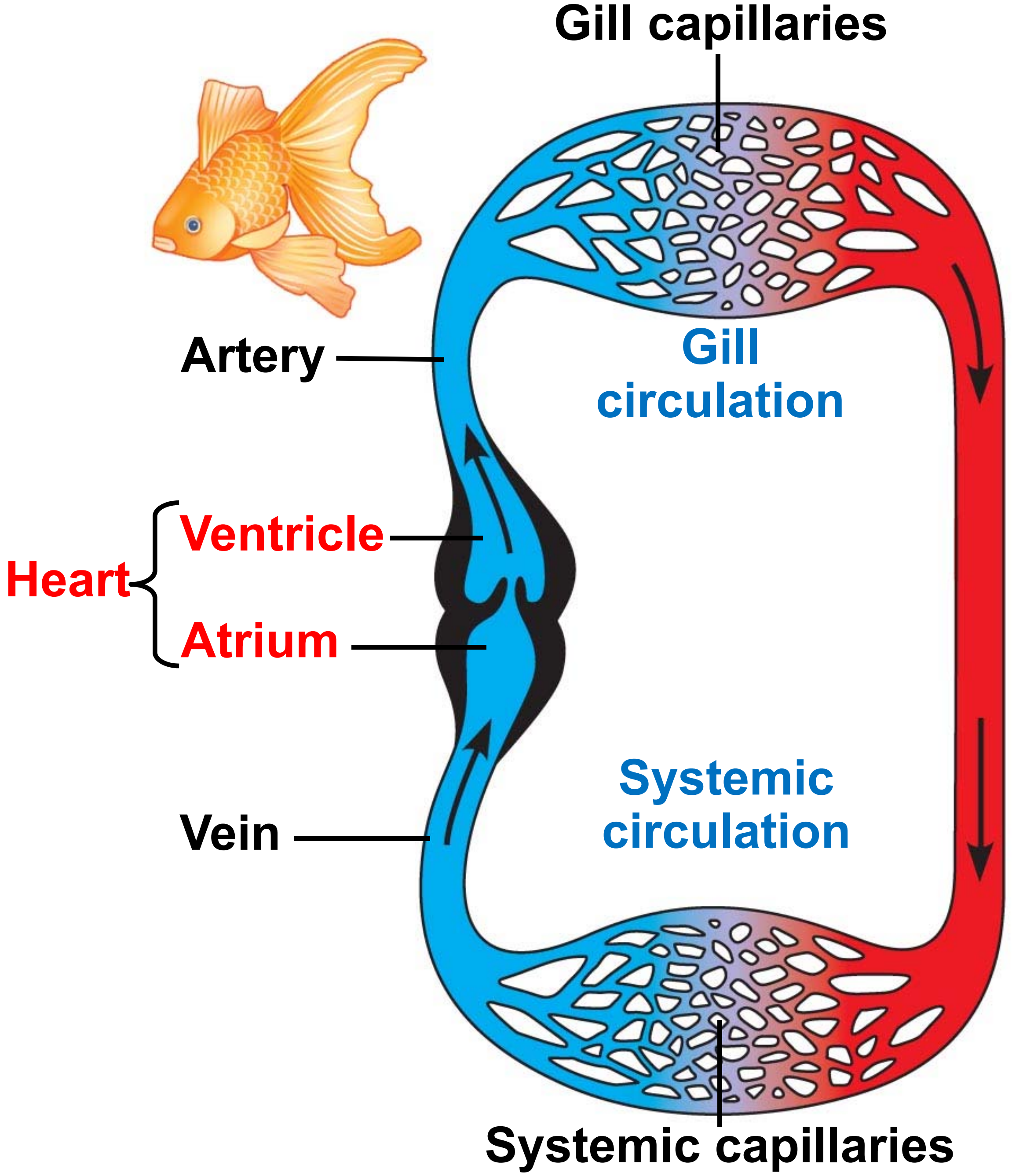
- **Arteries** branch into **arterioles** and carry blood to **capillaries**
- Networks of capillaries called **capillary beds** are the sites of chemical exchange between the blood and interstitial fluid
- **Venules** converge into **veins** and return blood from capillaries to the heart

- Vertebrate hearts contain **two or more chambers**
- Blood enters through an **atrium** and is pumped out through a **ventricle**

Single Circulation

- Bony fishes, rays, and sharks have **single circulation** with a two-chambered heart
- In single circulation, blood leaving the heart passes through two capillary beds before returning

Fig. 42-4

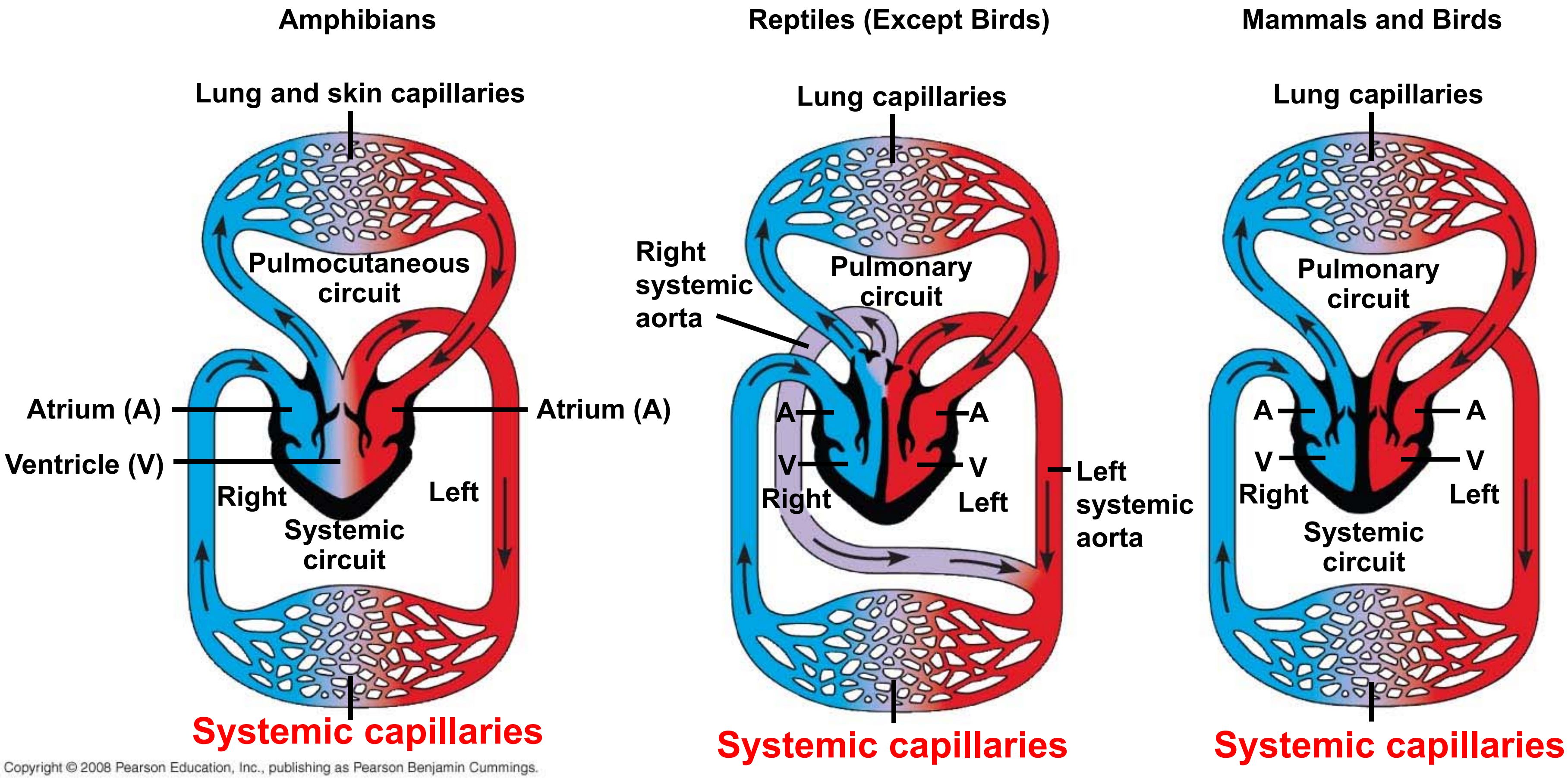


Gill capillaries
Artery
Gill circulation
Heart
Ventricle
Atrium
Vein
Systemic circulation
Systemic capillaries

Double Circulation

- Amphibian, reptiles, and mammals have **double circulation**
- Oxygen-poor and oxygen-rich blood are pumped separately from the right and left sides of the heart

Fig. 42-5



Amphibians
Lung and skin capillaries
Pulmocutaneous circuit
Atrium (A)
Ventricle (V)
Atrium (A)
Right
Left
Systemic circuit
Systemic capillaries
Reptiles (Except Birds)
Lung capillaries
Right systemic aorta
Pulmonary circuit
A
V
Right
A
V
Left
Left systemic aorta
Systemic capillaries
Mammals and Birds
Lung capillaries
Pulmonary circuit
A
V
Right
A
V
Left
Systemic circuit
Systemic capillaries

- In reptiles and mammals, oxygen-poor blood flows through the **pulmonary circuit** to pick up oxygen through the lungs
- In amphibians, oxygen-poor blood flows through a **pulmocutaneous circuit** to pick up oxygen through the lungs and skin
- Oxygen-rich blood delivers oxygen through the **systemic circuit**

Adaptations of Double Circulatory Systems

- Hearts vary in different vertebrate groups

Amphibians

- Frogs and other amphibians have a three-chambered heart: two atria and one ventricle
- The ventricle pumps blood into a forked artery that splits the ventricle's output into the pulmocutaneous circuit and the systemic circuit
- Underwater, blood flow to the lungs is nearly shut off

Reptiles (Except Birds)

- Turtles, snakes, and lizards have a three-chambered heart: two atria and one ventricle
- In alligators, caimans, and other crocodilians a septum divides the ventricle
- Reptiles have double circulation, with a pulmonary circuit (lungs) and a systemic circuit

Mammals and Birds

- Mammals and birds have a **four-chambered heart** with two atria and two ventricles
- The left side of the heart pumps and receives only oxygen-rich blood, while the right side receives and pumps only oxygen-poor blood
- Mammals and birds are endotherms and require more O_2 than ectotherms

Concept 42.2: Coordinated cycles of heart contraction drive double circulation in mammals

- The mammalian cardiovascular system meets the body's continuous demand for O_2

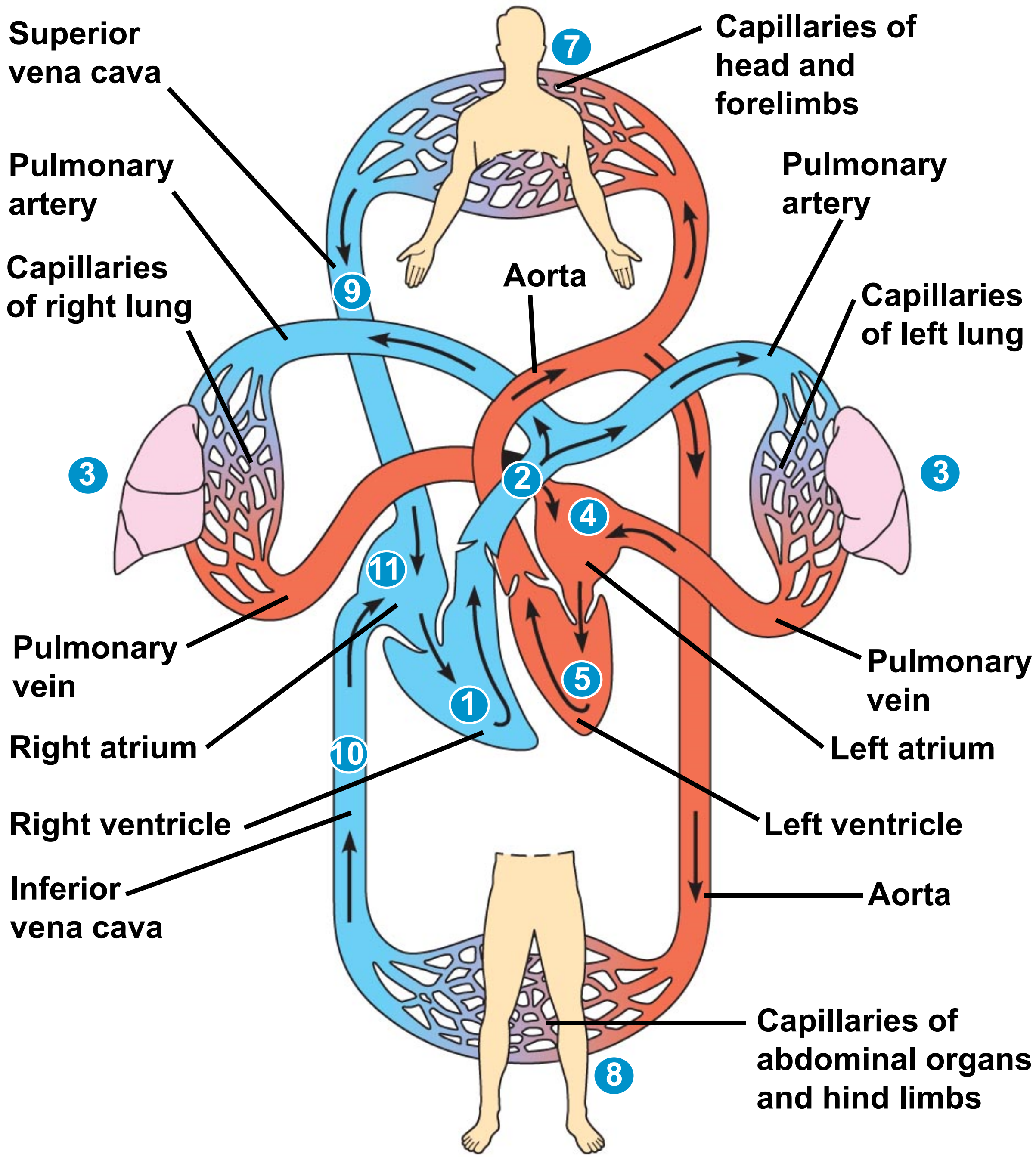
Mammalian Circulation

- Blood begins its flow with the right ventricle pumping blood to the lungs
- In the lungs, the blood loads O_2 and unloads CO_2
- Oxygen-rich blood from the lungs enters the heart at the left atrium and is pumped through the aorta to the body tissues by the left ventricle
- The aorta provides blood to the heart through the **coronary arteries**

- Blood returns to the heart through the **superior vena cava** (blood from head, neck, and forelimbs) and **inferior vena cava** (blood from trunk and hind limbs)
- The superior vena cava and inferior vena cava flow into the right atrium

PLAY Animation: Path of Blood Flow in Mammals

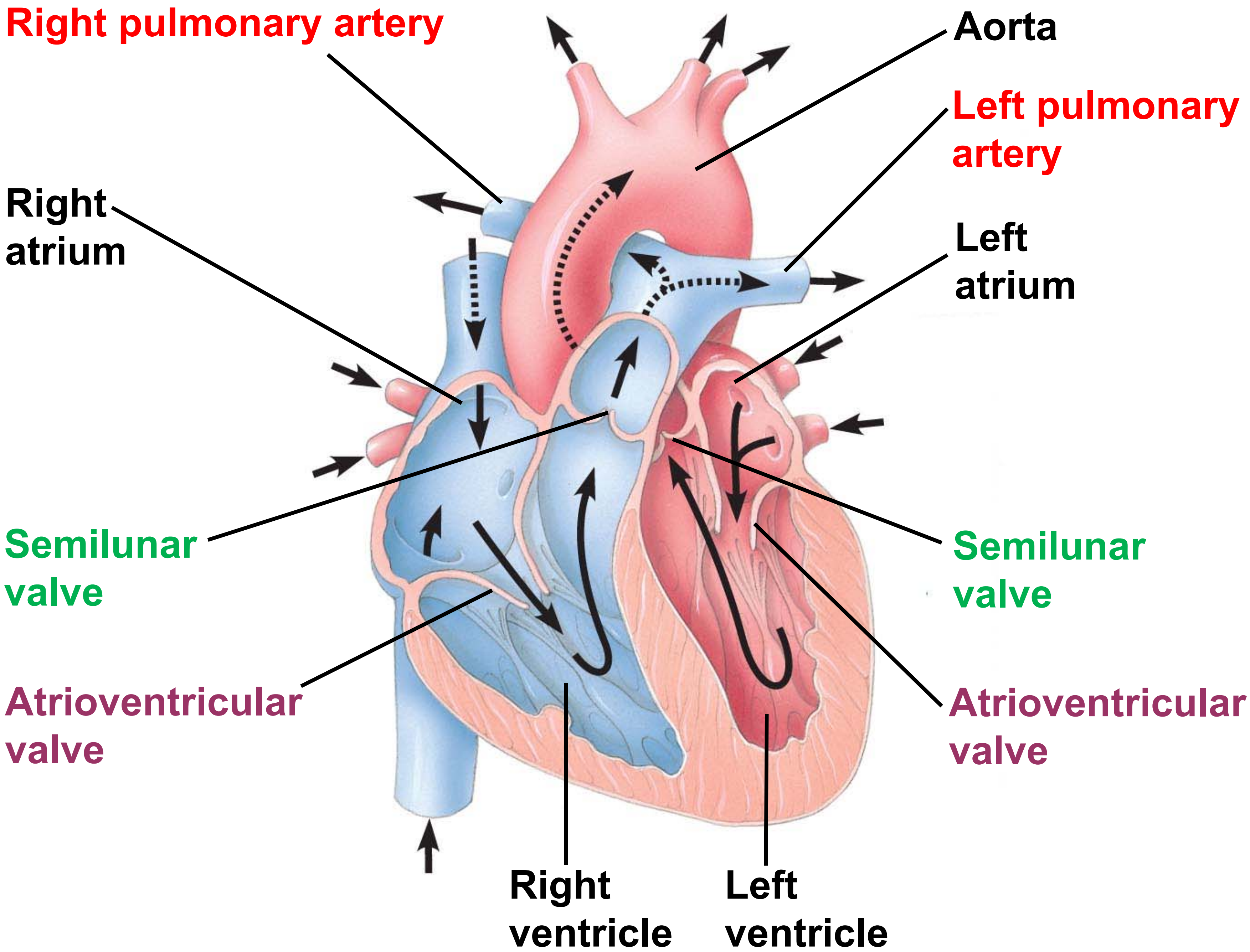
Fig. 42-6


Superior vena cava
Pulmonary artery
Capillaries of right lung
Pulmonary vein
Right atrium
Right ventricle
Inferior vena cava
Capillaries of head and forelimbs
Aorta
Pulmonary artery
Capillaries of left lung
Pulmonary vein
Left atrium
Left ventricle
Aorta
Capillaries of abdominal organs and hind limbs
1
2
3
3
4
5
7
8
9
10
11

The Mammalian Heart: *A Closer Look*

- A closer look at the mammalian heart provides a better understanding of double circulation

Fig. 42-7


Right pulmonary artery
Aorta
Left pulmonary artery
Right atrium
Left atrium
Semilunar valve
Semilunar valve
Atrioventricular valve
Atrioventricular valve
Right ventricle
Left ventricle

- The heart contracts and relaxes in a rhythmic cycle called the **cardiac cycle**
- The contraction, or pumping, phase is called **systole**
- The relaxation, or filling, phase is called **diastole**

Fig. 42-8-1

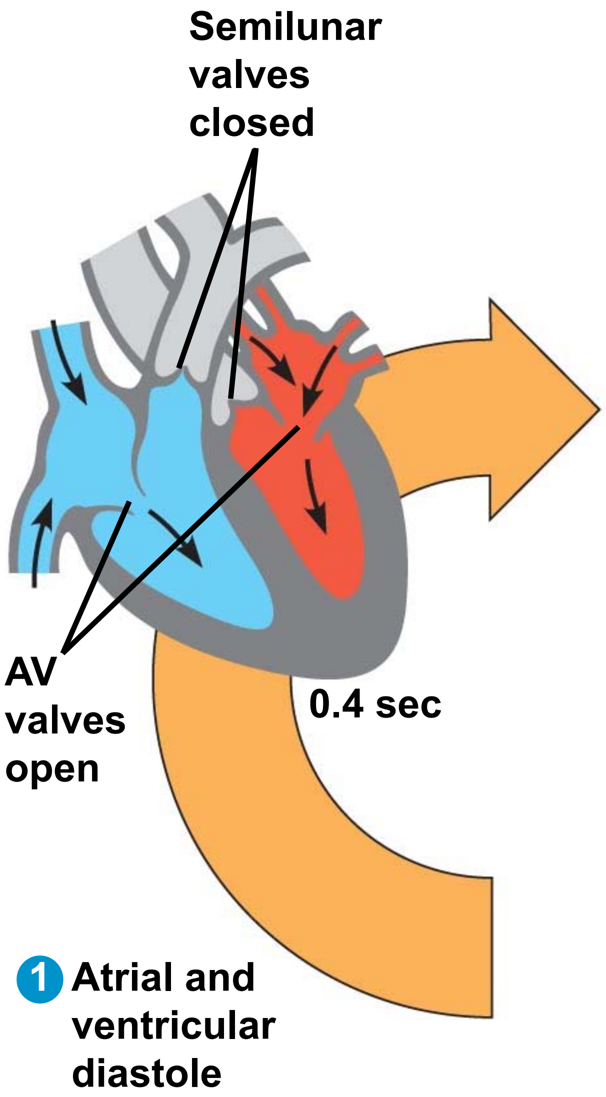
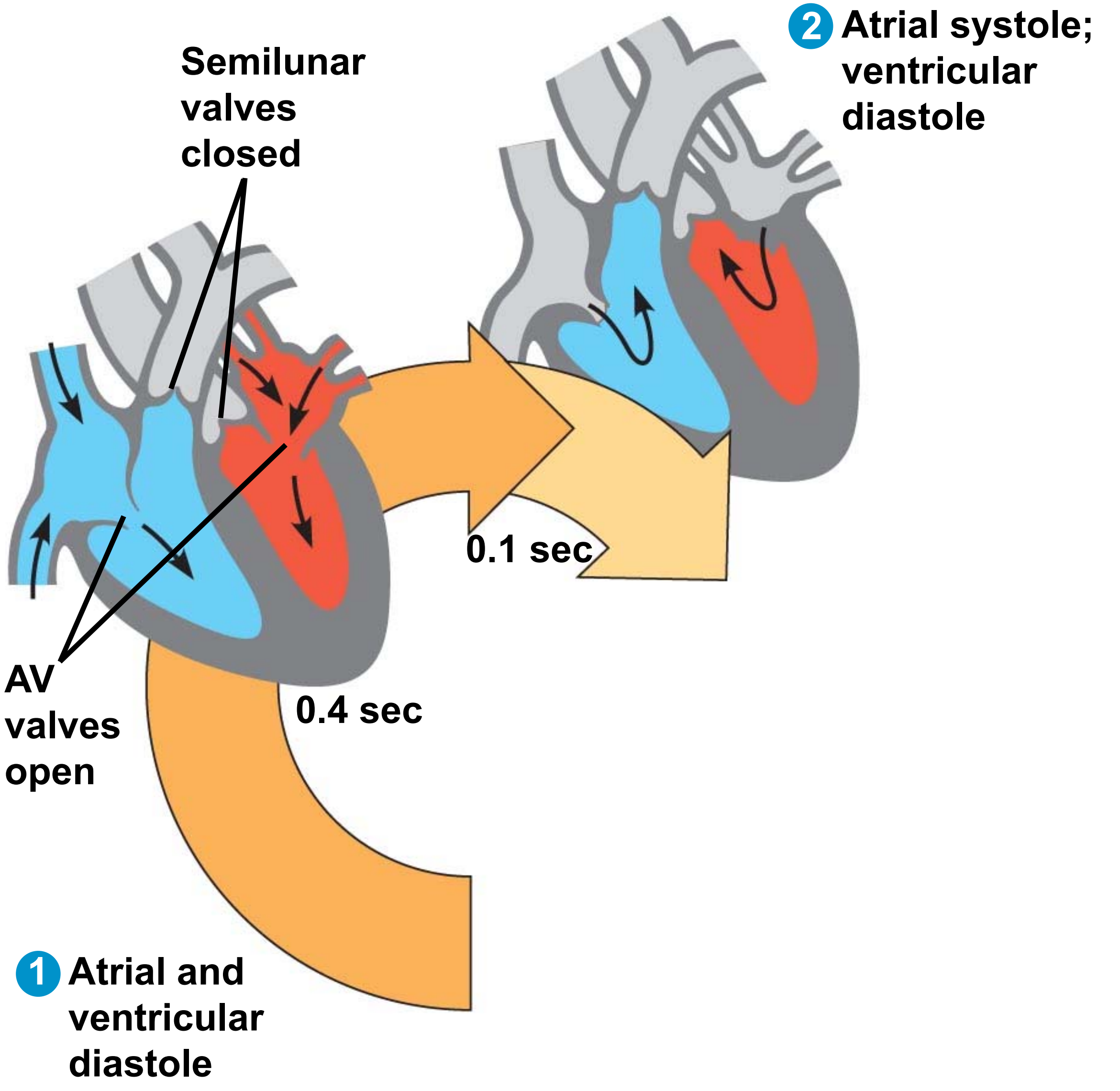
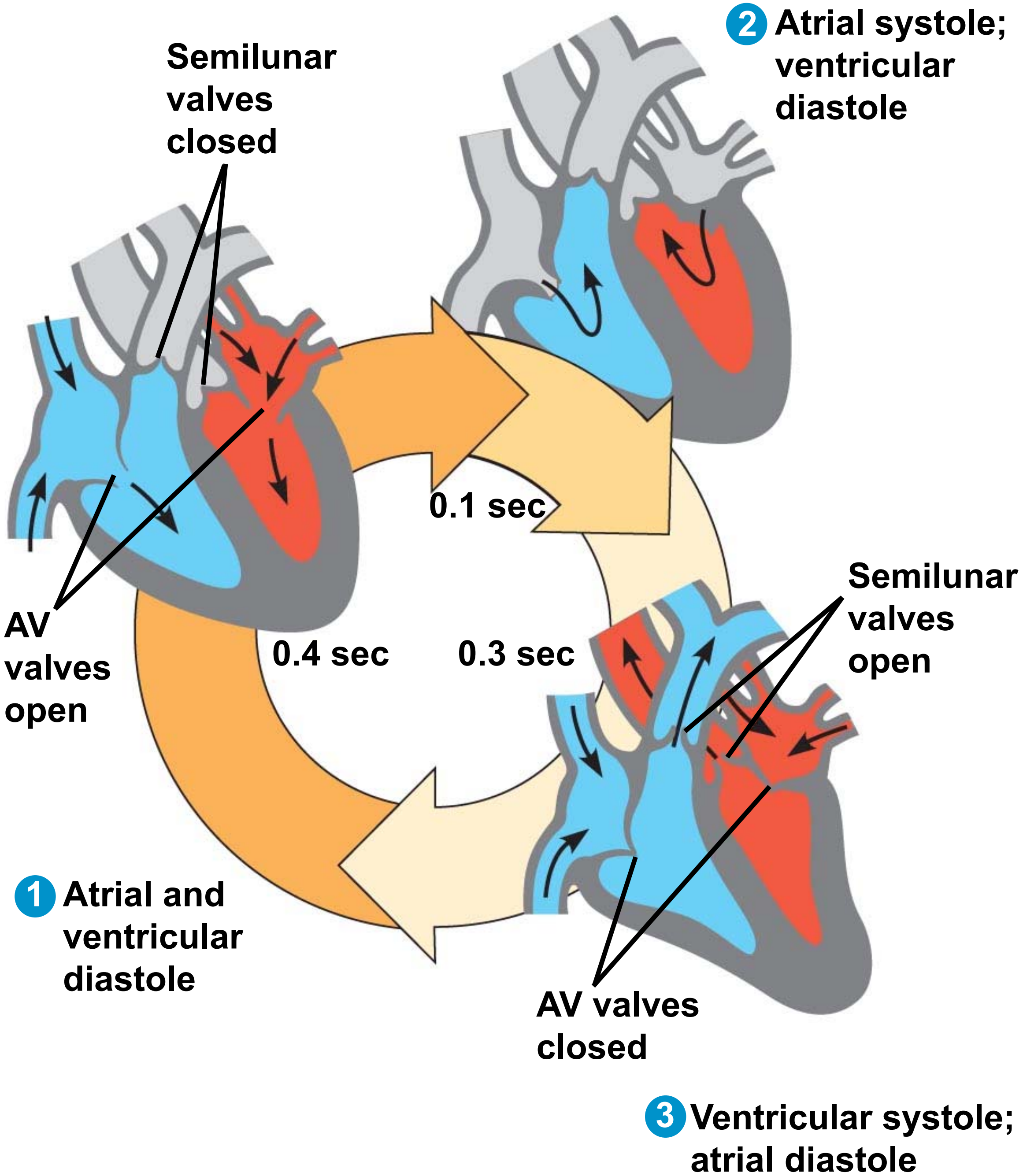

Semilunar valves closed
AV valves open
0.4 sec
1 Atrial and ventricular diastole

Fig. 42-8-2



Semilunar valves closed
2 Atrial systole; ventricular diastole
0.1 sec
AV valves open
0.4 sec
1 Atrial and ventricular diastole

Fig. 42-8


Semilunar
valves
closed
2 Atrial systole;
ventricular
diastole
0.1 sec
AV
valves
open
0.4 sec
0.3 sec
Semilunar
valves
open
1 Atrial and
ventricular
diastole
AV valves
closed
3 Ventricular systole;
atrial diastole

- The **heart rate**, also called the pulse, *is the number of beats per minute*
- The **stroke volume** *is the amount of blood pumped in a single contraction*
- The **cardiac output** *is the volume of blood pumped into the systemic circulation per minute* and depends on both the heart rate and stroke volume

- Four valves prevent backflow of blood in the heart
- The **atrioventricular (AV) valves** separate each atrium and ventricle
- The **semilunar valves** control blood flow to the aorta and the pulmonary artery

Maintaining the Heart's Rhythmic Beat

- Some cardiac muscle cells are self-excitable, *meaning they contract without any signal from the nervous system*

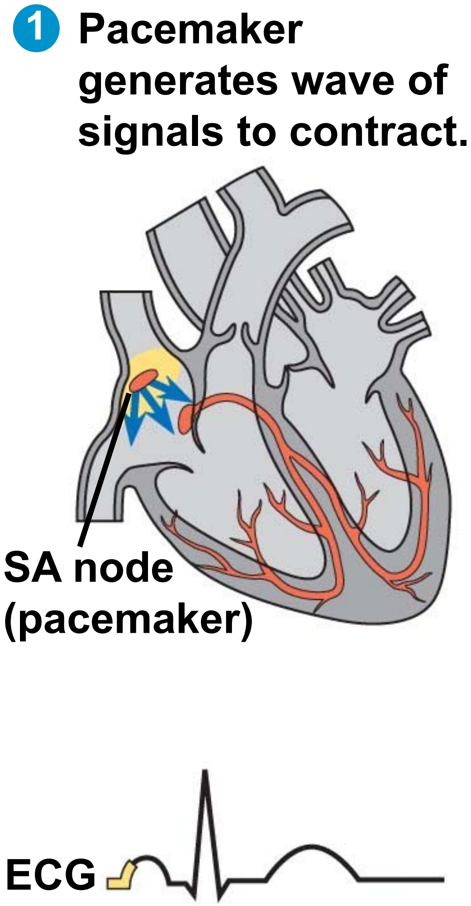
- The **sinoatrial (SA) node**, or *pacemaker*, sets the rate and timing at which cardiac muscle cells contract

- Impulses from the SA node travel to the **atrioventricular (AV) node**

- At the AV node, the impulses are delayed and then travel to the **Purkinje fibers** that make the ventricles contract

- Impulses that travel during the cardiac cycle can be recorded as an **electrocardiogram** (**ECG** or **EKG**)

Fig. 42-9-1



1 Pacemaker generates wave of signals to contract.
SA node (pacemaker)
ECG

Fig. 42-9-2

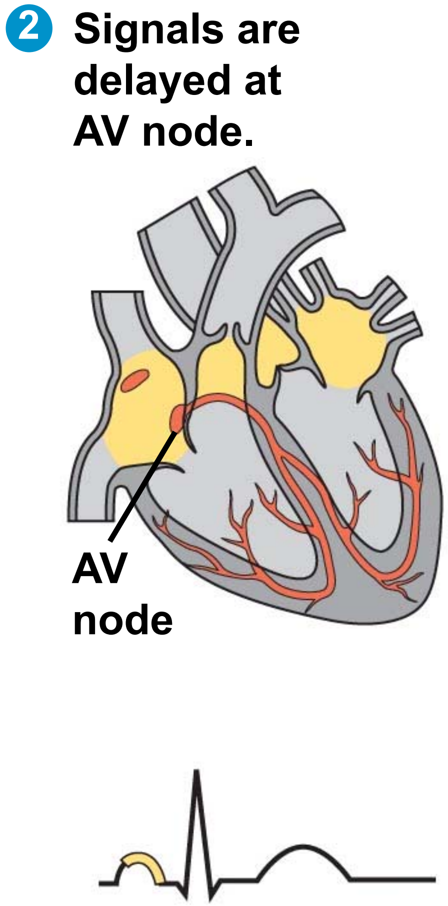


Fig. 42-9-3

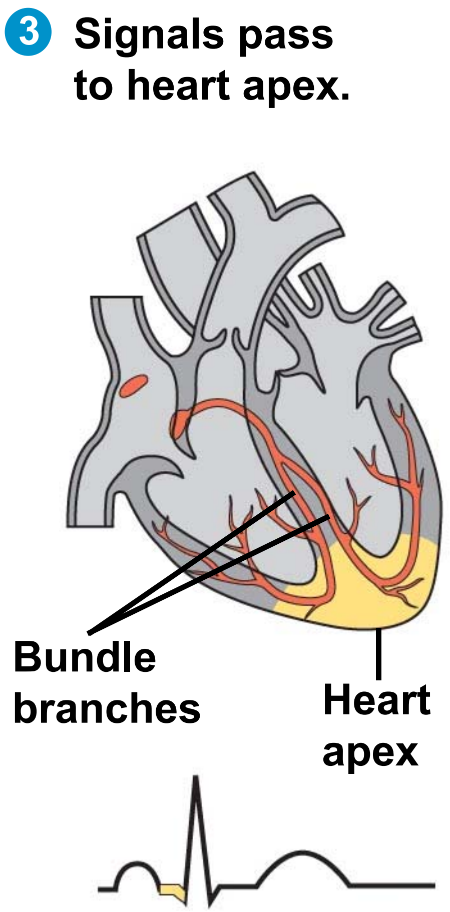


Fig. 42-9-4

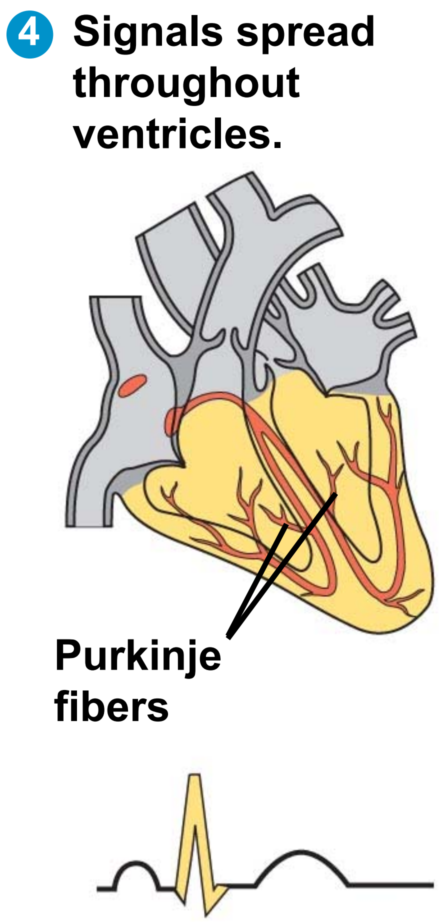
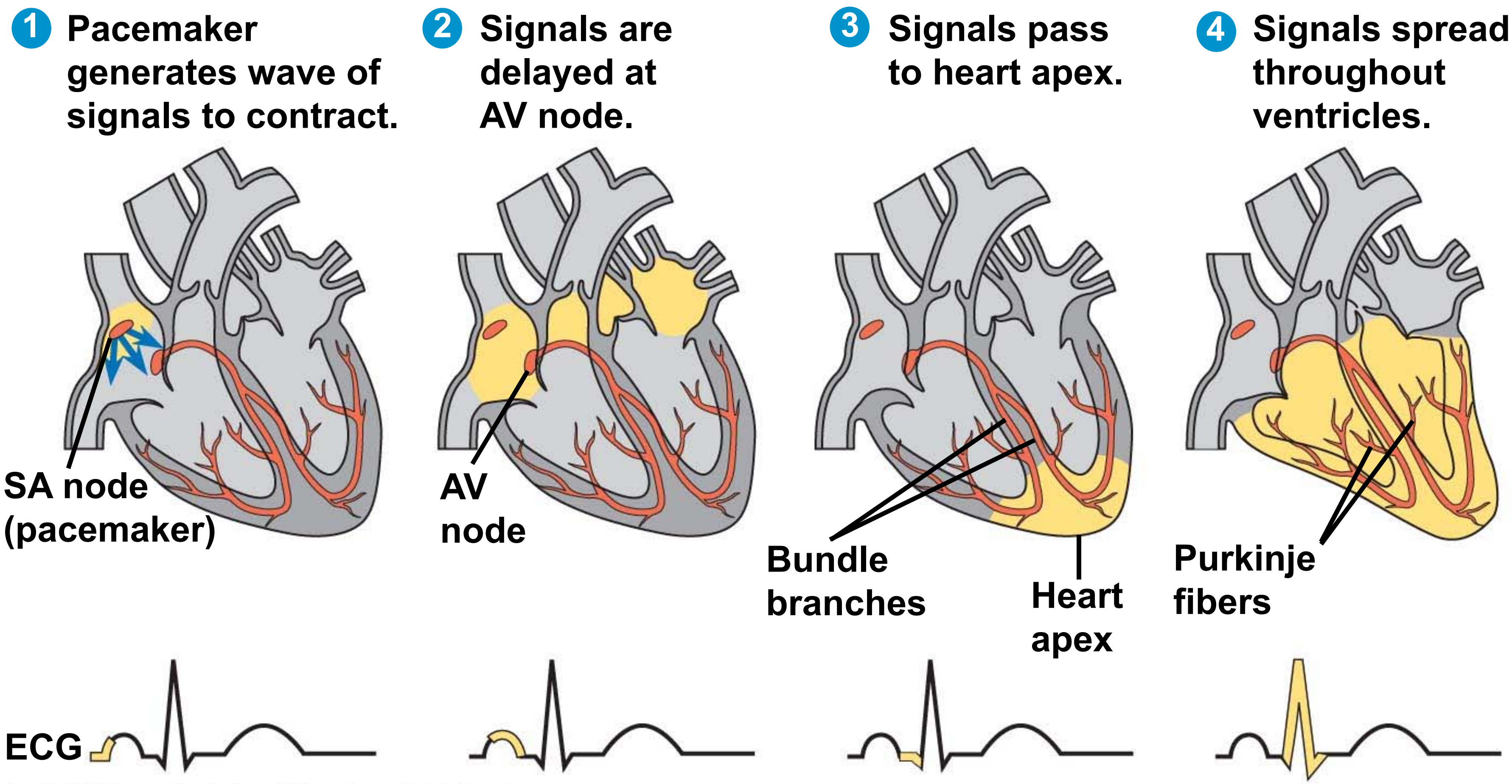


Fig. 42-9-5


1 Pacemaker generates wave of signals to contract.
2 Signals are delayed at AV node.
3 Signals pass to heart apex.
4 Signals spread throughout ventricles.
SA node (pacemaker)
AV node
Bundle branches
Heart apex
Purkinje fibers
ECG

- The pacemaker is influenced by nerves, hormones, body temperature, and exercise

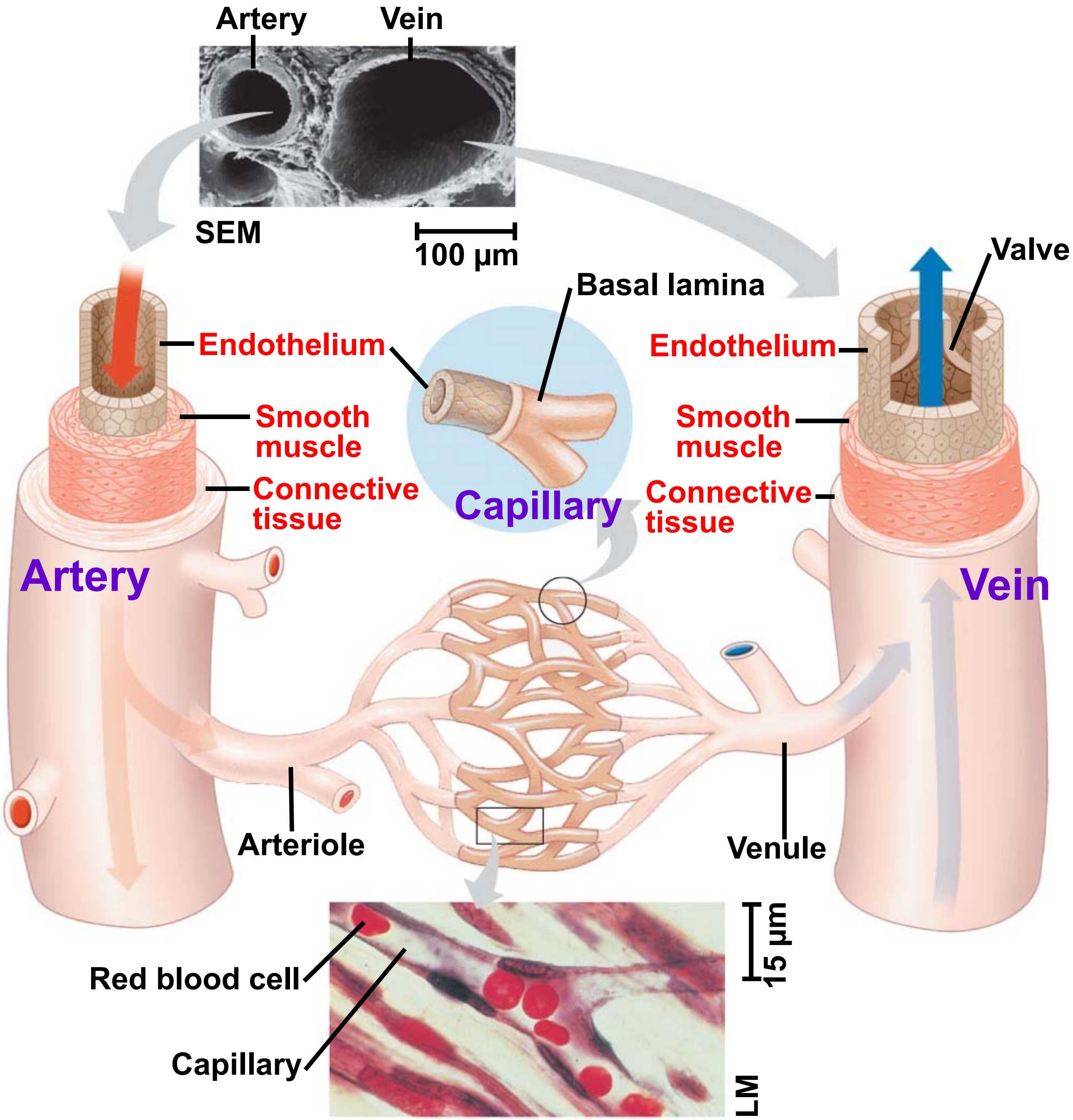
Concept 42.3: Patterns of blood pressure and flow reflect the structure and arrangement of blood vessels

- The physical principles that govern movement of water in plumbing systems also influence the functioning of animal circulatory systems

Blood Vessel Structure and Function

- The epithelial layer that lines blood vessels is called the **endothelium**

Fig. 42-10

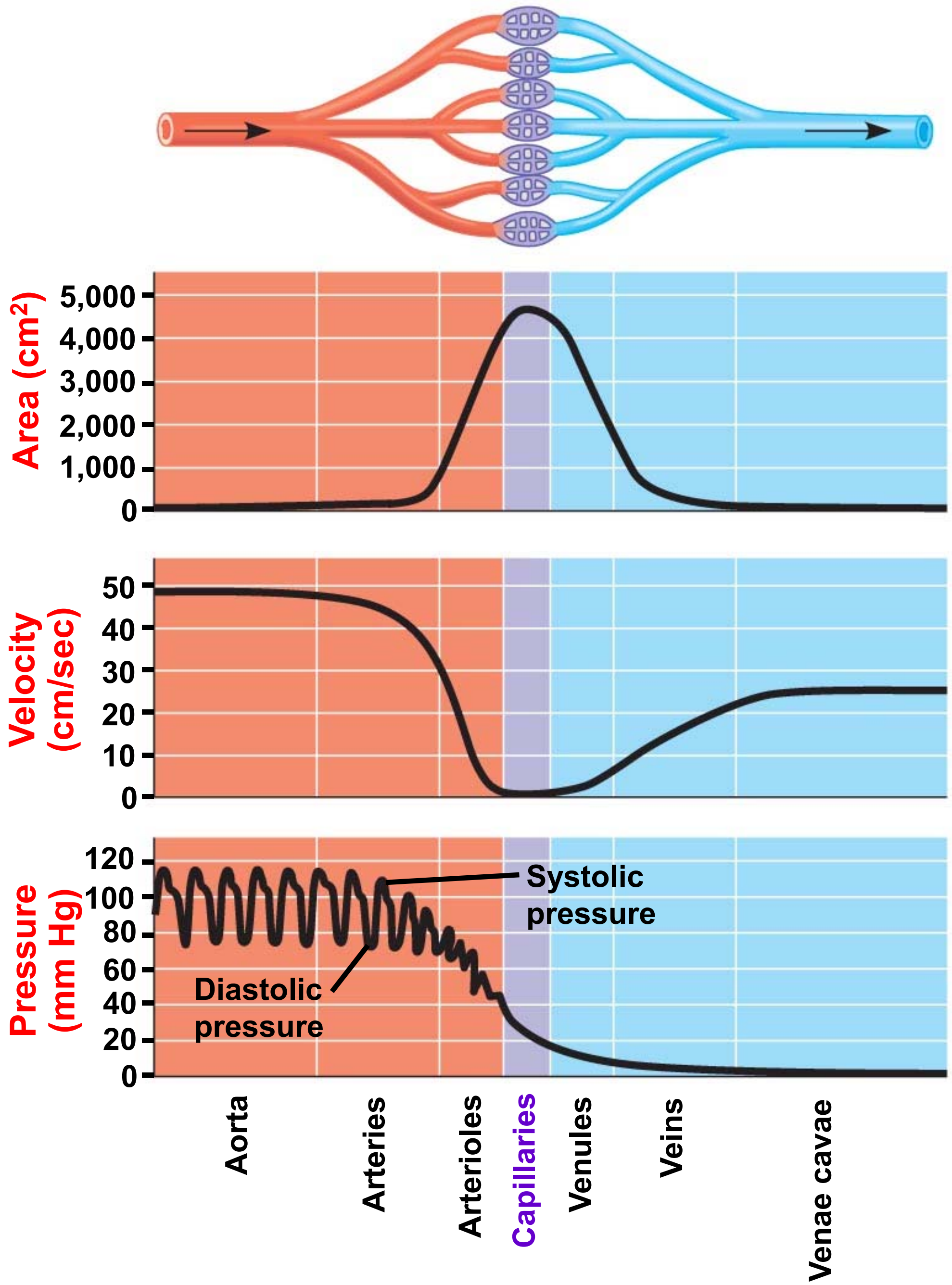

Artery
Vein
SEM
100 µm
Basal lamina
Valve
Endothelium
Smooth muscle
Connective tissue
Endothelium
Smooth muscle
Connective tissue
Capillary
Artery
Vein
Arteriole
Venule
15 µm
Red blood cell
Capillary
LM

- Arteries have thicker walls than veins to accommodate the high pressure of blood pumped from the heart
- In the thinner-walled veins, blood flows back to the heart mainly as a result of muscle action

Blood Flow Velocity

- Physical laws governing movement of fluids through pipes affect blood flow and blood pressure
- Velocity of blood flow is **slowest** in the capillary beds, as a result of the high resistance and large total cross-sectional area
- Blood flow in capillaries is necessarily slow for exchange of materials

Fig. 42-11



Area (cm²)
5,000
4,000
3,000
2,000
1,000
0
Velocity (cm/sec)
50
40
30
20
10
0
Pressure (mm Hg)
120
100
80
60
40
20
0
Systolic pressure
Diastolic pressure
Aorta
Arteries
Arterioles
Capillaries
Venules
Veins
Venae cavae

Blood Pressure

- **Blood pressure** is the *hydrostatic pressure that blood exerts against the wall of a vessel*

Changes in Blood Pressure During the Cardiac Cycle

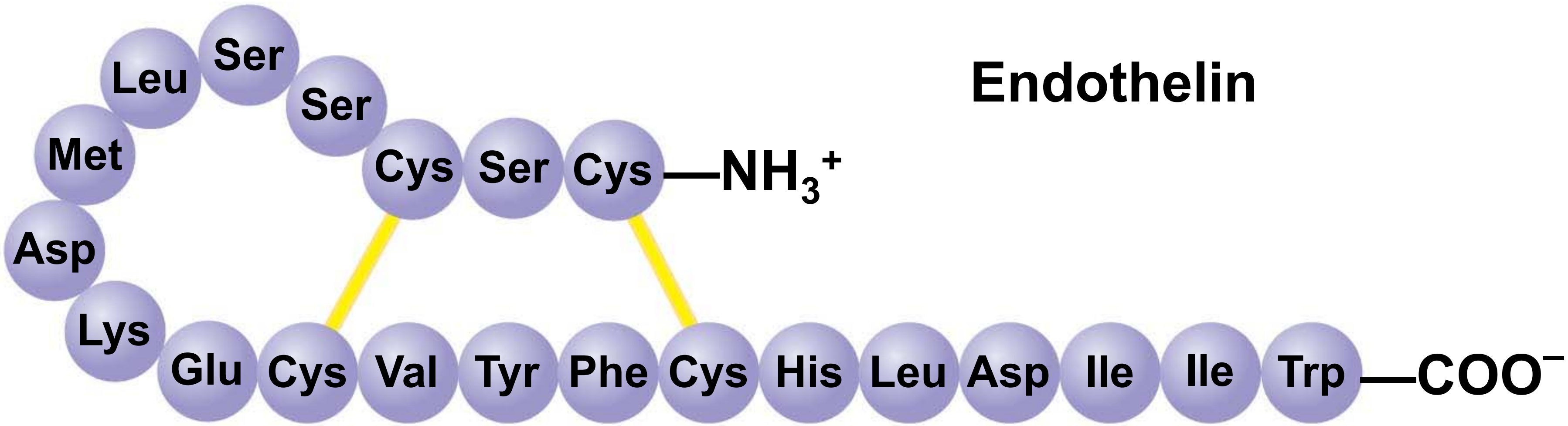
- **Systolic pressure** *is the pressure in the arteries during ventricular systole*; it is the highest pressure in the arteries
- **Diastolic pressure** *is the pressure in the arteries during diastole*; it is lower than systolic pressure
- A **pulse** is the rhythmic bulging of artery walls with each heartbeat

Regulation of Blood Pressure

- Blood pressure is determined by cardiac output and peripheral resistance due to constriction of arterioles
- **Vasoconstriction** *is the contraction of smooth muscle in arteriole walls*; it increases blood pressure
- **Vasodilation** *is the relaxation of smooth muscles in the arterioles*; it causes blood pressure to fall

- Vasoconstriction and vasodilation help maintain adequate blood flow as the body's demands change
- The peptide **endothelin** is an important inducer of vasoconstriction

Fig. 42-12a



Endothelin
Cys
Ser
Cys
—NH3+
Ser
Ser
Leu
Met
Asp
Lys
Glu
Cys
Val
Tyr
Phe
Cys
His
Leu
Asp
Ile
Ile
Trp
—COO−

Blood Pressure

- Blood pressure is generally measured for an artery in the arm at the same height as the heart
- Blood pressure for a healthy 20 year old at rest is 120 mm Hg at systole and 70 mm Hg at diastole

Fig. 42-13-1

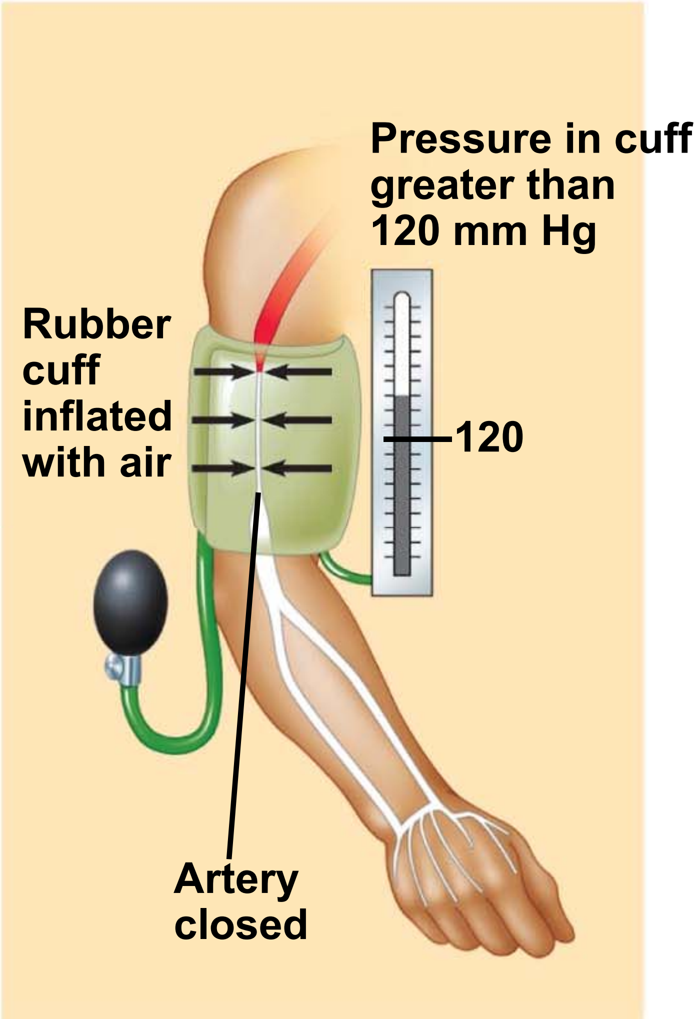
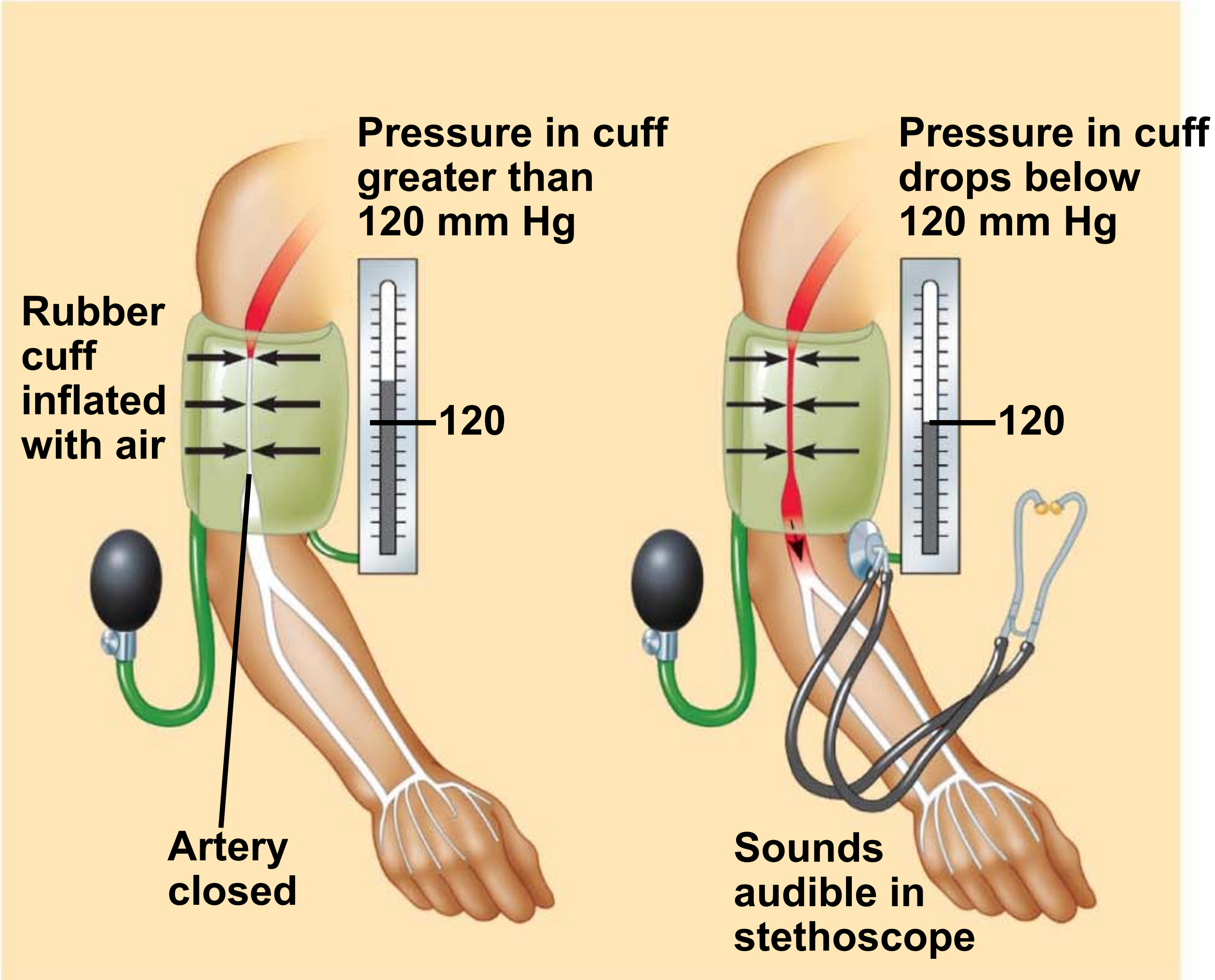
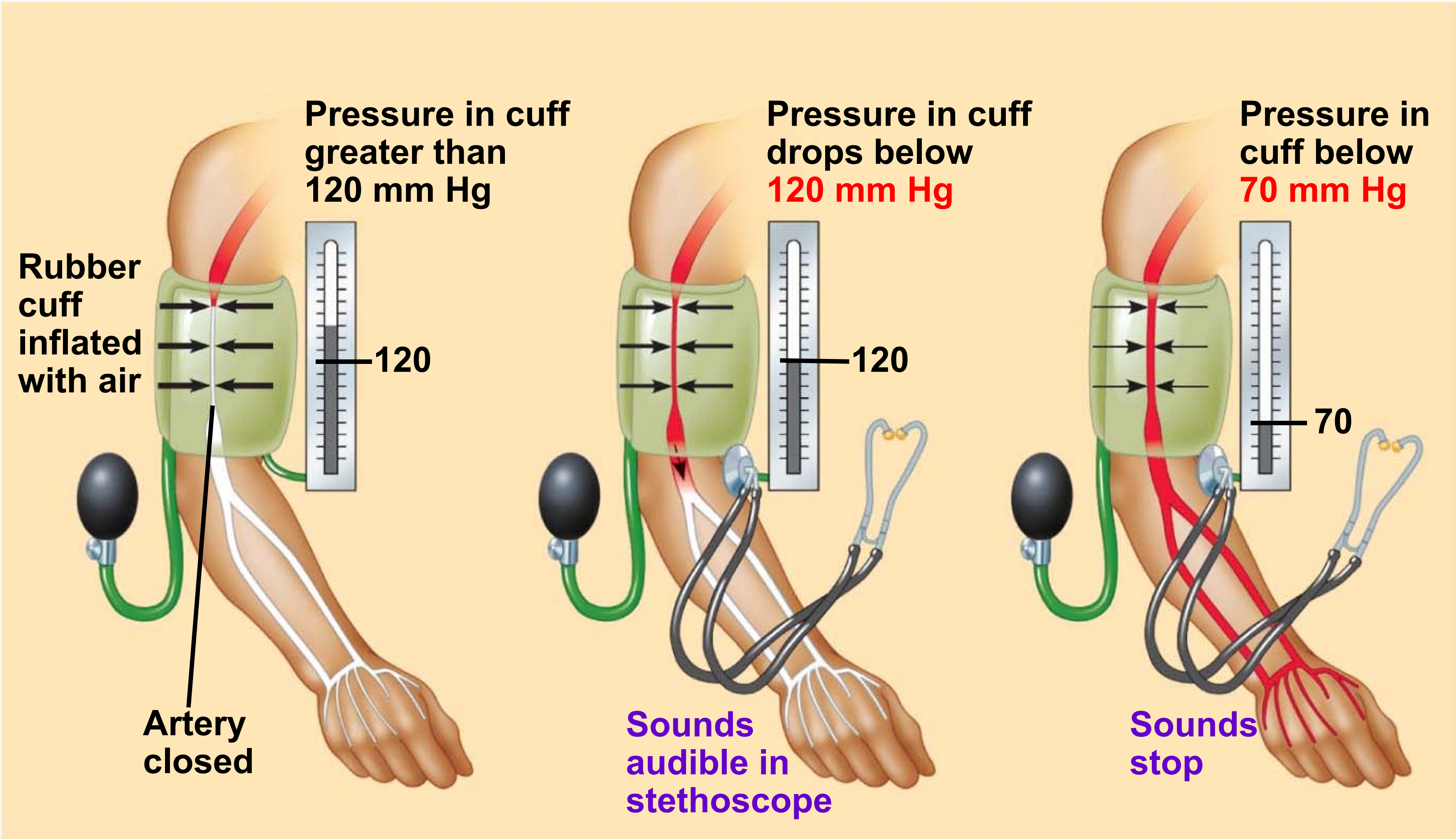

Pressure in cuff greater than 120 mm Hg
Rubber cuff inflated with air
120
Artery closed

Fig. 42-13-2



Pressure in cuff greater than 120 mm Hg
Rubber cuff inflated with air
120
Artery closed
Pressure in cuff drops below 120 mm Hg
120
Sounds audible in stethoscope

Fig. 42-13-3



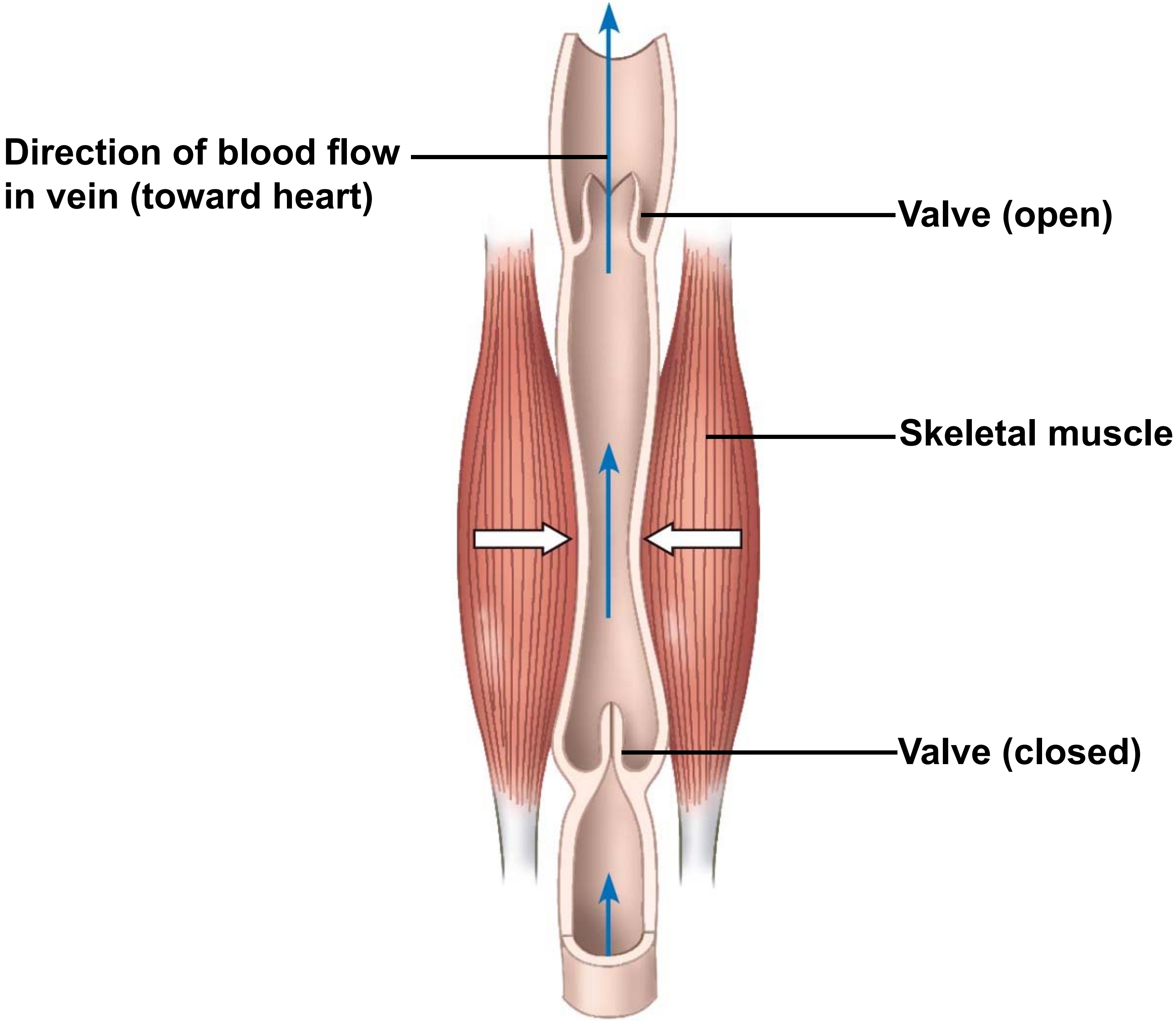
Blood pressure reading: 120/70

Blood Flow in veins

*Blood flows in veins with the help of skeletal muscle contraction.

*Valves prevent backflow of blood.

Fig. 42-14



Direction of blood flow in vein (toward heart)
Valve (open)
Skeletal muscle
Valve (closed)

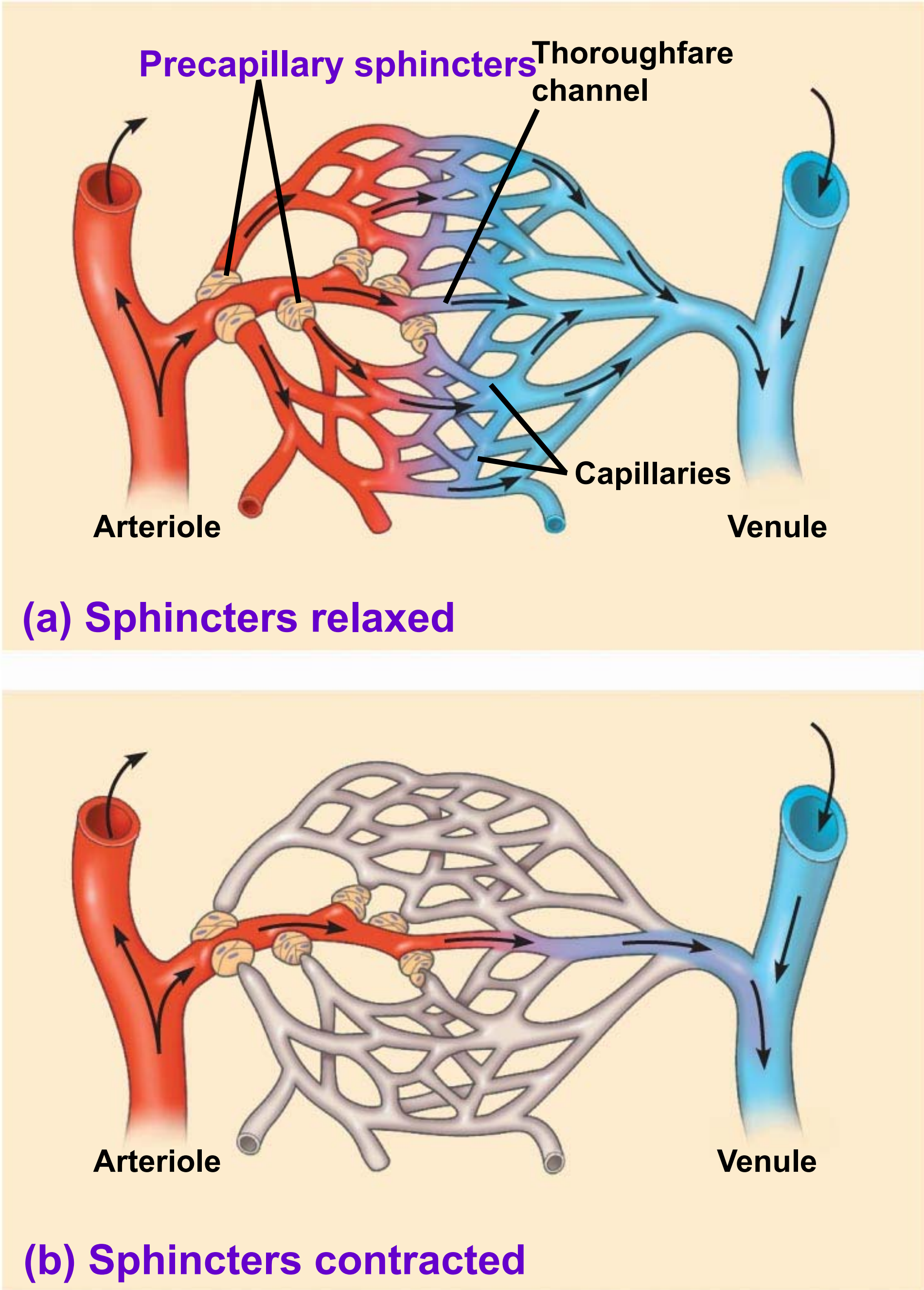
Capillary Function

- Capillaries in major organs are usually filled to capacity
- Blood supply varies in many other sites

Capillary Function

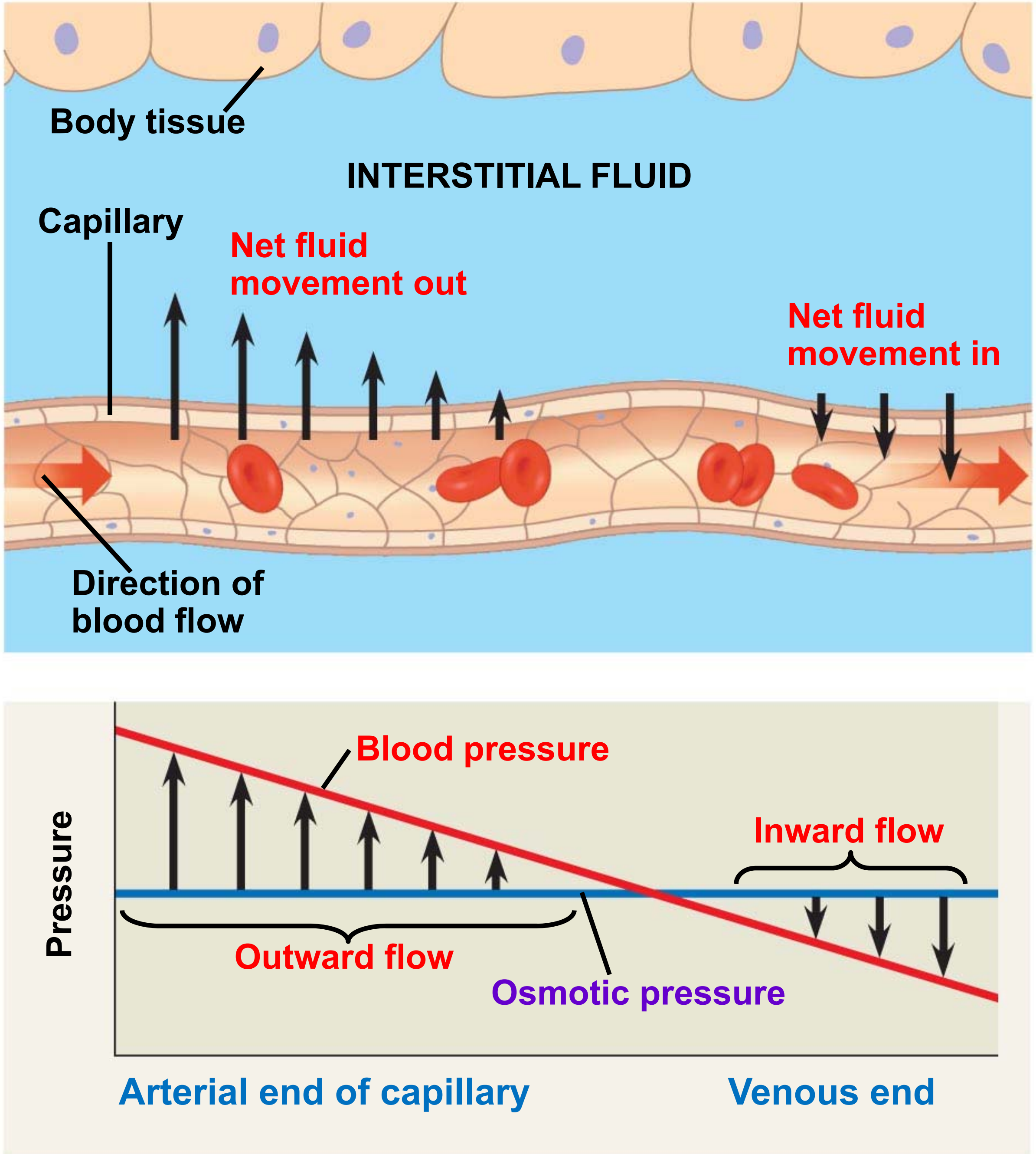
- Two mechanisms regulate distribution of blood in capillary beds:
  - **Contraction of the smooth muscle** layer in the wall of an arteriole constricts the vessel
  - **Precapillary sphincters** control flow of blood between arterioles and venules

Fig. 42-15


Precapillary sphincters
Thoroughfare channel
Capillaries
Arteriole
Venule
(a) Sphincters relaxed
Arteriole
Venule
(b) Sphincters contracted

- The difference between blood pressure and osmotic pressure *drives fluids out of capillaries at the arteriole end and into capillaries at the venule end*

Fig. 42-16


Body tissue
INTERSTITIAL FLUID
Capillary
Net fluid movement out
Net fluid movement in
Direction of blood flow
Blood pressure
Inward flow
Pressure
Outward flow
Osmotic pressure
Arterial end of capillary
Venous end

Fluid Return by the Lymphatic System

- The **lymphatic system** returns fluid that leaks out in the capillary beds
- This system aids in body defense
- Fluid, called **lymph**, reenters the circulation directly at the venous end of the capillary bed and indirectly through the lymphatic system
- The lymphatic system drains into veins in the neck

- **Lymph nodes** *are organs that filter lymph and play an important role in the body's defense*
- **Edema** is *swelling caused by disruptions in the flow of lymph*

Concept 42.4: Blood components function in exchange, transport, and defense

- In invertebrates with **open circulation**, blood (hemolymph) is not different from interstitial fluid
- Blood in the **circulatory systems of vertebrates** is a specialized connective tissue

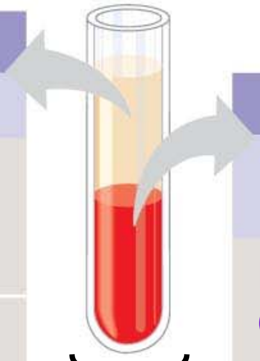
Blood Composition and Function

- Blood consists of **several kinds of cells** suspended in a liquid matrix called **plasma**
- The **cellular elements** occupy about **45%** of the volume of blood

Fig. 42-17

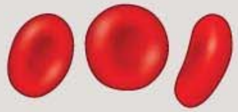
Plasma 55%

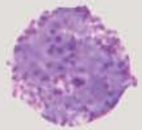
Constituent	Major functions
Water	Solvent for carrying other substances
Ions (blood electrolytes) Sodium Potassium Calcium Magnesium Chloride Bicarbonate	Osmotic balance, pH buffering, and regulation of membrane permeability
Plasma proteins	
Albumin	Osmotic balance pH buffering
Fibrinogen	Clotting
Immunoglobulins (antibodies)	Defense
Substances transported by blood Nutrients (such as glucose, fatty acids, vitamins) Waste products of metabolism Respiratory gases (O_2 and CO_2) Hormones	



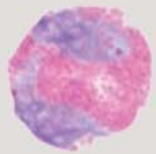
Cellular elements 45%

Cell type	Number per µL (mm^3) of blood	Functions
Erythrocytes (red blood cells)	5–6 million	Transport oxygen and help transport carbon dioxide
Leukocytes (white blood cells)	5,000–10,000	Defense and immunity
Platelets	250,000–400,000	Blood clotting





Basophil



Eosinophil

Lymphocyte

Neutrophil

Monocyte

Plasma

- Blood plasma is about 90% water
- Among its solutes are inorganic salts in the form of dissolved ions, sometimes called electrolytes
- Another important class of solutes is the plasma proteins, which influence blood pH, osmotic pressure, and viscosity
- Various plasma proteins function in lipid transport, immunity, and blood clotting

Cellular Elements

- Suspended in blood plasma are **two types of cells:**
  - **Red blood cells** (**erythrocytes**) transport oxygen
  - **White blood cells** (**leukocytes**) function in defense
- **Platelets**, a third cellular element, are fragments of cells that are **involved in clotting**

Erythrocytes

- Red blood cells, or **erythrocytes**, are by far the most numerous blood cells
- They transport oxygen throughout the body
- They contain **hemoglobin**, the iron-containing protein that transports oxygen

Leukocytes

- There are **five major types of white blood cells**, or **leukocytes**: monocytes, neutrophils, basophils, eosinophils, and lymphocytes
- They function in **defense** by phagocytizing bacteria and debris or by producing antibodies
- They are found both **in and outside** of the circulatory system

Platelets

- Platelets are fragments of cells and function in blood clotting

Blood Clotting

- When the endothelium of a blood vessel is damaged, the clotting mechanism begins
- A cascade of complex reactions converts fibrinogen to **fibrin**, forming a clot
- A blood clot formed within a blood vessel is called a **thrombus** and can block blood flow

Fig. 42-18-1

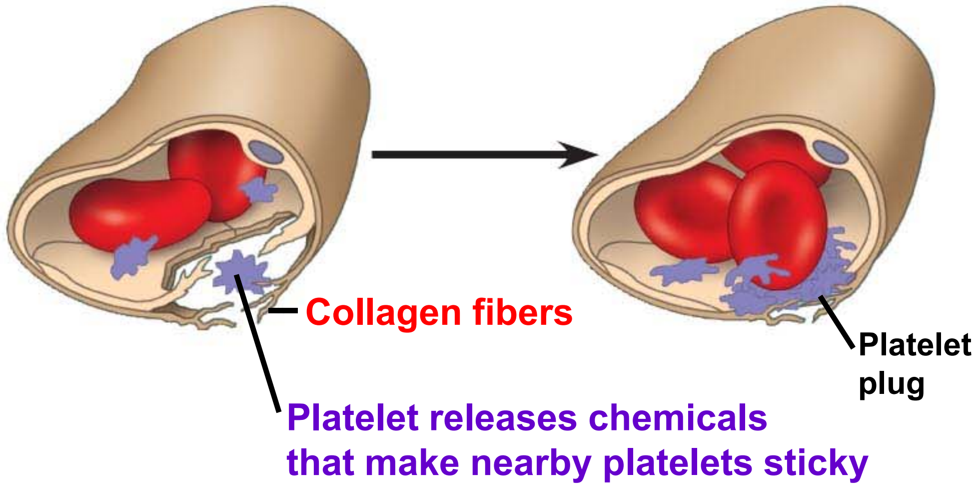
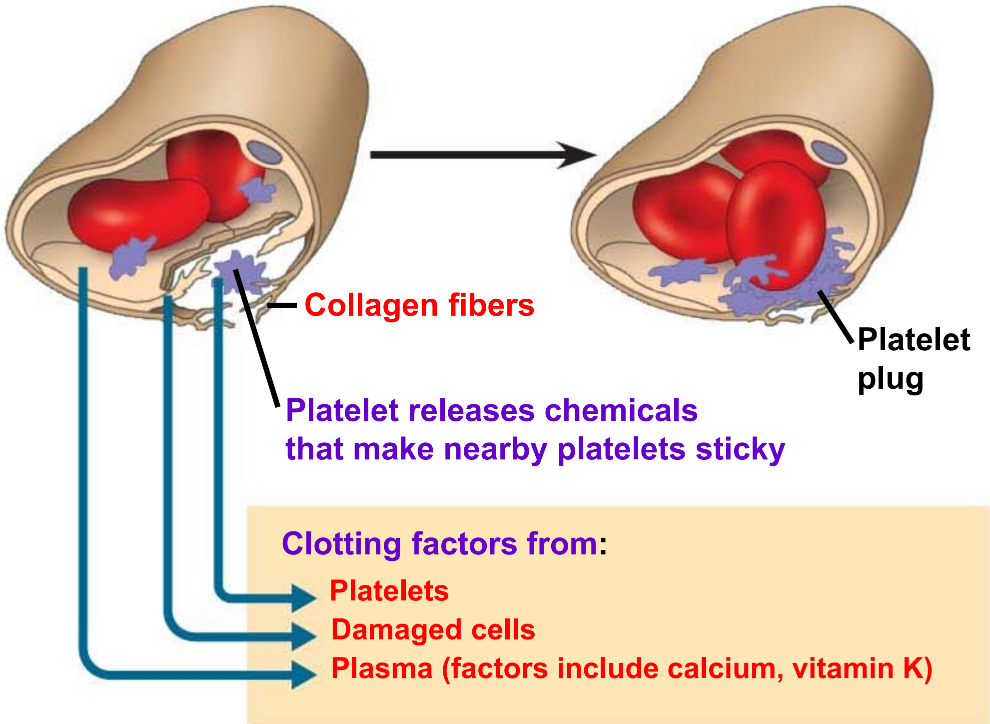

Collagen fibers
Platelet plug
Platelet releases chemicals
that make nearby platelets sticky

Fig. 42-18-2



Collagen fibers
Platelet plug
Platelet releases chemicals
that make nearby platelets sticky
Clotting factors from:
Platelets
Damaged cells
Plasma (factors include calcium, vitamin K)

Fig. 42-18-3

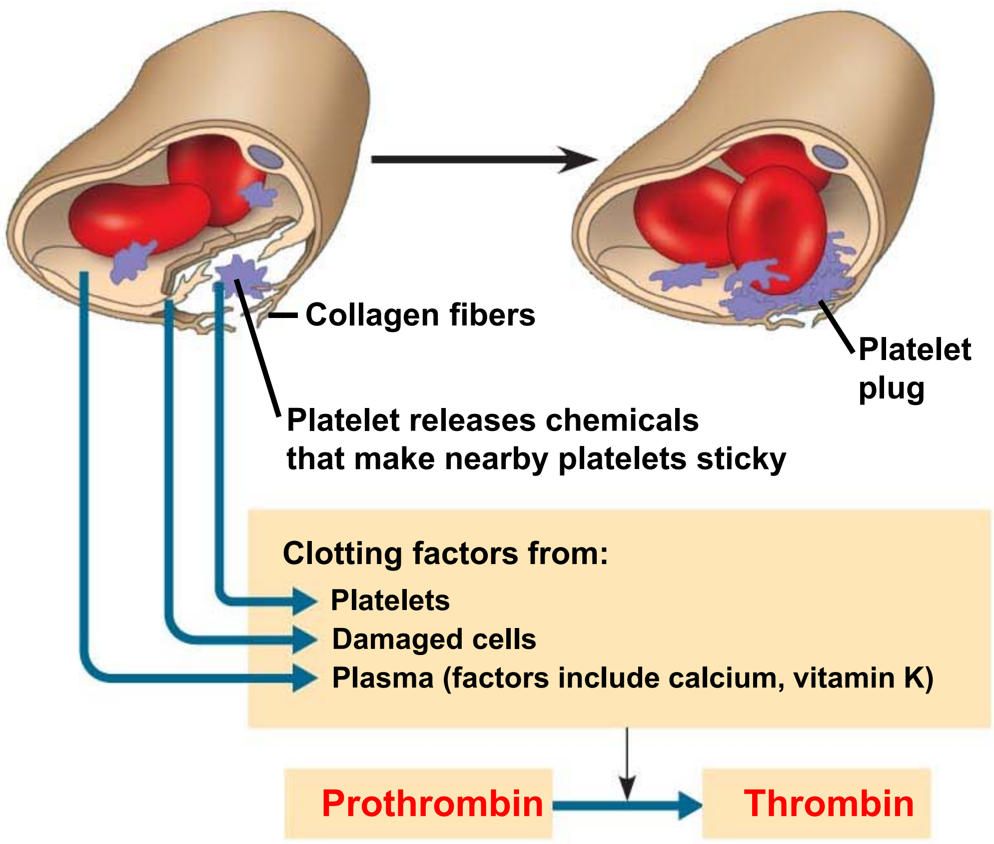
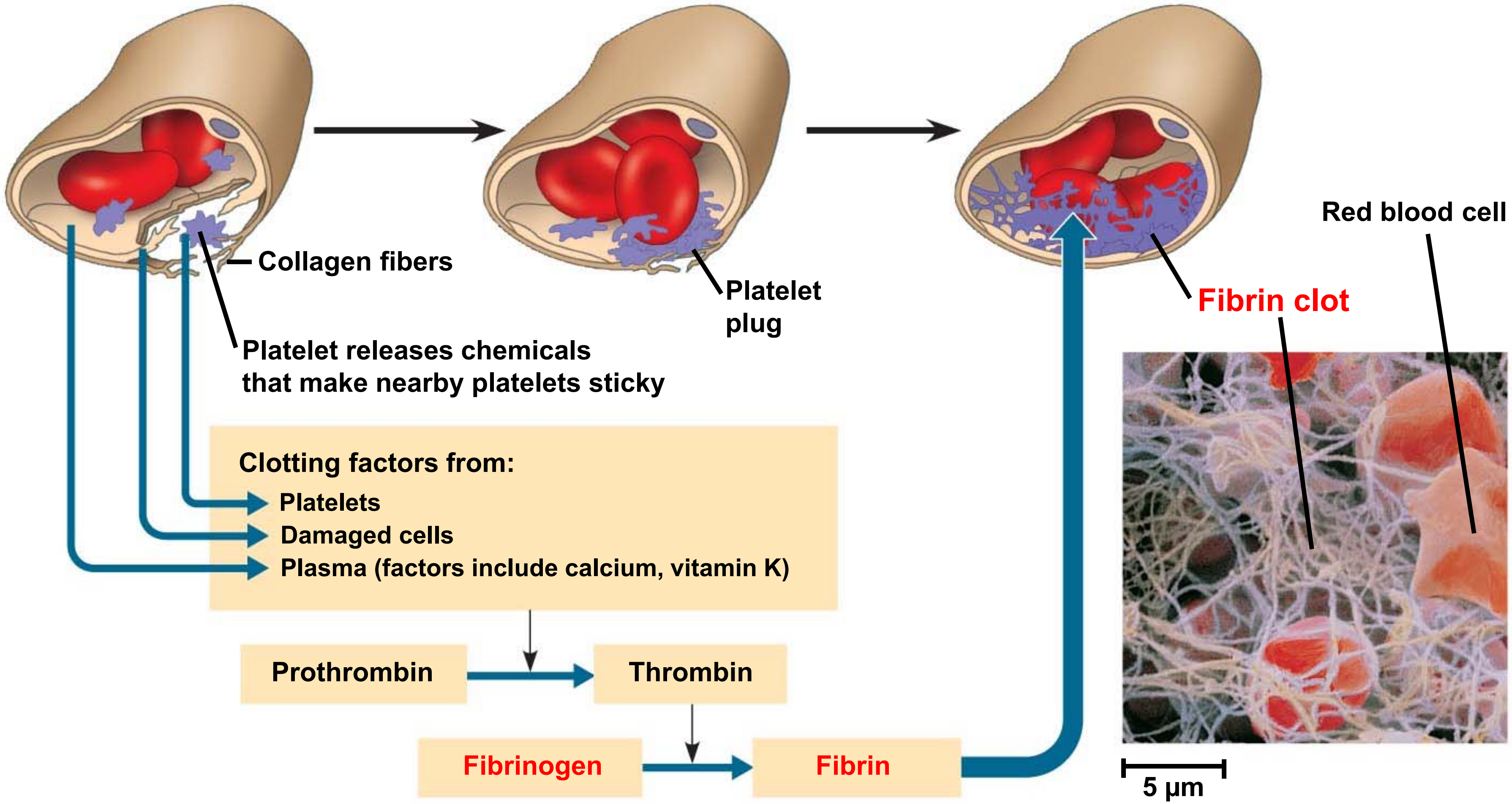

Collagen fibers
Platelet plug
Platelet releases chemicals that make nearby platelets sticky
Clotting factors from:
Platelets
Damaged cells
Plasma (factors include calcium, vitamin K)
Prothrombin
Thrombin

Fig. 42-18-4

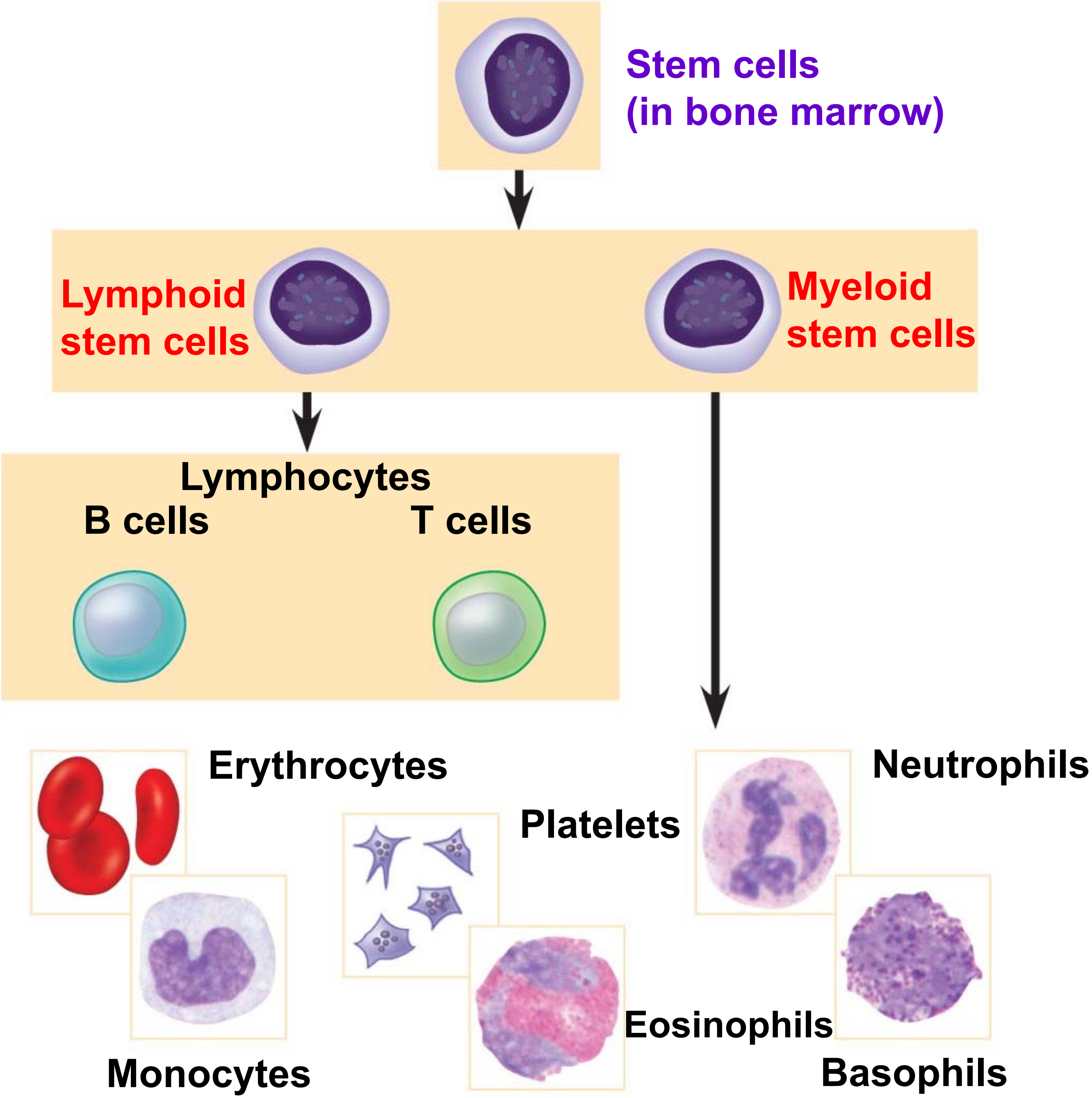


Collagen fibers
Platelet plug
Fibrin clot
Red blood cell
Platelet releases chemicals that make nearby platelets sticky
Clotting factors from:
Platelets
Damaged cells
Plasma (factors include calcium, vitamin K)
Prothrombin
Thrombin
Fibrinogen
Fibrin
5 μm

Stem Cells and the Replacement of Cellular Elements

- The cellular elements of blood wear out and are replaced constantly throughout a person's life
- Erythrocytes, leukocytes, and platelets all develop from a common source of **stem cells** in the red marrow of bones
- The hormone <u>hormone</u> **erythropoietin (EPO)** stimulates erythrocyte production when oxygen delivery is low

Fig. 42-19


Stem cells
(in bone marrow)
Lymphoid
stem cells
Myeloid
stem cells
Lymphocytes
B cells
T cells
Erythrocytes
Neutrophils
Platelets
Eosinophils
Monocytes
Basophils

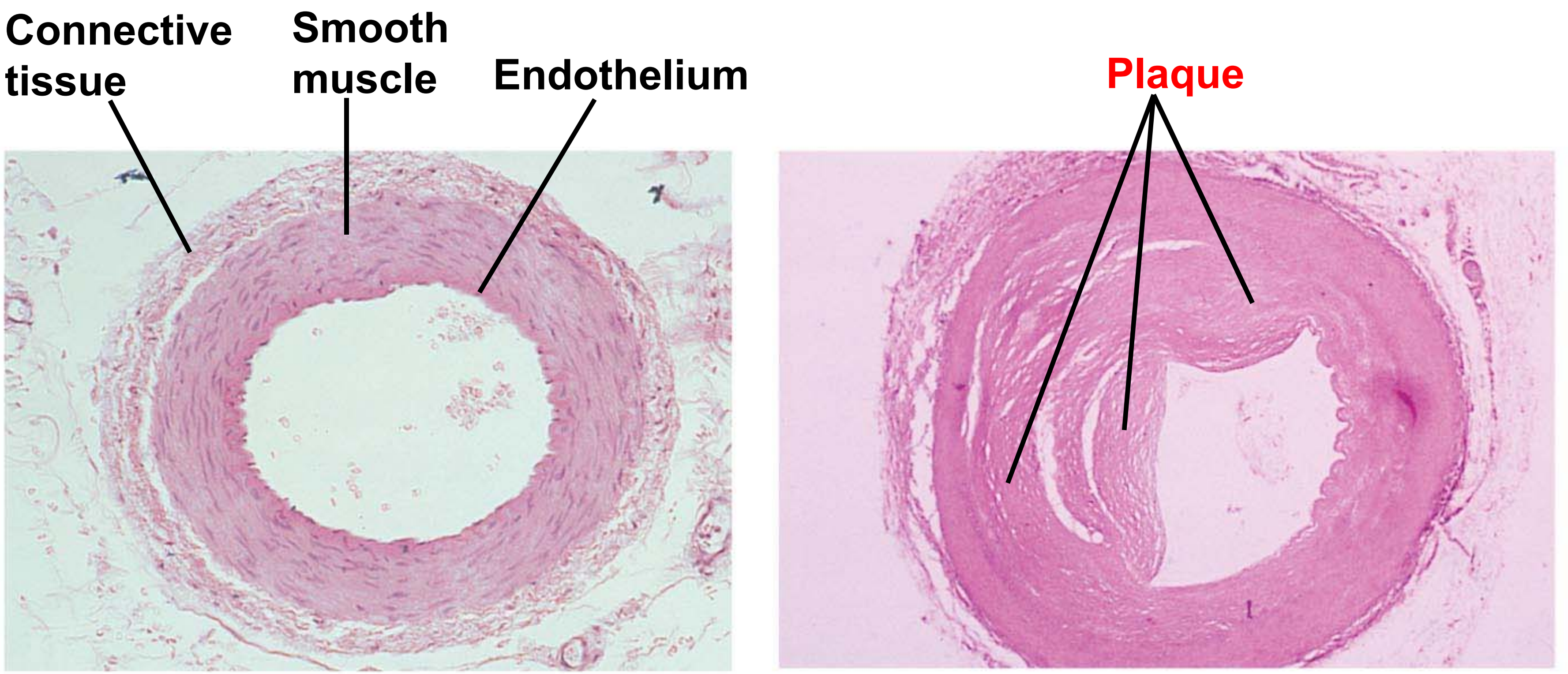
Cardiovascular Disease

- Cardiovascular diseases are disorders of the heart and the blood vessels
- They account for more than half the deaths in the United States

Atherosclerosis

- One type of cardiovascular disease, **atherosclerosis**, is caused by the buildup of plaque deposits within arteries

Fig. 42-20



(a) Normal artery 50 µm

(b) Partly clogged artery 250 µm

Heart Attacks and Stroke

- A **heart attack** is the **death of cardiac muscle** tissue resulting from blockage of one or more coronary arteries
- A **stroke** is the death of nervous tissue in the **brain**, usually resulting from **rupture or blockage of arteries in the head**

Treatment and Diagnosis of Cardiovascular Diseases

- **Cholesterol** is a major contributor to **atherosclerosis**
- **Low-density lipoproteins (LDLs)** are associated with plaque formation; these are "bad cholesterol"
- **High-density lipoproteins (HDLs)** reduce the deposition of cholesterol; these are "good cholesterol"
- The proportion of LDL relative to HDL can be decreased by exercise, not smoking, and avoiding foods with *trans* fats

- **Hypertension**, or high blood pressure, promotes atherosclerosis and increases the risk of heart attack and stroke
- Hypertension can be reduced by dietary changes, exercise, and/or medication

Concept 42.5: Gas exchange occurs across specialized respiratory surfaces

- **Gas exchange** supplies oxygen for cellular respiration and disposes of carbon dioxide

Partial Pressure Gradients in Gas Exchange

- Gases diffuse down pressure gradients in the lungs and other organs as a result of differences in partial pressure
- **Partial pressure** is the pressure exerted by a particular gas in a mixture of gases

- A gas diffuses from a region of higher partial pressure to a region of lower partial pressure
- In the lungs and tissues, O_2 and CO_2 diffuse from where their partial pressures are higher to where they are lower

Respiratory Media

- Animals can use air or water as a source of O_2, or respiratory medium
- In a given volume, there is less O_2 available in water than in air
- Obtaining O_2 from water requires greater efficiency than air breathing

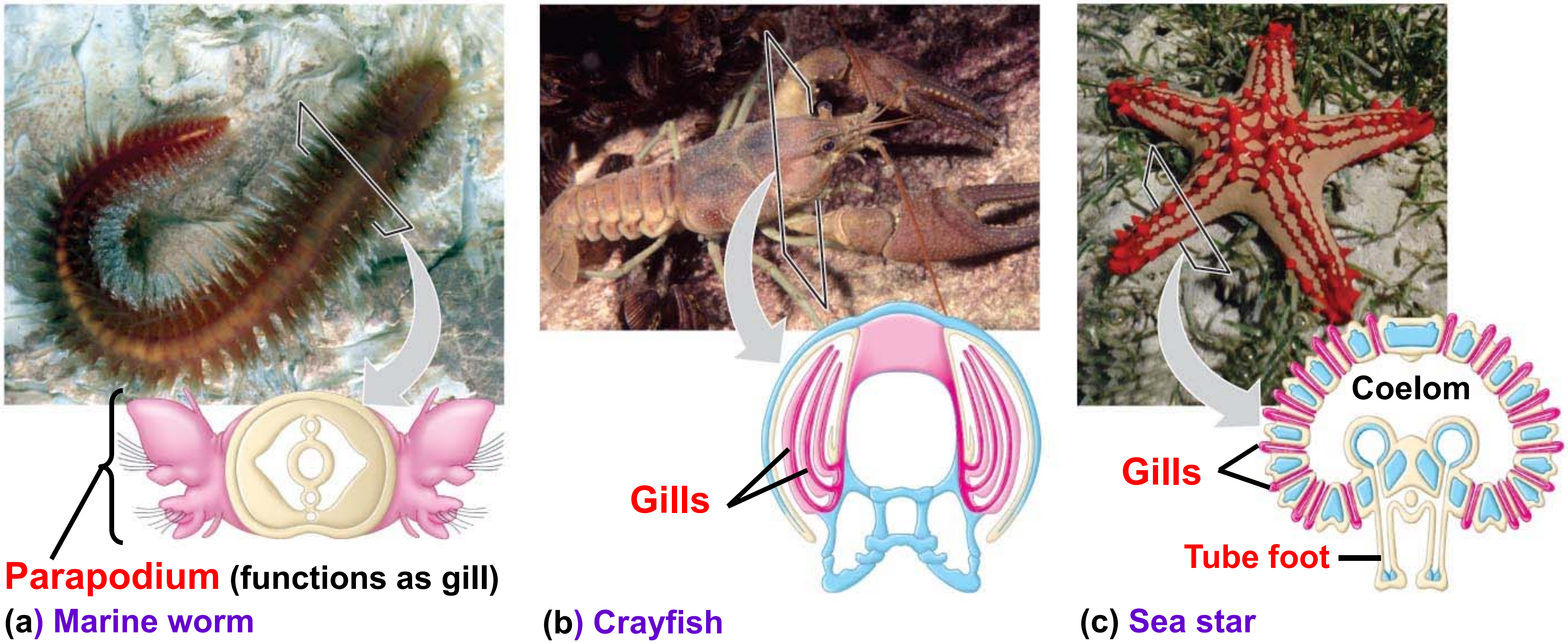
Respiratory Surfaces

- Animals require **large**, **moist respiratory** surfaces for exchange of gases between their cells and the respiratory medium, either air or water
- Gas exchange across respiratory surfaces takes place by diffusion
- Respiratory surfaces vary by animal and can include the outer surface, ***skin, gills, tracheae, and lungs***

Gills in Aquatic Animals

- Gills are *outfoldings of the body that create a large surface area for gas exchange*

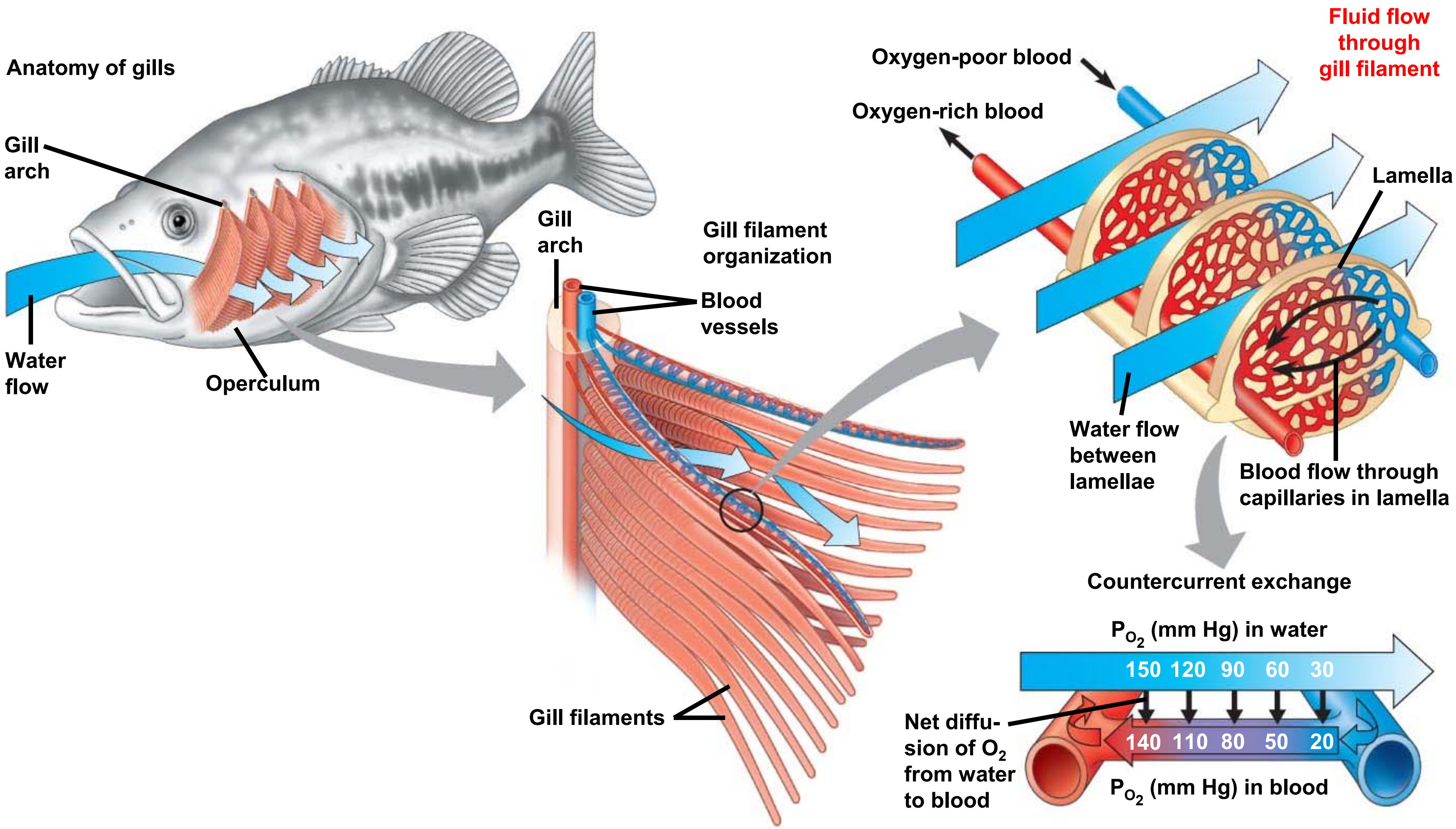
Fig. 42-21



Parapodium (functions as gill)
(a) Marine worm
Gills
(b) Crayfish
Coelom
Gills
Tube foot
(c) Sea star

- **Ventilation** moves the respiratory medium over the respiratory surface
- Aquatic animals move through water or move water over their gills for ventilation
- Fish gills use a **countercurrent exchange** system, where blood flows in the opposite direction to water passing over the gills; blood is always less saturated with O_2 than the water it meets

Fig. 42-22

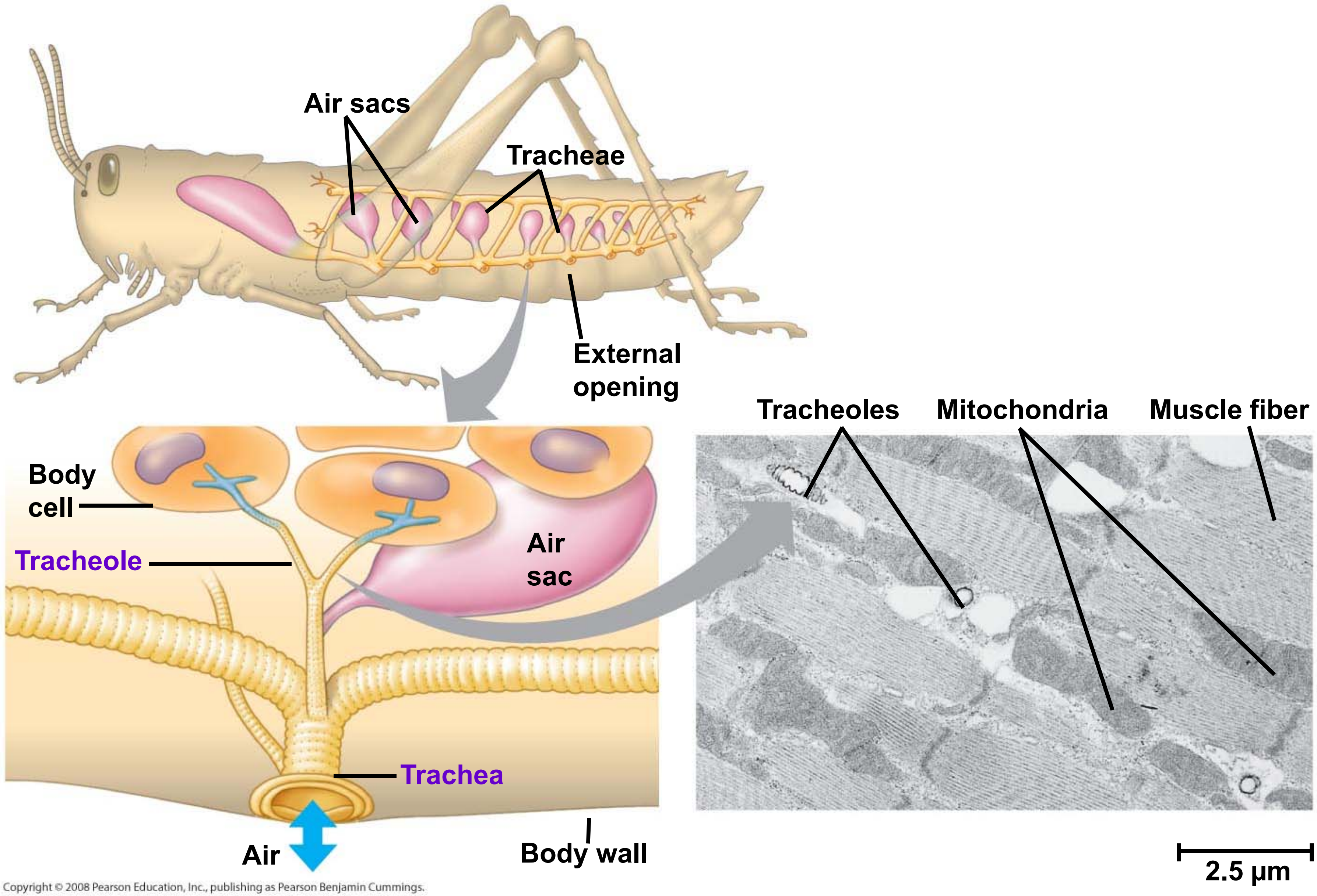


Anatomy of gills
Gill arch
Water flow
Operculum
Gill arch
Gill filament organization
Blood vessels
Gill filaments
Oxygen-poor blood
Oxygen-rich blood
Fluid flow through gill filament
Lamella
Water flow between lamellae
Blood flow through capillaries in lamella
Countercurrent exchange
P_{O_2} (mm Hg) in water
150 120 90 60 30
Net diffusion of O_2 from water to blood
140 110 80 50 20
P_{O_2} (mm Hg) in blood

Tracheal Systems in Insects

- The **tracheal system** of insects consists of tiny branching tubes that penetrate the body
- The tracheal tubes supply O_2 directly to body cells
- The respiratory and circulatory systems are separate
- Larger insects must ventilate their tracheal system to meet O_2 demands

Fig. 42-23


Air sacs
Tracheae
External opening
Body cell
Tracheole
Air sac
Trachea
Air
Body wall
Tracheoles
Mitochondria
Muscle fiber
2.5 μm

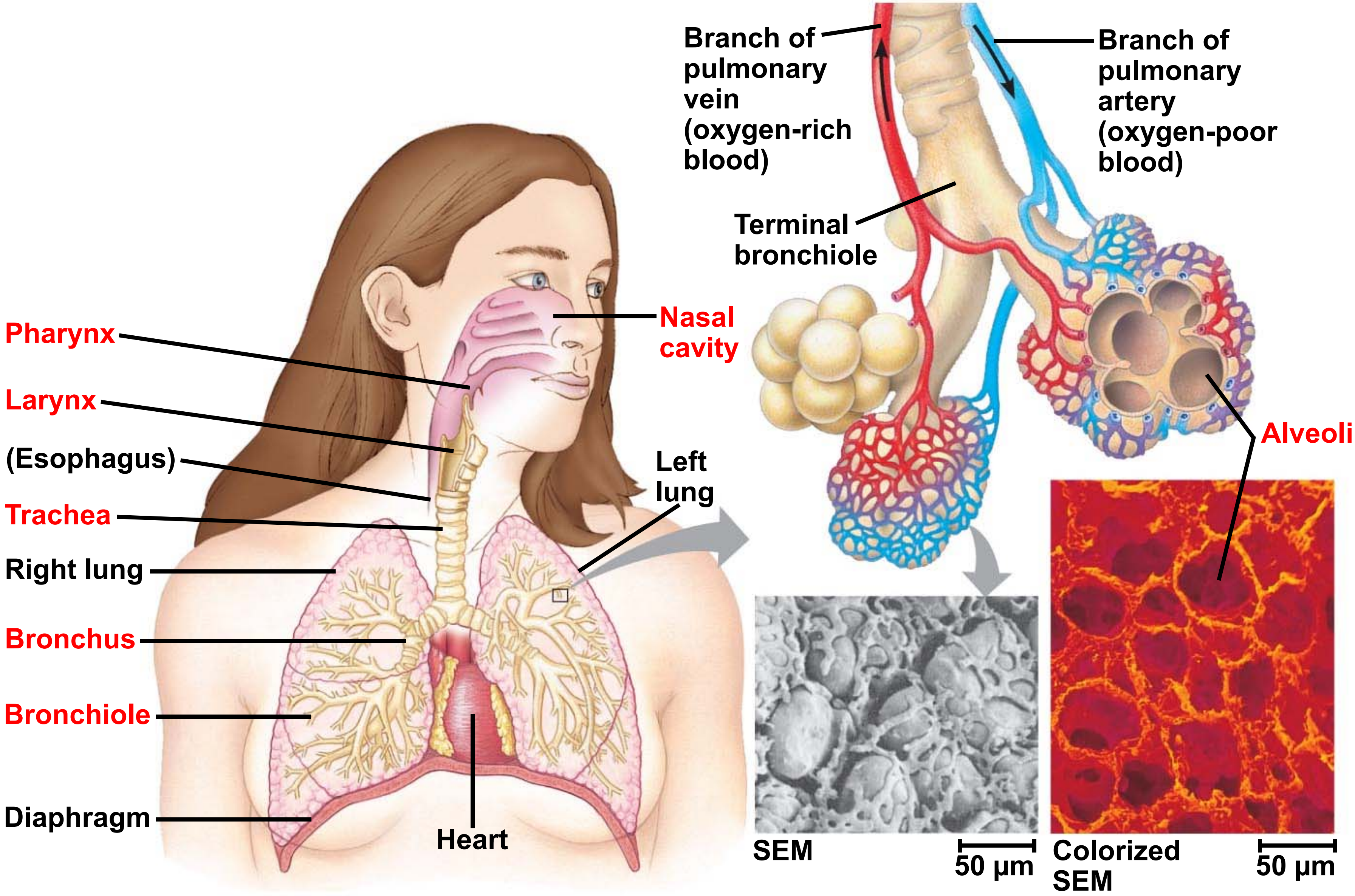
Lungs

- **Lungs** are an infolding of the body surface
- The circulatory system (open or closed) transports gases between the lungs and the rest of the body
- The size and complexity of lungs correlate with an animal's metabolic rate

Mammalian Respiratory Systems: A Closer Look

- A system of branching ducts conveys air to the lungs
- Air inhaled through the nostrils passes through the pharynx via the **larynx**, **trachea**, **bronchi**, **bronchioles**, and **alveoli**, where gas exchange occurs
- Exhaled air passes over the **vocal cords** to create sounds
- Secretions called **surfactants** coat the surface of the alveoli

Fig. 42-24



Pharynx
Larynx
(Esophagus)
Trachea
Right lung
Bronchus
Bronchiole
Diaphragm
Heart
Nasal cavity
Left lung
Branch of pulmonary vein (oxygen-rich blood)
Branch of pulmonary artery (oxygen-poor blood)
Terminal bronchiole
Alveoli
SEM
50 µm
Colorized SEM
50 µm

Concept 42.6: Breathing ventilates the lungs

- The process that ventilates the lungs is **breathing**, the alternate inhalation and exhalation of air

How an Amphibian Breathes

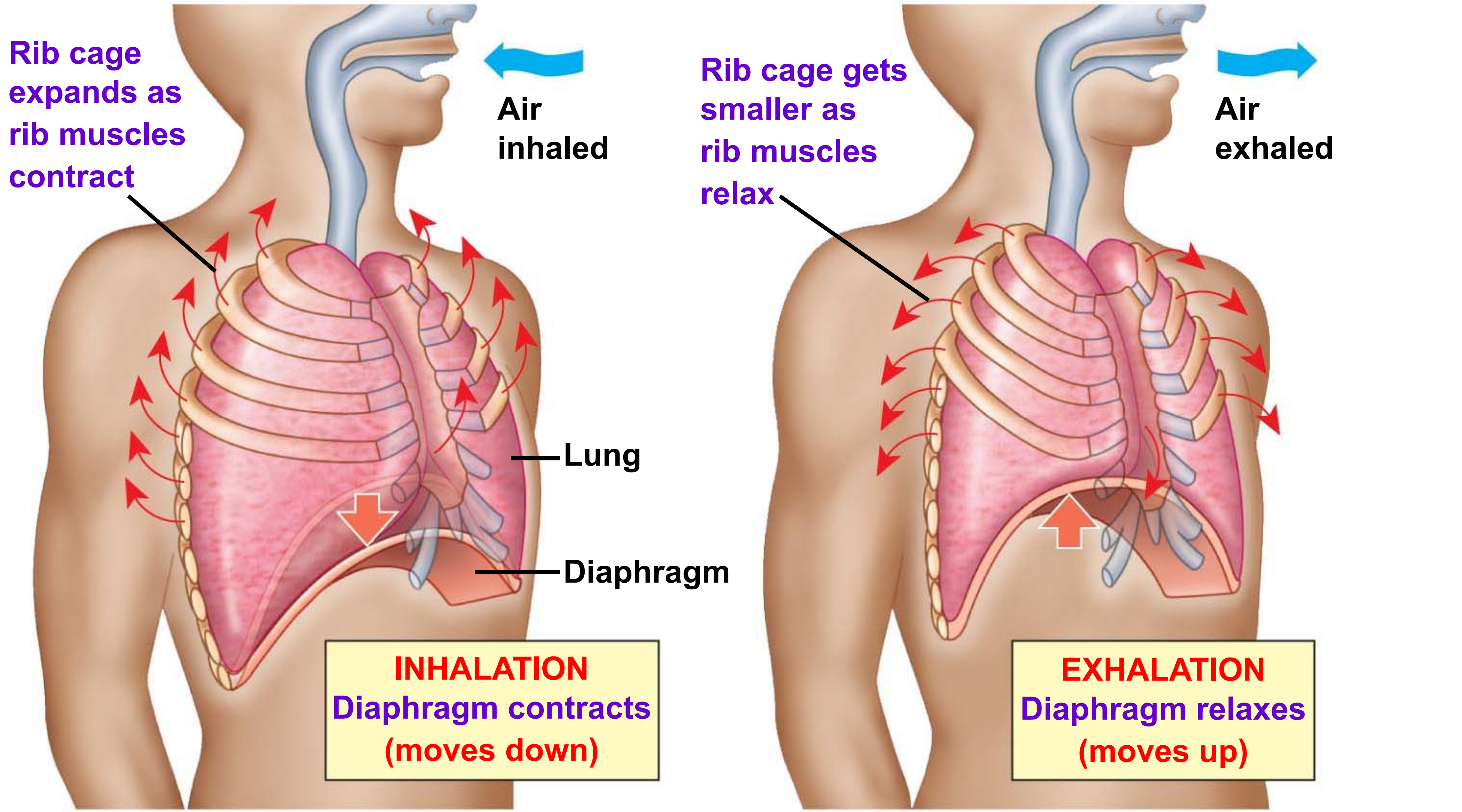
- An amphibian such as a frog ventilates its lungs by **positive pressure breathing**, which forces air down the trachea

How a Mammal Breathes

- Mammals ventilate their lungs by **negative pressure breathing**, which pulls air into the lungs
- **Lung volume increases** as the **rib muscles and diaphragm contract**
- The **tidal volume** *is the volume of air inhaled with each breath*

- The maximum tidal volume is the **vital capacity**
- After exhalation, a **residual volume** of air remains in the lungs

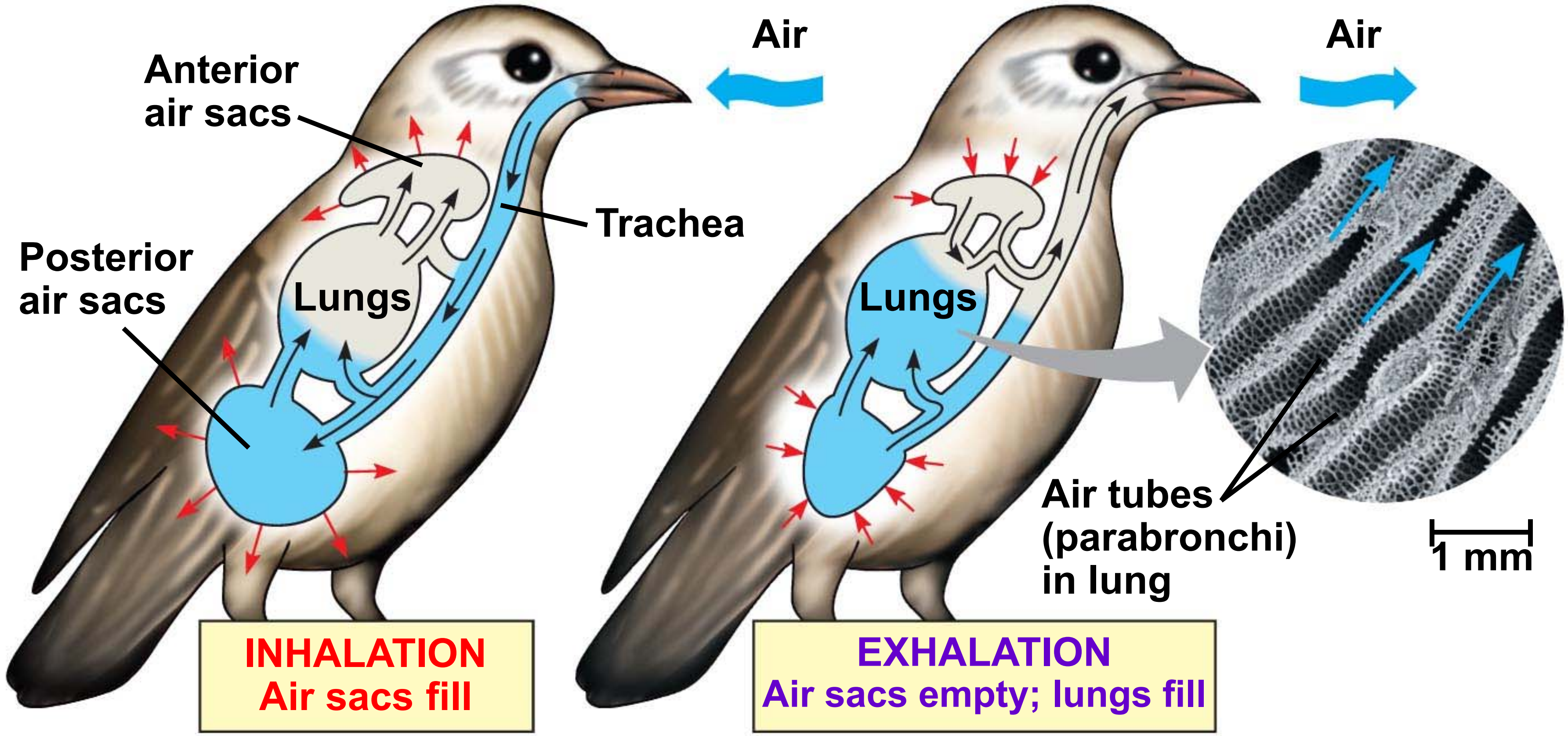
Fig. 42-25


Rib cage expands as rib muscles contract
Air inhaled
Lung
Diaphragm
INHALATION
Diaphragm contracts
(moves down)
Rib cage gets smaller as rib muscles relax
Air exhaled
EXHALATION
Diaphragm relaxes
(moves up)

How a Bird Breathes

- Birds have eight or nine air sacs that function as bellows that keep air flowing through the lungs
- Air passes through the lungs in one direction only
- Every exhalation completely renews the air in the lungs

Fig. 42-26



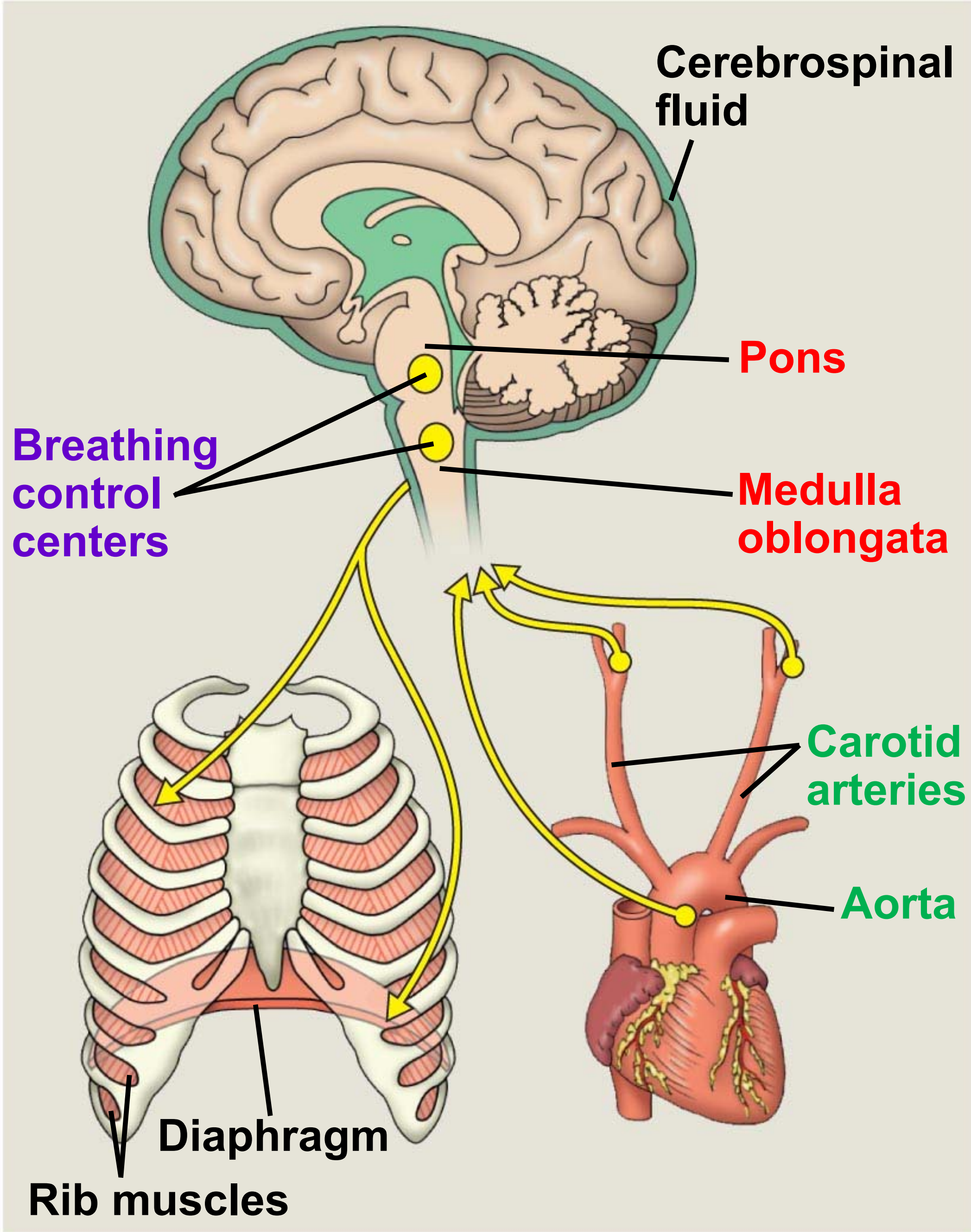
Anterior air sacs
Posterior air sacs
Lungs
Trachea
Air
INHALATION
Air sacs fill
Air
Lungs
Air tubes (parabronchi) in lung
1 mm
EXHALATION
Air sacs empty; lungs fill

Control of Breathing in Humans

- In humans, the main **breathing control centers** are in two regions of the brain, the medulla oblongata and the pons
- The medulla regulates the **rate** and **depth** of breathing in response to pH changes in the cerebrospinal fluid
- The medulla adjusts breathing rate and depth to match metabolic demands
- The pons regulates the tempo

- Sensors in the aorta and carotid arteries monitor O_2 and CO_2 concentrations in the blood
- These sensors exert secondary control over breathing

Fig. 42-27


Cerebrospinal fluid
Pons
Breathing control centers
Medulla oblongata
Carotid arteries
Aorta
Diaphragm
Rib muscles

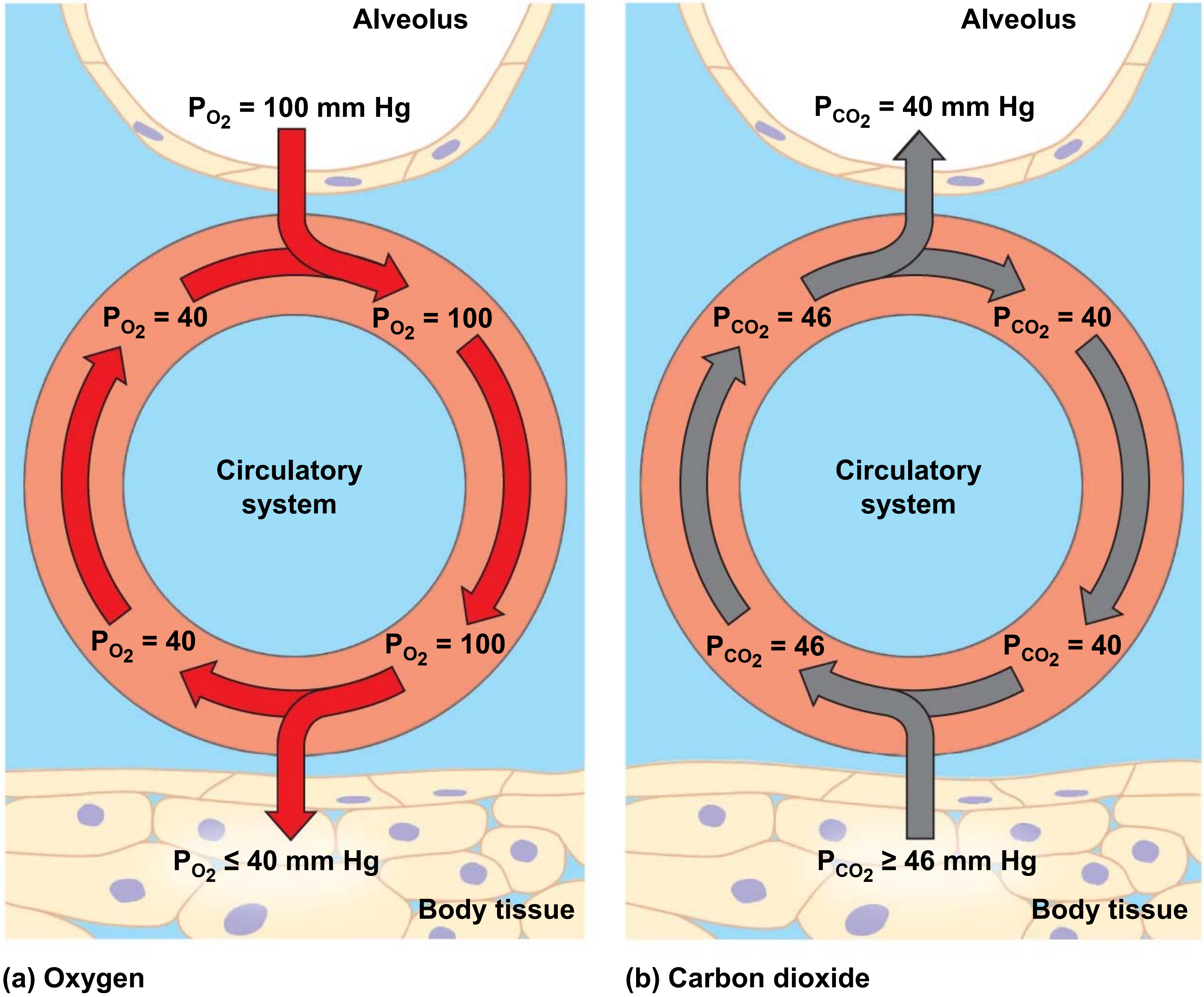
Concept 42.7: Adaptations for gas exchange include pigments that bind and transport gases

- The metabolic demands of many organisms require that the blood transport large quantities of O_2 and CO_2

Coordination of Circulation and Gas Exchange

- Blood arriving in the lungs has a low partial pressure of O_2 and a high partial pressure of CO_2 relative to air in the alveoli
- In the alveoli, O_2 diffuses into the blood and CO_2 diffuses into the air
- In tissue capillaries, partial pressure gradients favor diffusion of O_2 into the interstitial fluids and CO_2 into the blood

Fig. 42-28



Alveolus
P_{O_2} = 100 mm Hg
P_{O_2} = 40
P_{O_2} = 100
Circulatory system
P_{O_2} = 40
P_{O_2} = 100
P_{O_2} ≤ 40 mm Hg
Body tissue
(a) Oxygen
Alveolus
P_{CO_2} = 40 mm Hg
P_{CO_2} = 46
P_{CO_2} = 40
Circulatory system
P_{CO_2} = 46
P_{CO_2} = 40
P_{CO_2} ≥ 46 mm Hg
Body tissue
(b) Carbon dioxide

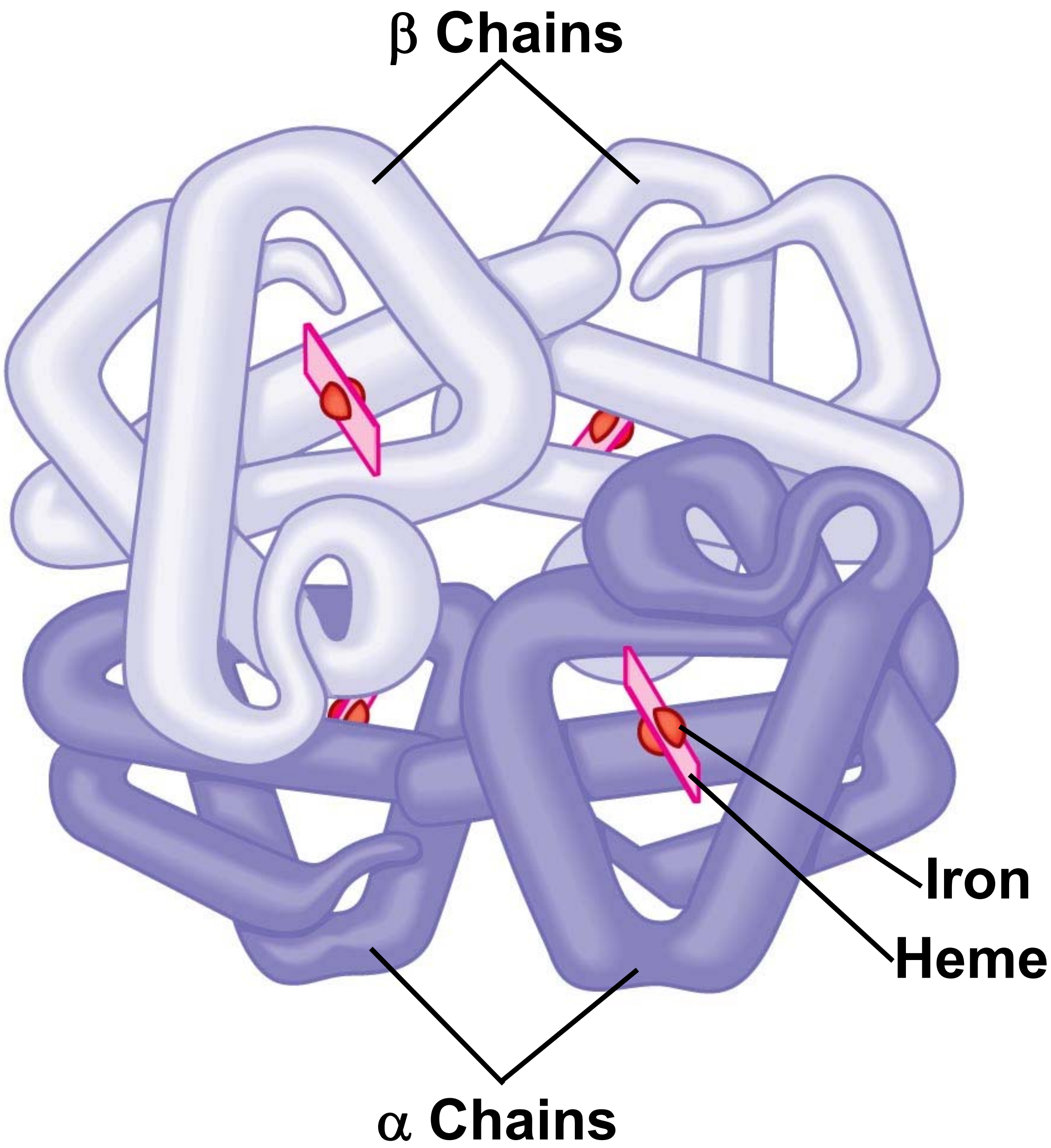
Respiratory Pigments

- **Respiratory pigments**, proteins that transport oxygen, greatly increase the amount of oxygen that blood can carry
- Arthropods and many molluscs have hemocyanin with copper as the oxygen-binding component
- Most vertebrates and some invertebrates use **hemoglobin** contained within erythrocytes

Hemoglobin

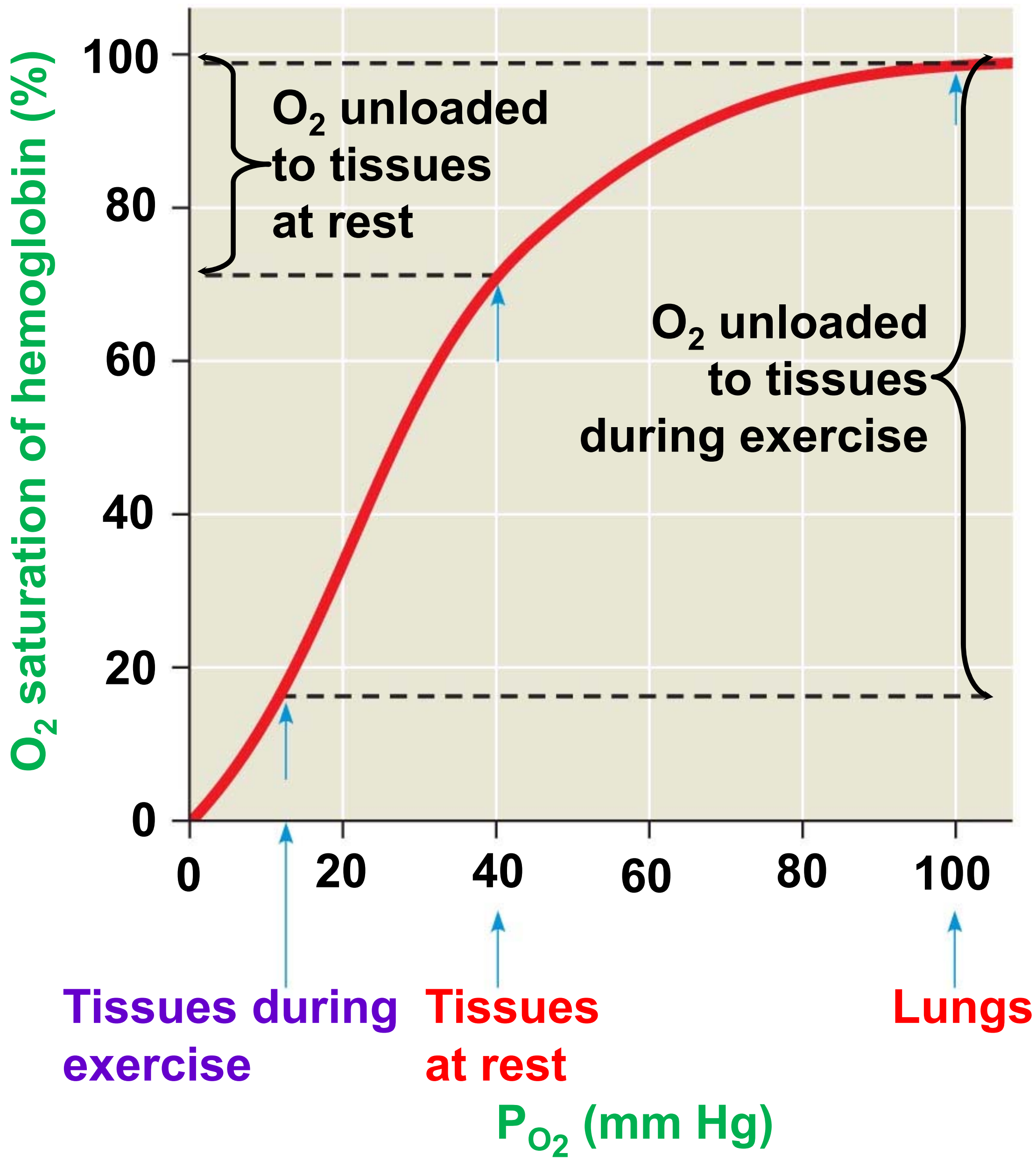
- A single hemoglobin molecule can **carry four molecules of O_2**
- The hemoglobin dissociation curve shows that a small change in the partial pressure of oxygen can result in a large change in delivery of O_2
- CO_2 produced during cellular respiration lowers blood pH and decreases the affinity of hemoglobin for O_2; this is called the **Bohr shift**

Fig. 42-UN1



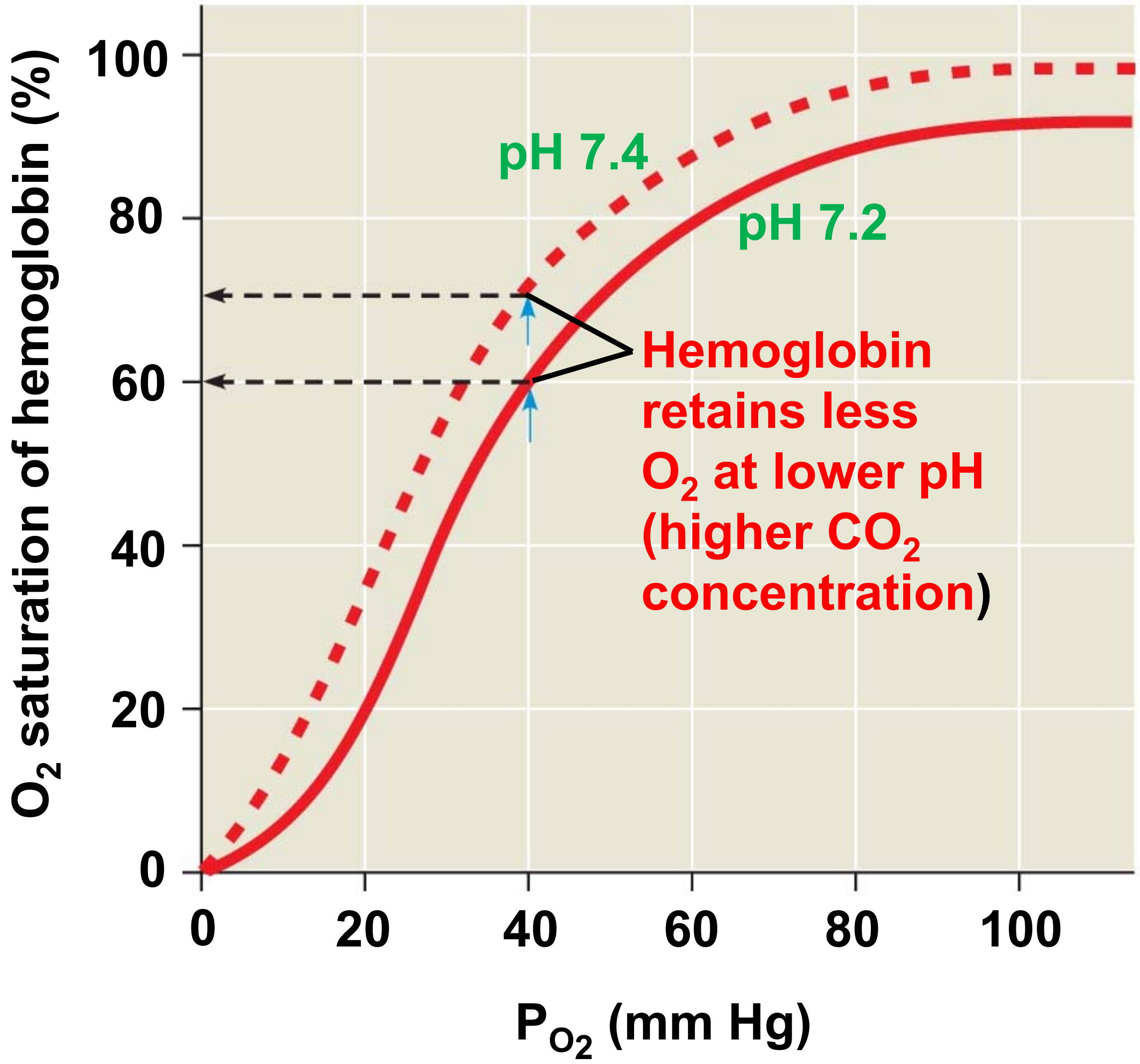
Hemoglobin

Fig. 42-29a



(a) P_{O_2} and hemoglobin dissociation at pH 7.4

Fig. 42-29b



(b) pH and hemoglobin dissociation

Carbon Dioxide Transport

- Hemoglobin also helps transport CO_2 and assists in buffering
- CO_2 from respiring cells diffuses into the blood and is transported either in blood plasma, bound to hemoglobin, or as bicarbonate ions (HCO_3^-)

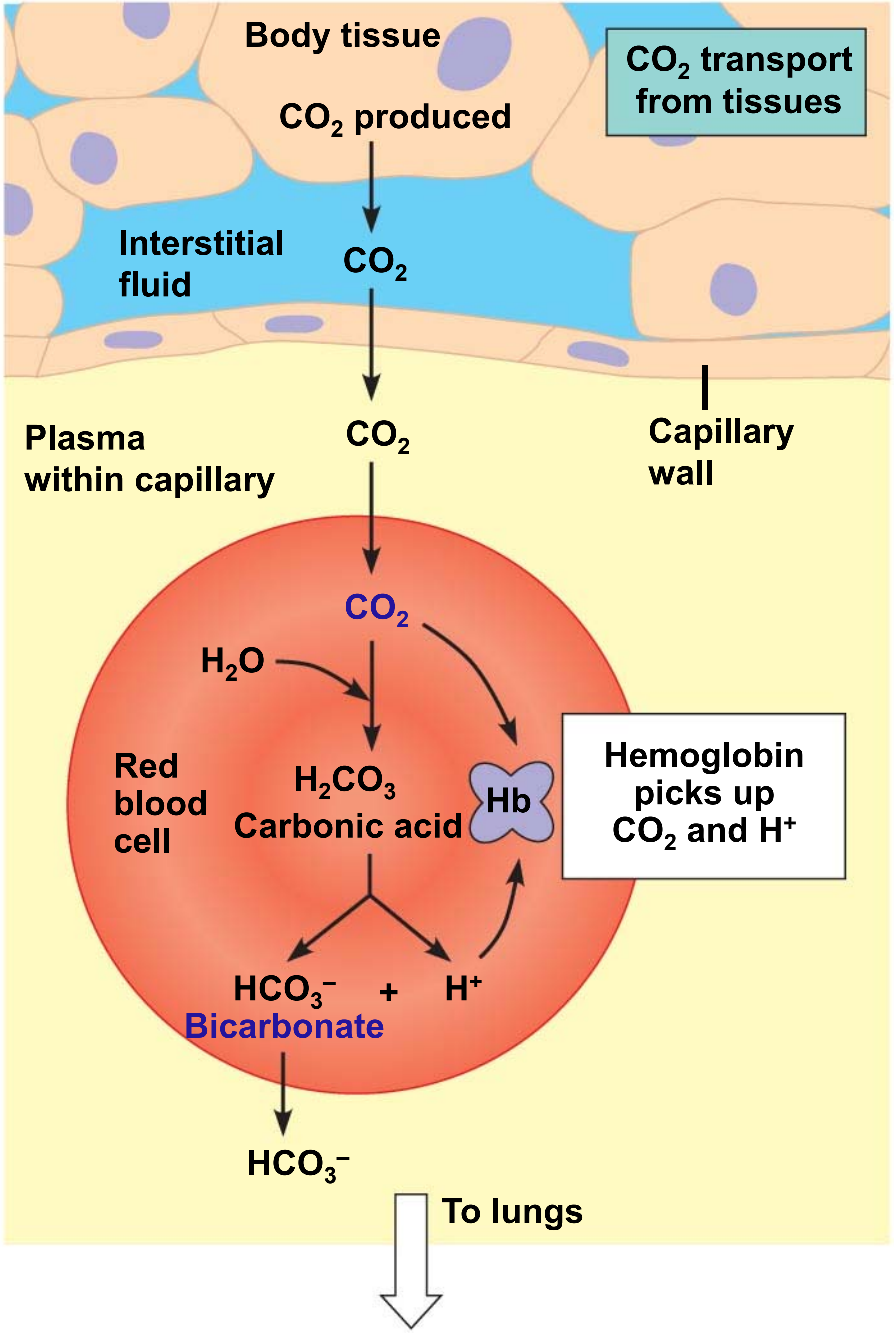
PLAY Animation: O_2 from Blood to Tissues

PLAY Animation: CO_2 from Tissues to Blood

PLAY Animation: CO_2 from Blood to Lungs

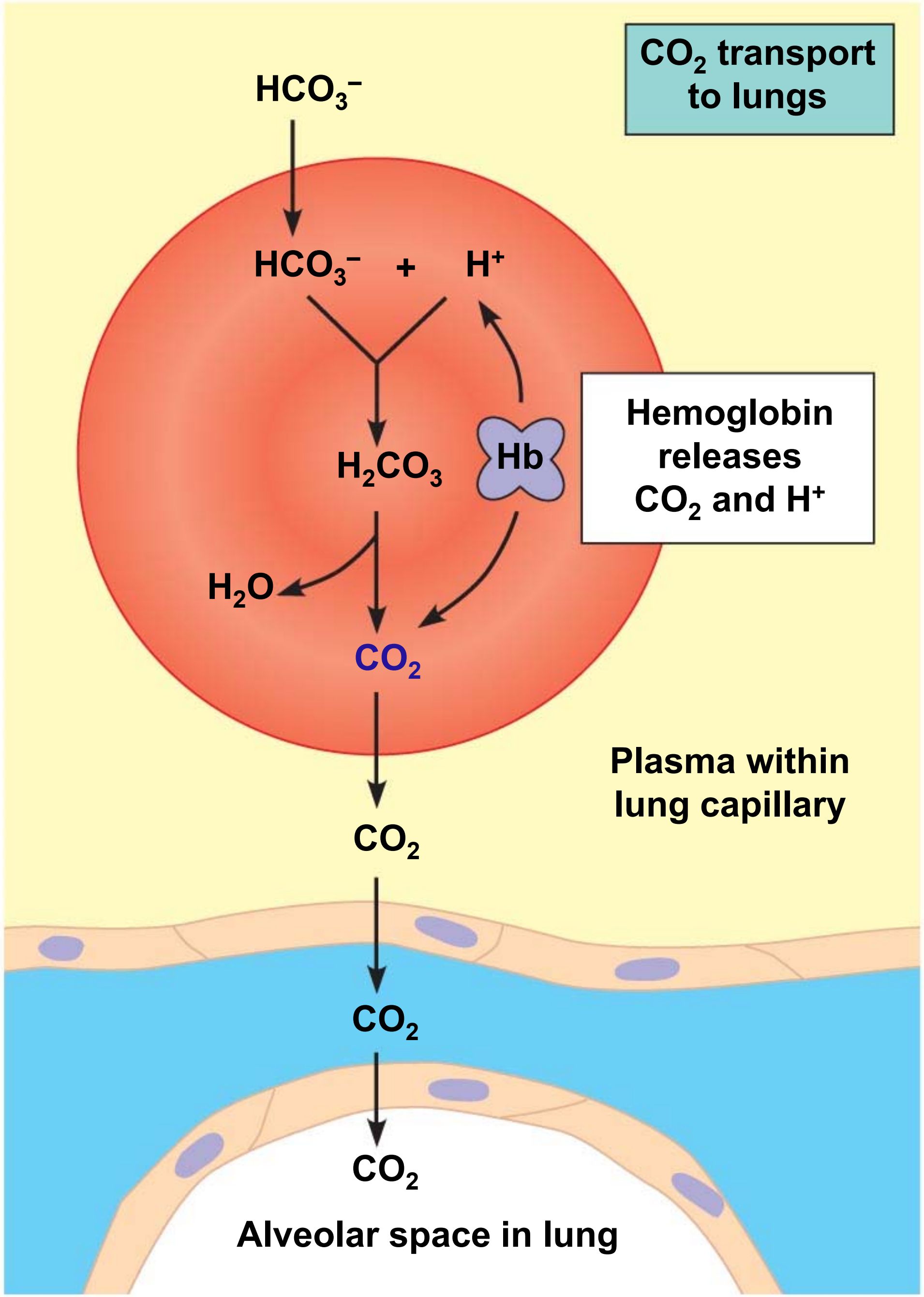
PLAY Animation: O_2 from Lungs to Blood

Fig. 42-30a



Body tissue
CO_2 transport from tissues
CO_2 produced
Interstitial fluid
CO_2
CO_2
Plasma within capillary
Capillary wall
CO_2
H_2O
Red blood cell
H_2CO_3
Carbonic acid
Hb
Hemoglobin picks up CO_2 and H^+
HCO_3^- + H^+
Bicarbonate
HCO_3^-
To lungs

Fig. 42-30b



CO_2 transport to lungs
HCO_3^-
HCO_3^- + H^+
H_2CO_3
Hb
Hemoglobin releases CO_2 and H^+
H_2O
CO_2
CO_2
Plasma within lung capillary
CO_2
CO_2
Alveolar space in lung