Chapter 4

The Energy of Life

Bicyclists: © Tyler Stableford/The Image Bank/Getty Images

Chapter 4 Outline

I. Energy, TheMetabolism
II. Networks of Chemical Reactions Sustain Life
III. Cellular Energy-ATP
IV. Enzymes
    I. Functions
    II. Regulations
V. Membrane Transport

All Cells Capture and Use Energy

Many of this biker's cells are extracting energy from food and using it to power his muscles.

All Cells Capture and Use Energy

But what is *energy*?

Energy is the ability to do work—to move matter.

Types of Energy:

Kinetic & Potential

Energy Has Different Forms

TABLE **4.1** **Examples of Energy in Biology**

Type of Energy	Examples
Potential energy 	Chemical energy (stored in bonds)
	Concentration gradient across a membrane
Kinetic energy 	Light
	Sound
	Movement of atoms and molecules
	Muscle contraction

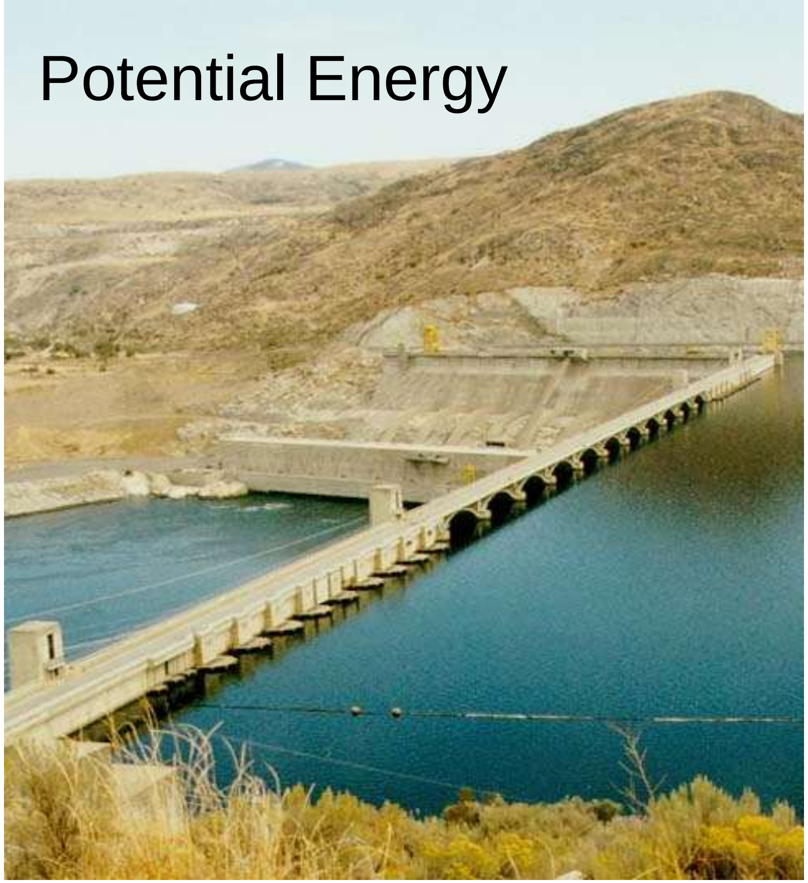
Section 4.1

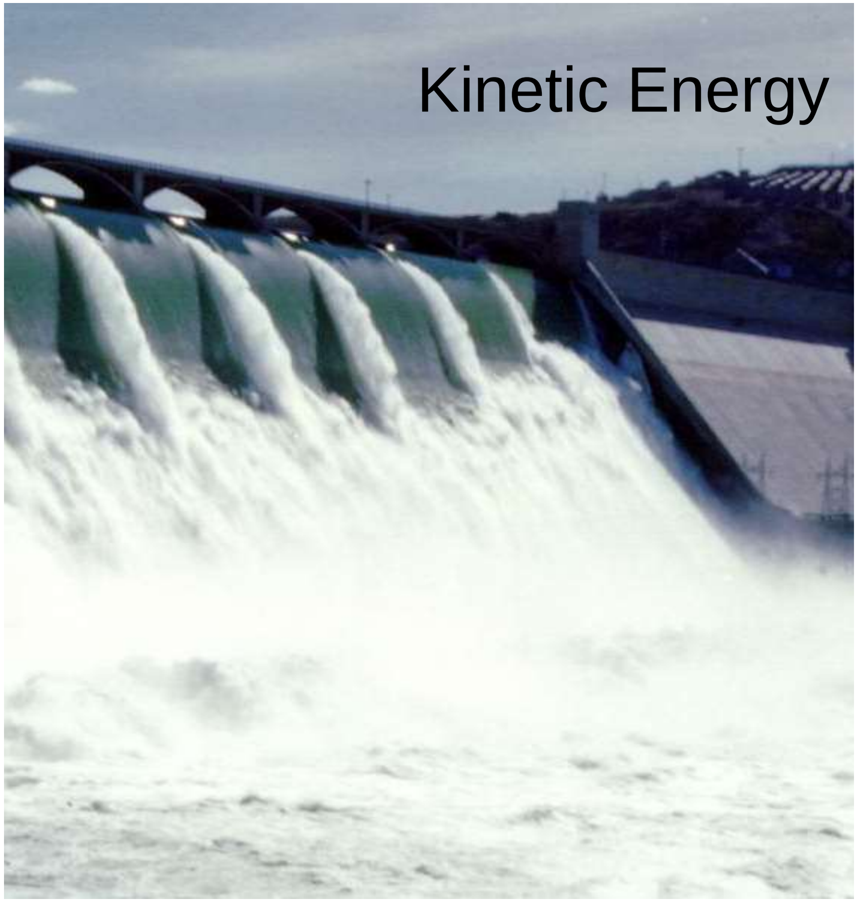
Figure 4.1

Thermodynamics

Thermodynamics – study of energy transformation in a system

Potential energy can be converted to kinetic energy (& vice versa)





Thermodynamics

Laws of Thermodynamics: Explain the characteristics of energy

1st Law:

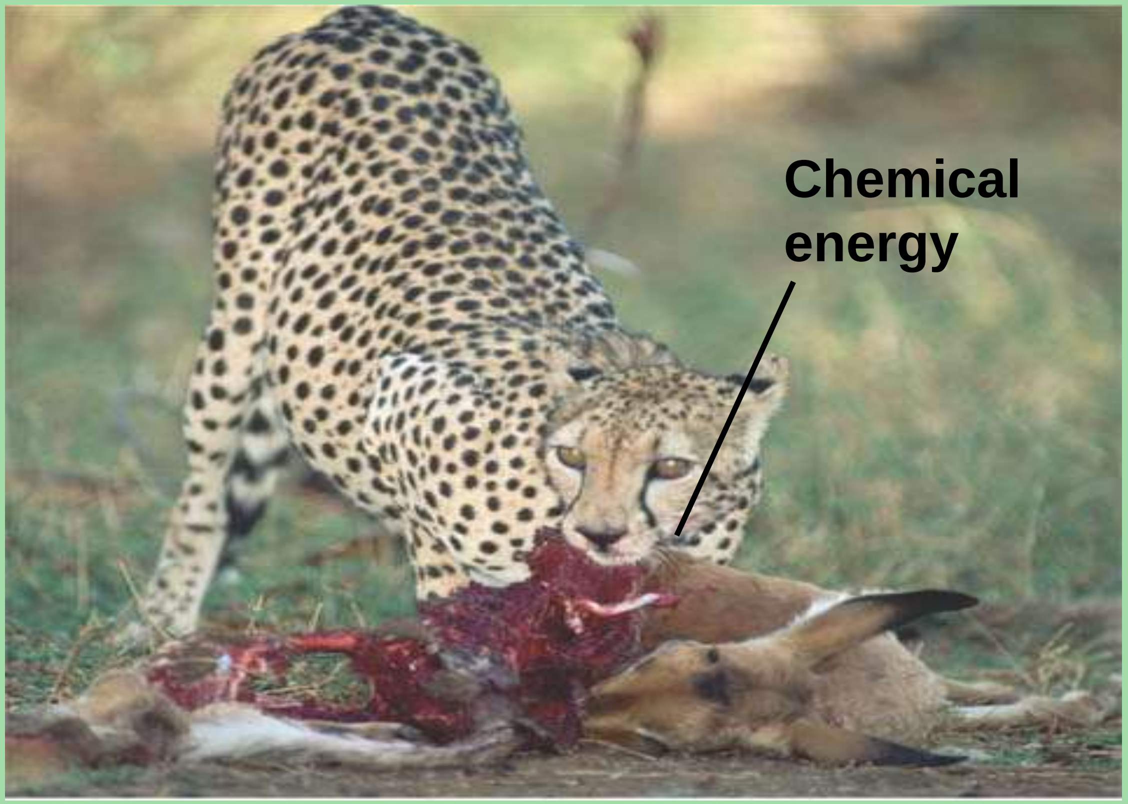
- Energy is conserved
  - Energy is not created or destroyed
  - Energy can be converted (Chemical $\rightarrow$ Heat)

2nd Law:

- During conversions, amount of useful energy decreases
  - No process is 100% efficient
  - Entropy (measure of disorder) is increased

Energy is converted from ***more useful*** to ***less useful*** forms

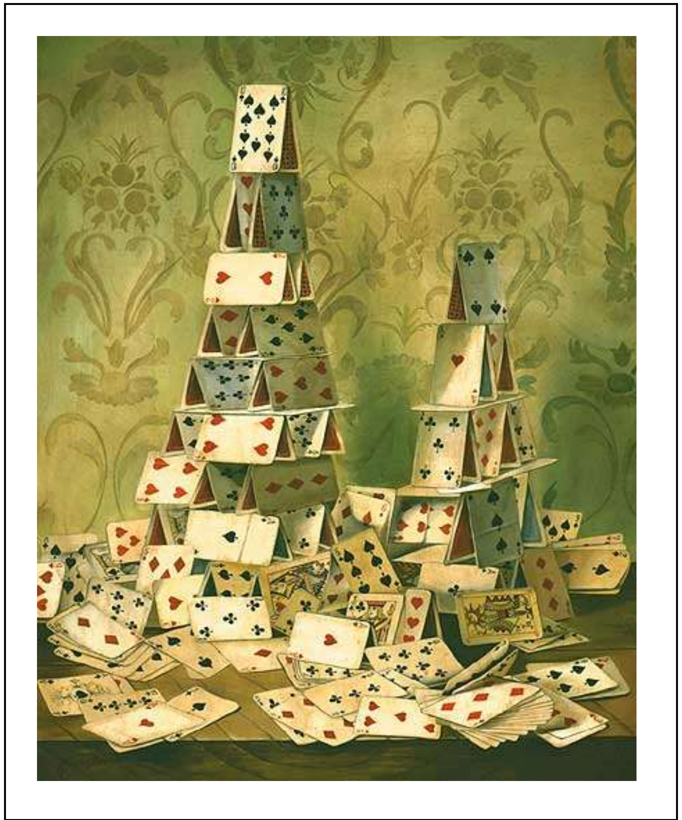
Ex. The First Law of Thermodynamics



For example, the chemical (potential) energy in food will be converted to the kinetic energy of the cheetah's movement

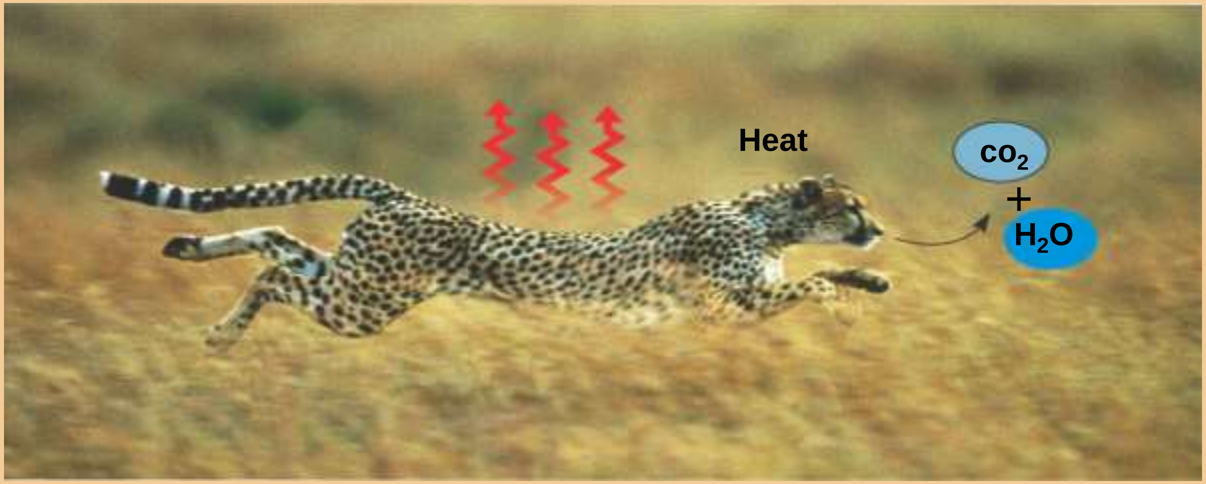
Second Law of Thermodynamics

- The disorder **(entropy)** in the universe is continuously increasing.
  - Energy transformations proceed spontaneously to convert matter from a more ordered, less stable form, to a less ordered, more stable form



Second Law of Thermodynamics

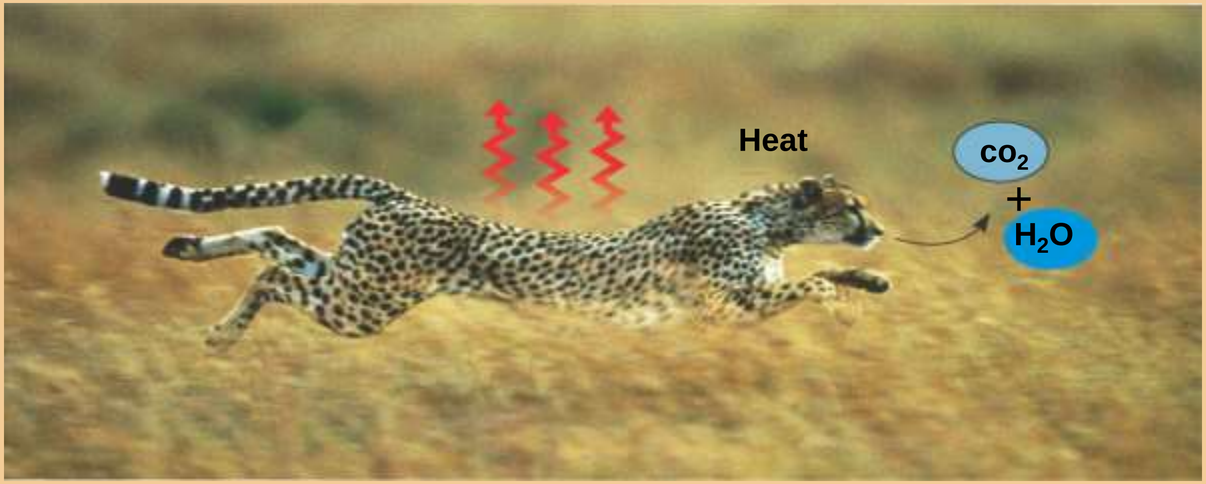
- During each conversion, some of the energy dissipates into the environment as heat.
- During every energy transfer or transformation, some energy is unusable, often lost as heat
- **Heat** is defined as the measure of the random motion of molecules



For example, disorder is added to the cheetah’ ssurroundings in the form of heat and the small molecules that are the by-products of metabolism.

Second Law of Thermodynamics

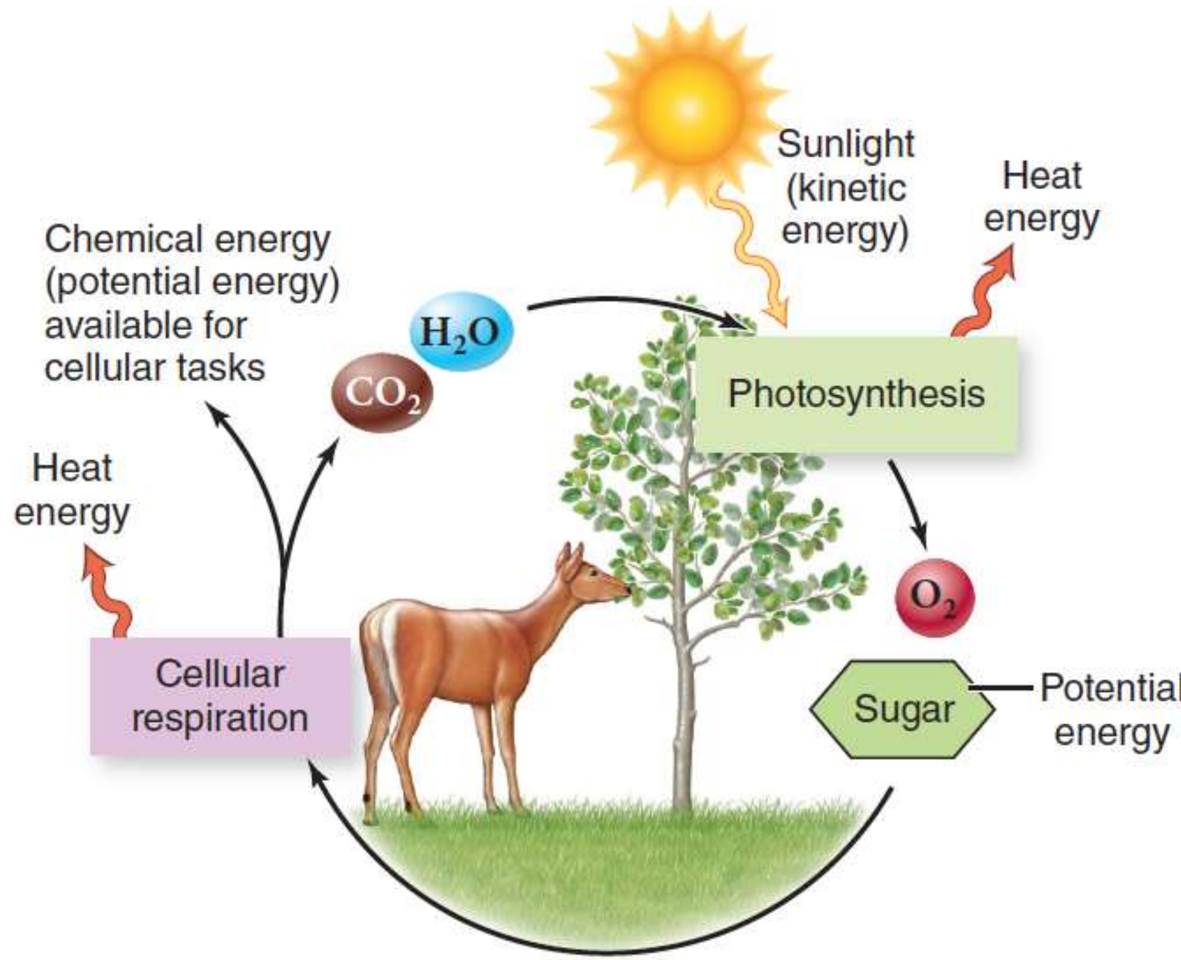
– Living cells unavoidably convert organized forms of energy to heat
– According to the second law of thermodynamics, every energy transfer or transformation increases the entropy (disorder) of the universe



For example, disorder is added to the cheetah's surroundings in the form of heat and the small molecules that are the by-products of metabolism.

Energy Transformations Are Inefficient

Notice that heat energy is lost at each step. Heat energy is disordered and cannot be converted back to a useful form of energy… **second law of thermodynamics**.



Section 4.1

Figure 4.2

Energy Transformations Are Inefficient

Entropy is a measure of the randomness, or disorder, of the universe.

Section 4.1 Light bulb photos: © Ryan McVay/Riser/Getty Images Figure 4.3

Energy Transformations Are Inefficient

Since heat energy is constantly being lost to the universe, and heat energy is disordered, the entropy of the universe is increasing. This is called the **second law of thermodynamics**.

Section 4.1

Light bulb photos: © Ryan McVay/Riser/Getty Images

Figure 4.3

Clicker Question #1

To the right, the same light bulb is shown at three different stages of falling (1, 2, and 3). Assume stage 2 is the moment *just before* impact, and stage 3 is just after impact. At what stage is potential energy the highest? At what stage is entropy the highest?

A. 2; 3
B. 1; 2
C. 3; 1
D. 3; 2
E. 1; 3

Clicker Question #1

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A. 2; 3
B. 1; 2
C. 3; 1
D. 3; 2
E. 1; 3

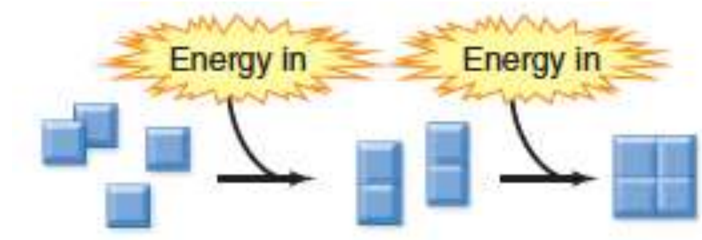
4.1 Mastering Concepts

Give an example of how your body has both potential and kinetic energy.

Chemical Reactions Sustain Life

Metabolism includes all chemical reactions in cells, including those that build new molecules and those that break down existing molecules.

Building complex molecules out of simple parts



Breaking complex molecules into simple parts

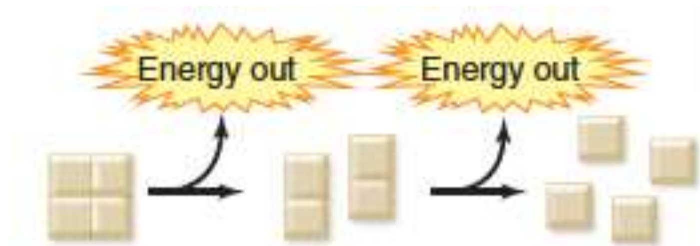


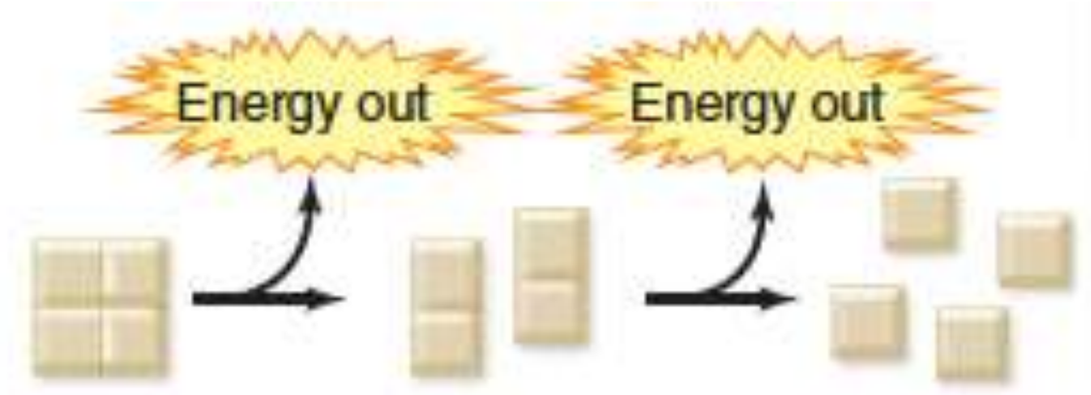
Figure 4.4

Metabolism

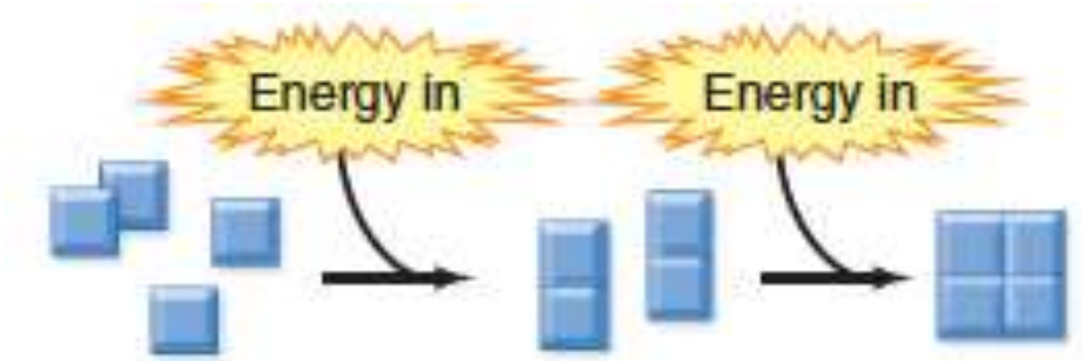
Metabolic reactions:

- Chemical reactions in organism

Two Types of *Metabolic* Reactions:



Catabolic = breaks down molecules



Anabolic = builds up molecules

Chemical Reactions Sustain Life

Chemical reactions can also be classified according energy requirements.

Endergonic- require energy
Exergonic- release energy

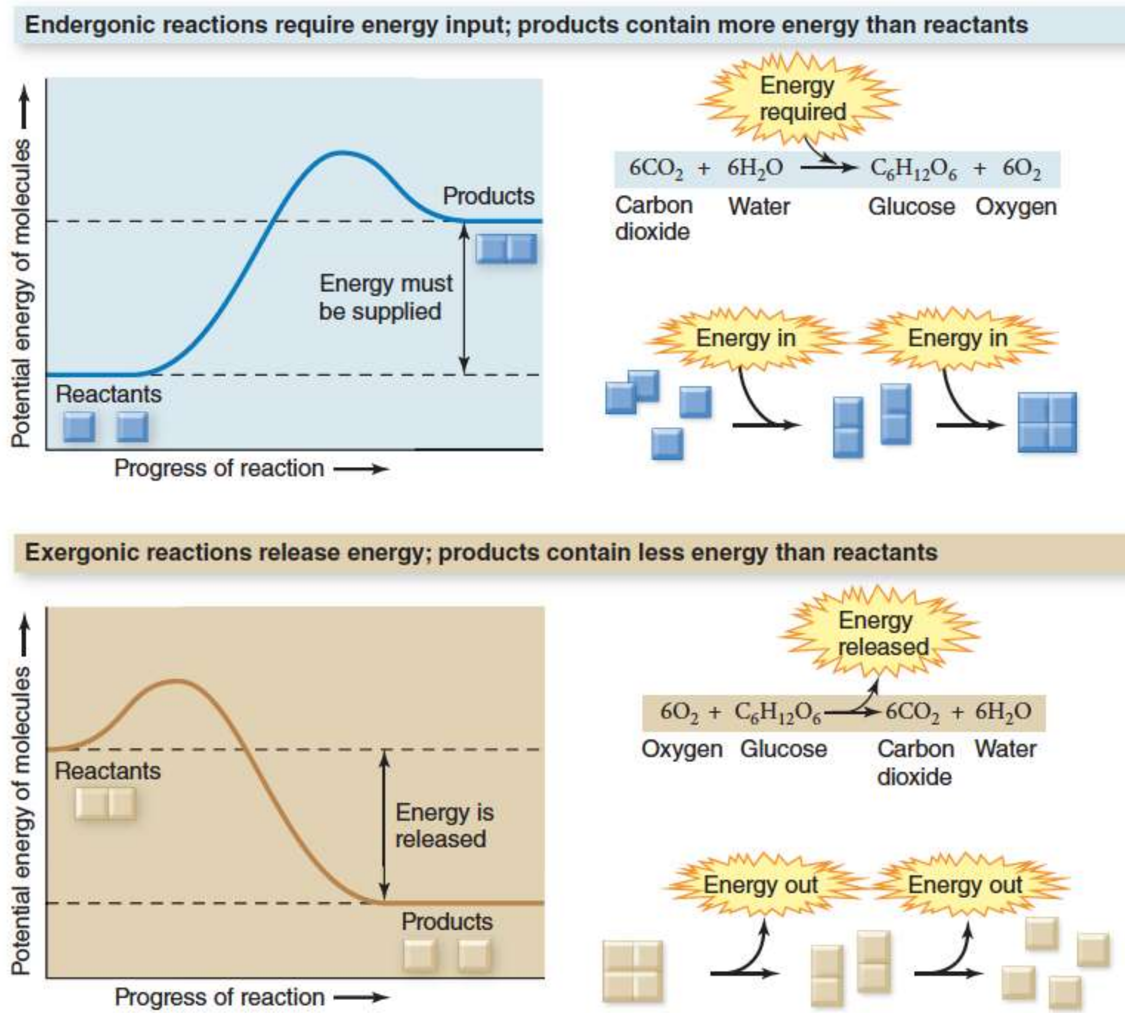


Figure 4.4

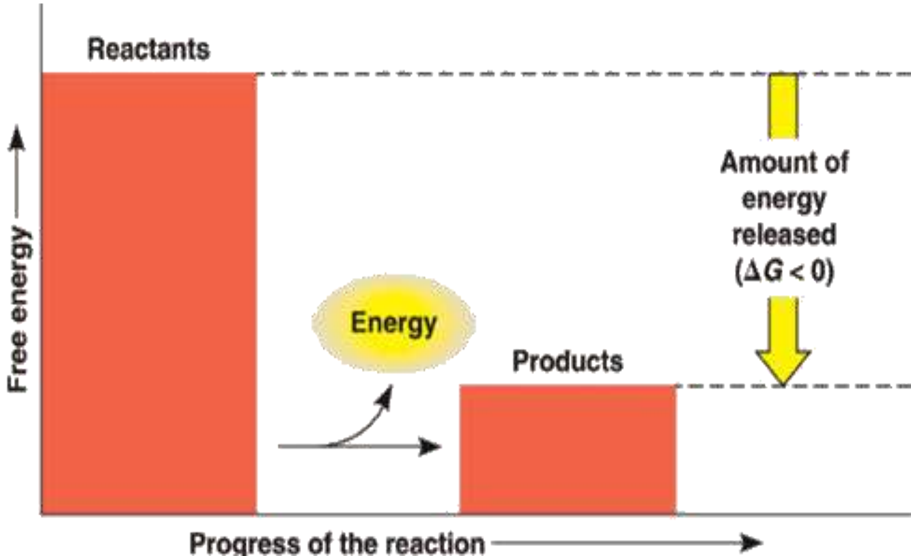
Free Energy

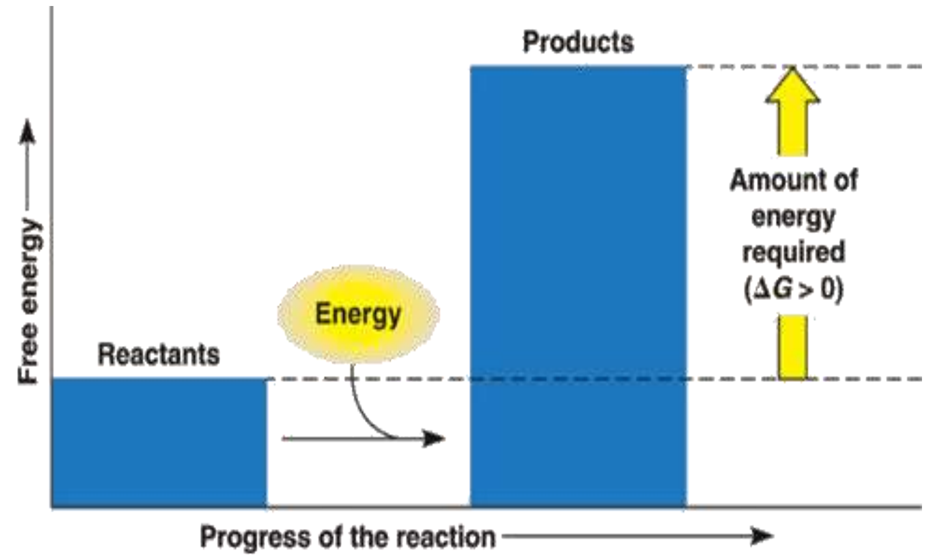
<u>Energy of a system</u>

- Gibb's free energy = energy available to cause change
- difference in free energy (ΔG) - predict if rxn will occur
- system – moves to more stable (lower energy)

- If ΔG (-), -release energy
  -process spontaneous
- If ΔG (+) or 0, -consume energy
  -process non-spontaneous

Chemical Reactions





Glucose $\rightarrow$ CO_2 + H_20

$-\Delta G$

release free energy

spontaneous

- <u>Exergonic</u> reaction

CO_2 + H_20 $\rightarrow$ Glucose

$+\Delta G$ (or 0)

intake free energy

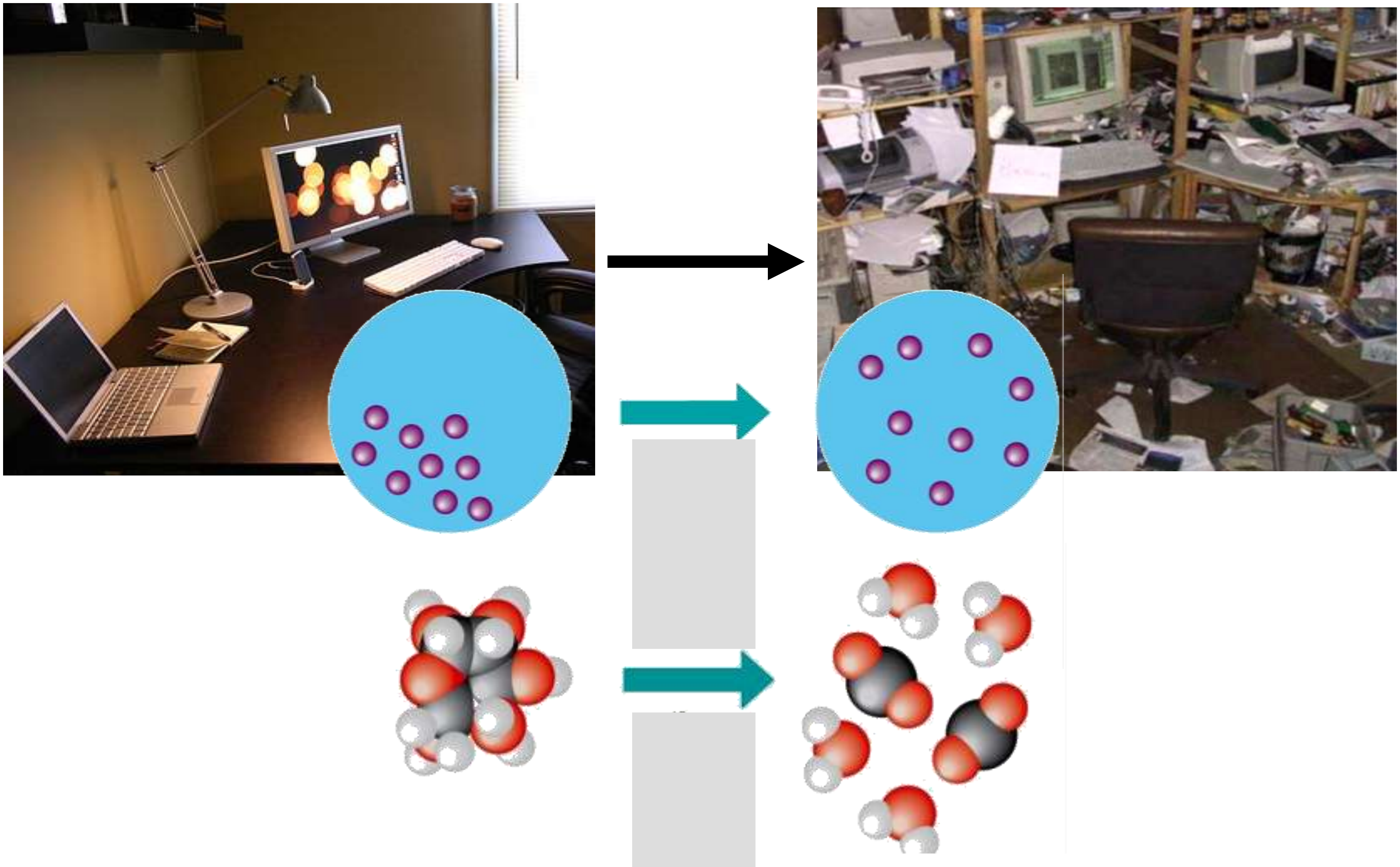
non-spontaneous

- <u>Endergonic</u> reaction

Chemical Reactions

Chemical Reactions:

- Like home offices – tend toward disorder



Chemical Reactions

Chemical Reactions:

- Endergonic – energy required to complete reaction
- Exergonic – energy given off

Exergonic

$\longrightarrow$

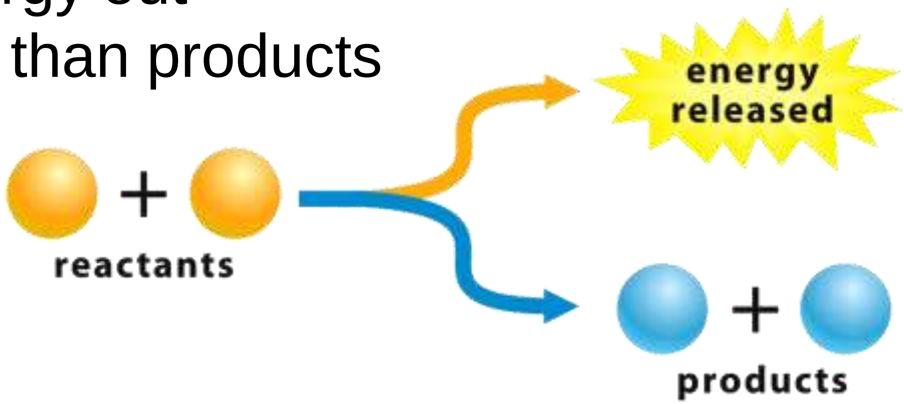
$\longleftarrow$

Endergonic

Chemical Reactions

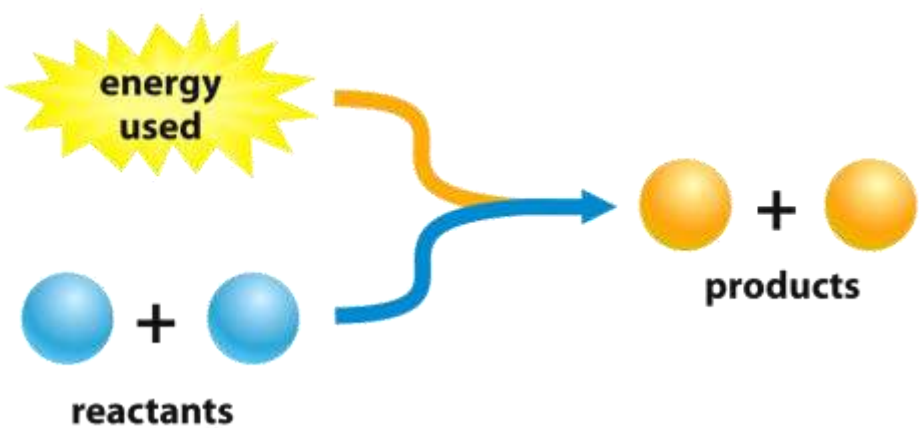
1. *Exergonic* reactions: “Energy out”

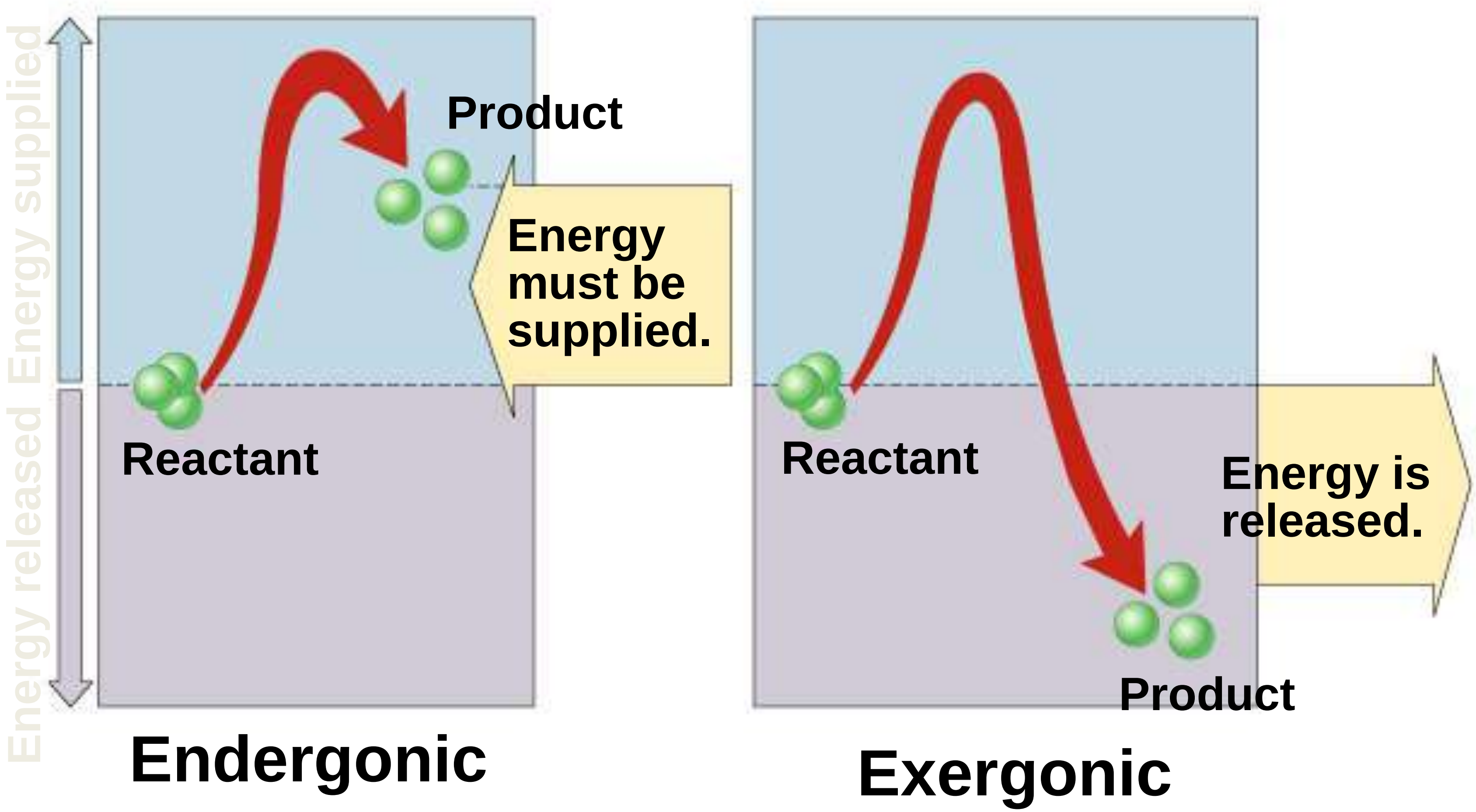
- Reactants have more energy than products
- Reaction releases energy



2. *Endergonic* reactions: “Energy in”

- Products have more energy than reactants
- Requires influx of energy »




Energy supplied
Energy released
Product
Energy must be supplied.
Reactant
Endergonic
Reactant
Energy is released.
Product
Exergonic

Chemical Reactions Sustain Life

Most energy transformations in organisms occur in **oxidation-reduction** reactions by simply transferring electrons from one molecule to another

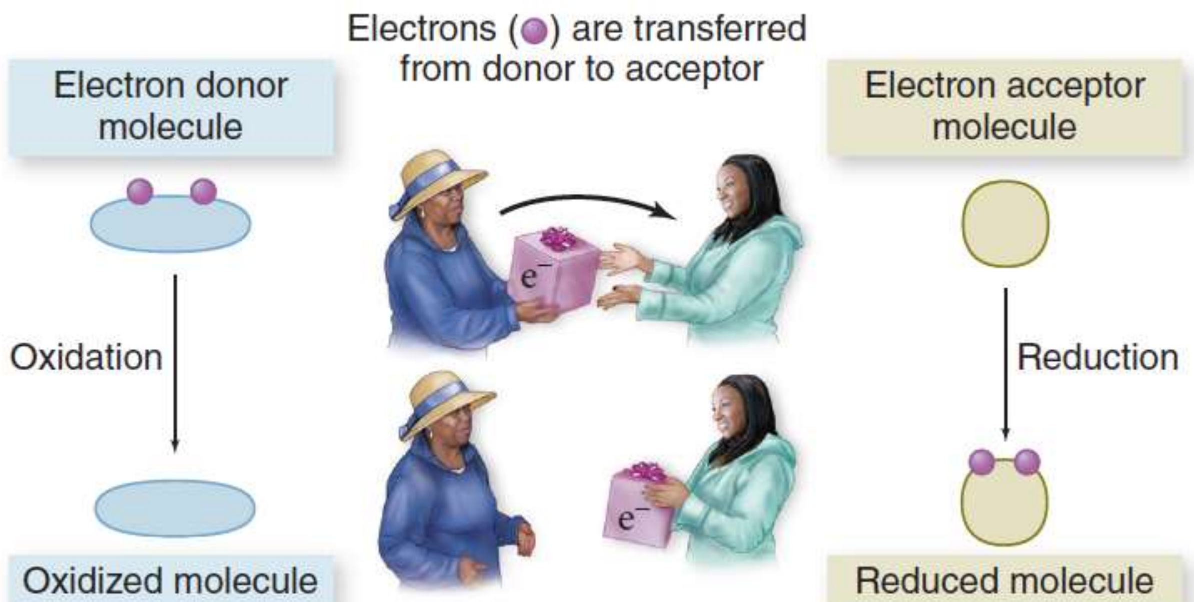


Figure 4.5

Chemical Reactions Sustain Life

Oxidation is the loss of electrons from an atom or molecule; these reactions release energy. “The Giver”

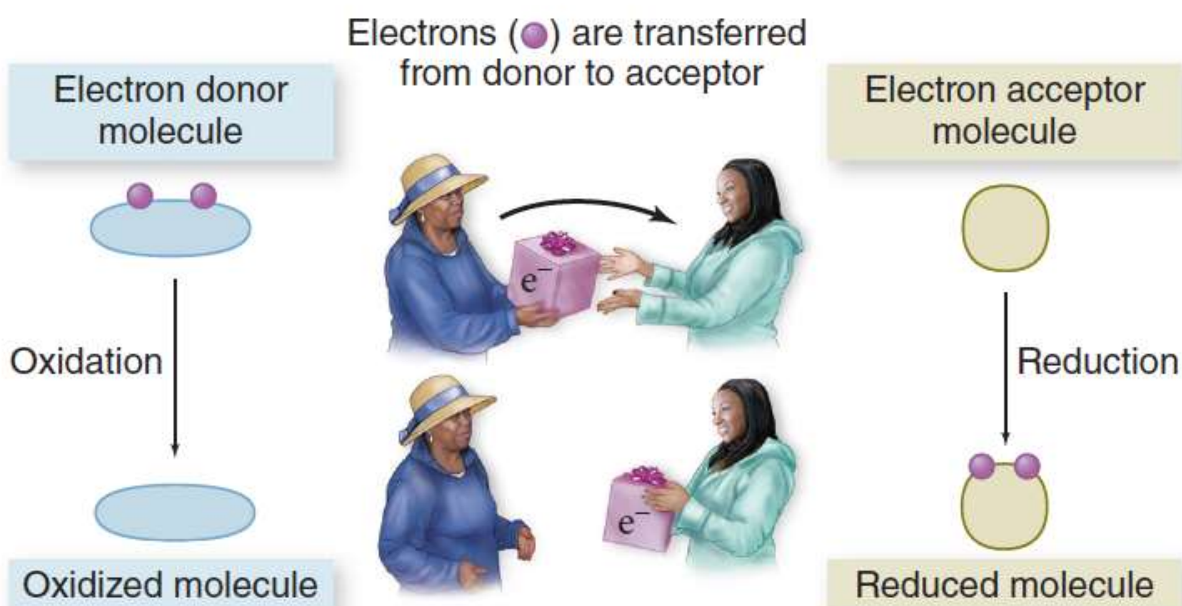


Figure 4.5

Chemical Reactions Sustain Life

Reduction is the gain of electrons (and whatever energy contained in the electrons) by an atom or molecule. These reactions require energy. (The Receiver)

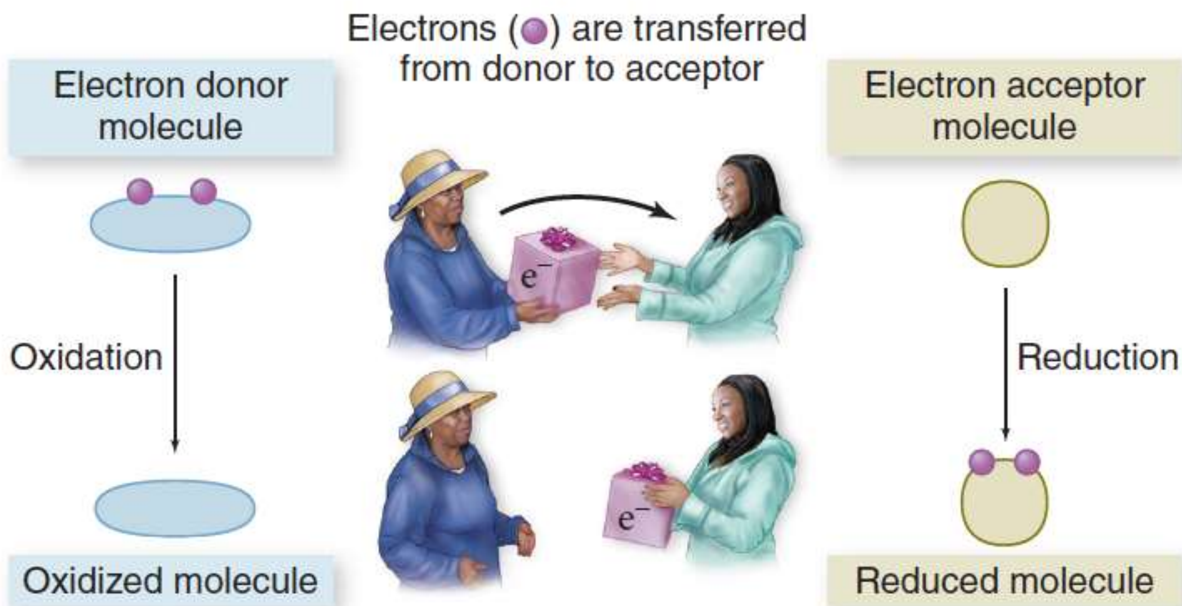


Figure 4.5

Chemical Reactions Sustain Life

An **electron transport chain** is a series of membrane proteins participating in sequential oxidation-reduction reactions. Energy is released at each step. (bucket brigade)

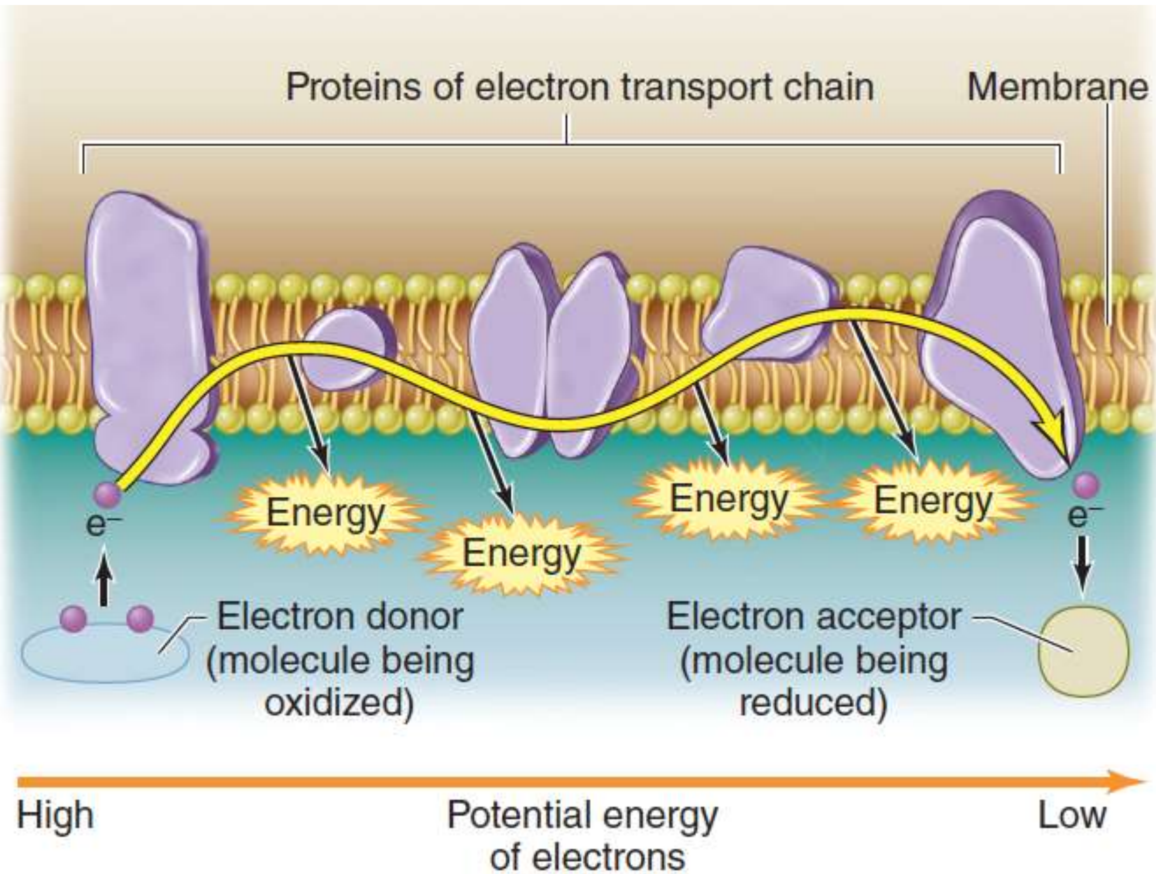


Figure 4.6

Chemical Reactions Sustain Life

Photosynthesis and cellular respiration both use electron transport chains.

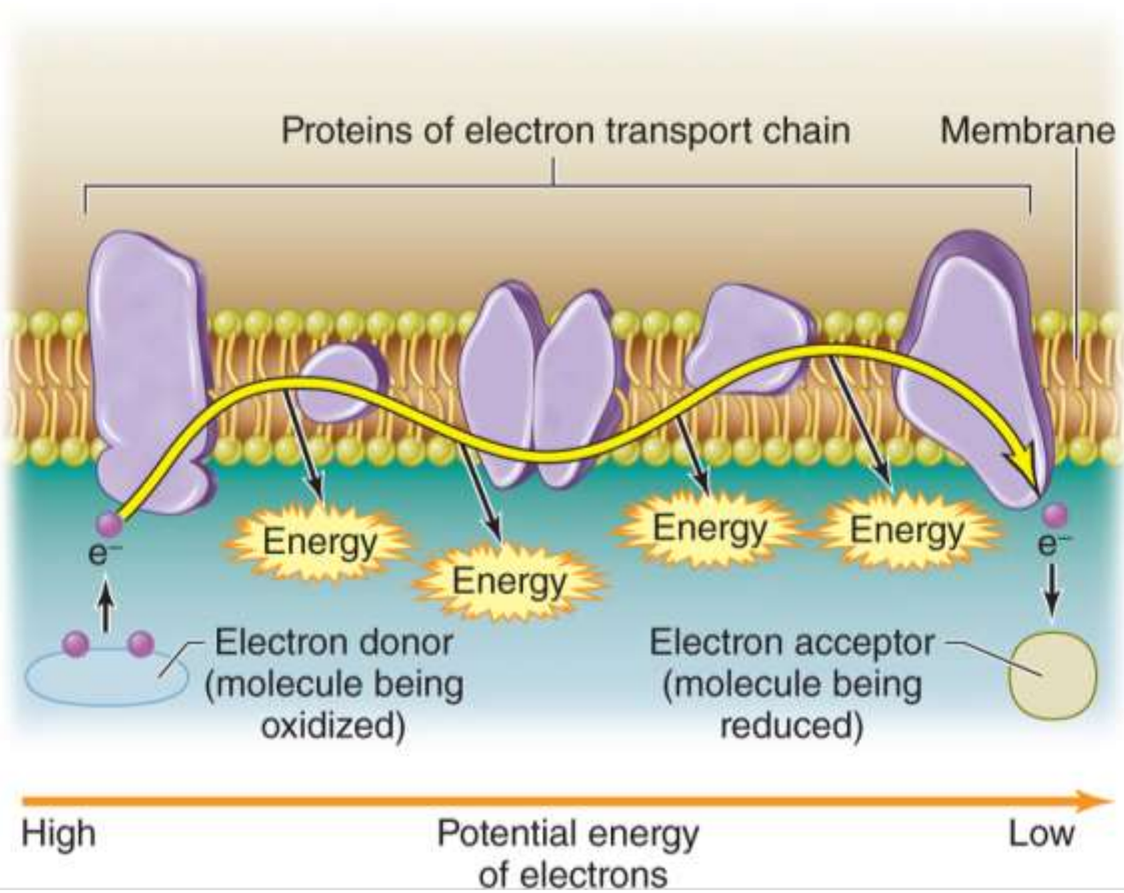
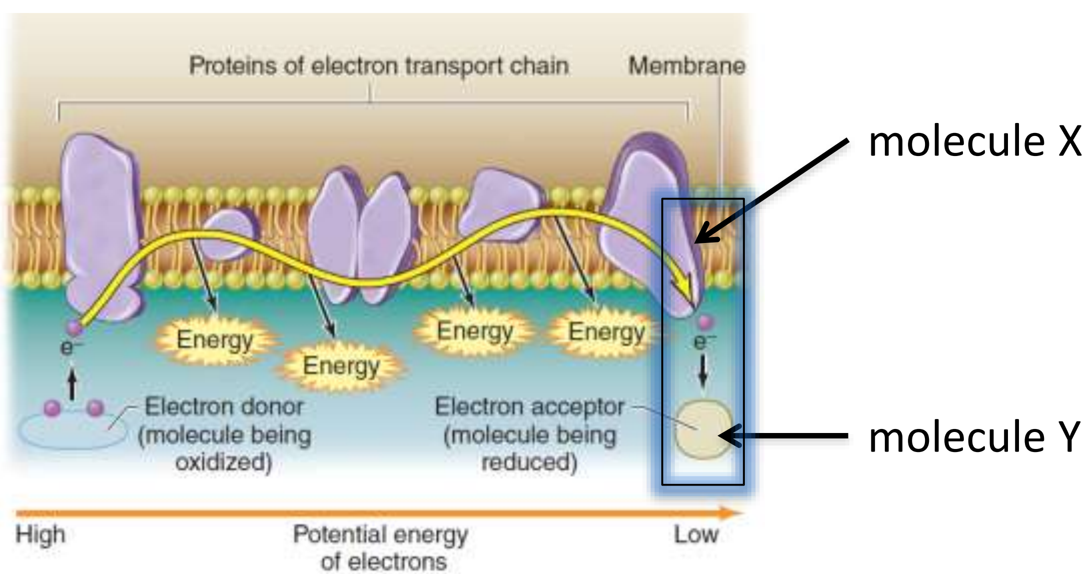


Figure 4.6

Clicker Question #2

In the reaction at the end of the electron transport chain, molecule X is being ___ and molecule Y is being ____.

A. oxidized … reduced
B. reduced … oxidized



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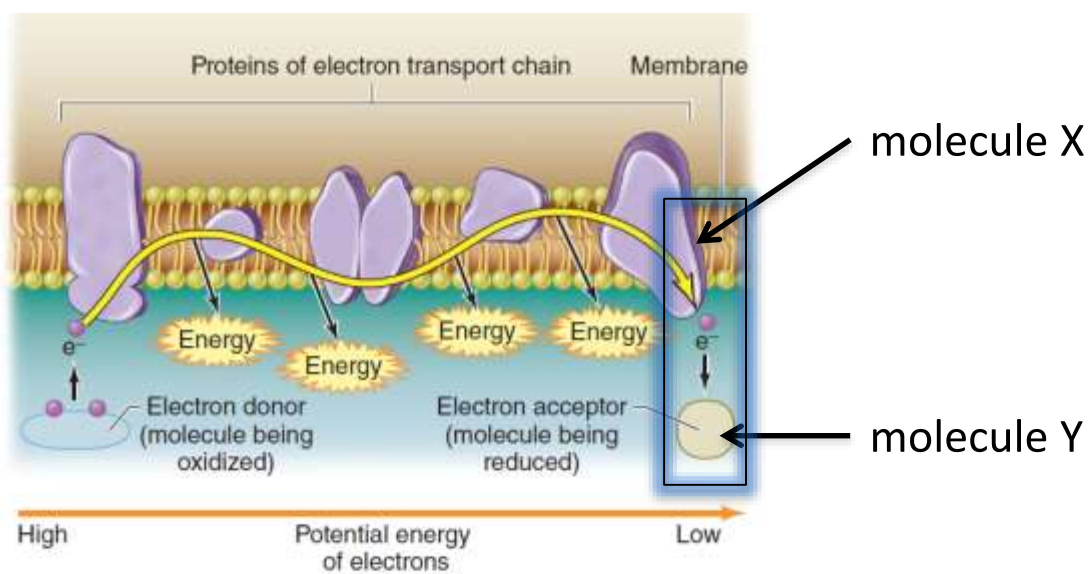
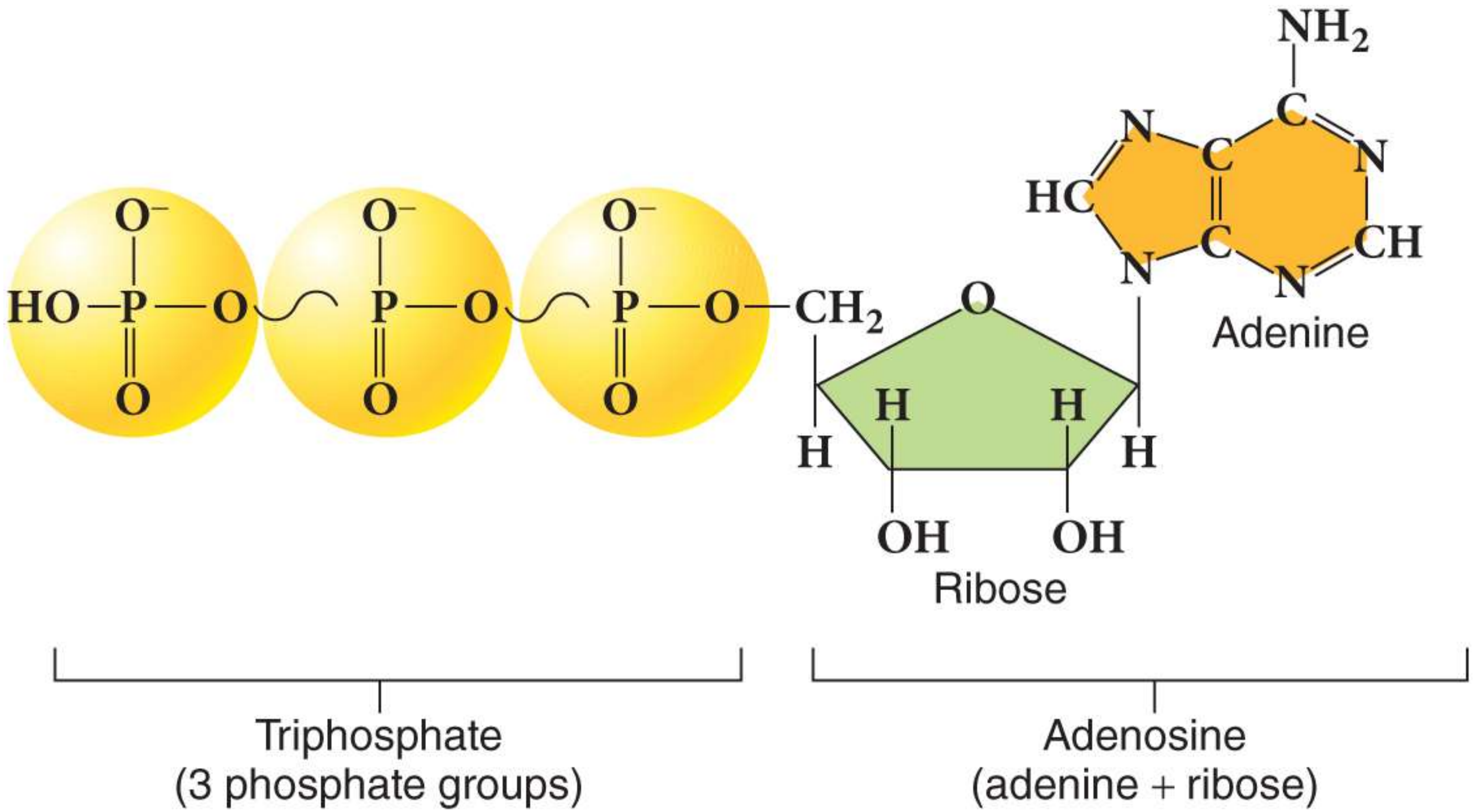


4.2 Mastering Concepts

What are oxidation and reduction, and why are they always linked?

ATP Is the Cellular Energy Currency

Adenosine triphosphate (**ATP**) is a nucleotide that temporarily stores energy.



Section 4.3

Figure 4.7

ATP Is the Cellular Energy Currency

All cells rely on the potential energy stored in ATP to power chemical reactions.

Bond with high potential energy

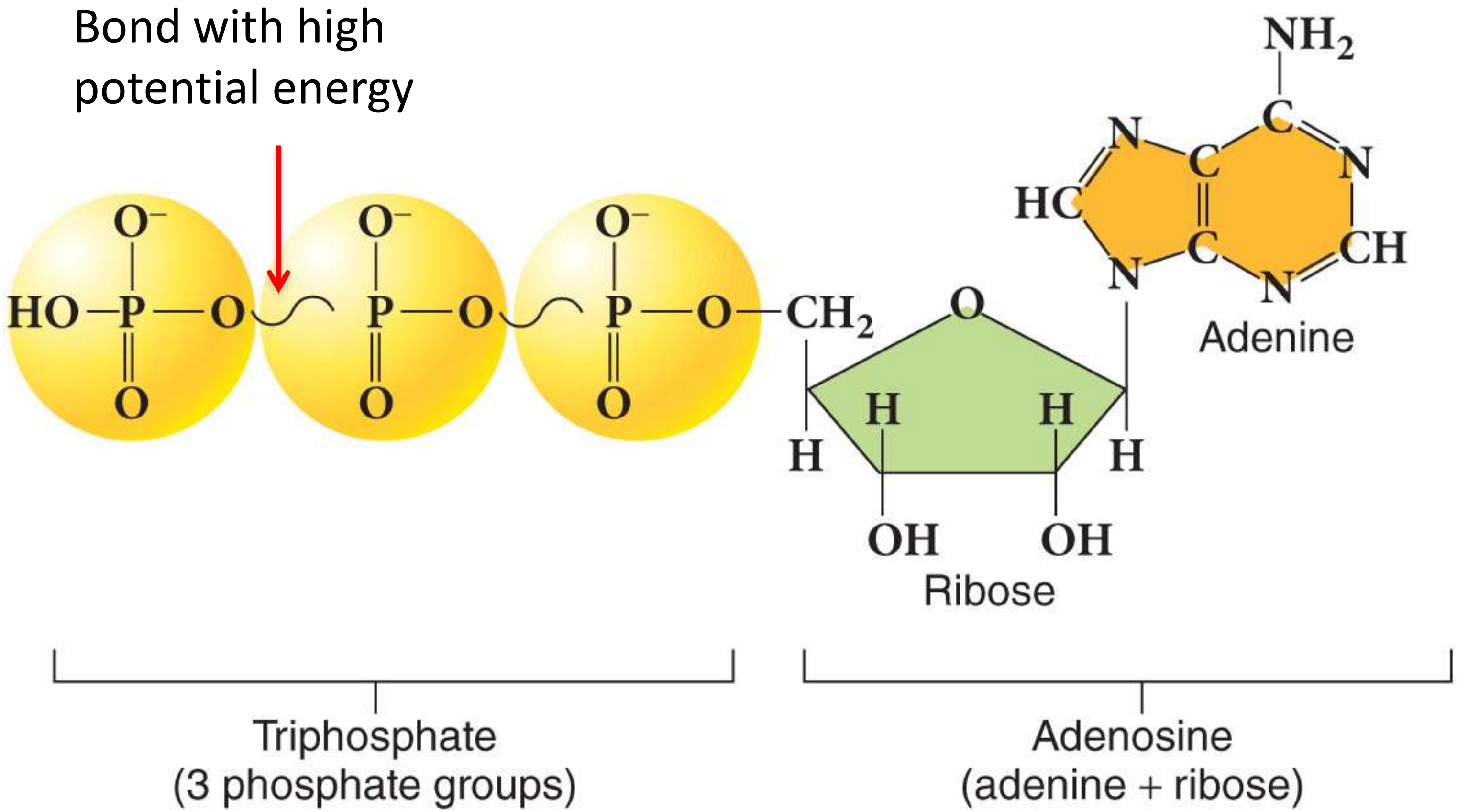
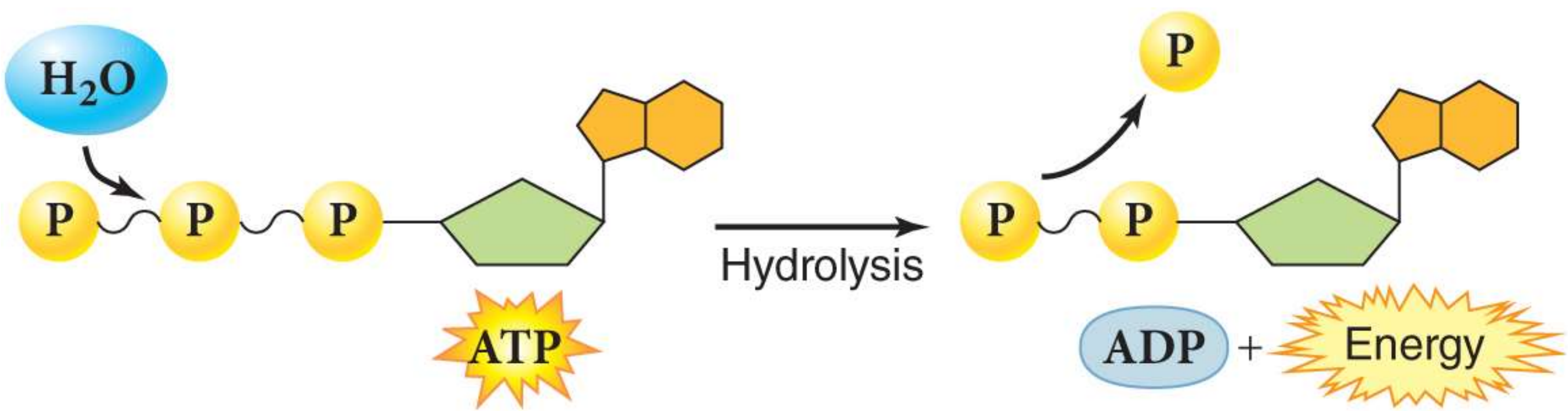


Figure 4.7

ATP Is the Cellular Energy Currency

Removing the endmost phosphate group by hydrolysis releases the potential energy stored in ATP.
The cell uses this energy to do work.



Section 4.3

Figure 4.8

ATP Is the Cellular Energy Currency

ATP must then be reformed. Mitochondria release energy from food, producing ATP from ADP.

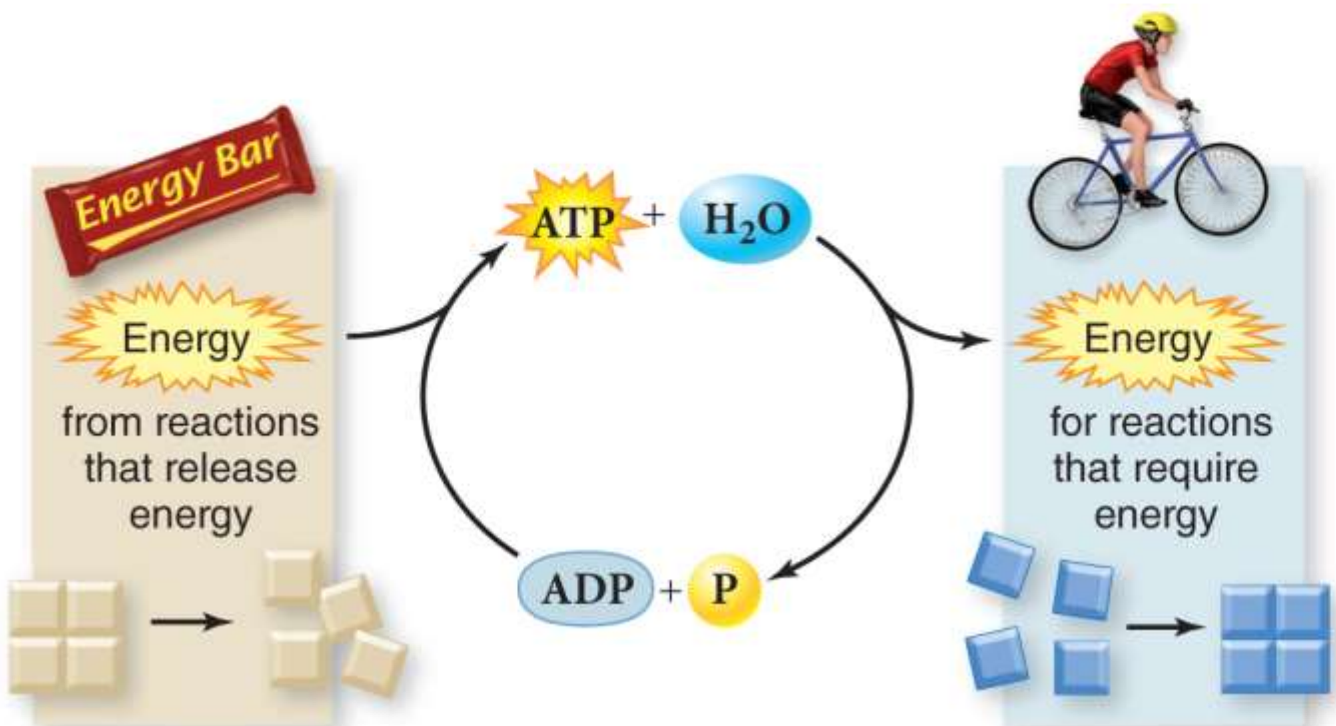


Figure 4.9

Cellular Work

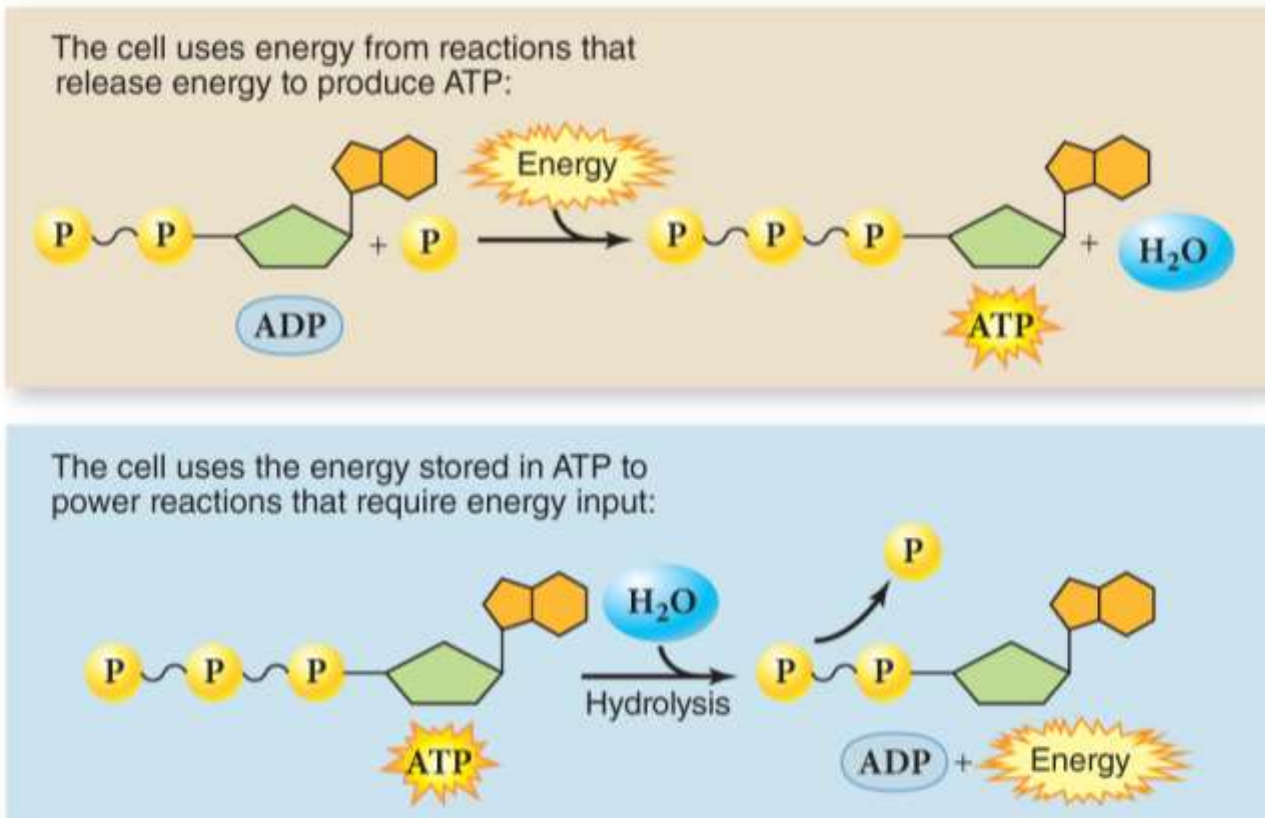
- A cell does three main kinds of work
  - Mechanical
  - Transport
  - Chemical
- **Energy coupling** is a key feature in the way cells manage their energy resources to do this work
- ATP powers cellular work by coupling exergonic reactions to endergonic reactions

ATP Is the Cellular Energy Currency

ATP *formation* is coupled with exergonic reactions.
ATP *breakdown* is coupled with endergonic reactions.

Producing ATP

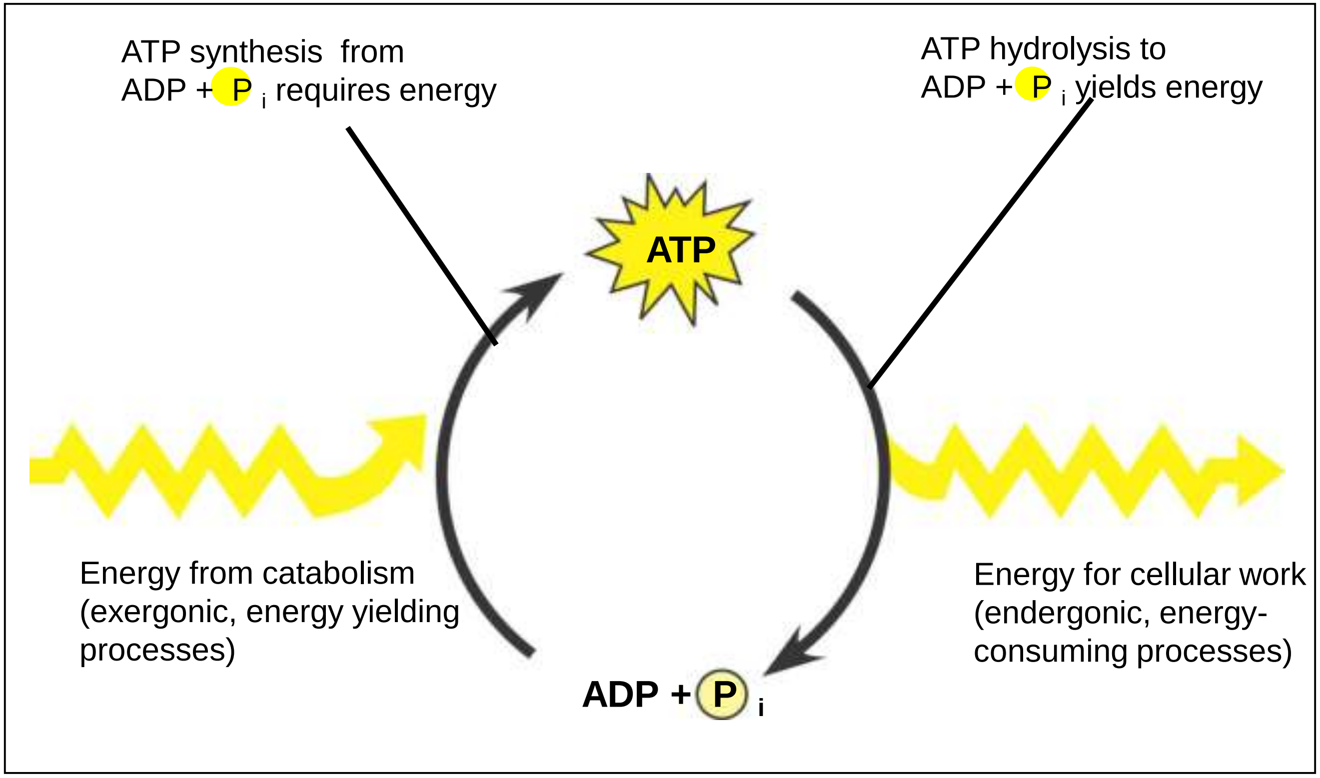
“Spending” ATP



Section 4.3

Energy Coupling - ATP / ADP Cycle

- Releasing the third phosphate from ATP to make ADP generates energy (exergonic):
- Linking the phosphates together requires energy - so making ATP from ADP and a third phosphate requires energy (endergonic),
- Catabolic pathways drive the regeneration of ATP from ADP and phosphate



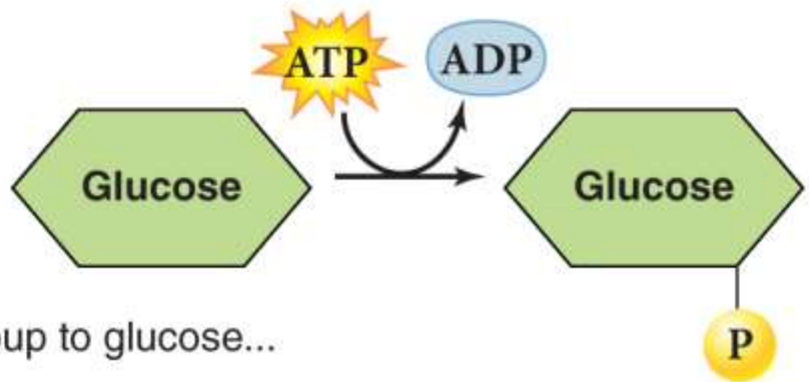
How ATP Performs Work

- ATP drives endergonic reactions by **phosphorylation**, transferring a phosphate group to some other molecule, such as a reactant
- The recipient molecule is now phosphorylated
- The three types of cellular work (mechanical, transport, and chemical) are powered by the hydrolysis of ATP

ATP Hydrolysis Is Coupled with Endergonic Reactions

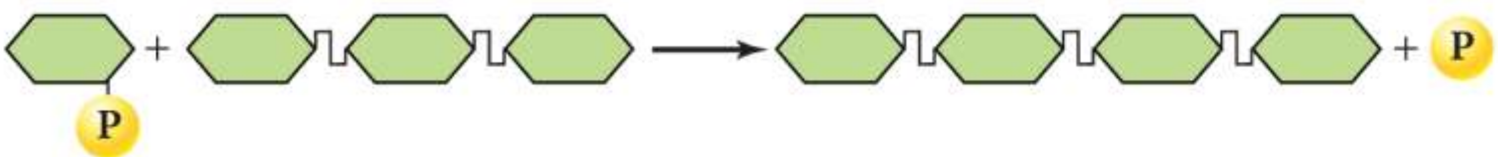
a. ATP energizes target molecule, making it more likely to bond with other molecules.

E.g., ATP provides the energy to build large molecules out of small subunits



Phosphorylation

ATP donates P group to glucose...

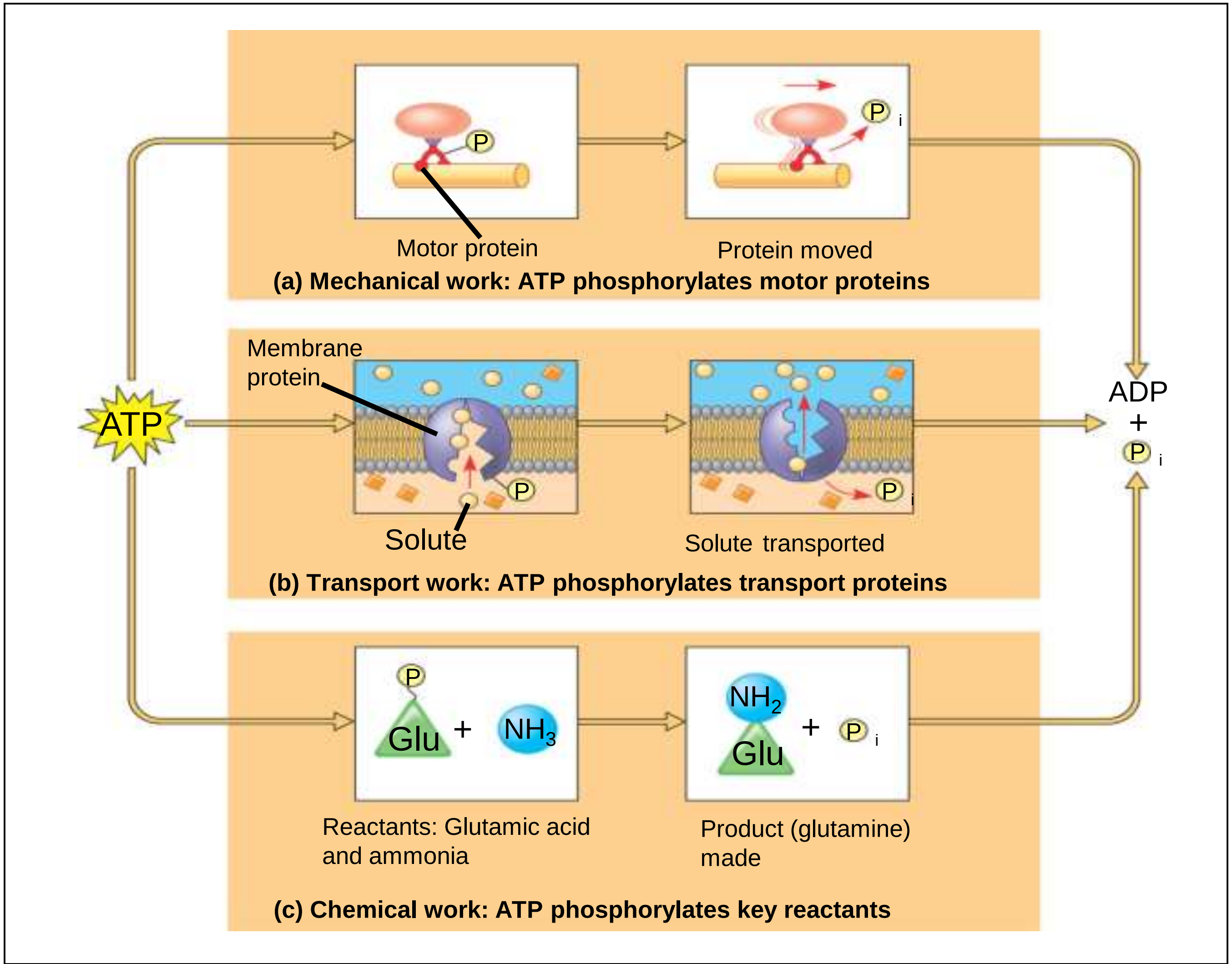


... glucose + P then reacts with short polysaccharide to build longer polysaccharide

Figure 4.10

How ATP Performs Work

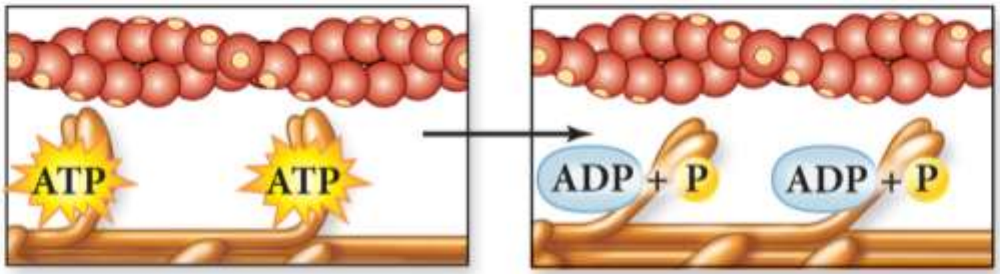
- ATP drives endergonic reactions by phosphorylation, transferring a phosphate to other molecules - hydrolysis of ATP



ATP Hydrolysis Is Coupled with Energy-Requiring Reactions

b. ATP donates a phosphate group that changes the shape of the target molecule.

E.g., ATP binding changes shape of proteins involved in muscle contraction



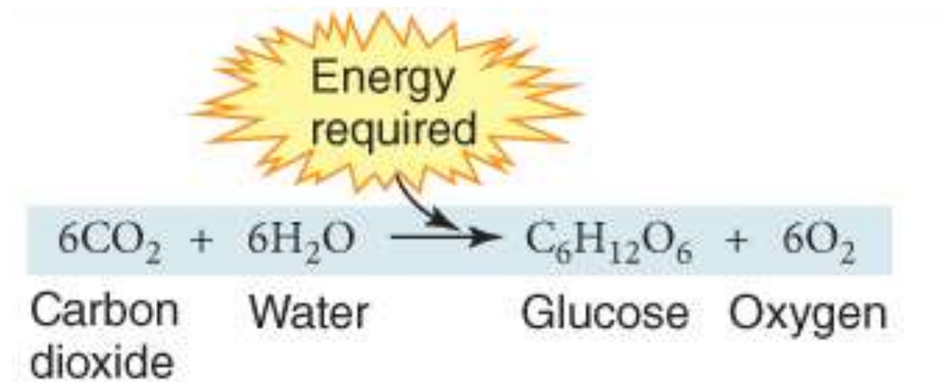
Section 4.3

Figure 4.10

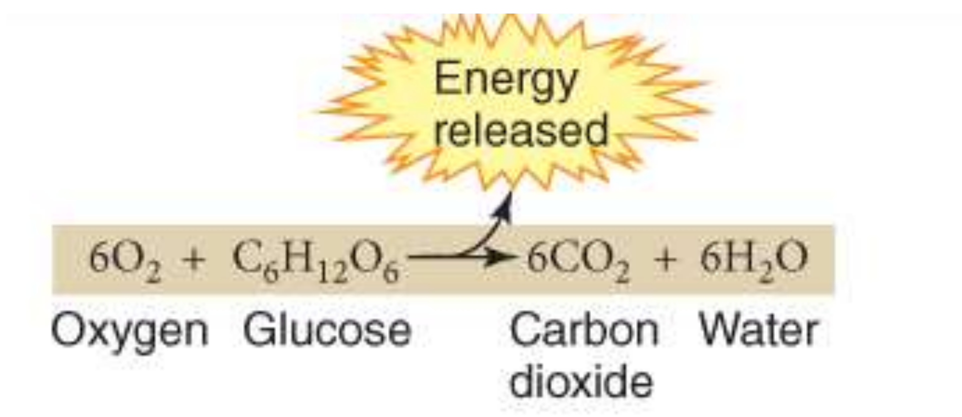
Clicker Question #3

Which reaction is likely coupled with hydrolysis of ATP?

A.



B.



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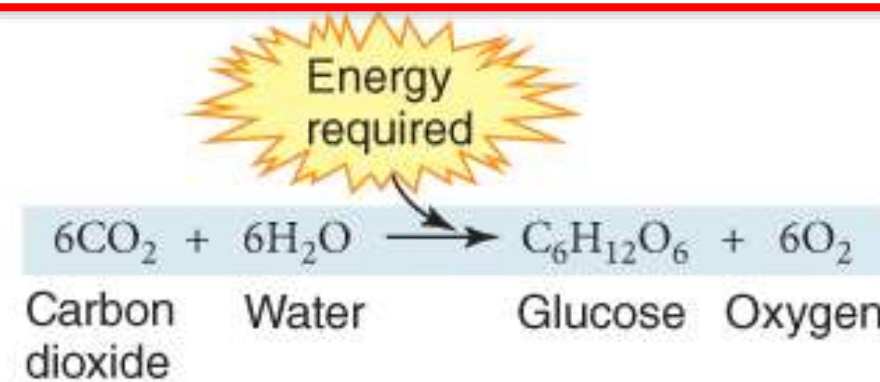
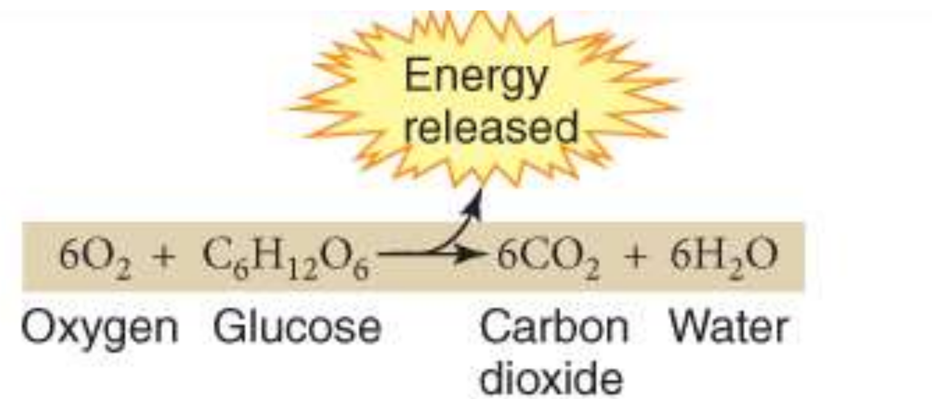


B.



4.3 Mastering Concepts

Describe the relationships among energy-requiring reactions, ATP hydrolysis, and cellular respiration.

Enzymes Speed Biochemical Reactions

Chemical reactions in cells must occur very quickly to sustain life.

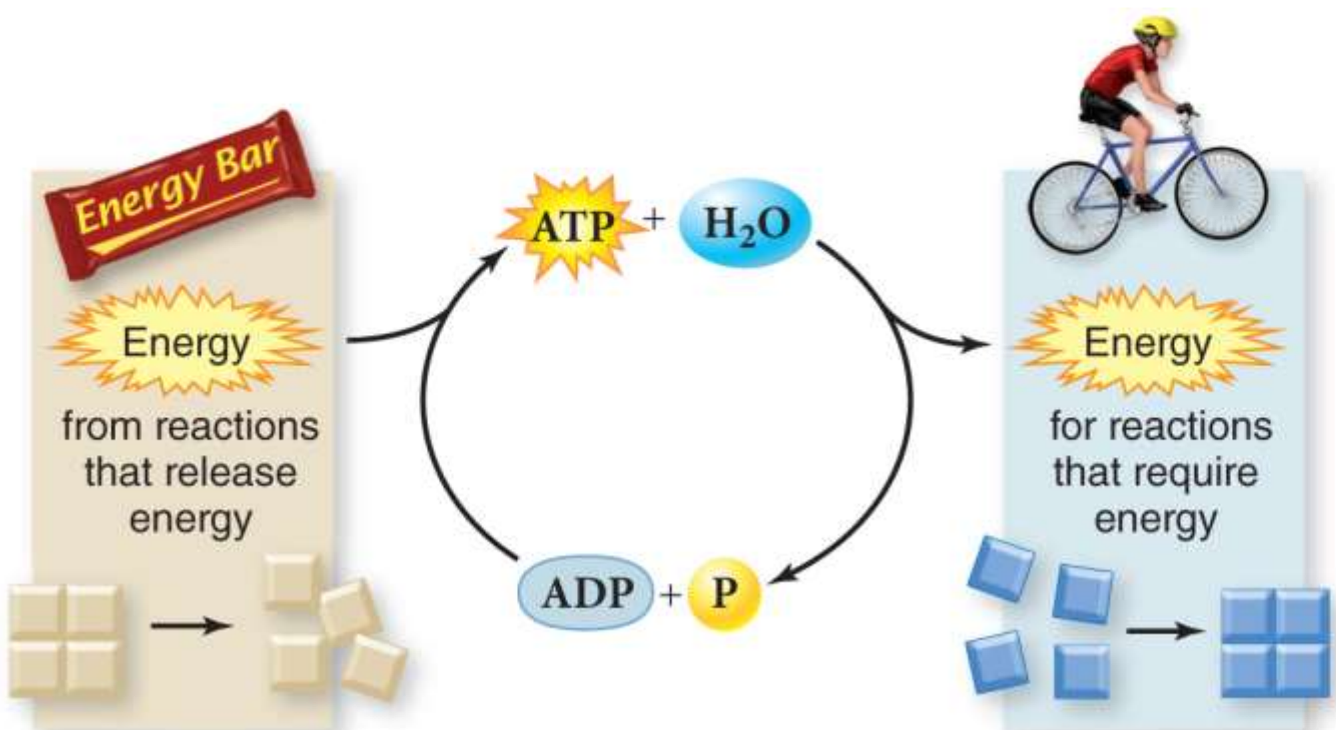


Figure 4.9

Enzymes Speed Biochemical Reactions

An **enzyme** is a protein that speeds up a chemical reaction without being consumed.

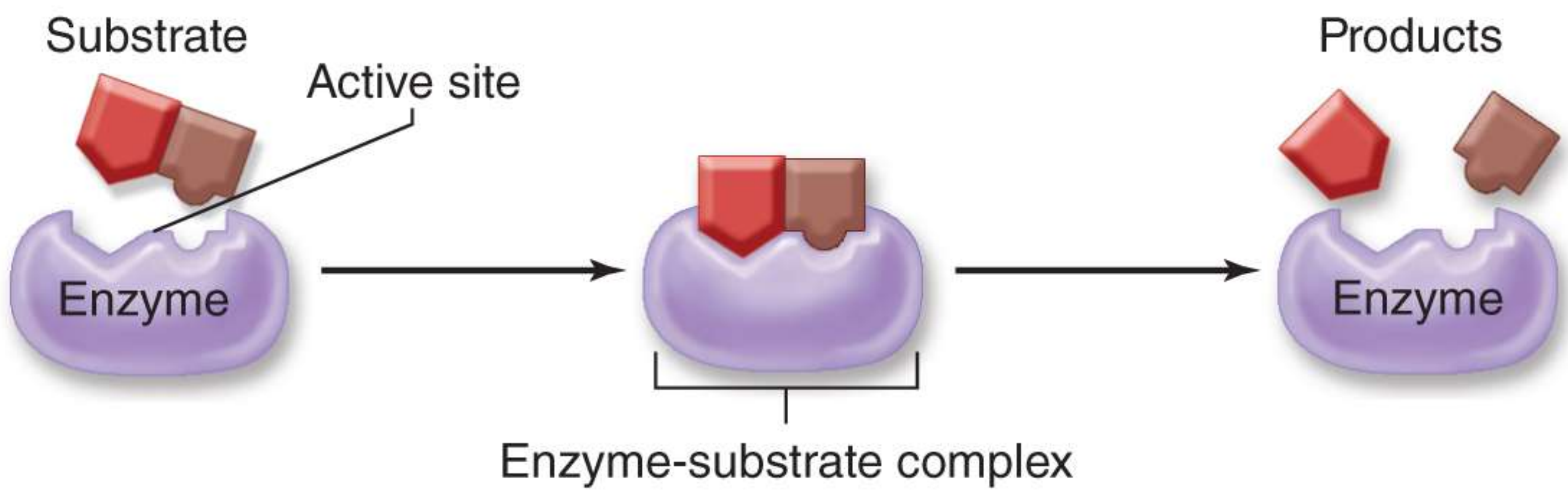


Figure 4.11

Enzymes Speed Biochemical Reactions

Substrate molecules bind to the enzyme's **active site,** where the chemical reaction occurs.

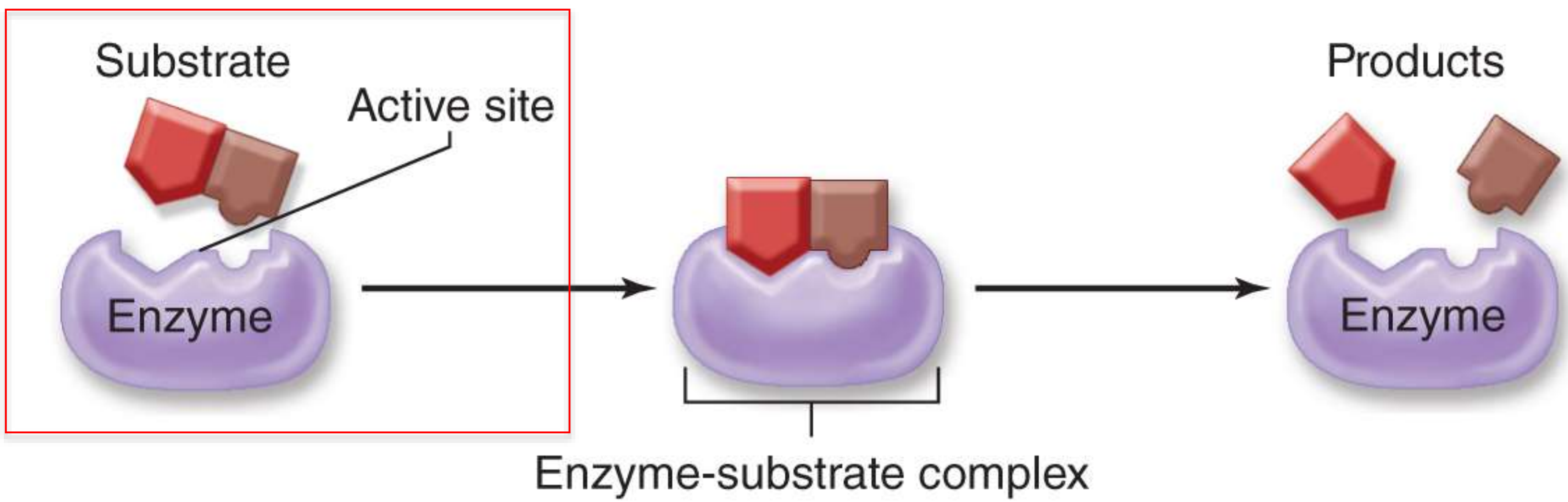


Figure 4.11

Enzymes Speed Biochemical Reactions

Once the chemical reaction occurs, product molecules are released. The enzyme retains its original form.

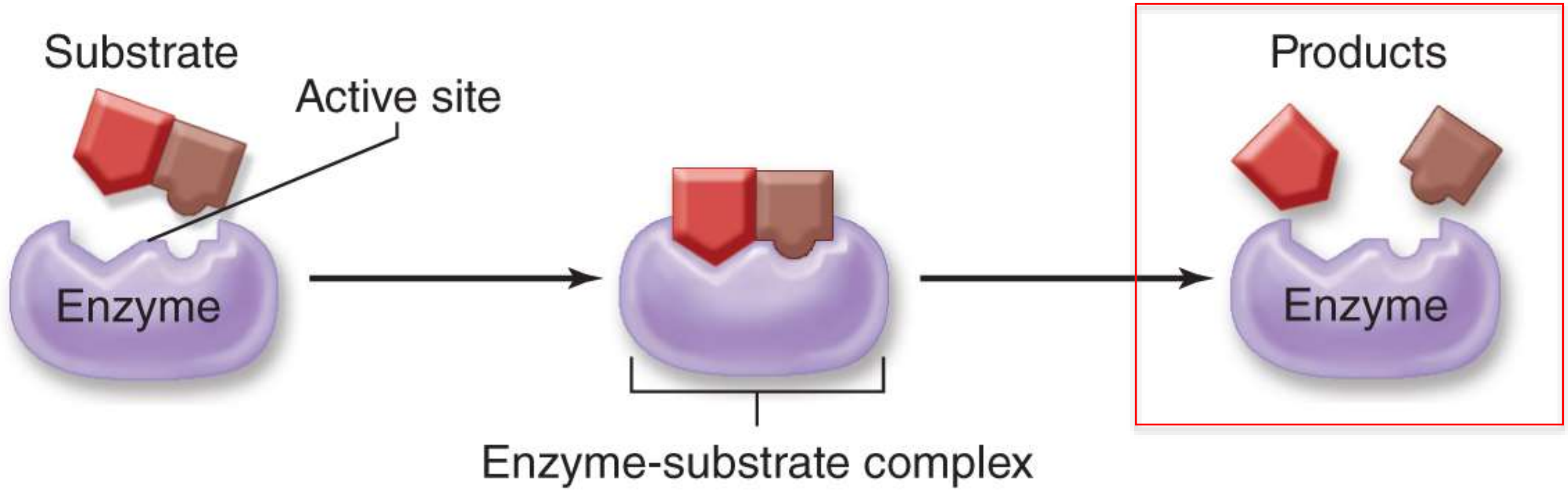


Figure 4.11

Enzymes Speed Biochemical Reactions

Note that not all enzymes break a single substrate into two products. Other enzymes combine two substrates into one product, for example.

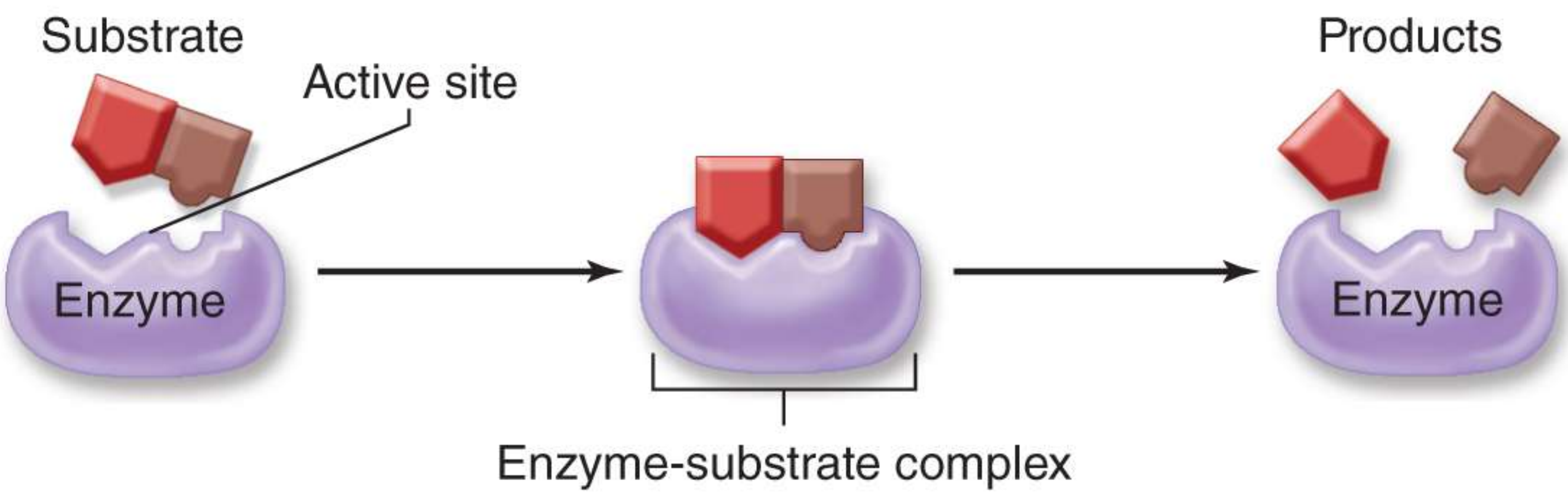
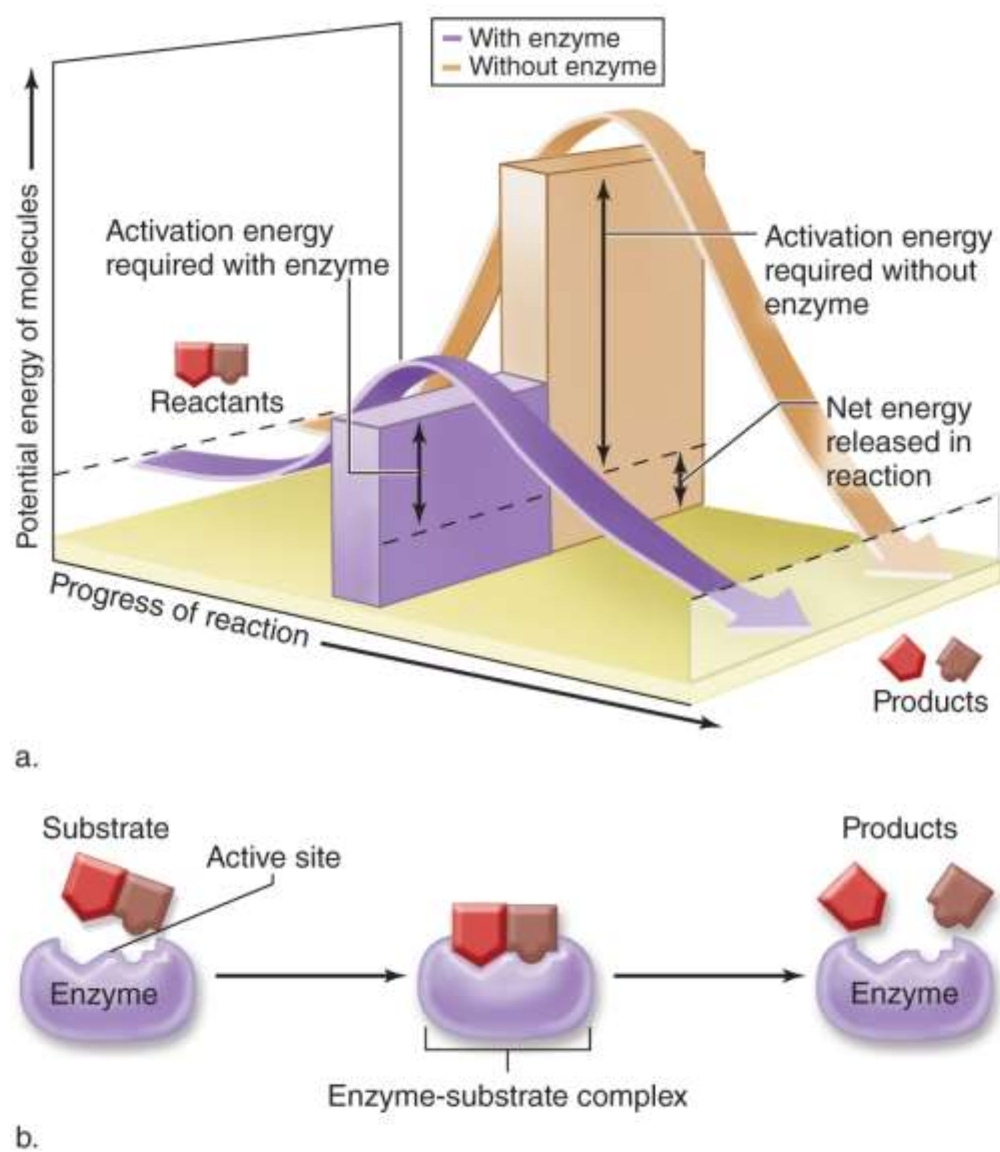


Figure 4.11

Enzymes Speed Biochemical Reactions

An enzyme speeds up a chemical reaction by lowering the **activation energy**—the energy required to start the reaction.

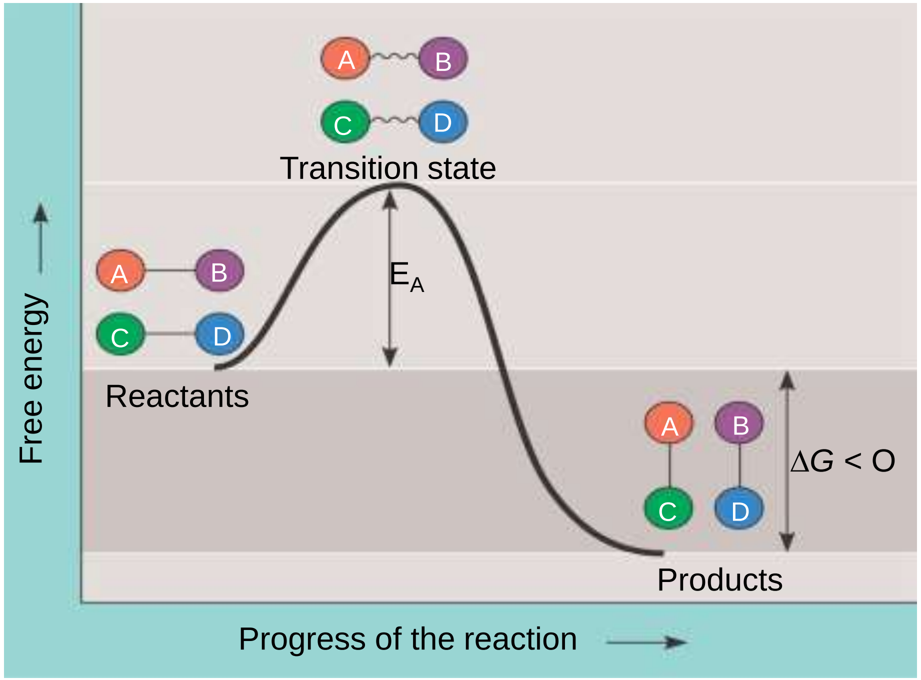


Section 4.4

Figure 4.11

Activation Energy

- All reactions, both endergonic and exergonic, require an input of energy to get started. This energy is called activation energy
- The activation energy, E_A
  - Is the initial amount of energy needed to start a chemical reaction
  - Activation energy is needed to bring the reactants close together and weaken existing bonds to initiate a chemical reaction.
  - Is often supplied in the form of heat from the surroundings in a system.



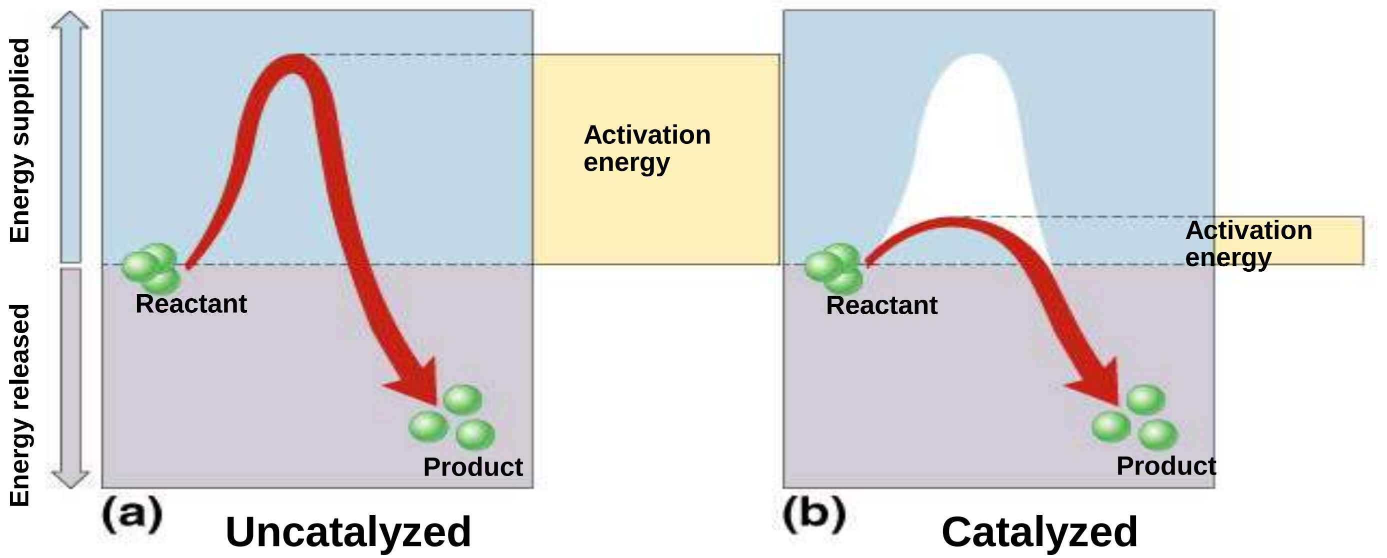
Reaction Rates

- In most cases, molecules do not have enough kinetic energy to reach the transition state when they collide.
- Therefore, most collisions are non-productive, and the reaction proceeds very slowly if at all.
- What can be done to speed up these reactions?

Increasing Reaction Rates

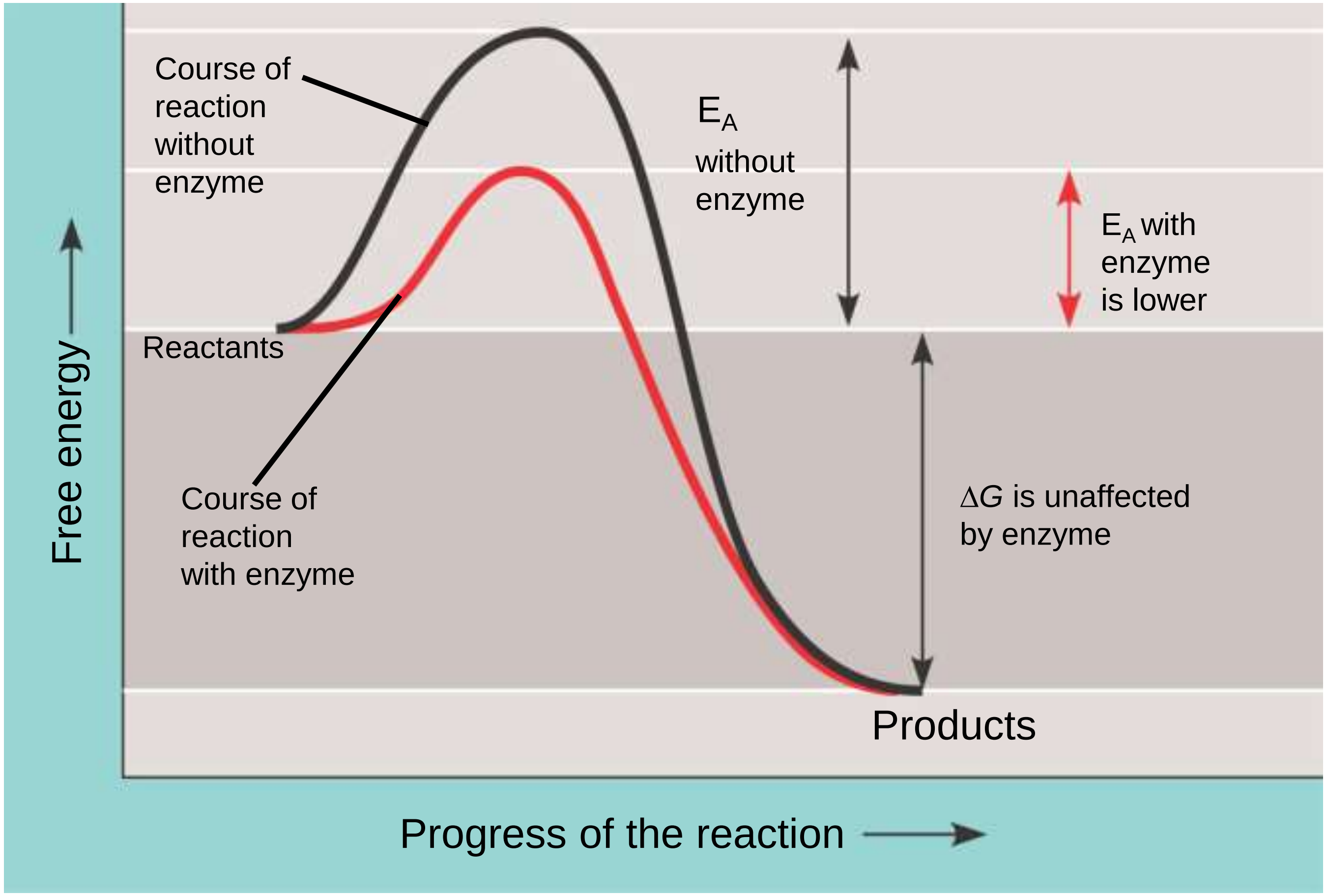
- Add Energy (Heat) - molecules move faster so they collide more frequently and with greater force.
- Add a **catalyst –** a catalyst reduces the energy needed to reach the activation state, without being changed itself. Proteins that function as catalysts are called enzymes.

Activation Energy and Catalysis



Enzymes Lower the E_A Barrier

- An enzyme catalyzes reactions by lowering the E_A barrier

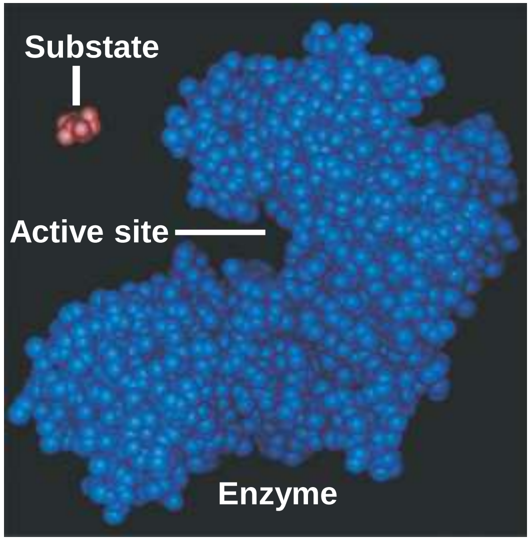


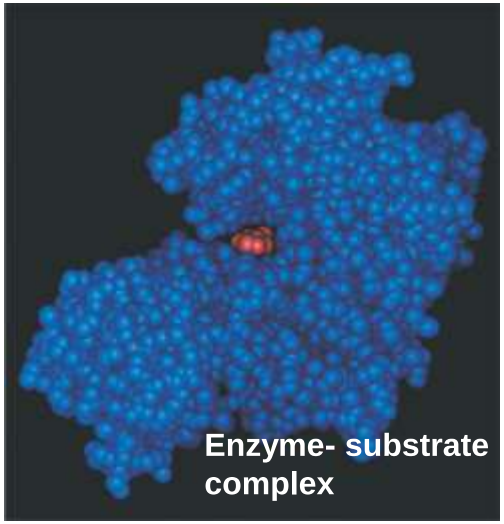
Enzymes Are Biological Catalysts

- Enzymes are proteins that carry out most catalysis in living organisms.
- Unlike heat, enzymes are highly specific. Each enzyme typically speeds up only one or a few chemical reactions.
- Unique three-dimensional shape enables an enzyme to stabilize a temporary association between substrates.
- Because the enzyme itself is not changed or consumed in the reaction, only a small amount is needed, and can then be reused.
- Therefore, by controlling which enzymes are made, a cell can control which reactions take place in the cell.

Substrate Specificity of Enzymes

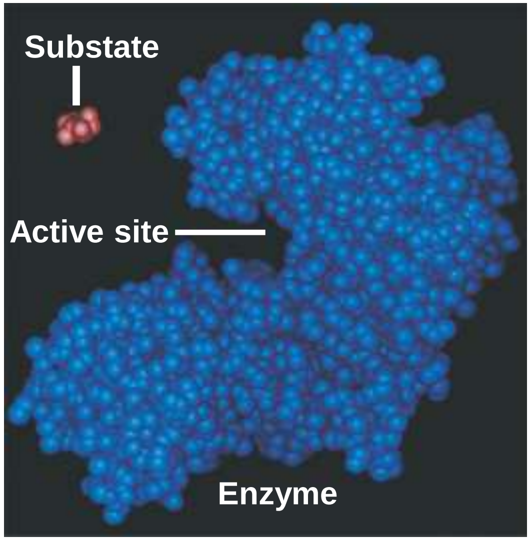
- Almost all enzymes are globular proteins with one or more active sites on their surface.
- The substrate is the reactant an enzyme acts on
- Reactants bind to the ***active site*** to form an **enzyme-substrate complex.**
- The 3-D shape of the active site and the substrates must match, like a lock and key

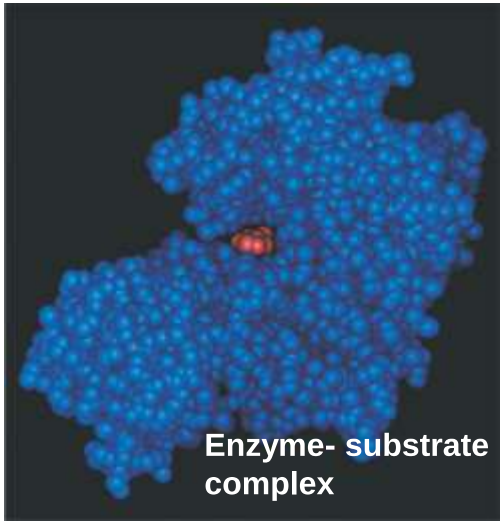




Substrate Specificity of Enzymes

- Binding of the substrates causes the enzyme to adjust its shape slightly, leading to a better induced fit.
- Induced fit of a substrate brings chemical groups of the active site into positions that enhance their ability to catalyze the chemical reaction
- When this happens, the substrates are brought close together **and existing bonds are stressed**. **This reduces the amount of energy needed to reach the transition state**.





The Catalytic Cycle Of An Enzyme

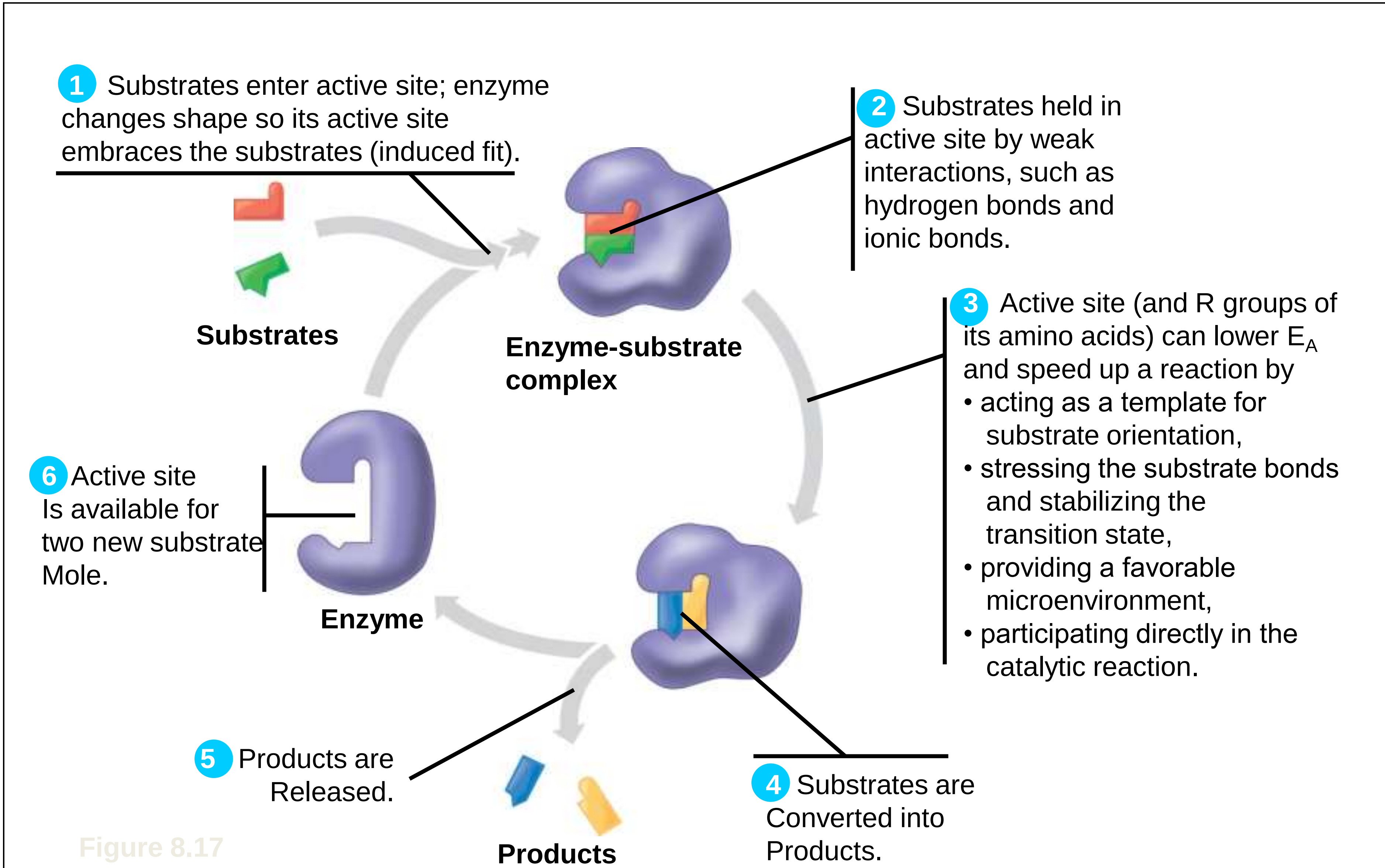
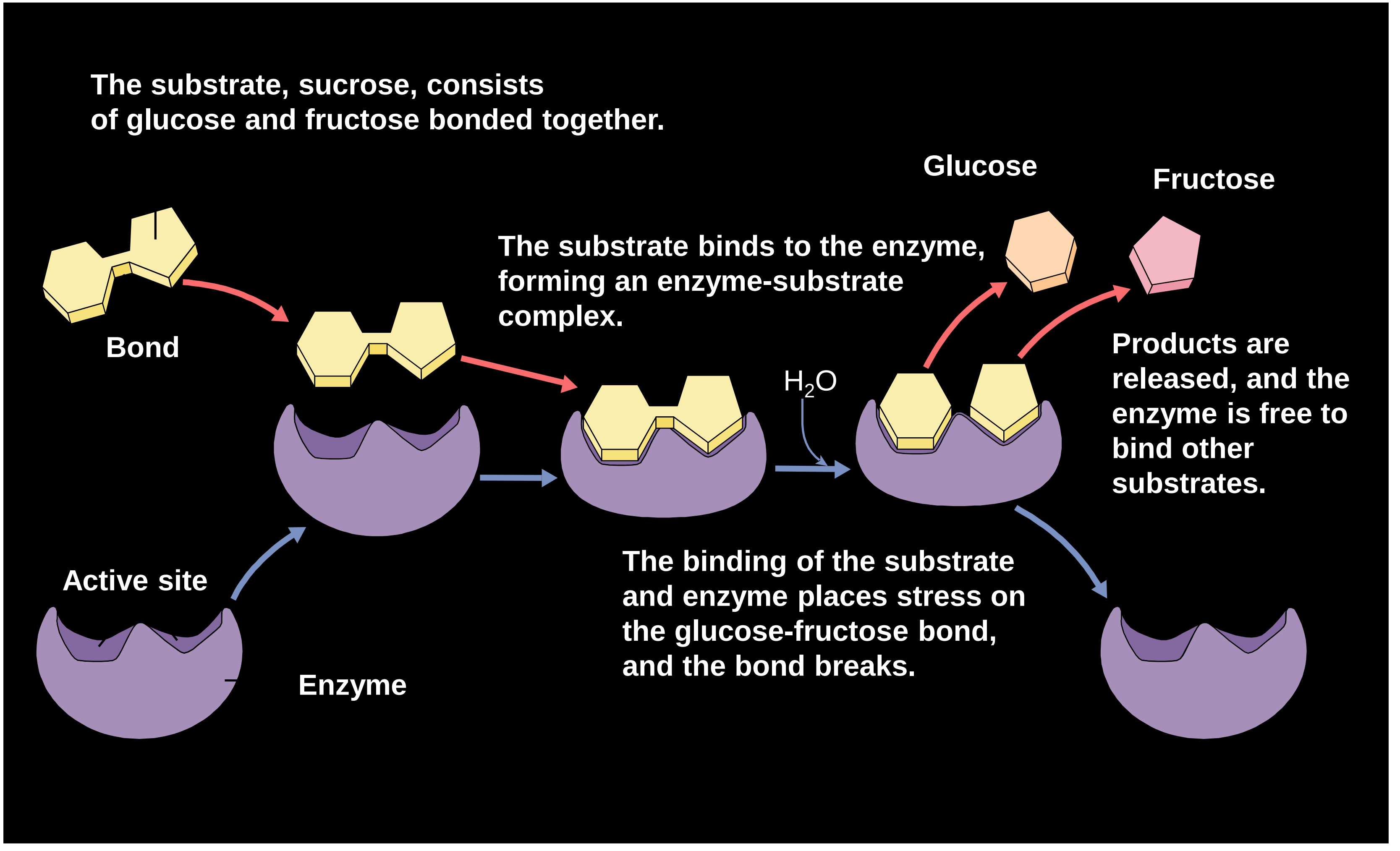


Figure 8.17

The Catalytic Cycle Of An Enzyme

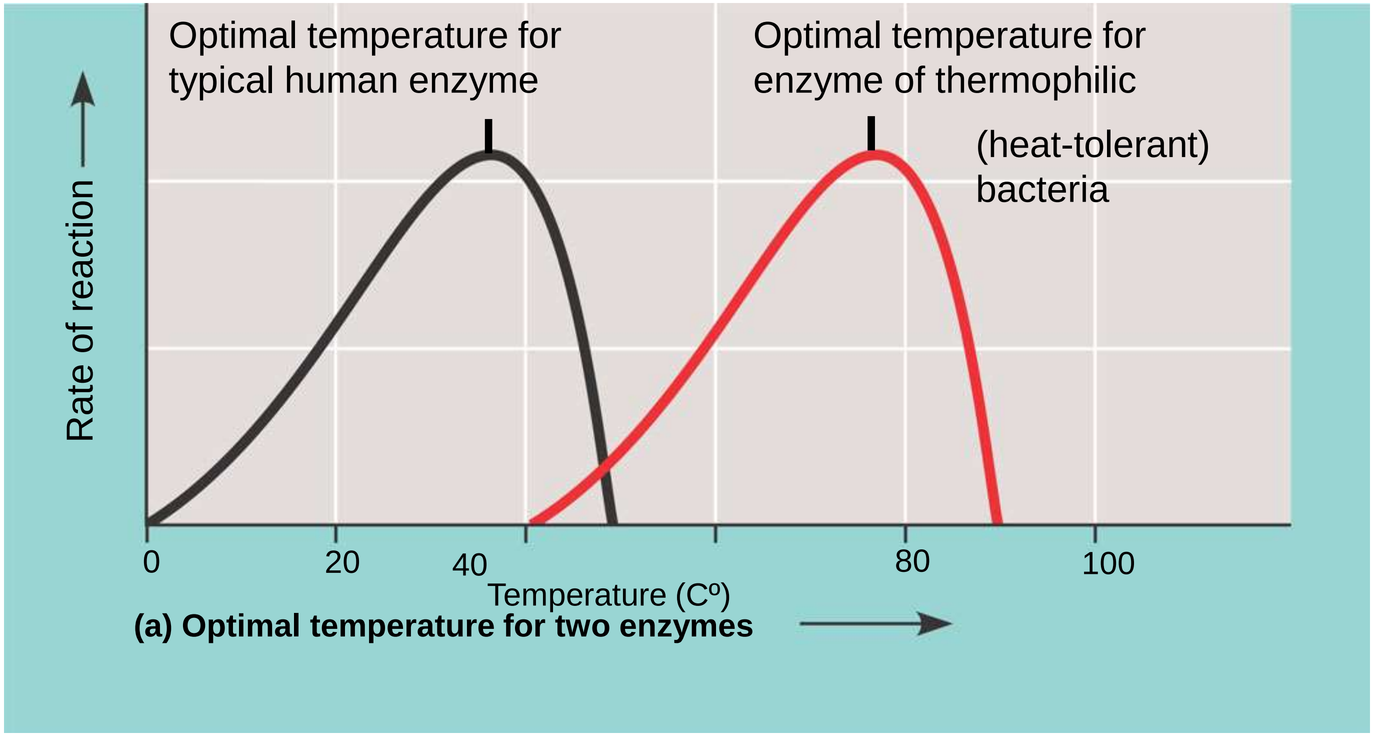


Factors Affecting Enzyme Activity

- **Temperature** - rate of an enzyme-catalyzed reaction increases with temperature, but only up to an optimum temperature.
- **pH -** ionic interactions also hold enzymes together.
- Inhibitors and Activators

Effects of Temperature and pH

- Each enzyme has an optimal temperature in which it can function



(a) Optimal temperature for two enzymes

Effects of Temperature and pH

– Each enzyme has an optimal pH in which it can function

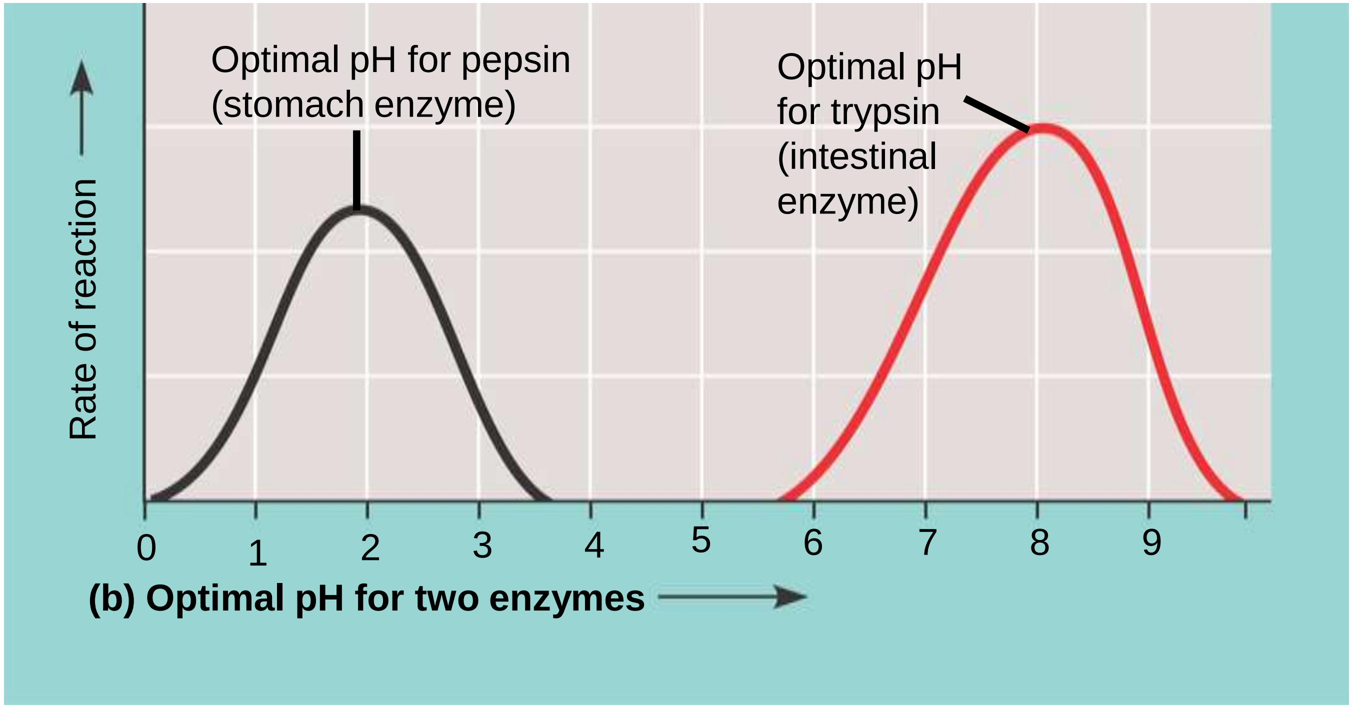
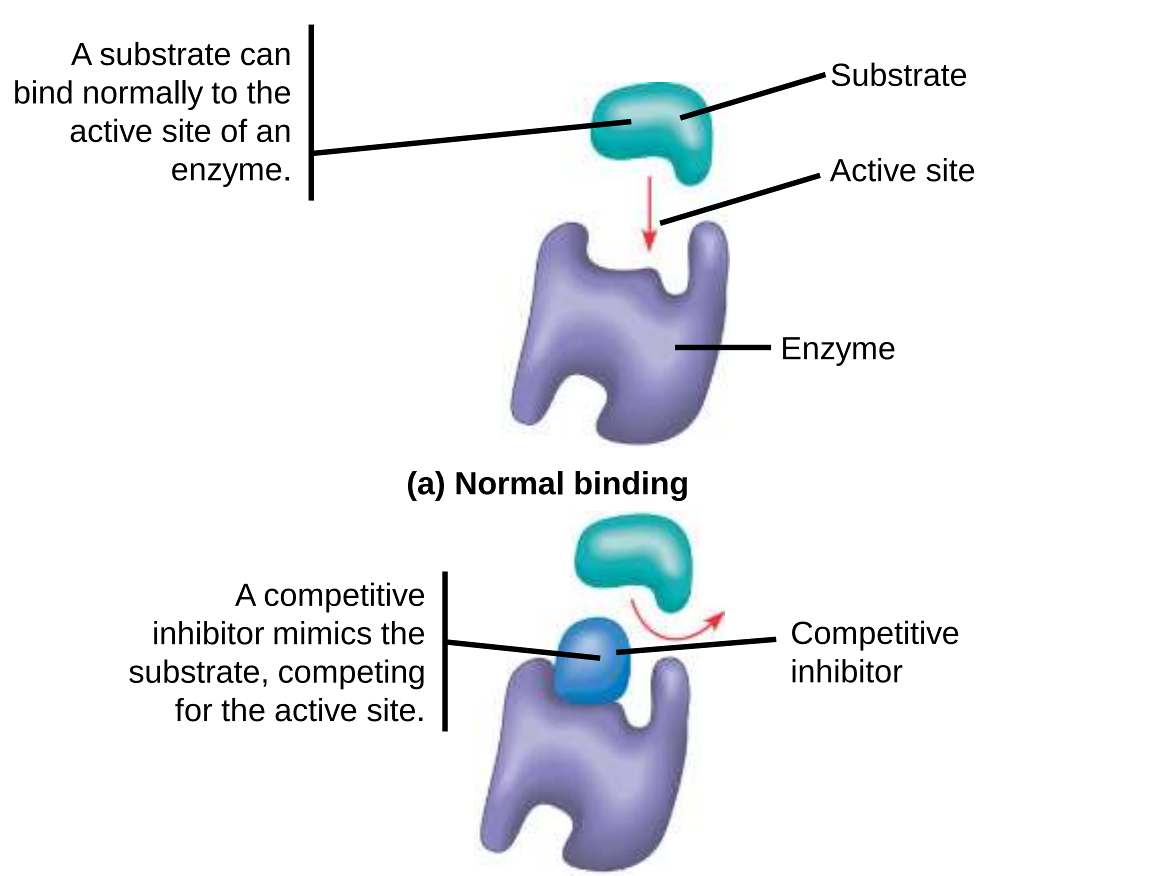


Figure 8.18

Enzyme Inhibitors

- Competitive inhibitors bind to the active site of an enzyme, competing with the substrate

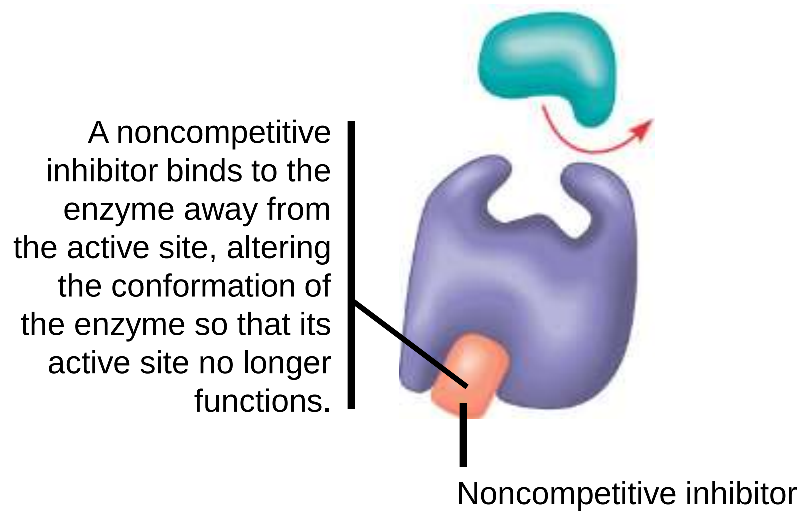


(a) Normal binding

(b) Competitive inhibition

Enzyme Inhibitors

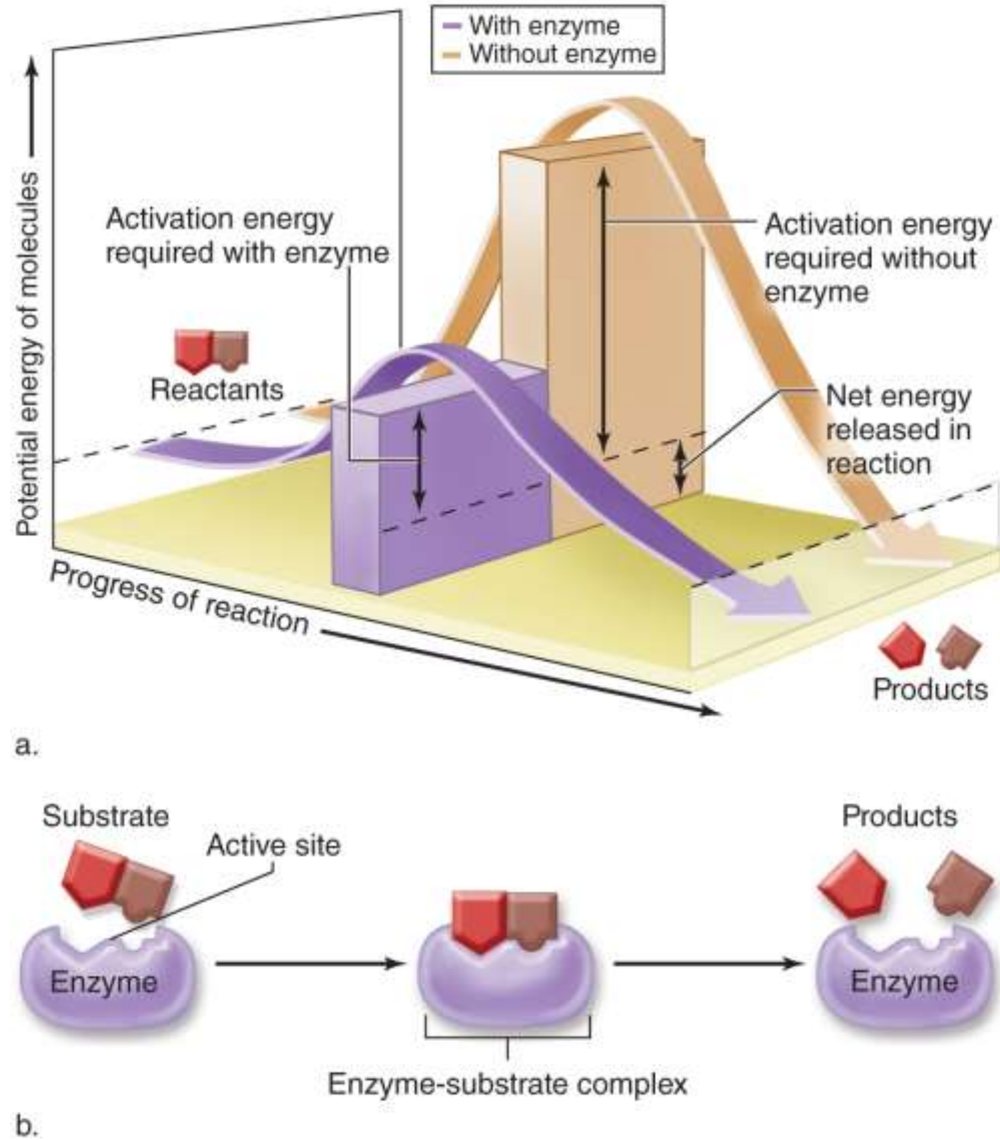
- Noncompetitive inhibitors bind to another part of an enzyme, changing the function



(c) Noncompetitive inhibition

Enzymes Speed Biochemical Reactions

Many enzymes have non-protein partners called **cofactors** that help catalyze reactions.
Some cofactors are metals (e.x. Zn, Fe, Cu, Mg)
Others are organic molecules called **coenzymes** (e.x. B-vitamins)



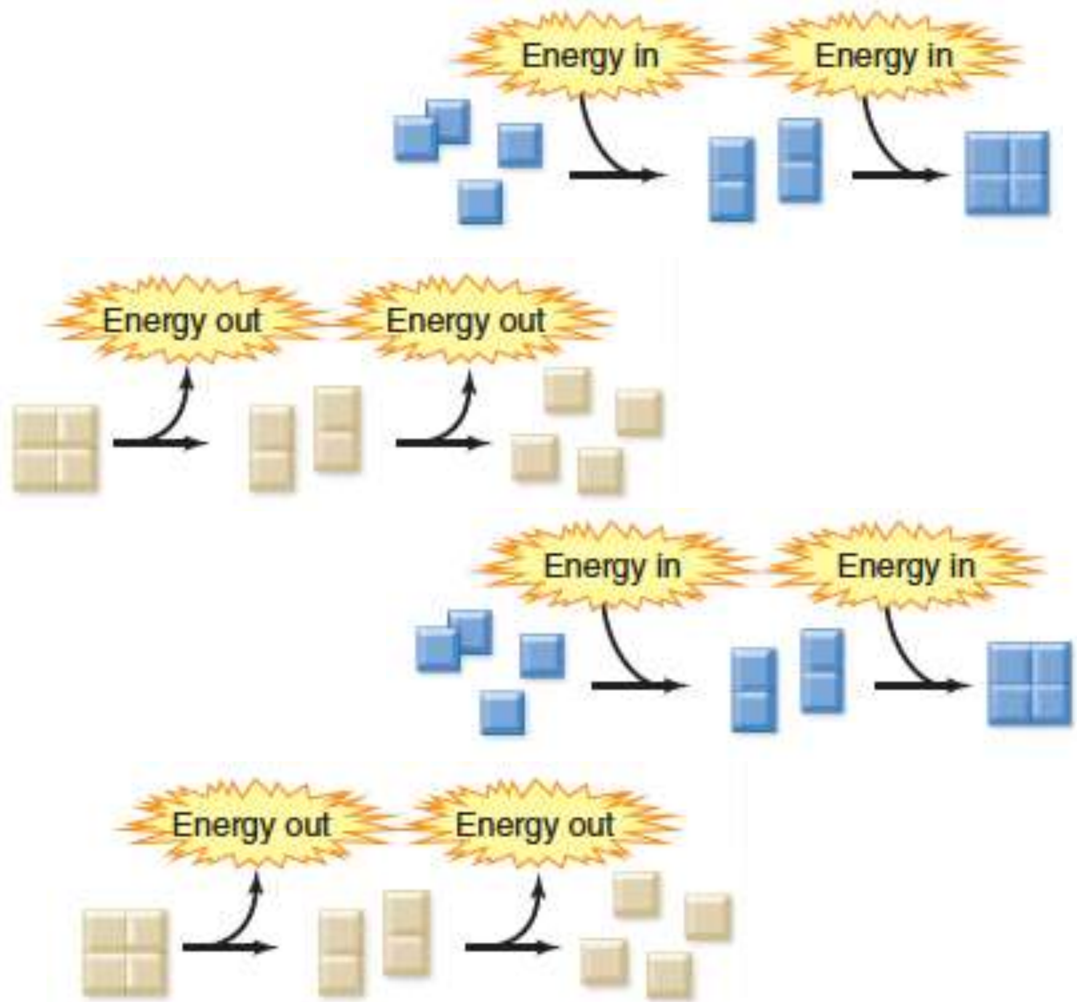
Section 4.4

Figure 4.11

Enzymes Speed Biochemical Reactions

Only some chemical reactions are occurring in a cell at a given time. How does the cell control the rate of chemical reactions?

Feedback loops



Section 4.4

Figure 4.4

Many Factors Affect Enzyme Activity

In a process called **negative feedback**, the product of a reaction slows the production of more product.

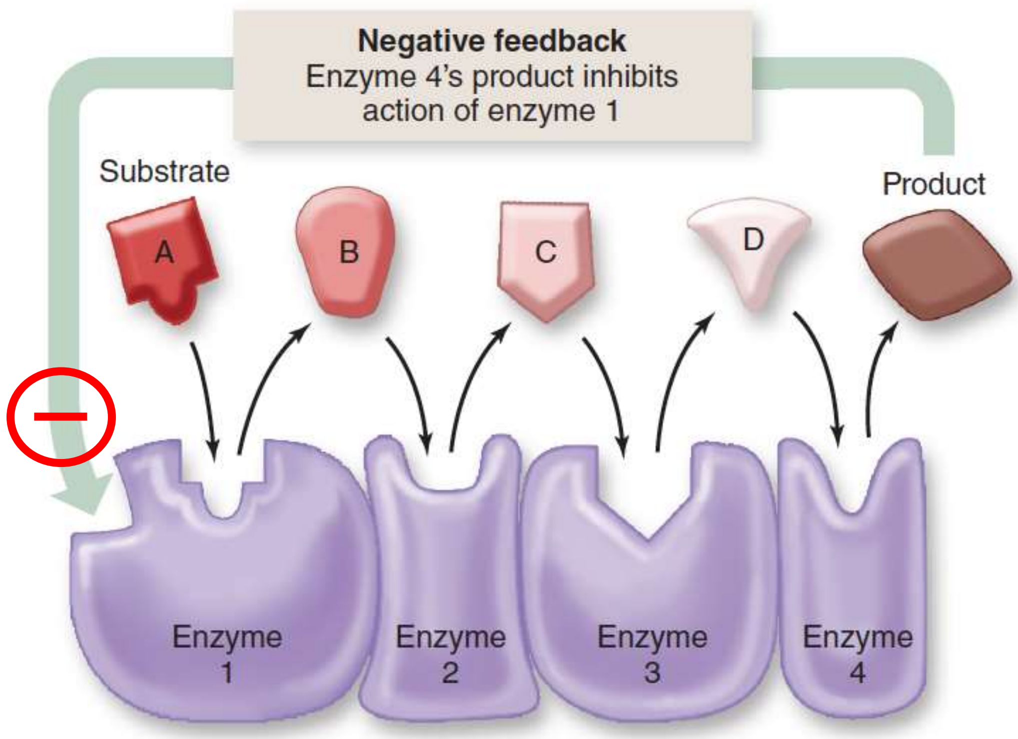
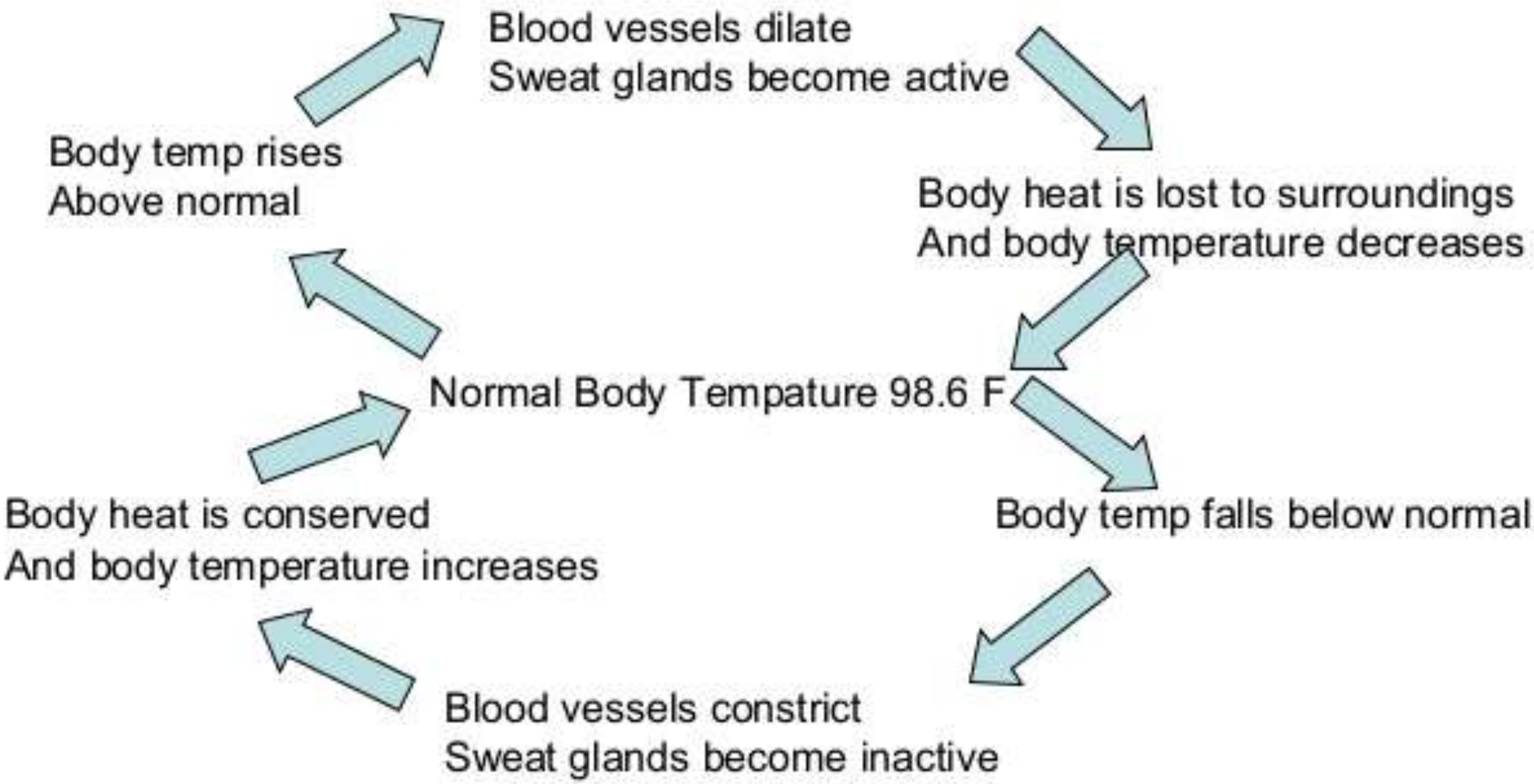


Figure 4.13

Negative Feedback



Many Factors Affect Enzyme Activity

In the opposite process, called **positive feedback**, the product of a reaction stimulates its own production.

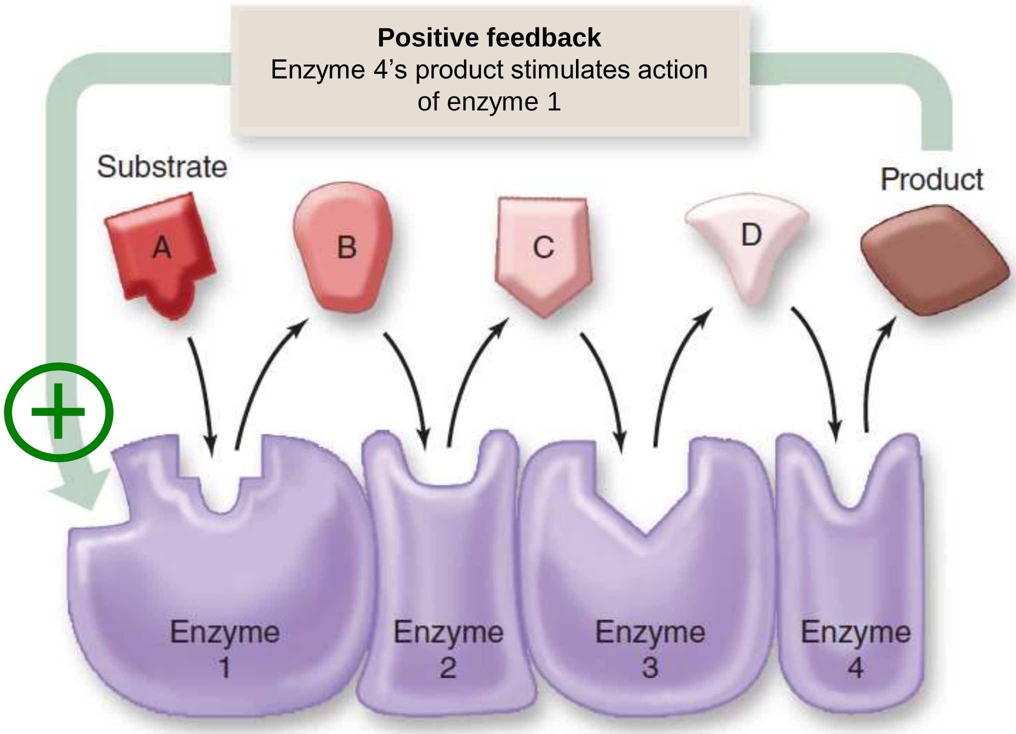
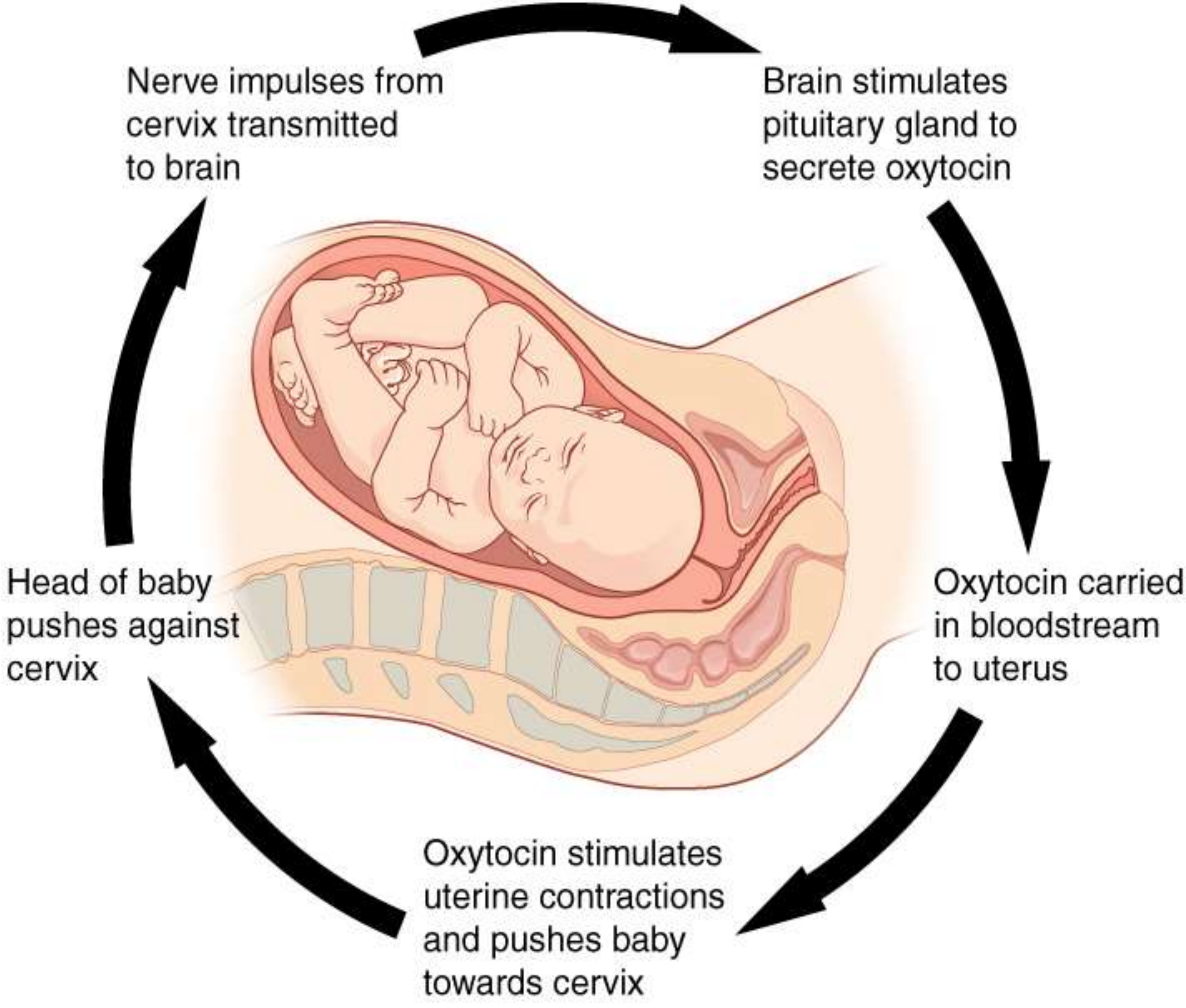


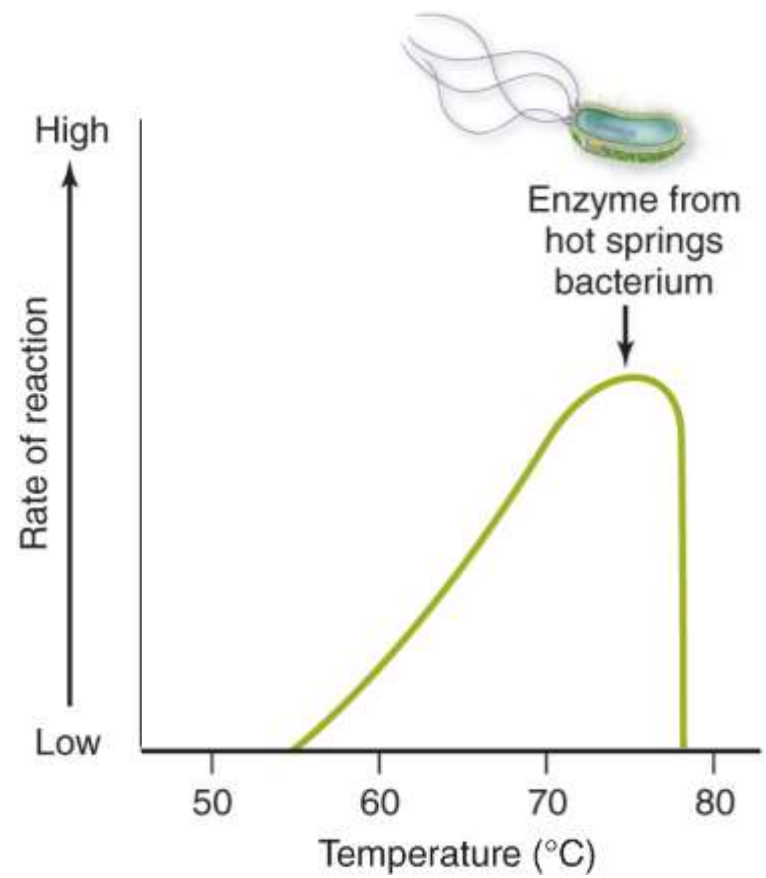
Figure 4.13


Nerve impulses from cervix transmitted to brain
Brain stimulates pituitary gland to secrete oxytocin
Oxytocin carried in bloodstream to uterus
Oxytocin stimulates uterine contractions and pushes baby towards cervix
Head of baby pushes against cervix

Clicker Question #4

According to the graph, at what temperature do you predict the bacterial enzyme becomes denatured?

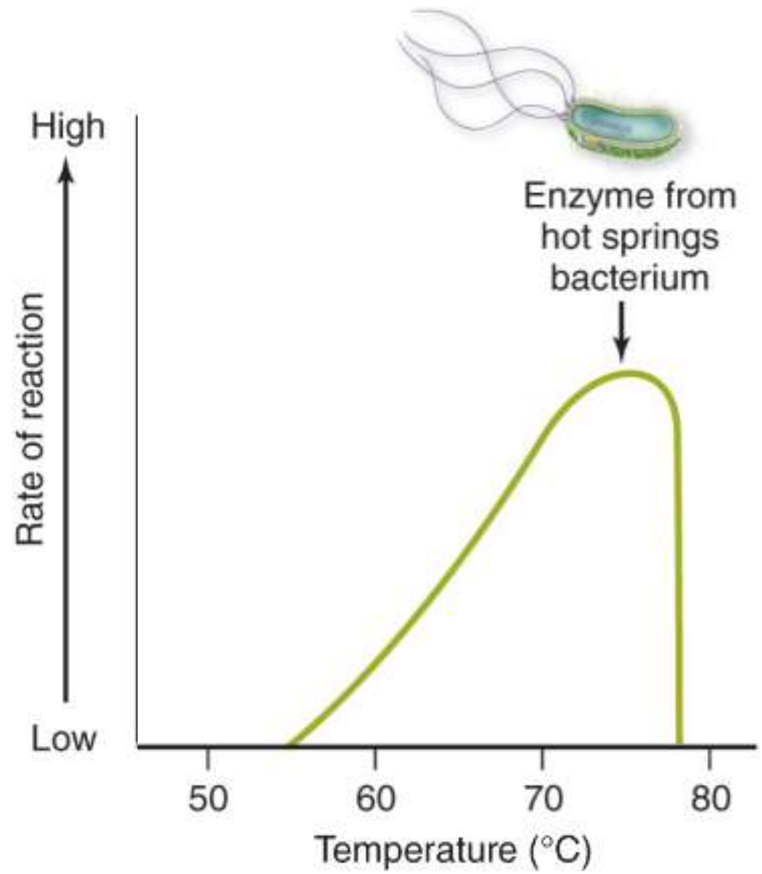
A. 55˚ C
B. 66˚ C
C. 73˚ C
D. 78˚ C



Clicker Question #4

According to the graph, at what temperature do you predict the bacterial enzyme becomes denatured?

A. 55° C
B. 66° C
C. 73° C
D. 78° C

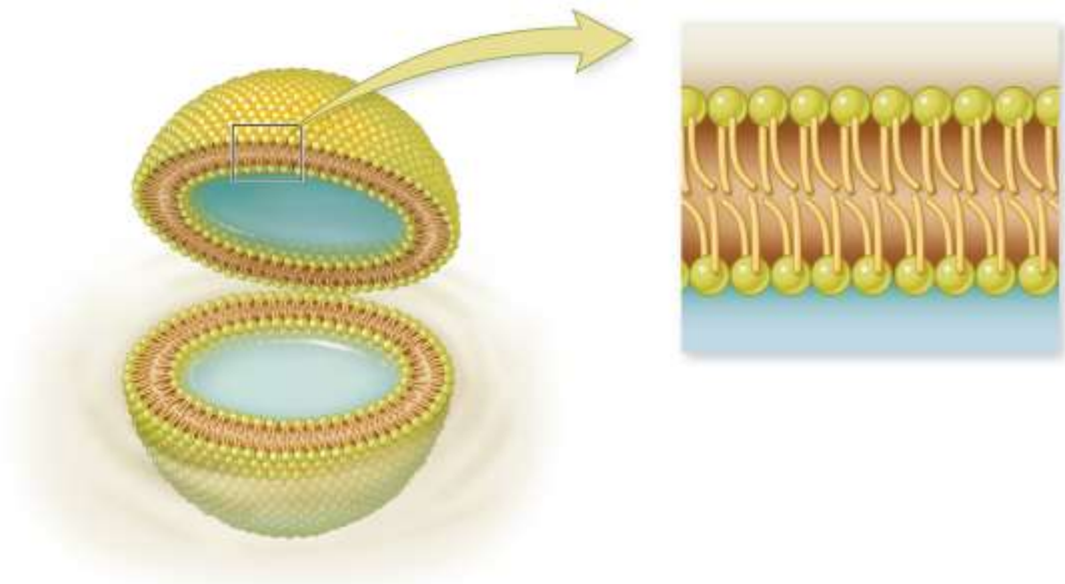


4.4 Mastering Concepts

What do enzymes do in cells?

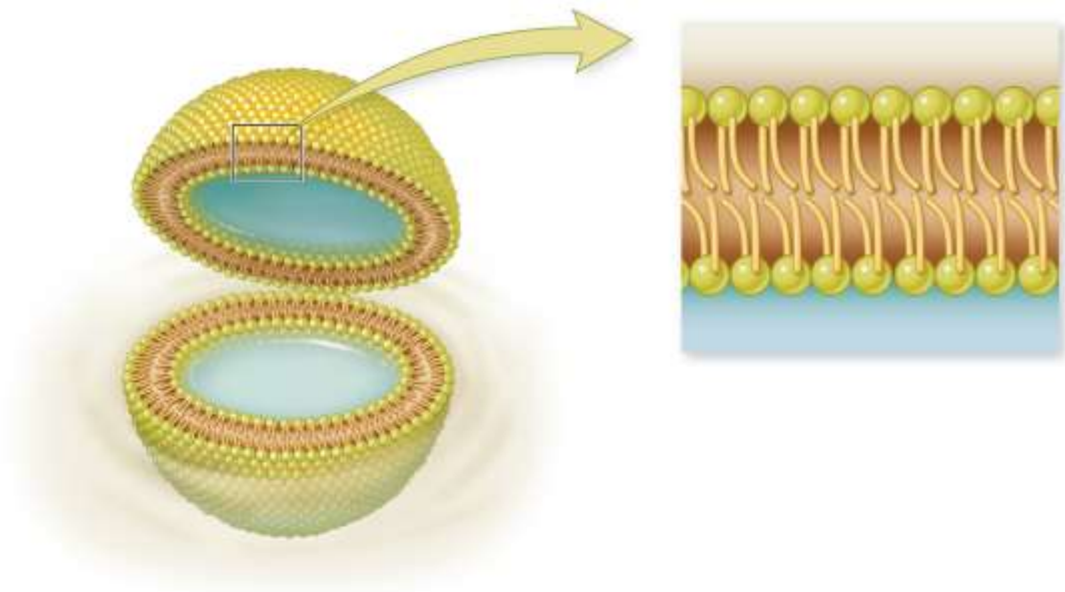
Substances Enter and Exit Cells By Multiple Methods

A cell's interior is chemically different from its exterior.
It maintains this difference by regulating transport of dissolved substances (solutes) across its membrane.



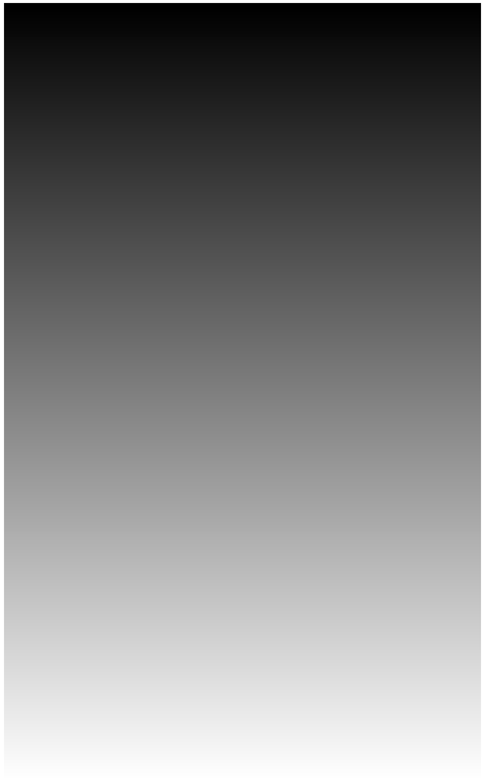
Substances Enter and Exit Cells By Multiple Methods

Solutes enter and exit cells by different methods, depending on two factors: concentration gradients and the chemical nature of the substance (polarity, charge, and size).



Section 4.5

"Gradient" Describes a Difference Between Neighboring Regions



Section 4.5

“Gradient” Describes a Difference Between Neighboring Regions

High concentration of black pixels

At the top, the black pixels are abundant and close together.

Section 4.5

“Gradient” Describes a Difference Between Neighboring Regions

High concentration of black pixels

Low concentration of black pixels

At the top, the black pixels are abundant and close together.

At the bottom, the black pixels are sparse.

“Gradient” Describes a Difference Between Neighboring Regions

This image is a **concentration gradient** of black pixels, with high concentration at the top and low concentration at the bottom.

High concentration of black pixels

At the top, the black pixels are abundant and close together.

Low concentration of black pixels

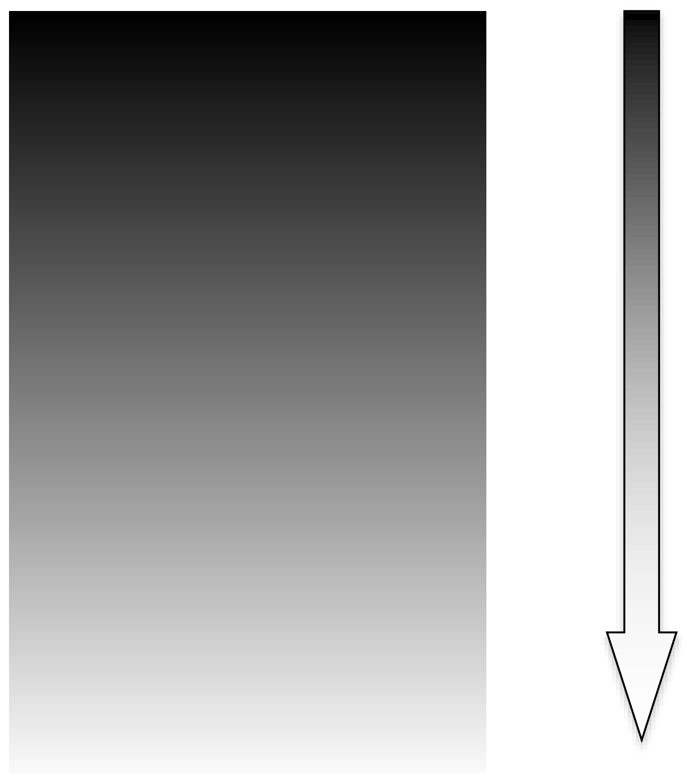
At the bottom, the black pixels are sparse.

Section 4.5

“Gradient” Describes a Difference Between Neighboring Regions

This image is a **concentration gradient** of black pixels, with high concentration at the top and low concentration at the bottom.

High concentration of black pixels



Low concentration of black pixels

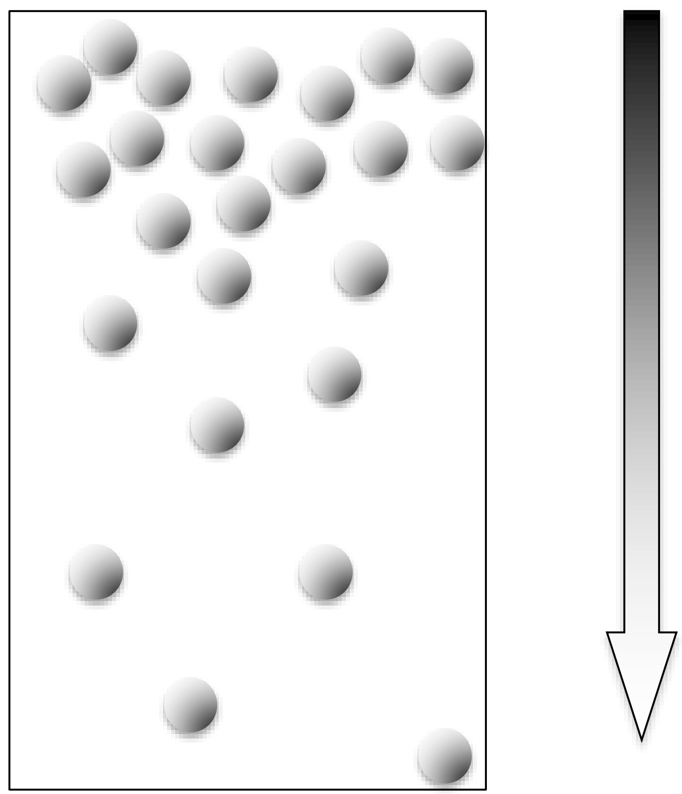
This arrow points *down the concentration gradient* since it starts at high concentration and ends at low concentration of black pixels.

Section 4.5

Concentration Gradients Have a Tendency to Dissipate

The balls within this box have the same concentration gradient as the black pixels did.

High concentration of balls

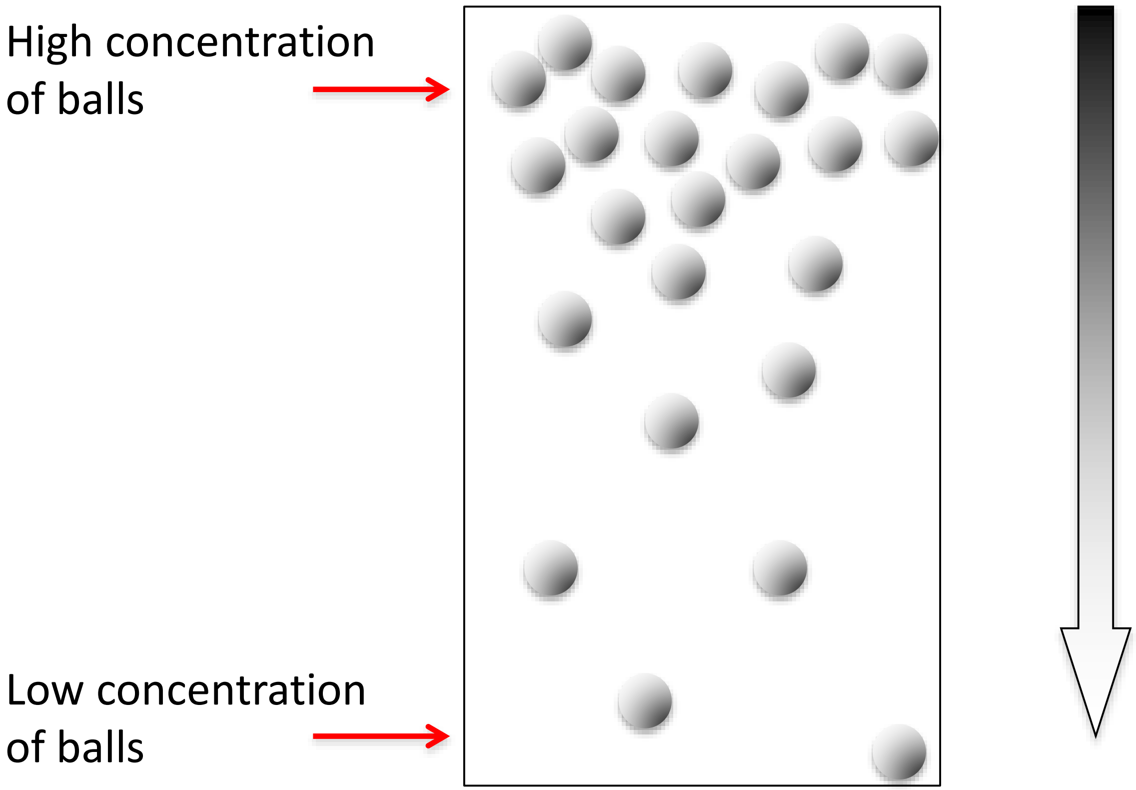


Low concentration of balls

This arrow points *down the concentration gradient* since it starts at high concentration and ends at low concentration of balls.

Concentration Gradients Have a Tendency to Dissipate

If the balls started bouncing around the box at random, they would become more evenly distributed over time.



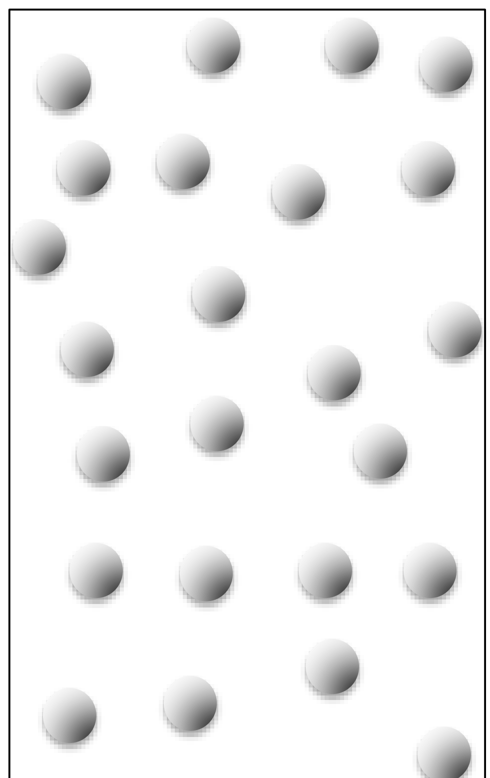
This arrow points *down the concentration gradient* since it starts at high concentration and ends at low concentration of balls.

Concentration Gradients Have a Tendency to Dissipate

This is how it would look after time has passed. No energy is required to dissipate the gradient; it occurs by random motion.

Equal distribution of balls

No concentration gradient



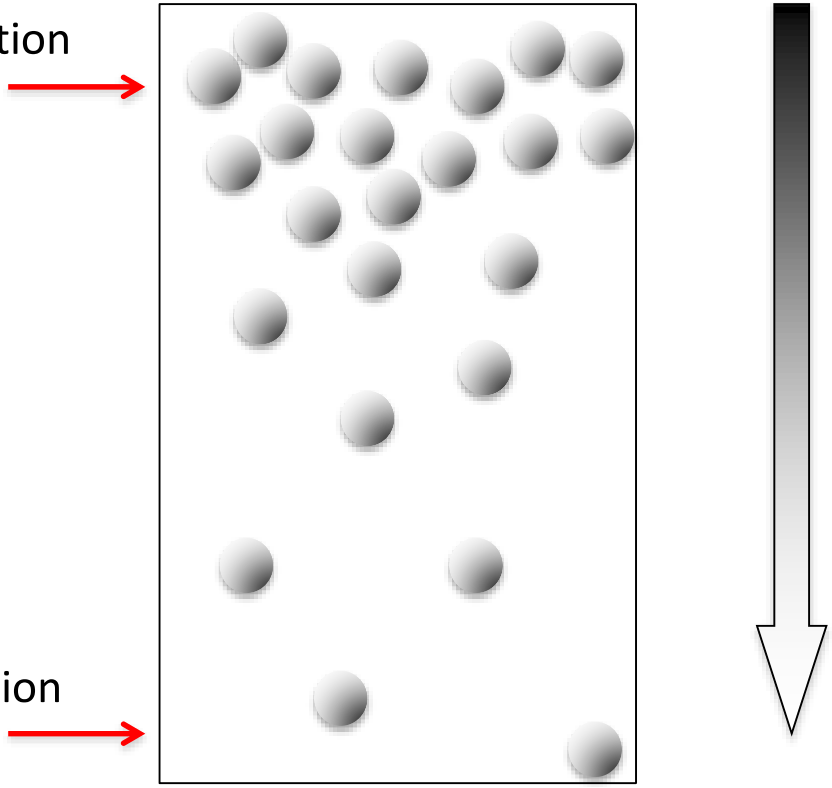
Section 4.5

Concentration Gradients Have a Tendency to Dissipate

Maintaining this distribution of balls within the box *requires energy*, since the concentration gradient has a tendency to dissipate.

High concentration of balls

Low concentration of balls

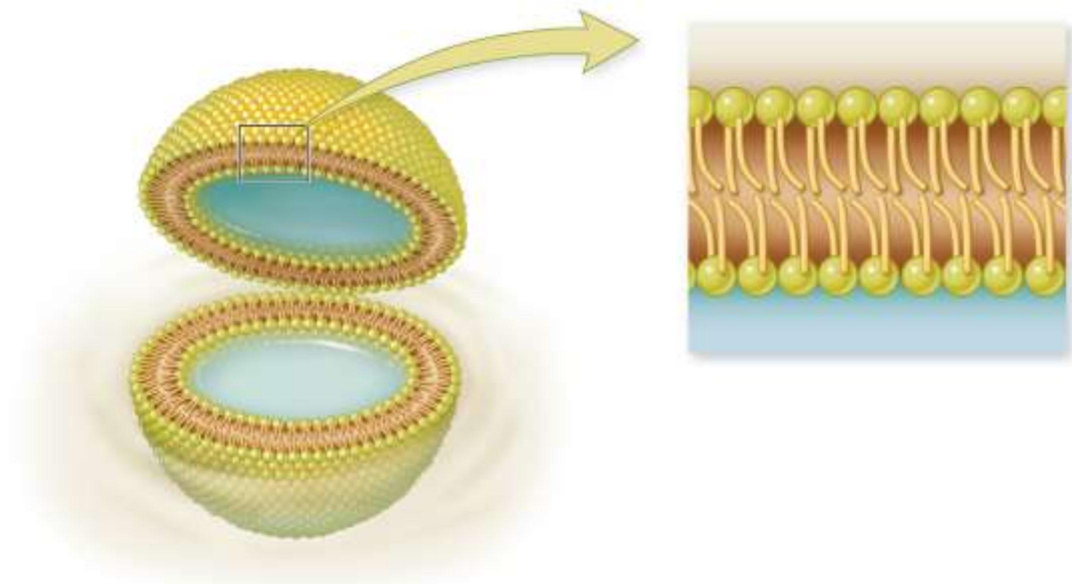


This arrow points *down the concentration gradient* since it starts at high concentration and ends at low concentration of balls.

Membrane Transport May Release or Cost Energy

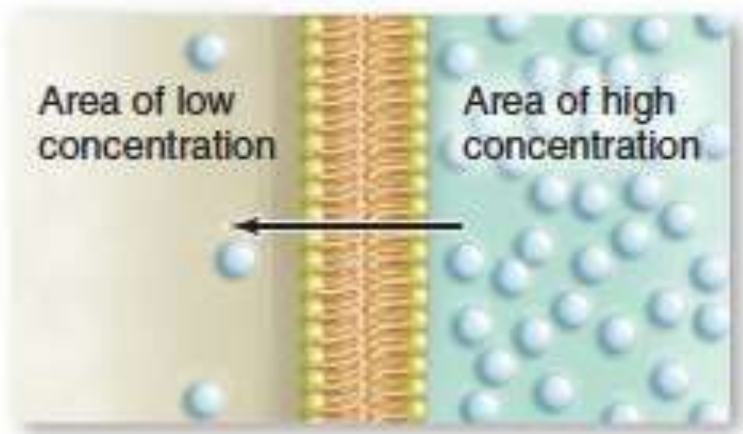
How cells transport substances across their membranes:

- Passive transport
  - Simple diffusion
  - Facilitated diffusion
  - Osmosis
- Active transport
- Endocytosis/exocytosis



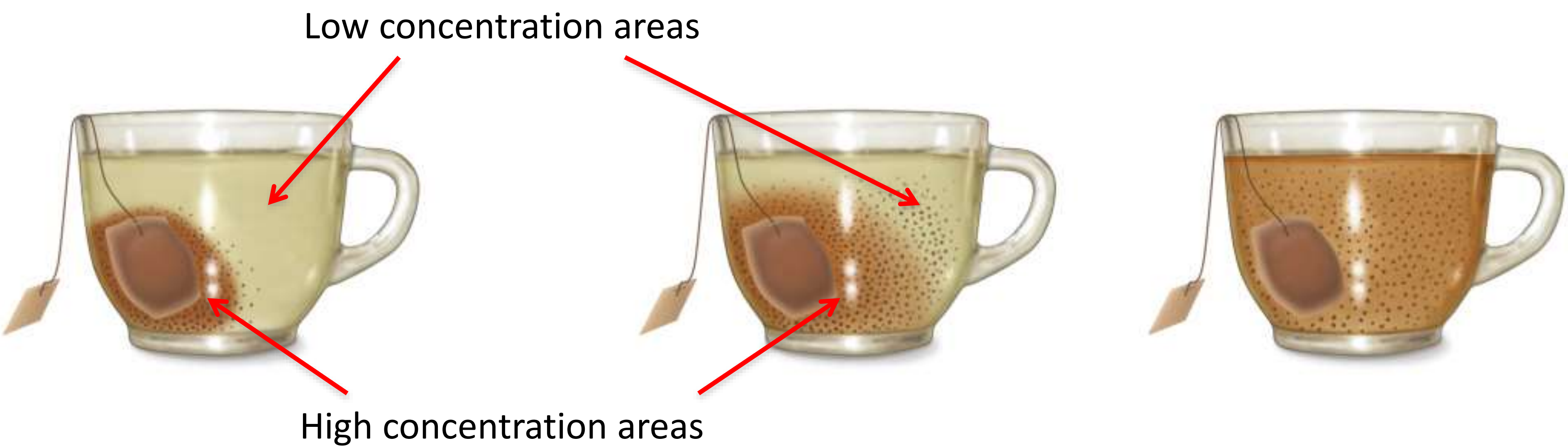
Passive Transport Does Not Require Energy

Passive transport occurs when concentration gradients dissipate across a biological membrane.

Simple diffusion	Substance moves across membrane without assistance of transport proteins. 

Passive Transport Does Not Require Energy

In **simple diffusion**, particles move from high concentration to low concentration—that is, they move down their concentration gradient.



Section 4.5

Figure 4.15

Passive Transport Does Not Require Energy

Osmosis, the diffusion of water down its concentration gradient, is also a type of passive transport.

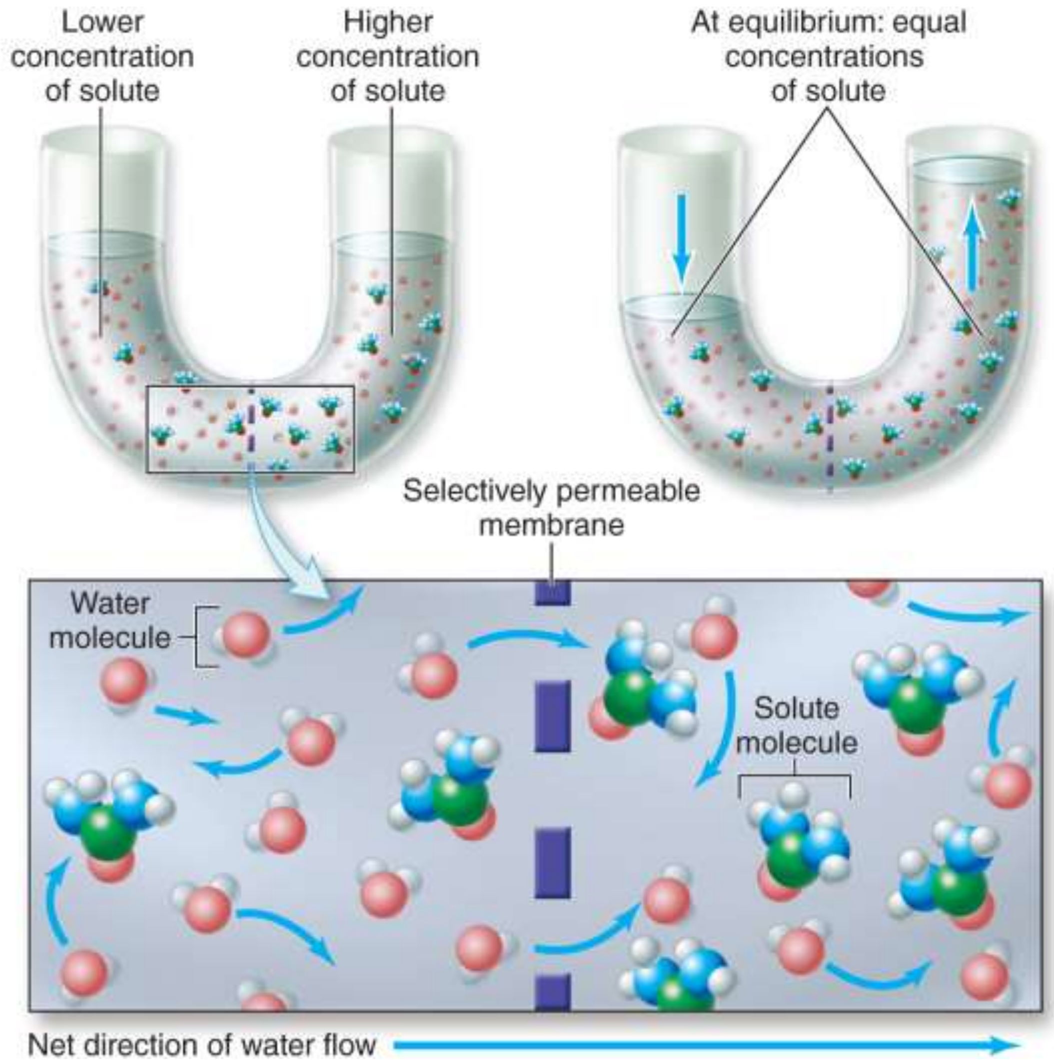


Figure 4.16

Passive Transport Does Not Require Energy

Water moves toward high solute concentrations as it moves down its concentration gradient.

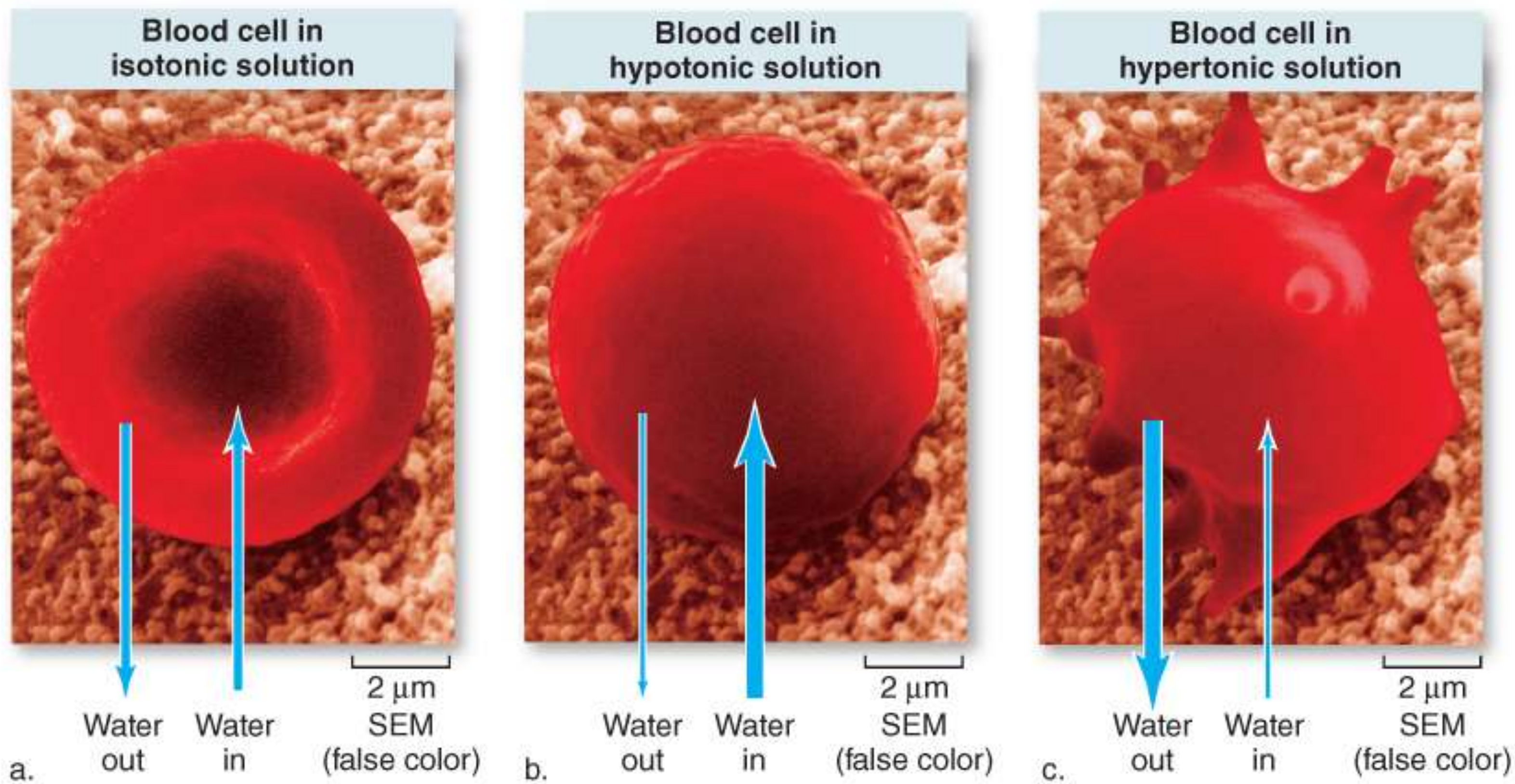


Figure 4.17

Passive Transport Does Not Require Energy

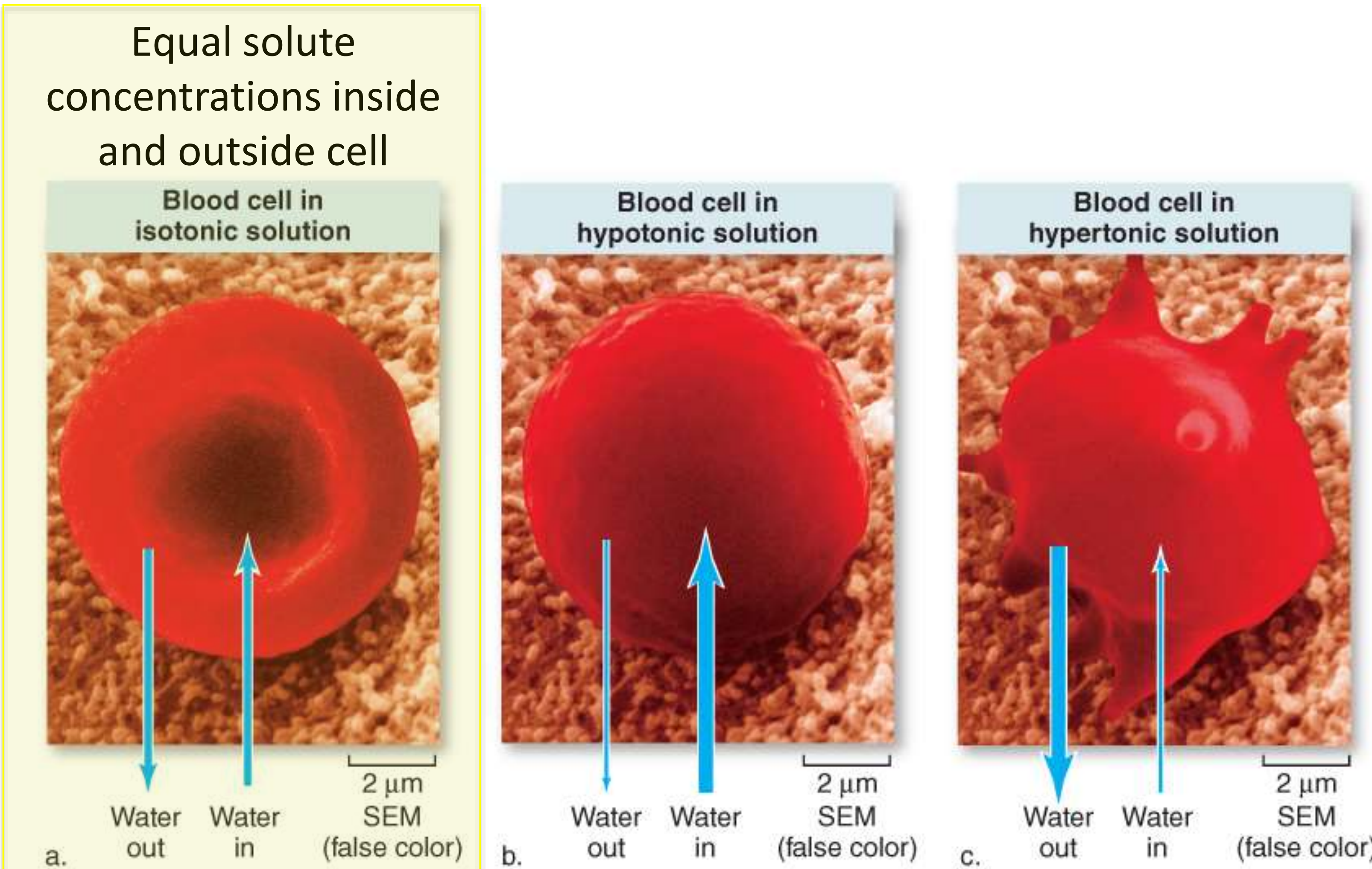


Figure 4.17

Passive Transport Does Not Require Energy

Higher solute concentration inside cell

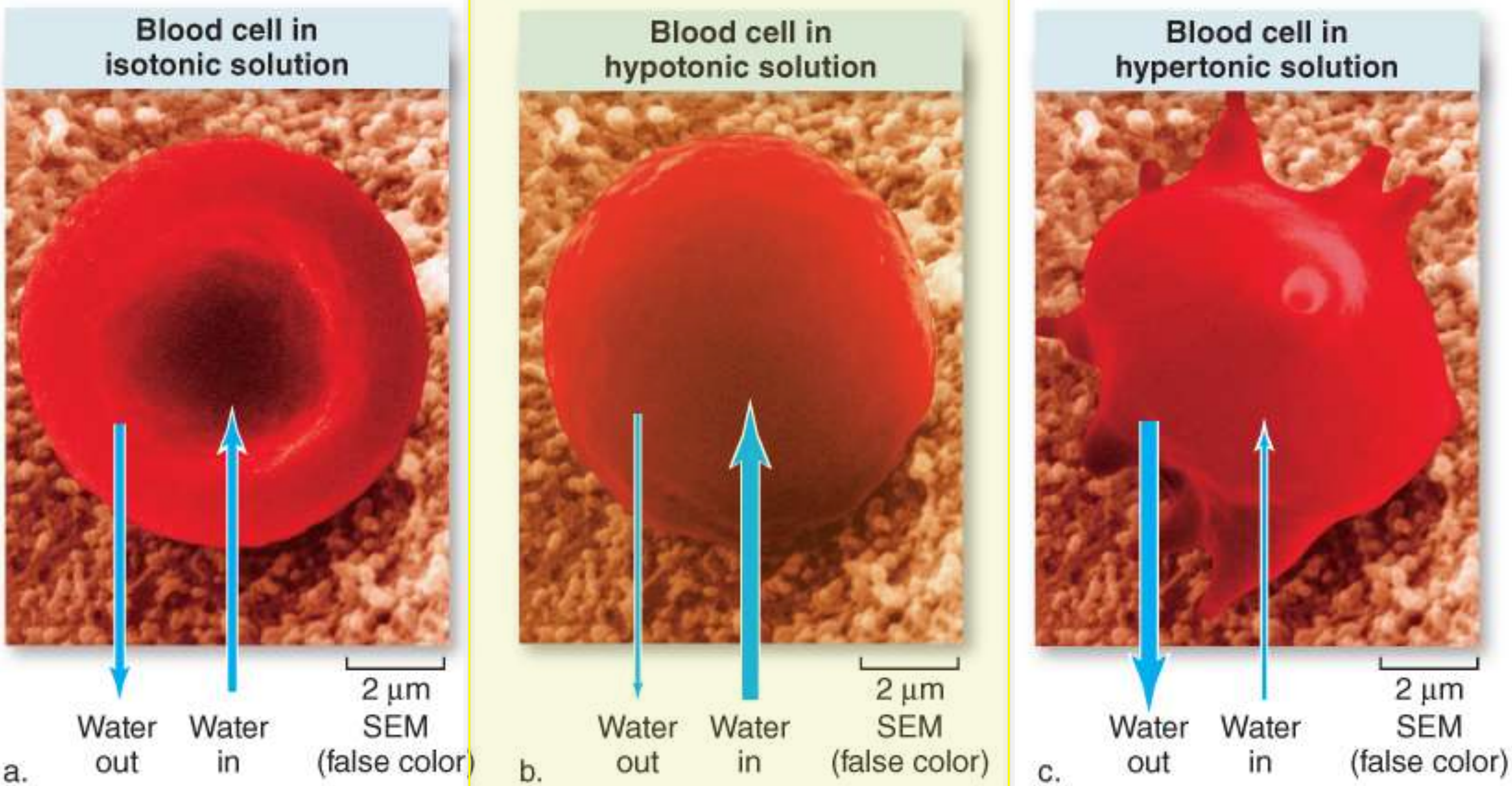


Figure 4.17

Passive Transport Does Not Require Energy

Lower solute concentration inside cell

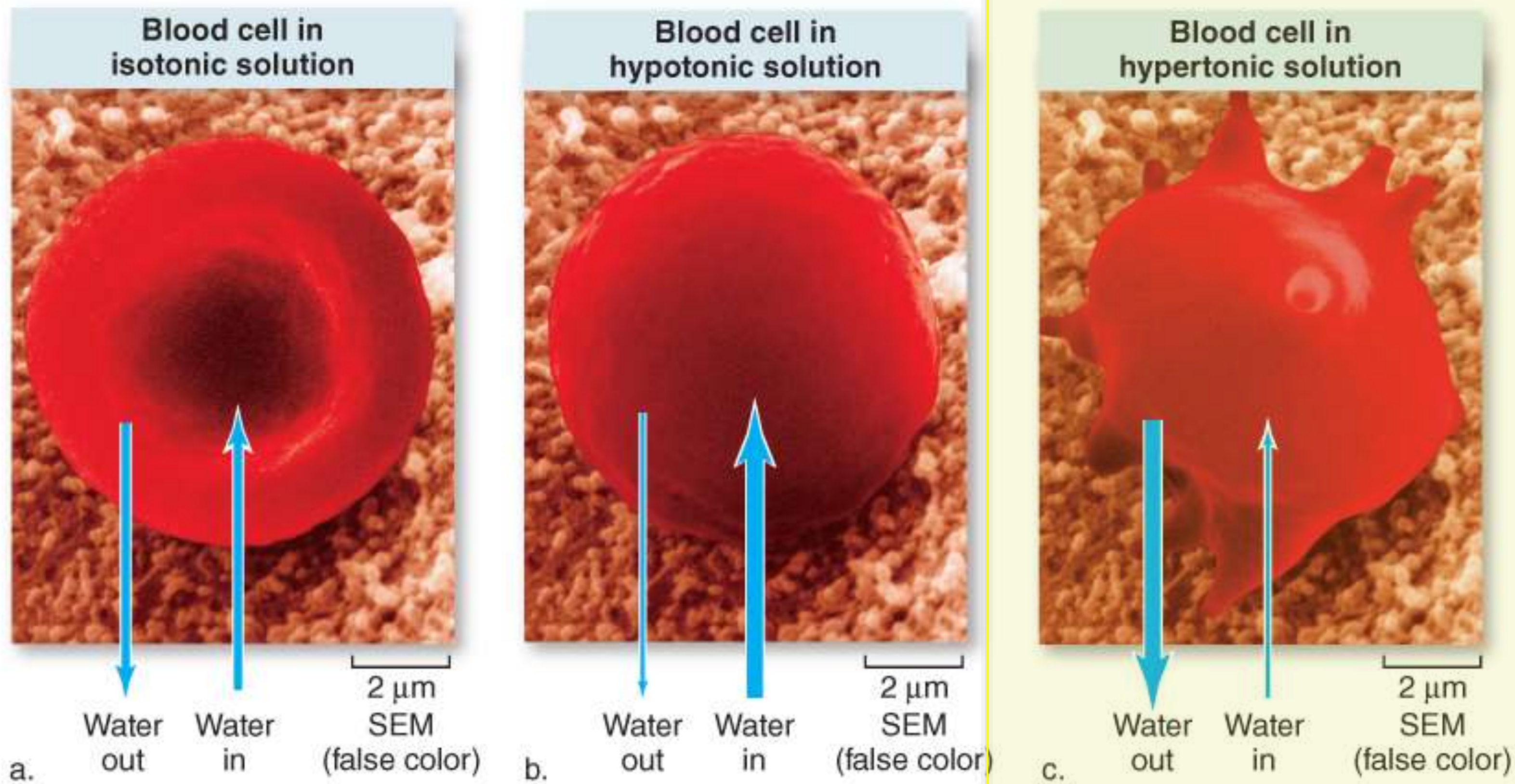
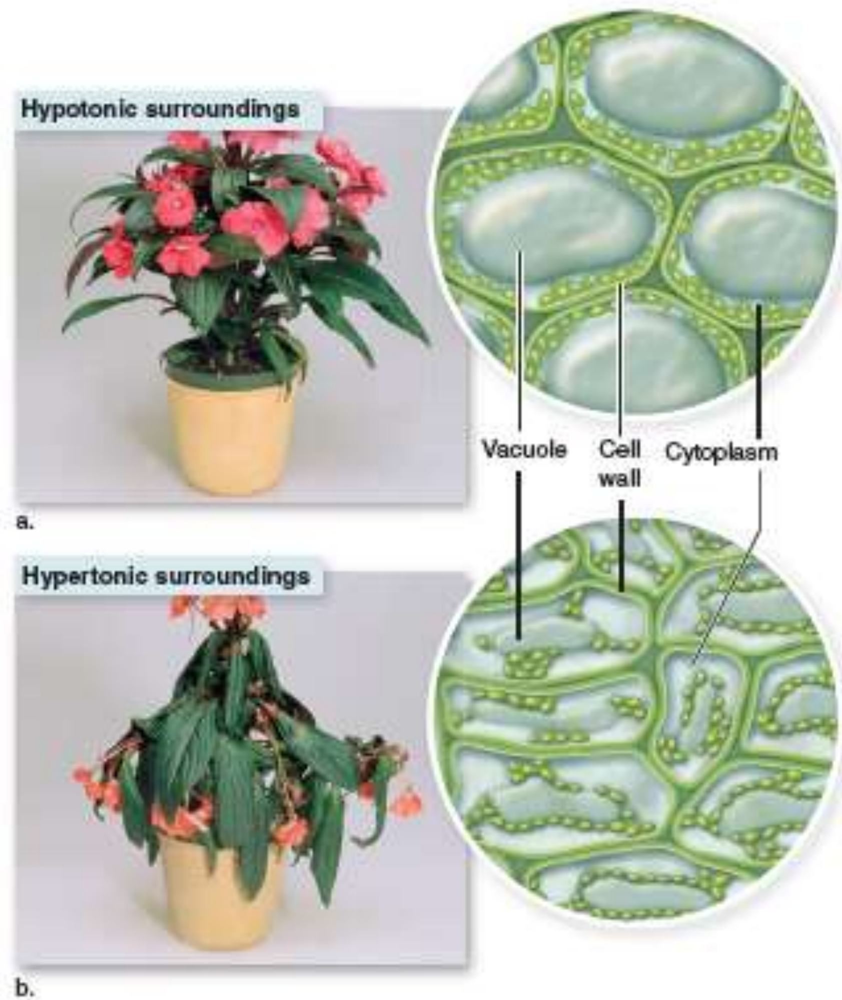


Figure 4.17

Passive Transport Does Not Require Energy

Osmosis determines how much water is in plant cells. Hypotonic surroundings result in a loss of **turgor pressure**, causing the plant to wilt.



Passive Transport Does Not Require Energy

Facilitated diffusion is passive transport that requires membrane proteins.

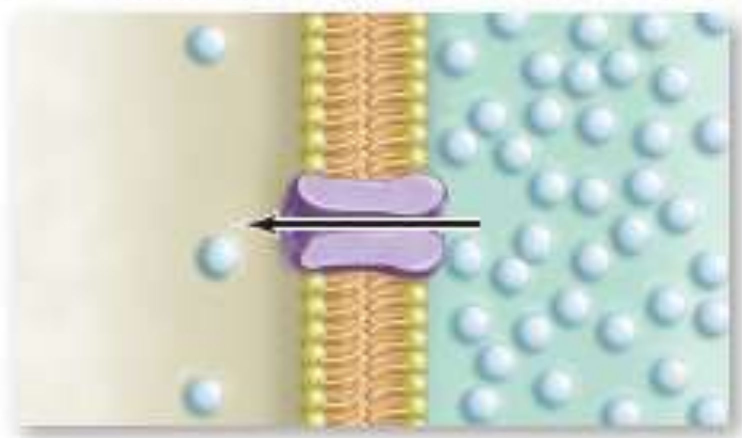
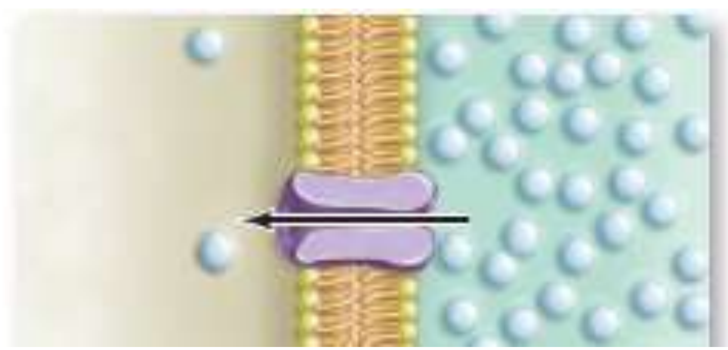
Facilitated diffusion	Substance moves across membrane with assistance of transport proteins. 

Table 4.2

Membrane Proteins Transport Ions and Polar Molecules

The hydrophobic tails of phospholipids repel hydrophilic substances. Therefore, ions (such as Cl^- and Na^+) and polar substances must pass through a protein channel to cross the membrane.



Active Transport Requires Energy

In **active transport,** the cell uses energy and a transport protein to move a substance *against* its concentration gradient.

Active transport	Net movement is against concentration gradient; requires transport protein and energy input, often from ATP.

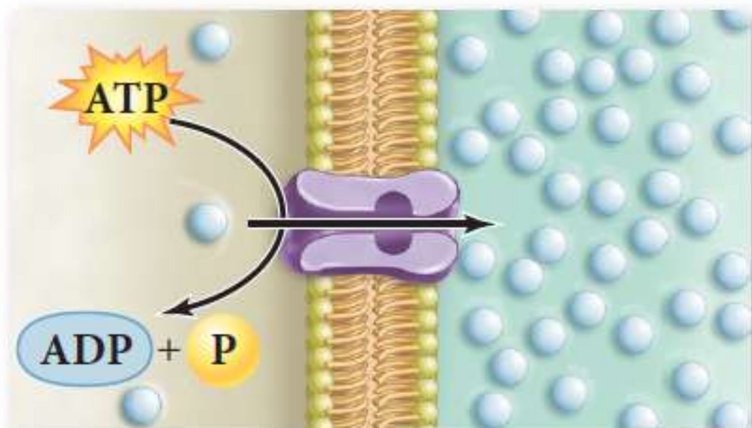
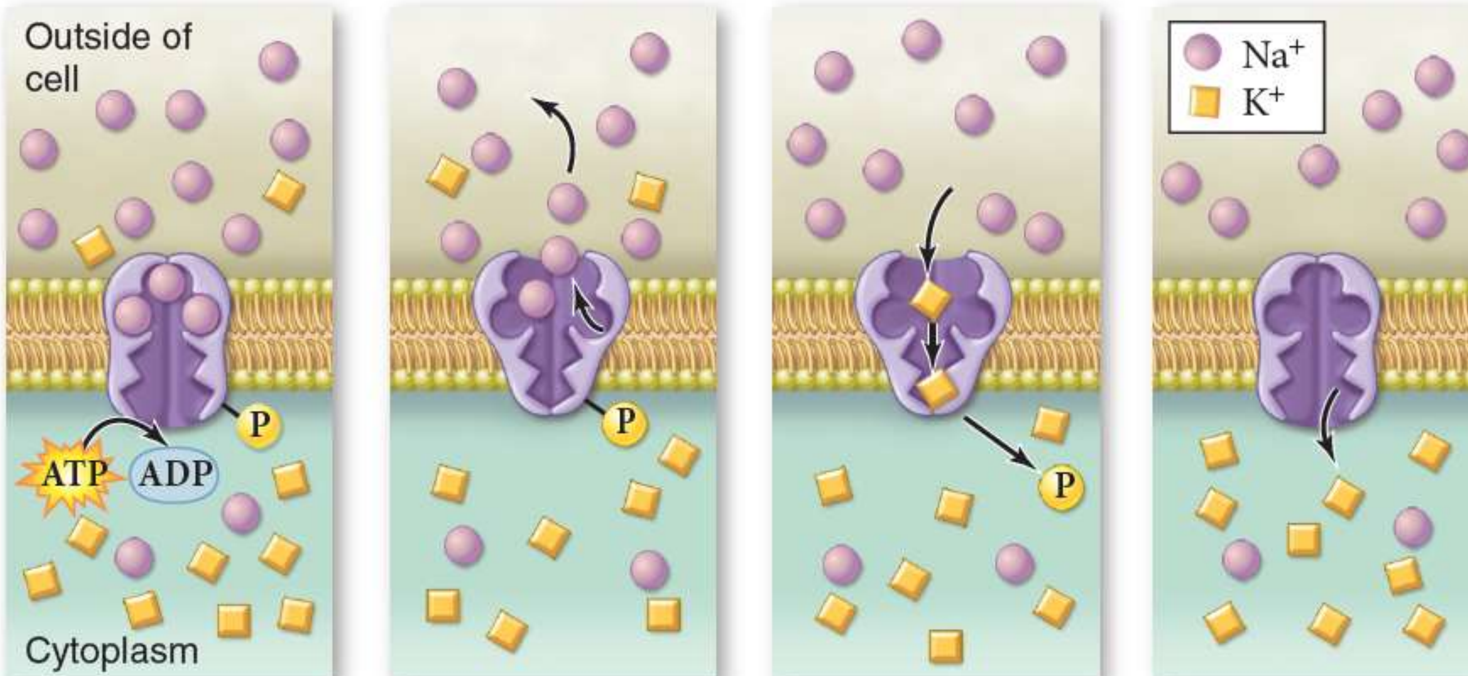


Table 4.2

Active Transport Requires Energy

For example, the sodium-potassium pump uses ATP to transport Na^+ and K^+ across the membrane.



1 ATP binds to transport protein along with three Na^+ from cytoplasm. ATP transfers phosphate to protein.

2 Phosphate changes the shape of the protein, moving Na^+ across the membrane.

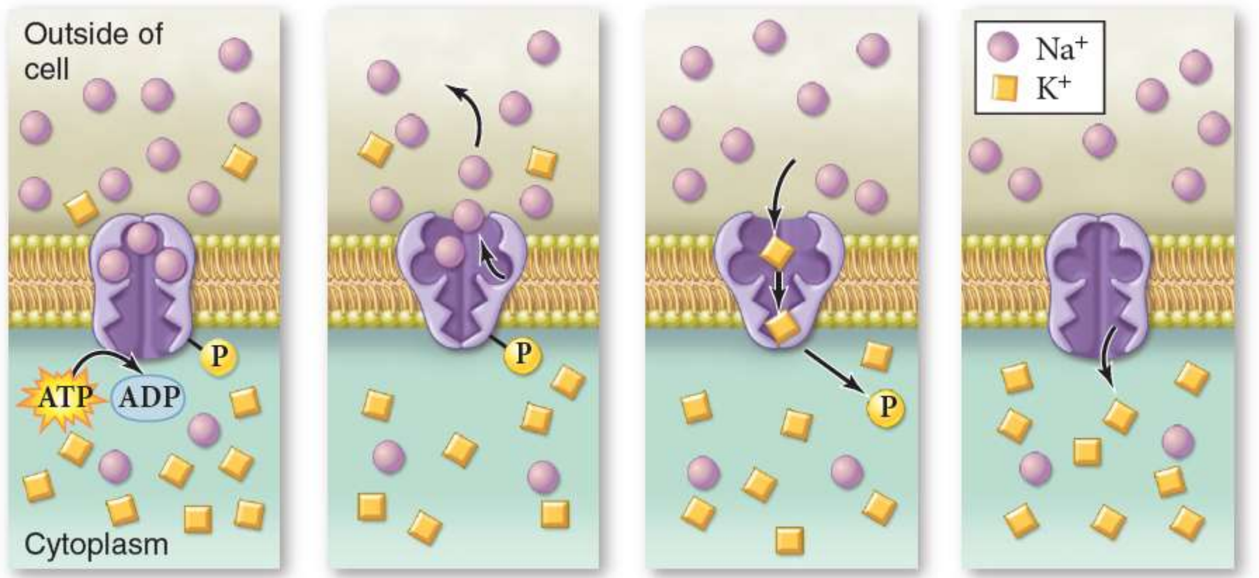
3 Two K^+ from outside of cell bind to protein, causing phosphate release.

4 Release of phosphate changes the shape of the protein, moving K^+ into the cytoplasm.

Figure 4.19

Clicker Question #5

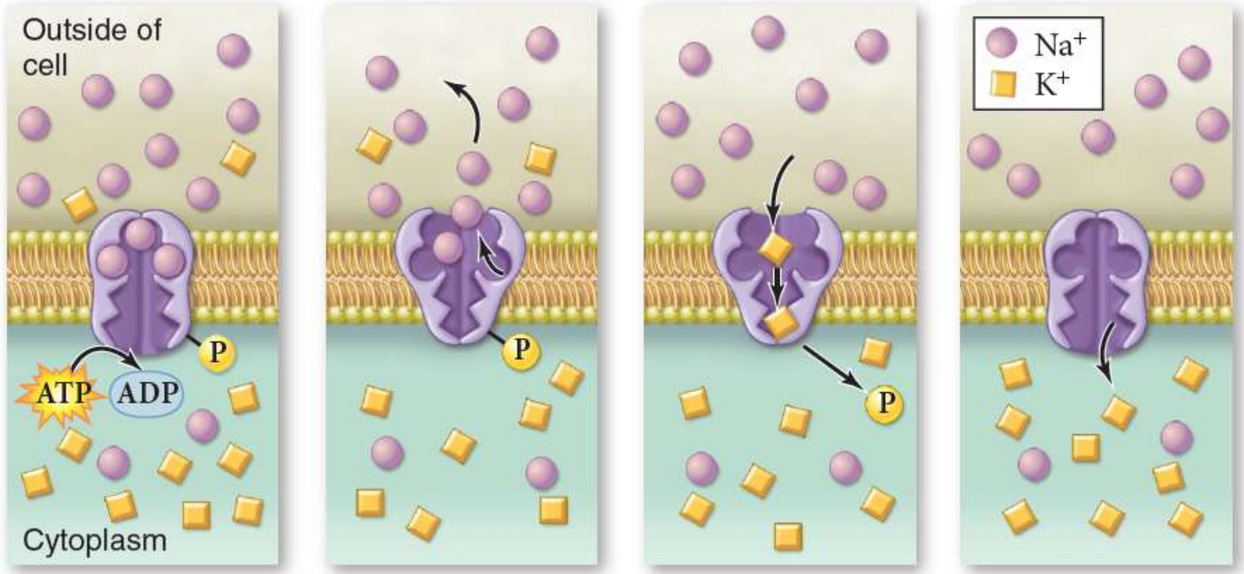
Why does the sodium-potassium pump require energy? Refer to the image below.



A. It uses a membrane protein.
B. It transports ions.
C. It moves solutes against their concentration gradients.
D. All of the choices are correct.

Clicker Question #5

Why does the sodium-potassium pump require energy? Refer to the image below.



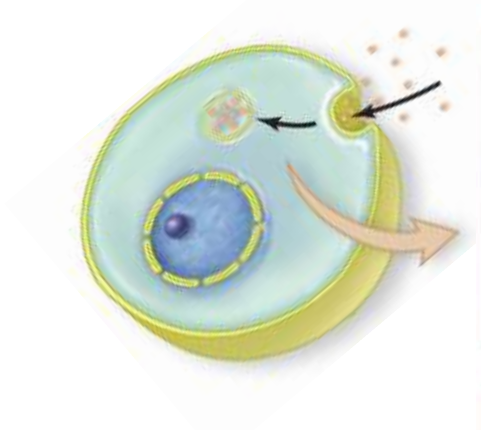
A. It uses a membrane protein.

B. It transports ions.

C. It moves solutes against their concentration gradients.

D. All of the choices are correct.

Large Substances Enter or Leave Cells in Vesicles



Endocytosis allows a cell to engulf fluids and large molecules and bring them into the cell.

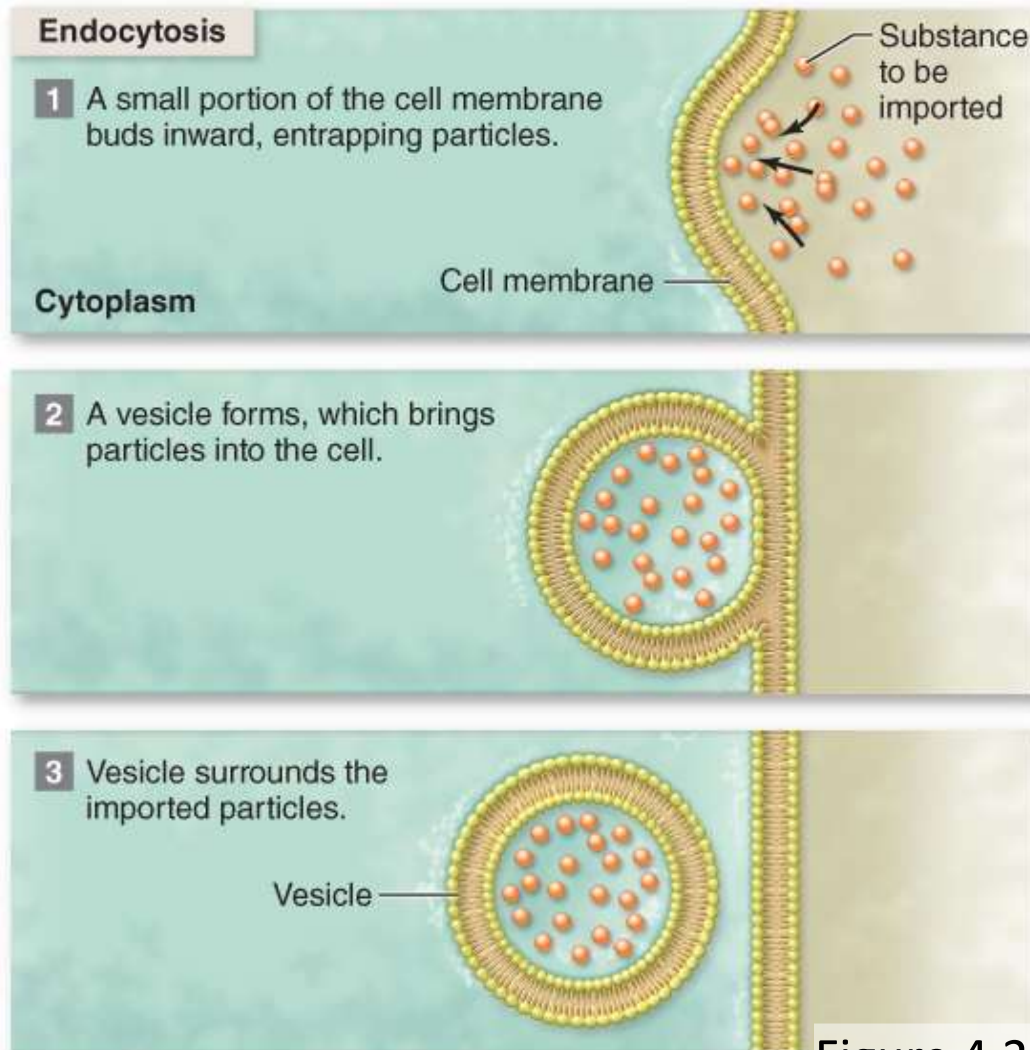
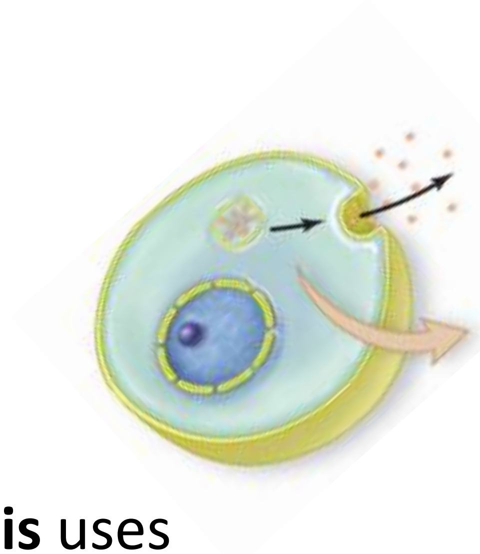
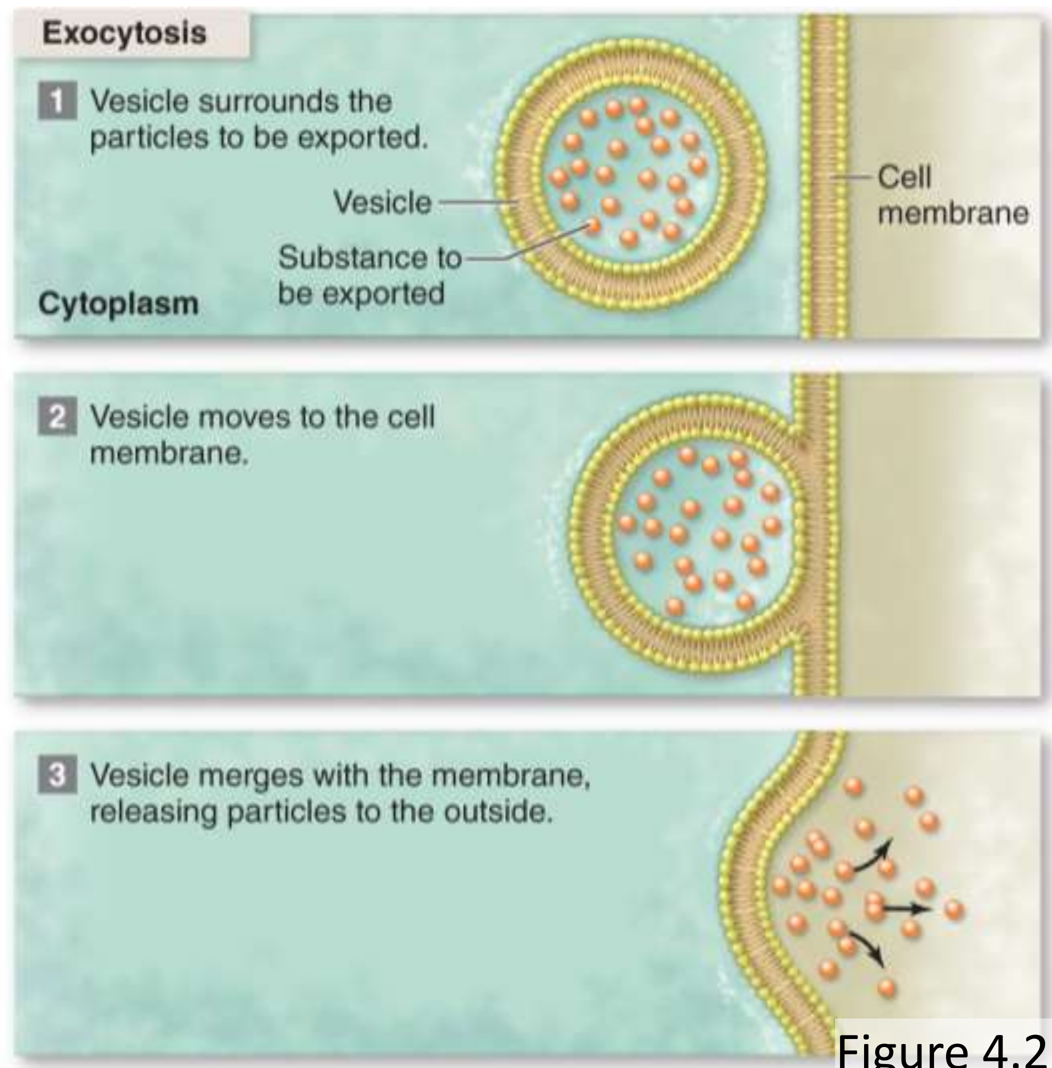


Figure 4.20

Large Substances Enter or Leave Cells in Vesicles



Exocytosis uses vesicles to transport substances out of cells.



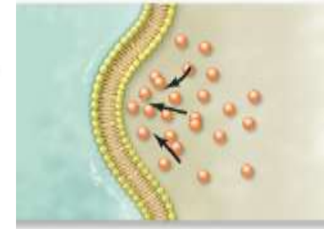
Section 4.5

Figure 4.21

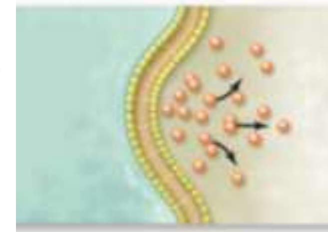
Membrane Transport Summary

Is the substance very large? — Yes → Is the substance entering or leaving the cell?

- Entering → **Endocytosis** →

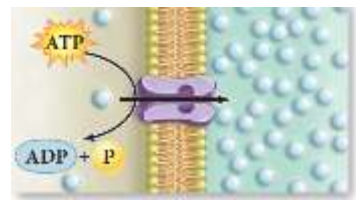


- Leaving → **Exocytosis** →



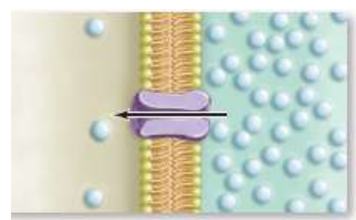
Is the substance very large? — No ↓

Is the substance moving down its concentration gradient? — No → **Active transport** →



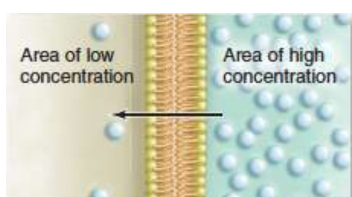
Is the substance moving down its concentration gradient? — Yes ↓

Is the substance nonpolar? — No → **Facilitated diffusion** →



Is the substance nonpolar? — Yes ↓

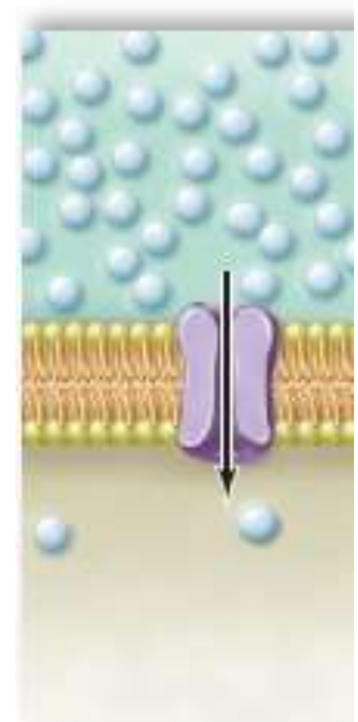
Simple diffusion →



Clicker Question #6

This solute is ____, and its transport _____ require ATP.

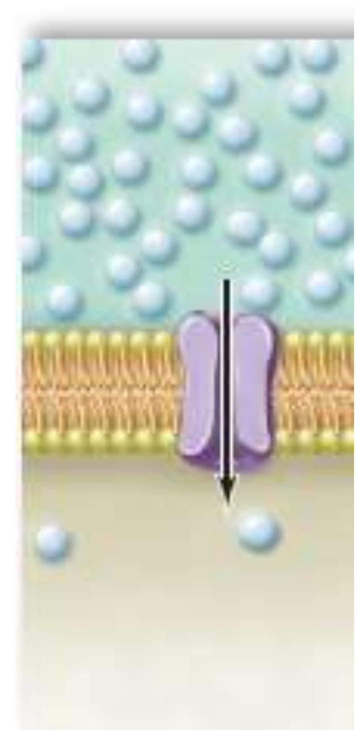
A. polar … does not
B. polar … does
C. nonpolar … does not
D. nonpolar … does



Clicker Question #6

This solute is ____, and its transport _____ require ATP.

A. polar … does not
B. polar … does
C. nonpolar … does not
D. nonpolar … does

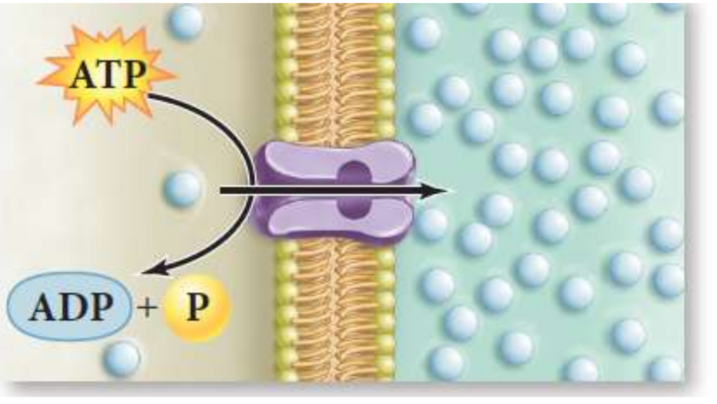


4.5 Mastering Concepts

Distinguish between simple diffusion, facilitated diffusion, and active transport.

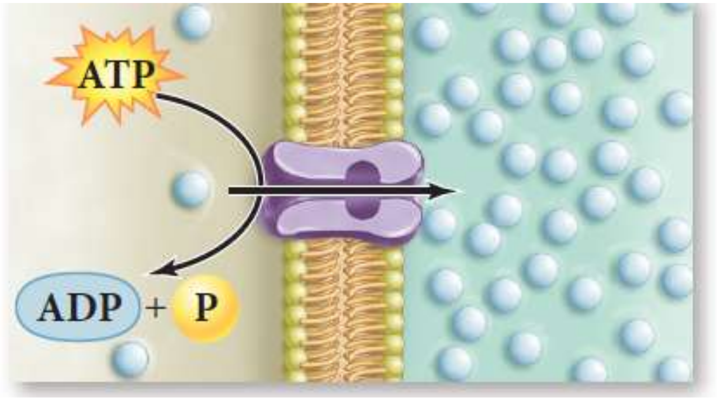
Investigating Life: Does Natural Selection Some Genetic Illnesses?

Membrane proteins called CFTR occur in tissues that secrete watery fluids, such as the linings of the lungs and intestines.



Investigating Life: Does Natural Selection Maintain Cystic Fibrosis?

CFTR proteins move chloride ions out of cells by active transport. Water follows by osmosis.



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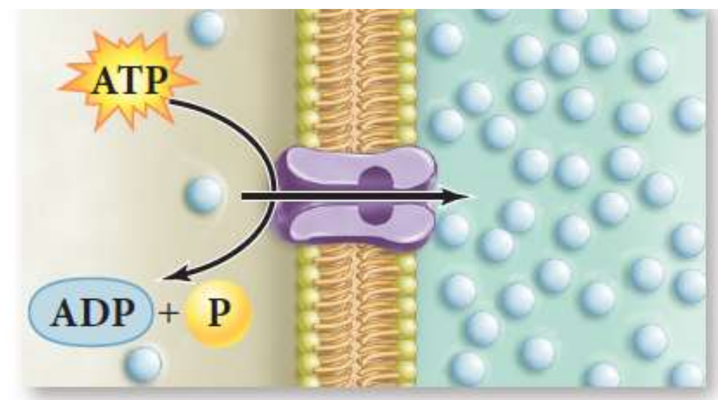
In the lungs, CFTR proteins help to thin the mucus. Patients with cystic fibrosis lack functional CFTR proteins. The mucus remains thick, making breathing difficult.



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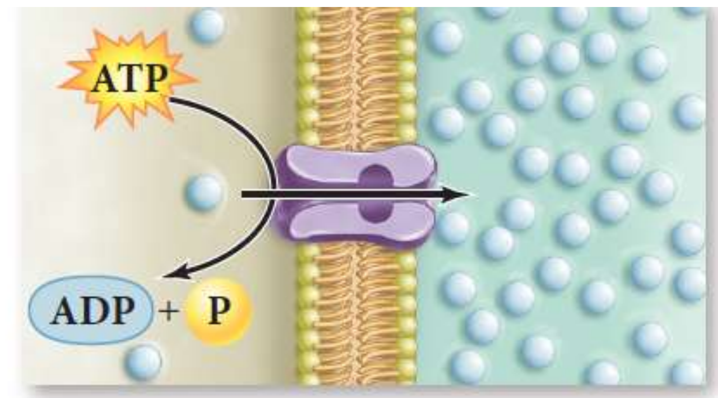
In contrast, the cholera toxin overstimulates CFTR proteins, resulting in watery diarrhea and severe dehydration.



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The faulty CFTR proteins that cause cystic fibrosis might be maintained in the population by protecting against cholera.

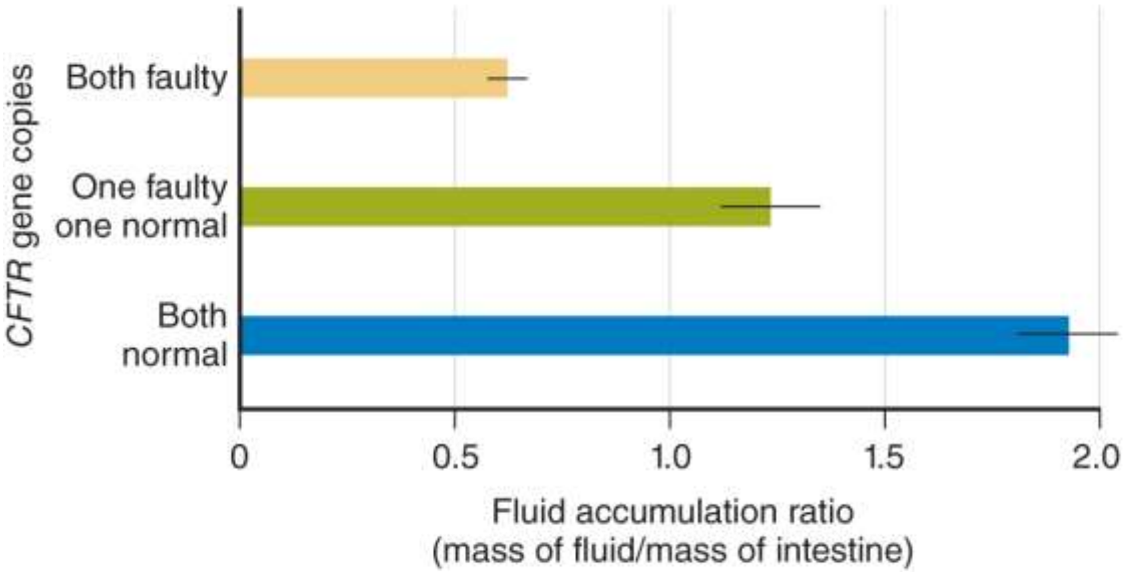

Figure 4.22