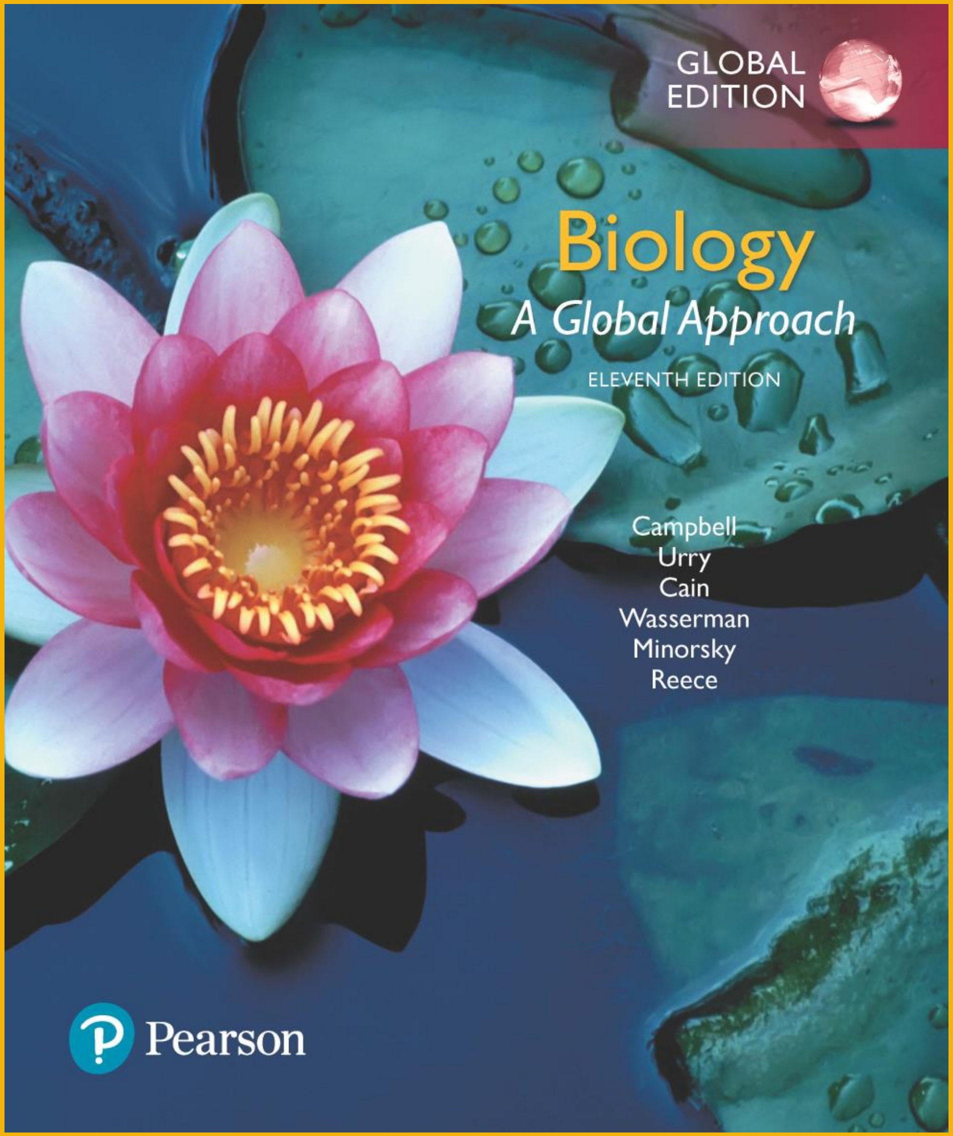


Chapter 6

Energy and Life

Lecture Presentations by
Nicole Tunbridge and
Kathleen Fitzpatrick

© 2018 Pearson Education Ltd.

The Energy of Life

- The living cell is a miniature chemical factory where thousands of reactions occur
- Cellular respiration extracts energy stored in sugars and other fuels
- Cells apply this energy to perform work
- Some organisms even convert energy to light, as in bioluminescence

© 2018 Pearson Education Ltd.

Figure 6.1

© 2018 Pearson Education Ltd.

Figure 6.1a

© 2018 Pearson Education Ltd.

Concept 6.1: An organism's metabolism transforms matter and energy, subject to the laws of thermodynamics

- **Metabolism** is the totality of an organism's chemical reactions
- Metabolism is an emergent property of life that arises from orderly interactions between molecules

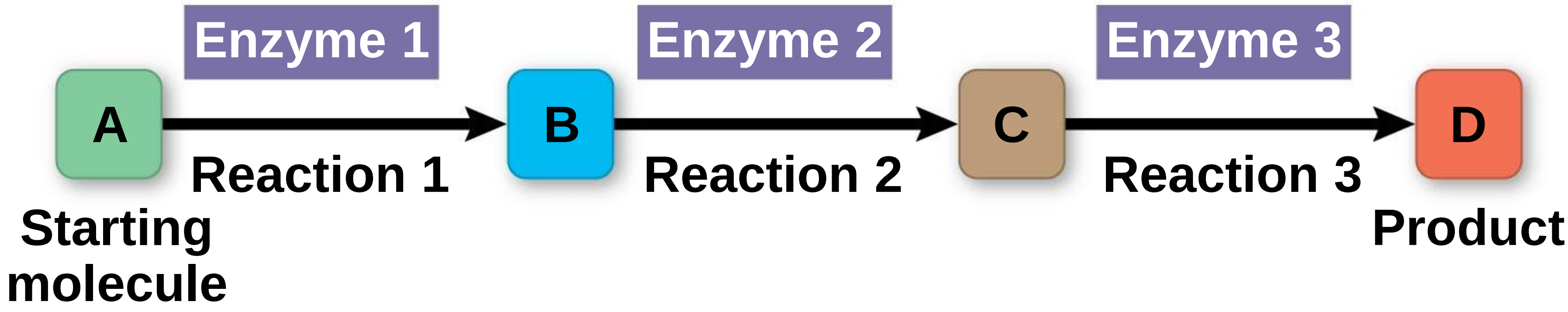
© 2018 Pearson Education Ltd.

Organization of the Chemistry of Life into Metabolic Pathways

- A **metabolic pathway** begins with a specific molecule and ends with a product
- Each step is catalyzed by a specific enzyme

© 2018 Pearson Education Ltd.

Figure 6.UN01



© 2018 Pearson Education Ltd.

- **Catabolic pathways** release energy by breaking down complex molecules into simpler compounds
- Cellular respiration, the breakdown of glucose in the presence of oxygen, is an example of a pathway of catabolism

© 2018 Pearson Education Ltd.

- **Anabolic pathways** consume energy to build complex molecules from simpler ones
  - For example, the synthesis of protein from amino acids is an anabolic pathway
- **Bioenergetics** is the study of how energy flows through living organisms

© 2018 Pearson Education Ltd.

Forms of Energy

- **Energy** is the capacity to cause change
- Energy exists in various forms, some of which can perform work

© 2018 Pearson Education Ltd.

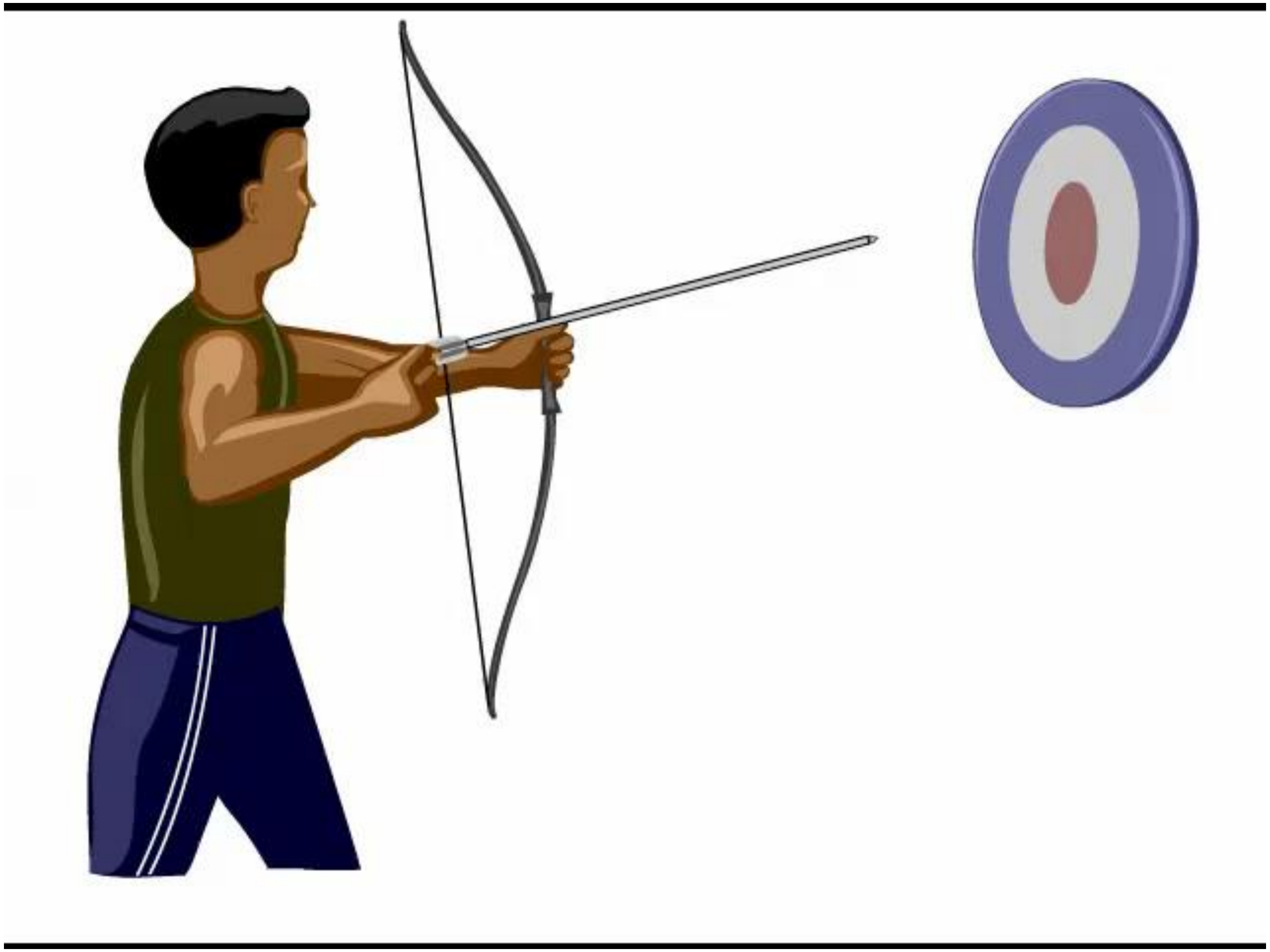
- **Kinetic energy** is energy associated with motion
- **Thermal energy** is the kinetic energy associated with random movement of atoms or molecules
  - **Heat** is thermal energy in transfer between objects
- **Potential energy** is energy that matter possesses because of its location or structure
- **Chemical energy** is potential energy available for release in a chemical reaction
- Energy can be converted from one form to another

© 2018 Pearson Education Ltd.

Figure 6.2

© 2018 Pearson Education Ltd.

Animation: Energy Concepts



© 2018 Pearson Education Ltd.

The Laws of Energy Transformation

- **Thermodynamics** is the study of energy transformations
- An isolated system, such as that approximated by liquid in a thermos, is unable to exchange energy or matter with its surroundings
- In an open system, energy and matter can be transferred between the system and its surroundings
- Organisms are open systems

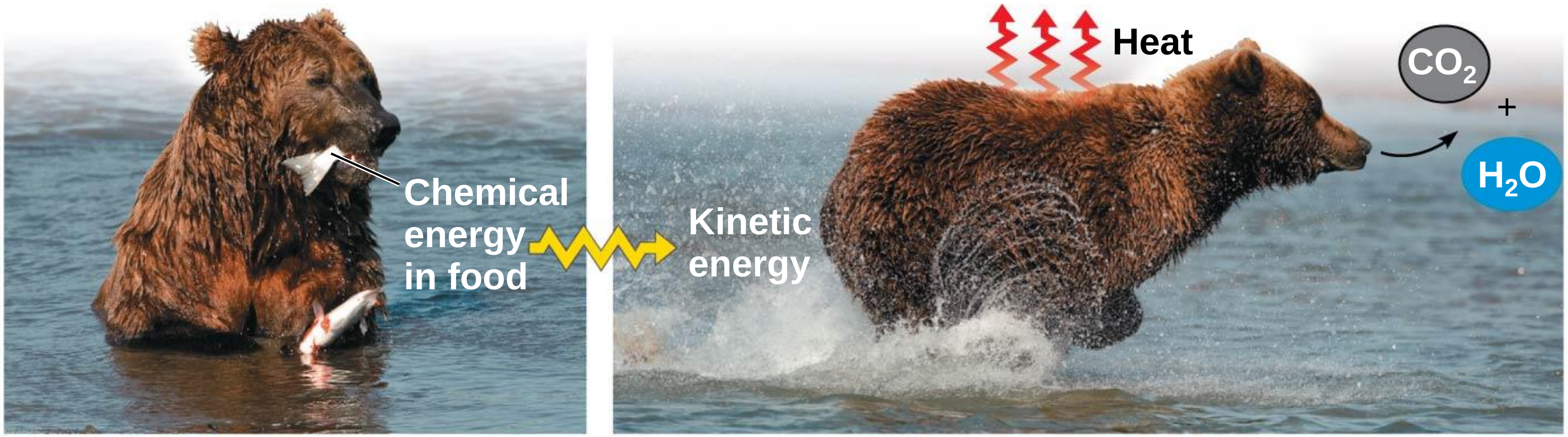
© 2018 Pearson Education Ltd.

The First Law of Thermodynamics

- According to the **first law of thermodynamics**, the energy of the universe is constant
  - Energy can be transferred and transformed, but it cannot be created or destroyed
- The first law is also called the principle of conservation of energy

© 2018 Pearson Education Ltd.

Figure 6.3



(a) First law of thermodynamics

(b) Second law of thermodynamics

© 2018 Pearson Education Ltd.

Figure 6.3a

(a) First law of thermodynamics

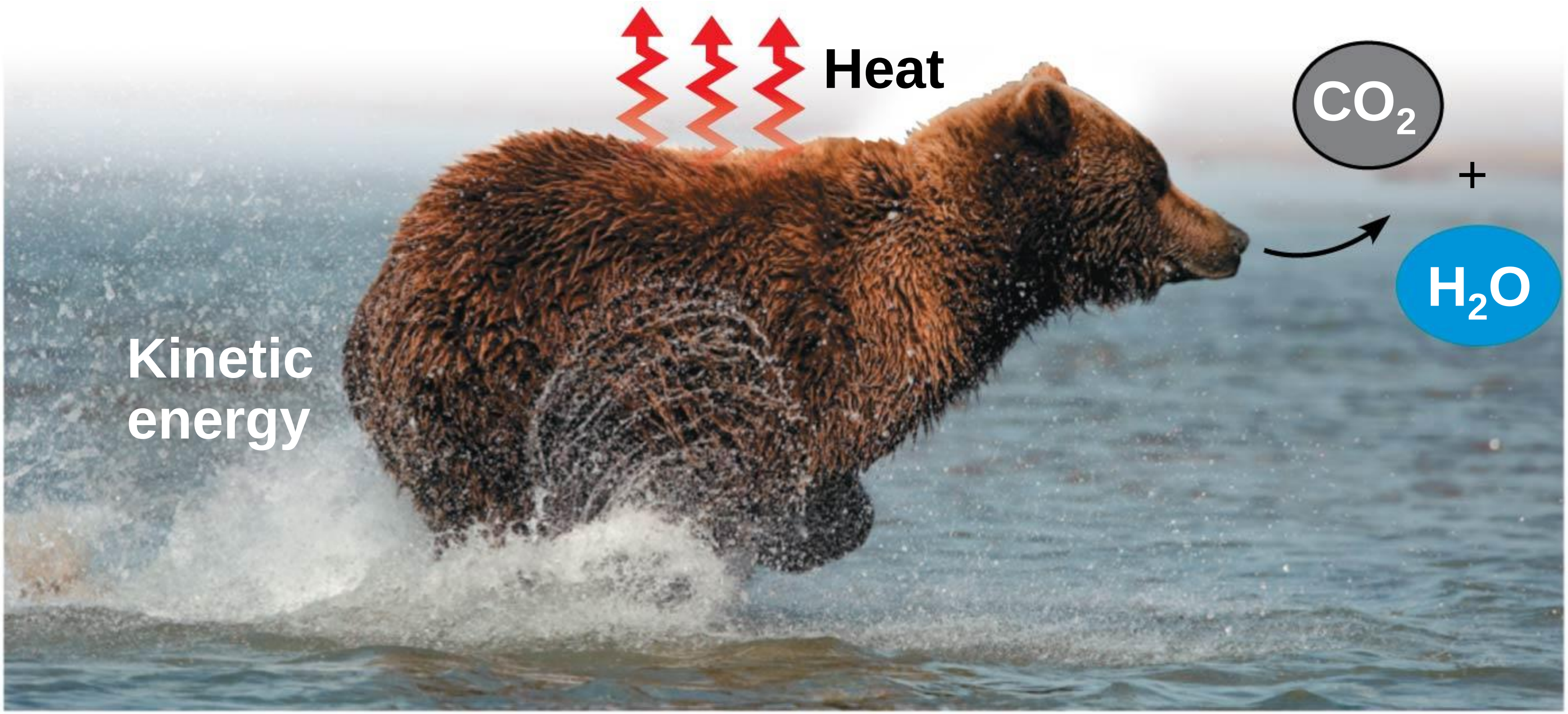
© 2018 Pearson Education Ltd.

The Second Law of Thermodynamics

- During every energy transfer or transformation, some energy is unusable and is often lost as heat
- According to the **second law of thermodynamics**,
  - Every energy transfer or transformation increases the **entropy** of the universe
  - Entropy is a measure of molecular disorder, or randomness

© 2018 Pearson Education Ltd.

Figure 6.3b



(b) Second law of thermodynamics

© 2018 Pearson Education Ltd.

- Living cells unavoidably convert organized forms of energy to heat, a more disordered form of energy
- **Spontaneous processes** occur without energy input; they can happen quickly or slowly
- For a process to occur spontaneously, it must increase the entropy of the universe
- Processes that decrease entropy are nonspontaneous; they will occur only if energy is provided

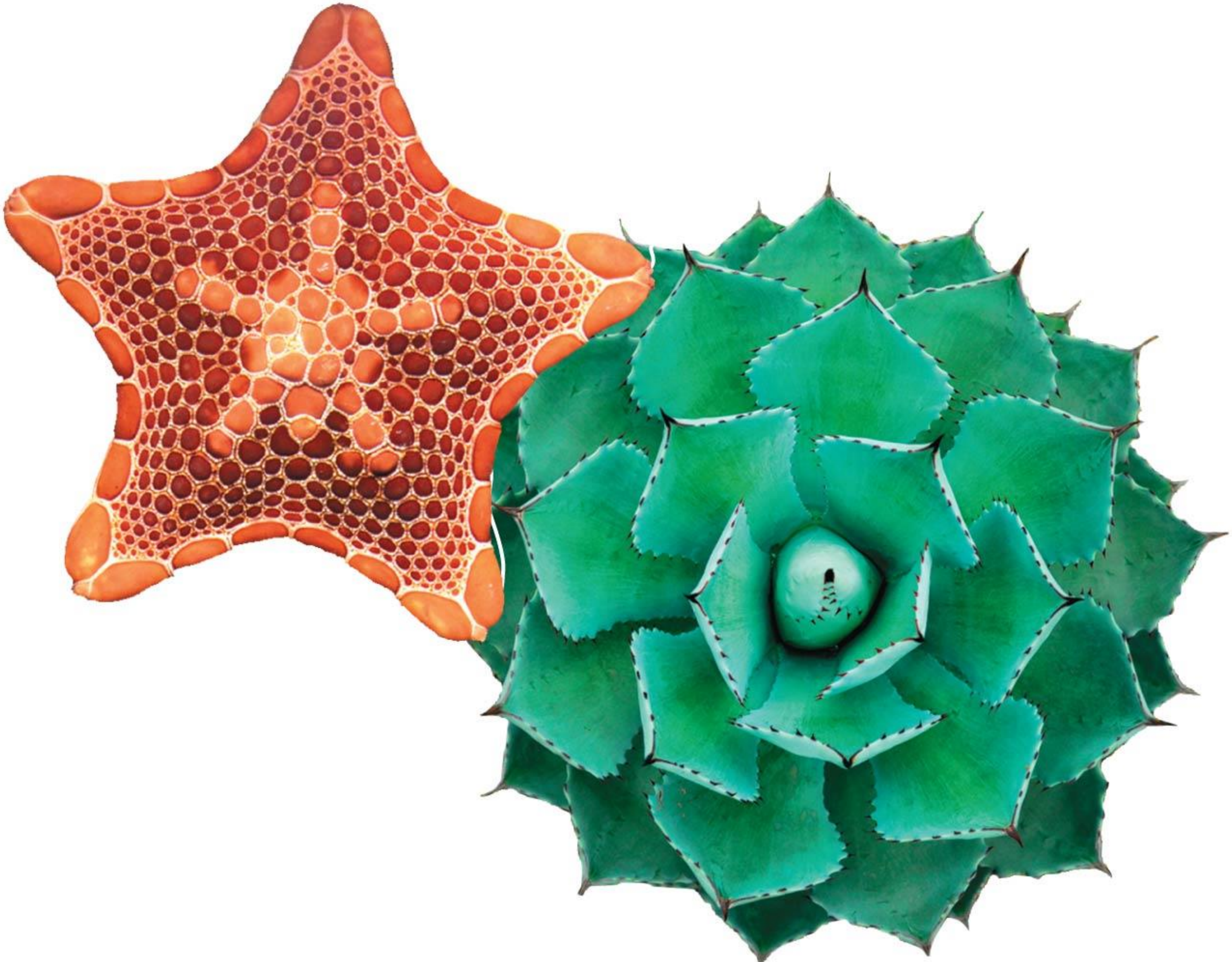
© 2018 Pearson Education Ltd.

Biological Order and Disorder

- Organisms create ordered structures from less organized forms of energy and matter
- Organisms also replace ordered forms of matter and energy in their surroundings with less ordered forms
  - For example, animals consume complex molecules in their food and release smaller, lower energy molecules and heat into the surroundings

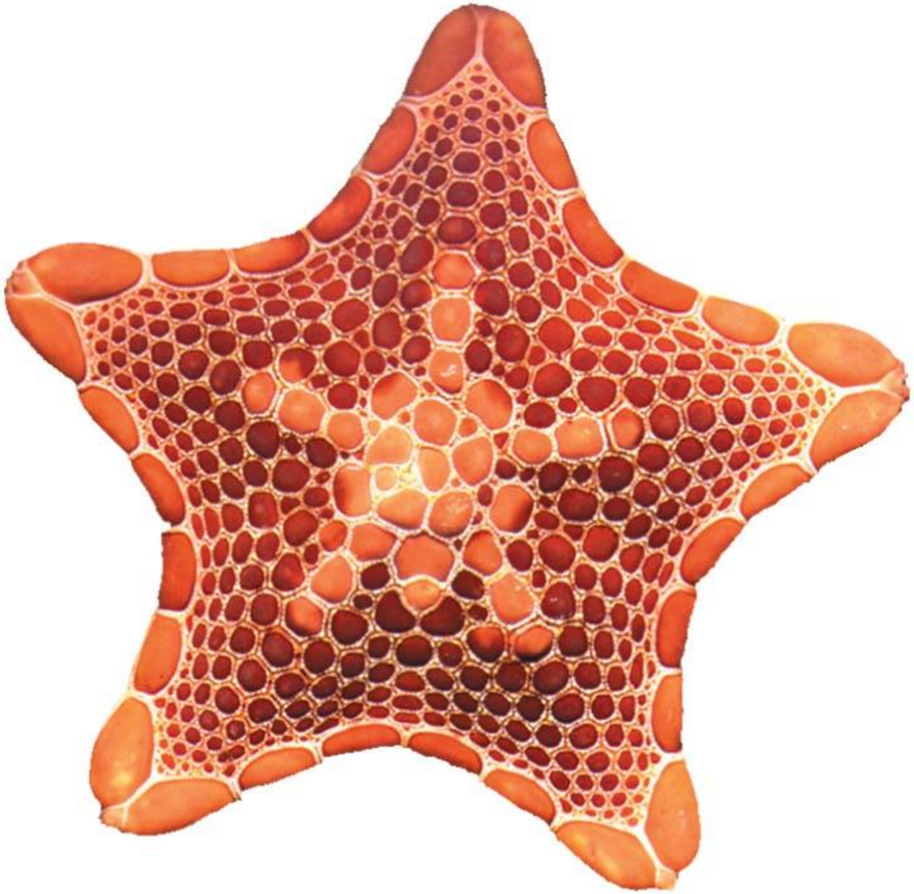
© 2018 Pearson Education Ltd.

Figure 6.4



© 2018 Pearson Education Ltd.

Figure 6.4a



© 2018 Pearson Education Ltd.

Figure 6.4b

© 2018 Pearson Education Ltd.

- The evolution of more complex organisms does not violate the second law of thermodynamics
- Entropy (disorder) may decrease in a particular system, such as an organism, as long as the total entropy of the system and surroundings increases

© 2018 Pearson Education Ltd.

Concept 6.2: The free-energy change of a reaction tells us whether or not the reaction occurs spontaneously

- Biologists want to know which reactions occur spontaneously and which require input of energy
- To do so, they need to determine the energy and entropy changes that occur in chemical reactions

© 2018 Pearson Education Ltd.

Free-Energy Change, Δ*G*

- A living system's **free energy** is energy that can do work when temperature and pressure are uniform, as in a living cell

© 2018 Pearson Education Ltd.

- The change in free energy (ΔG) during a process is related to the change in enthalpy—change in total energy (ΔH)—change in entropy (ΔS), and temperature in Kelvin units (T)

$$\Delta G = \Delta H - T\Delta S$$

- ΔG is negative for all spontaneous processes; processes with zero or positive ΔG are never spontaneous
- Spontaneous processes can be harnessed to perform work

© 2018 Pearson Education Ltd.

Free Energy, Stability, and Equilibrium

- Free energy is a measure of a system's instability, its tendency to change to a more stable state
- During a spontaneous change, free energy decreases and the stability of a system increases
- Equilibrium is a state of maximum stability
- A process is spontaneous and can perform work only when it is moving toward equilibrium

© 2018 Pearson Education Ltd.

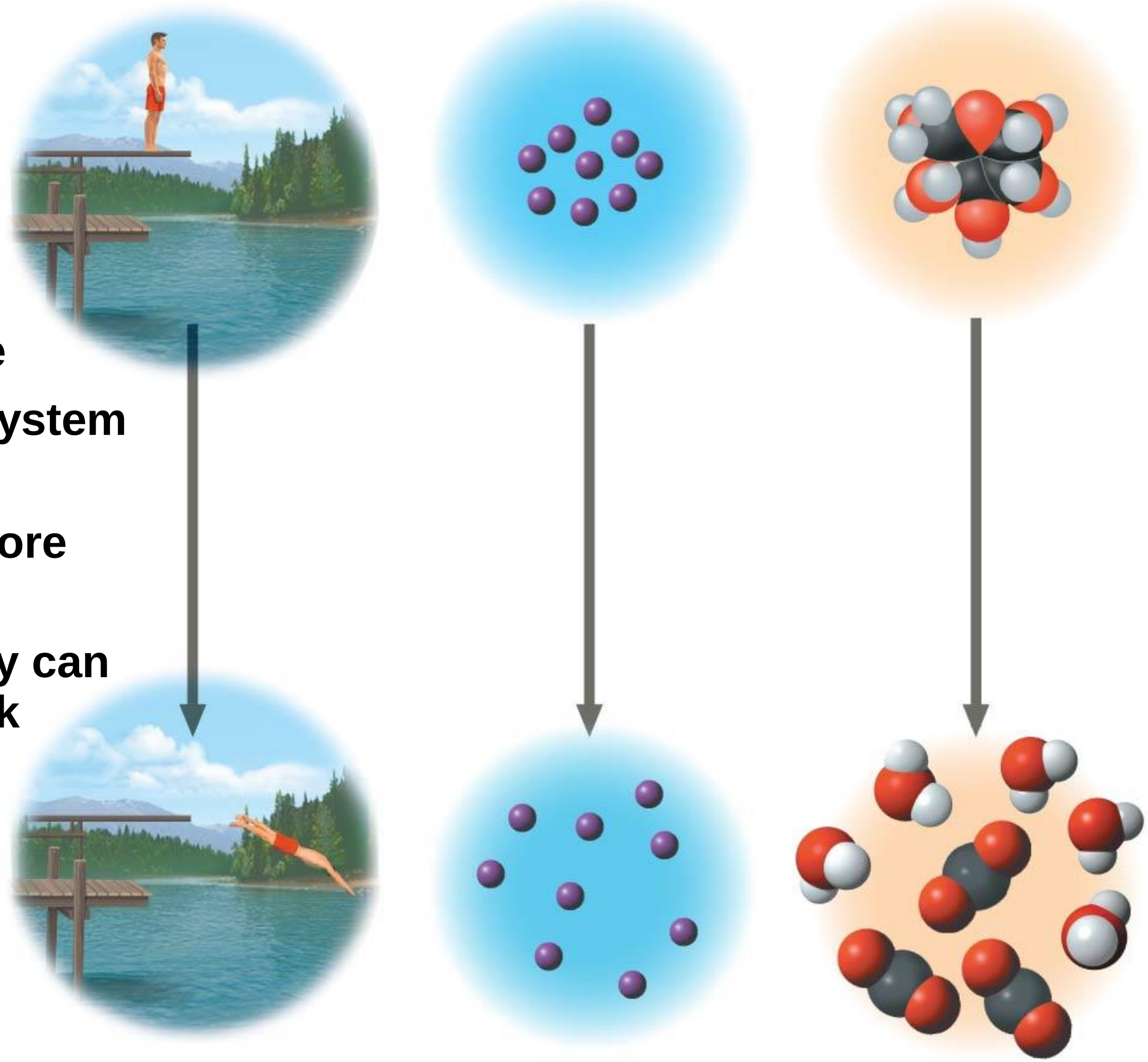
Figure 6.5

- **More free energy (higher *G*)**
- **Less stable**
- **Greater work capacity**

In a spontaneous change

- **The free energy of the system decreases ($\Delta G < 0$)**
- **The system becomes more stable**
- **The released free energy can be harnessed to do work**

- **Less free energy (lower *G*)**
- **More stable**
- **Less work capacity**



(a) Gravitational motion **(b) Diffusion** **(c) Chemical reaction**

© 2018 Pearson Education Ltd.

Figure 6.5a

- More free energy (higher *G*)
- Less stable
- Greater work capacity

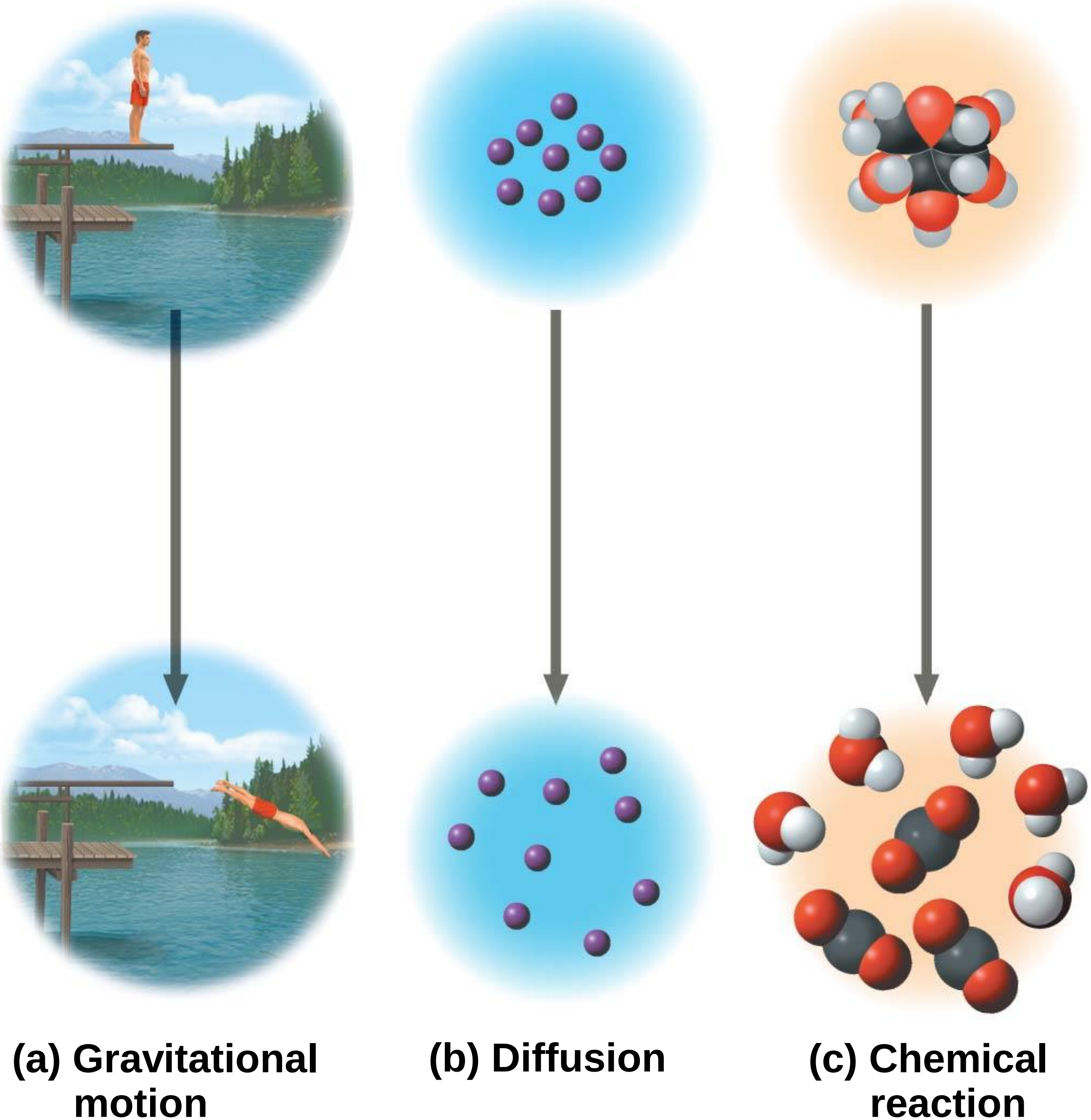
In a spontaneous change

- The free energy of the system decreases ($\Delta G < 0$)
- The system becomes more stable
- The released free energy can be harnessed to do work

- Less free energy (lower *G*)
- More stable
- Less work capacity

© 2018 Pearson Education Ltd.

Figure 6.5b



© 2018 Pearson Education Ltd.

Free Energy and Metabolism

- The concept of free energy can be applied to the chemistry of life's processes

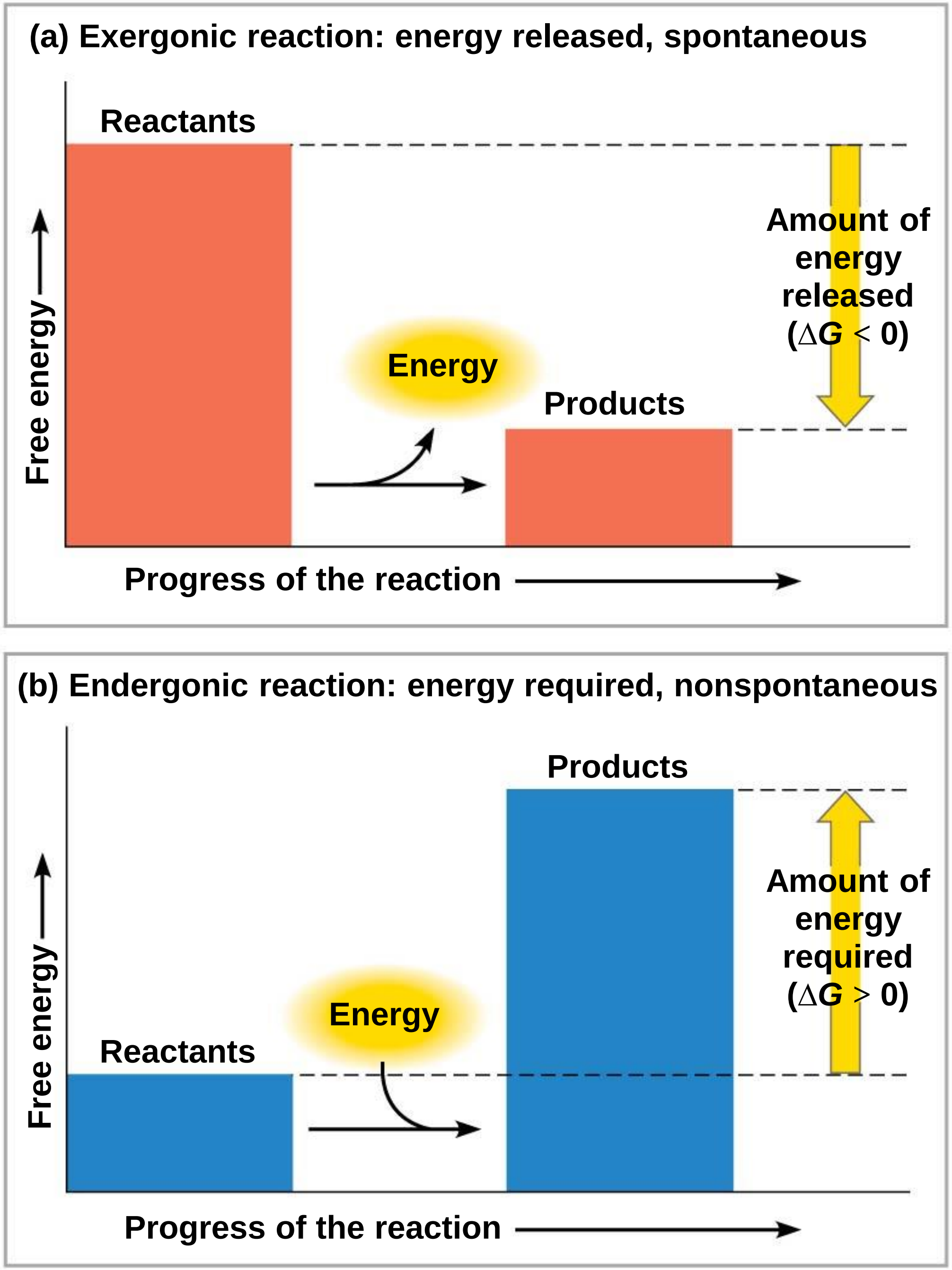
© 2018 Pearson Education Ltd.

Exergonic and Endergonic Reactions in Metabolism

- An **exergonic reaction** proceeds with a net release of free energy and is spontaneous
- An **endergonic reaction** absorbs free energy from its surroundings and is nonspontaneous

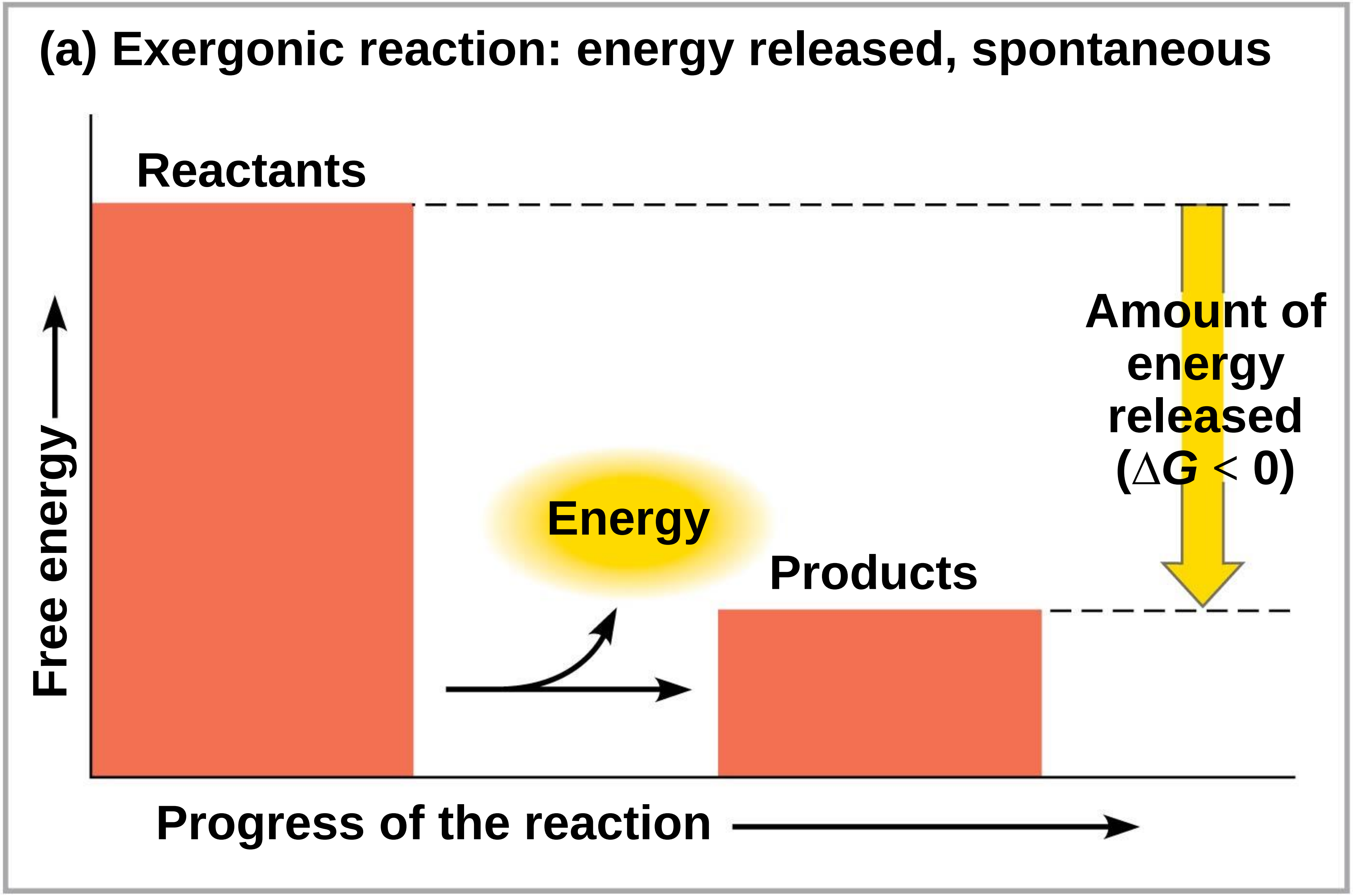
© 2018 Pearson Education Ltd.

Figure 6.6



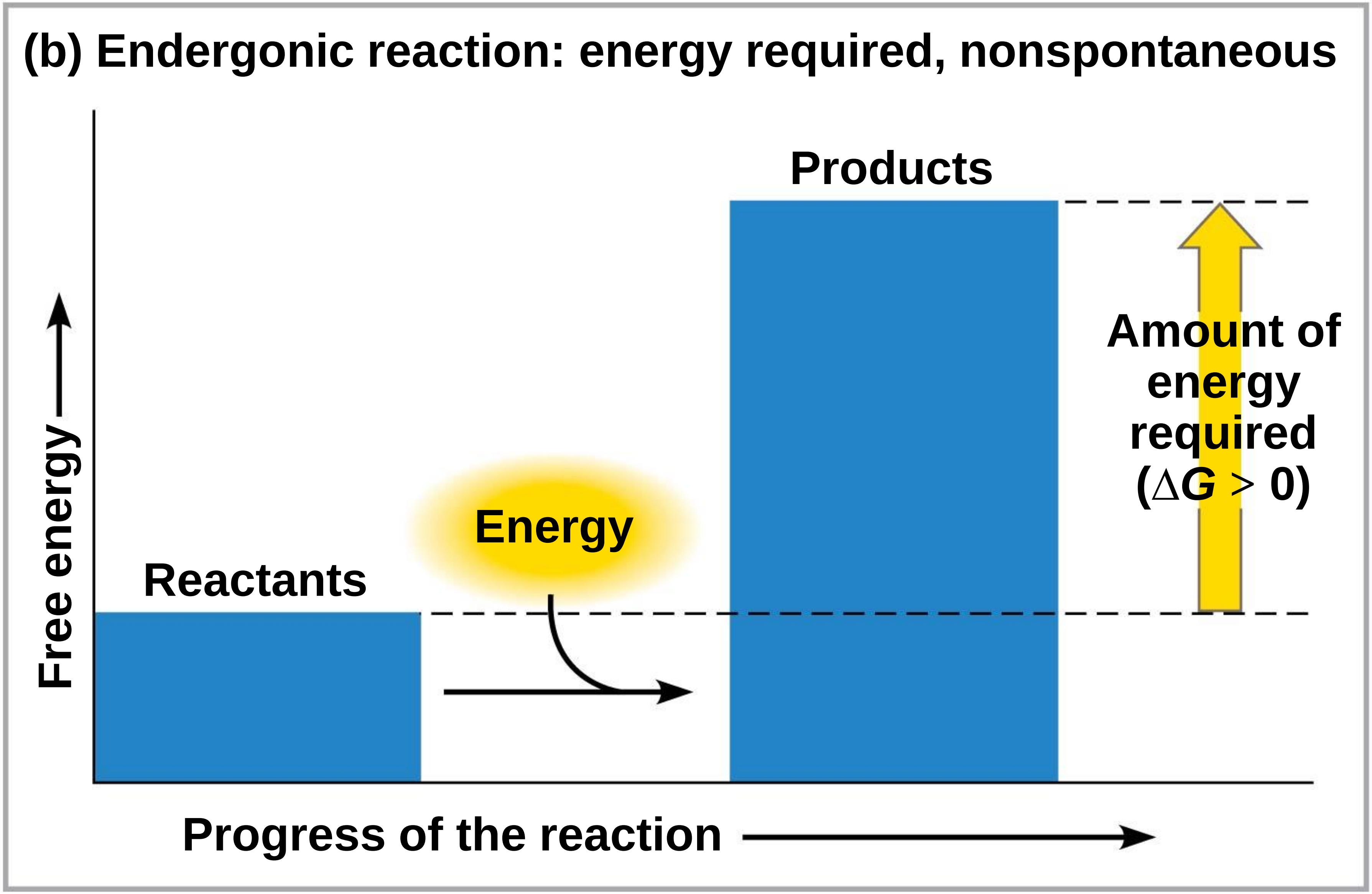
© 2018 Pearson Education Ltd.

Figure 6.6a



© 2018 Pearson Education Ltd.

Figure 6.6b



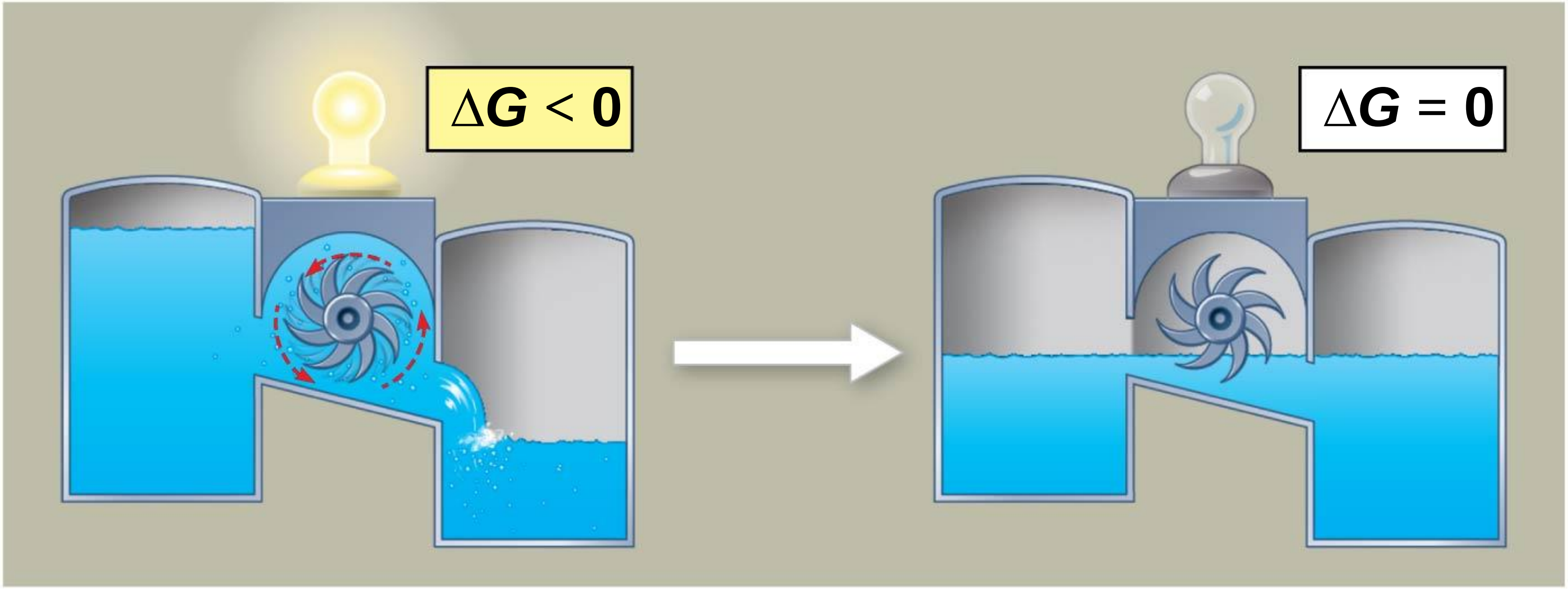
© 2018 Pearson Education Ltd.

Equilibrium and Metabolism

- Reactions in a closed system eventually reach equilibrium and can then do no work

© 2018 Pearson Education Ltd.

Figure 6.7



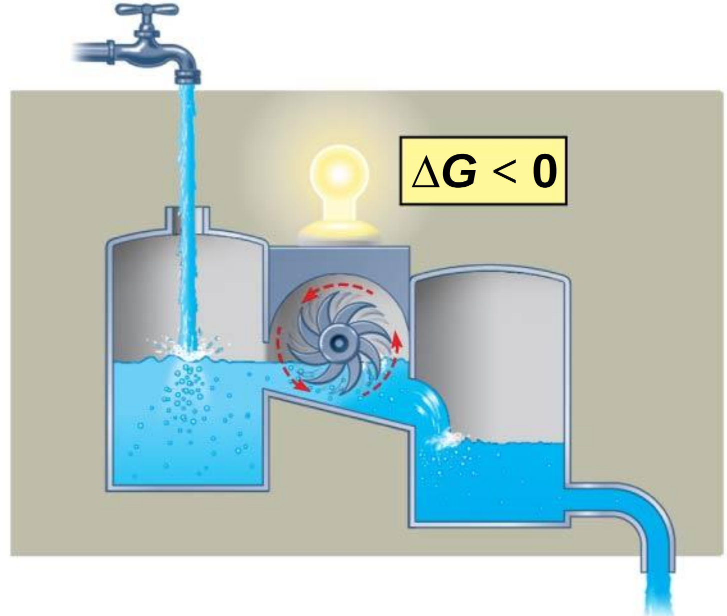
© 2018 Pearson Education Ltd.

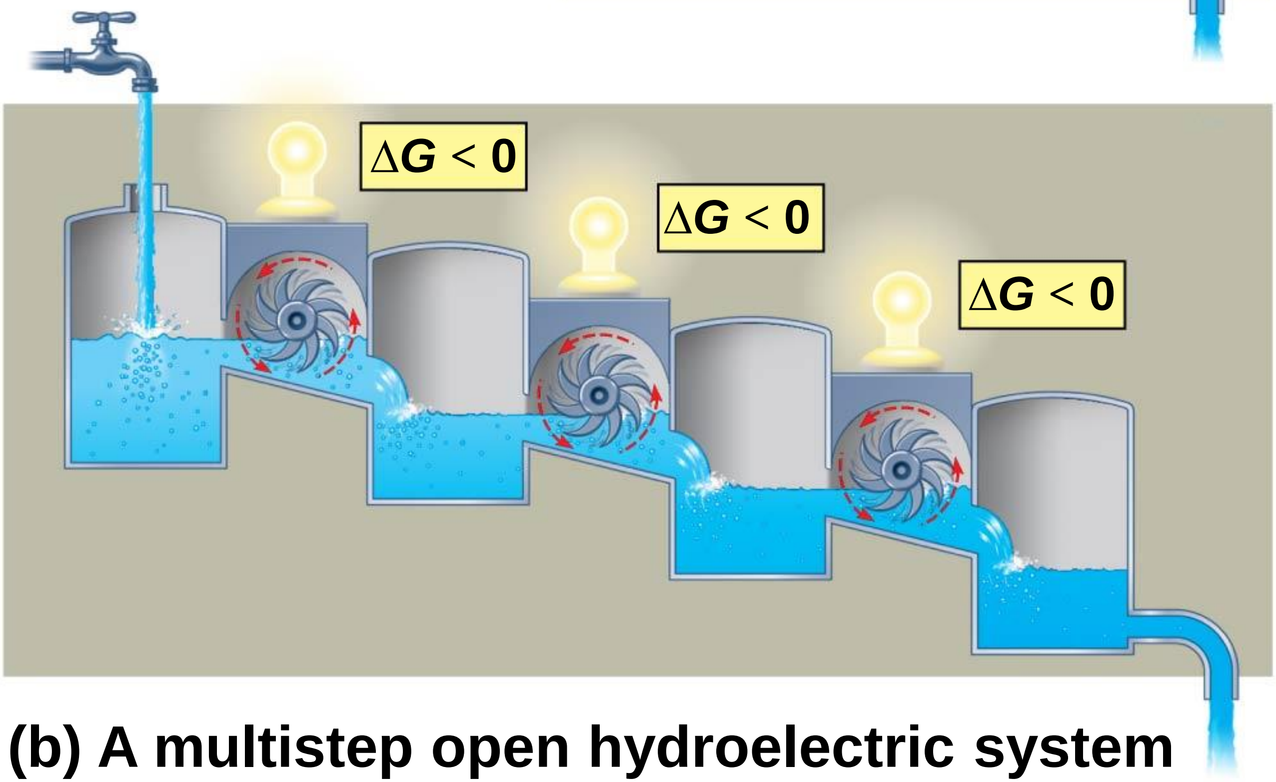
- Cells are not in equilibrium; they are open systems experiencing a constant flow of materials
- A defining feature of life is that metabolism is never at equilibrium
- A catabolic pathway in a cell releases free energy in a series of reactions

© 2018 Pearson Education Ltd.

Figure 6.8

(a) An open hydroelectric system

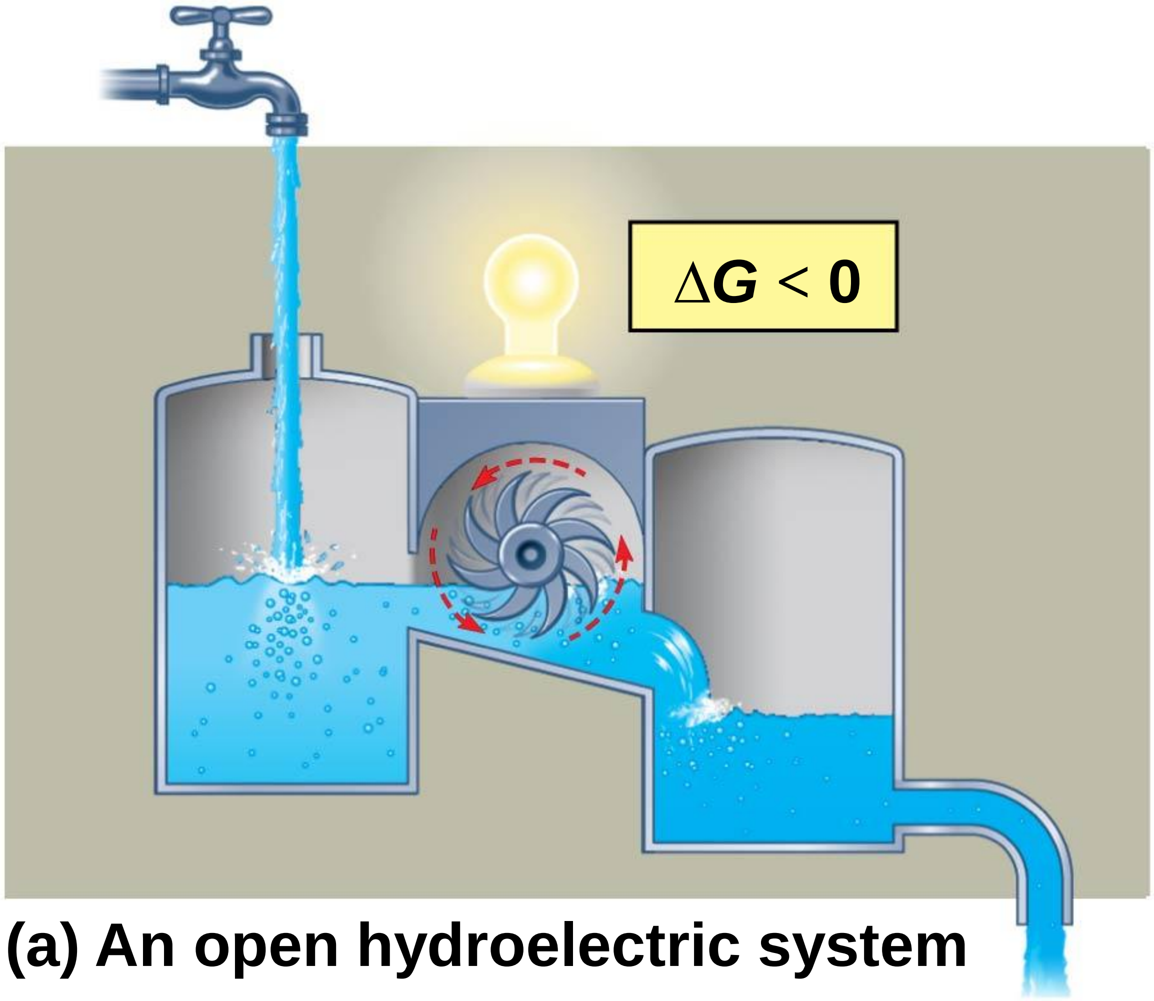




(b) A multistep open hydroelectric system

© 2018 Pearson Education Ltd.

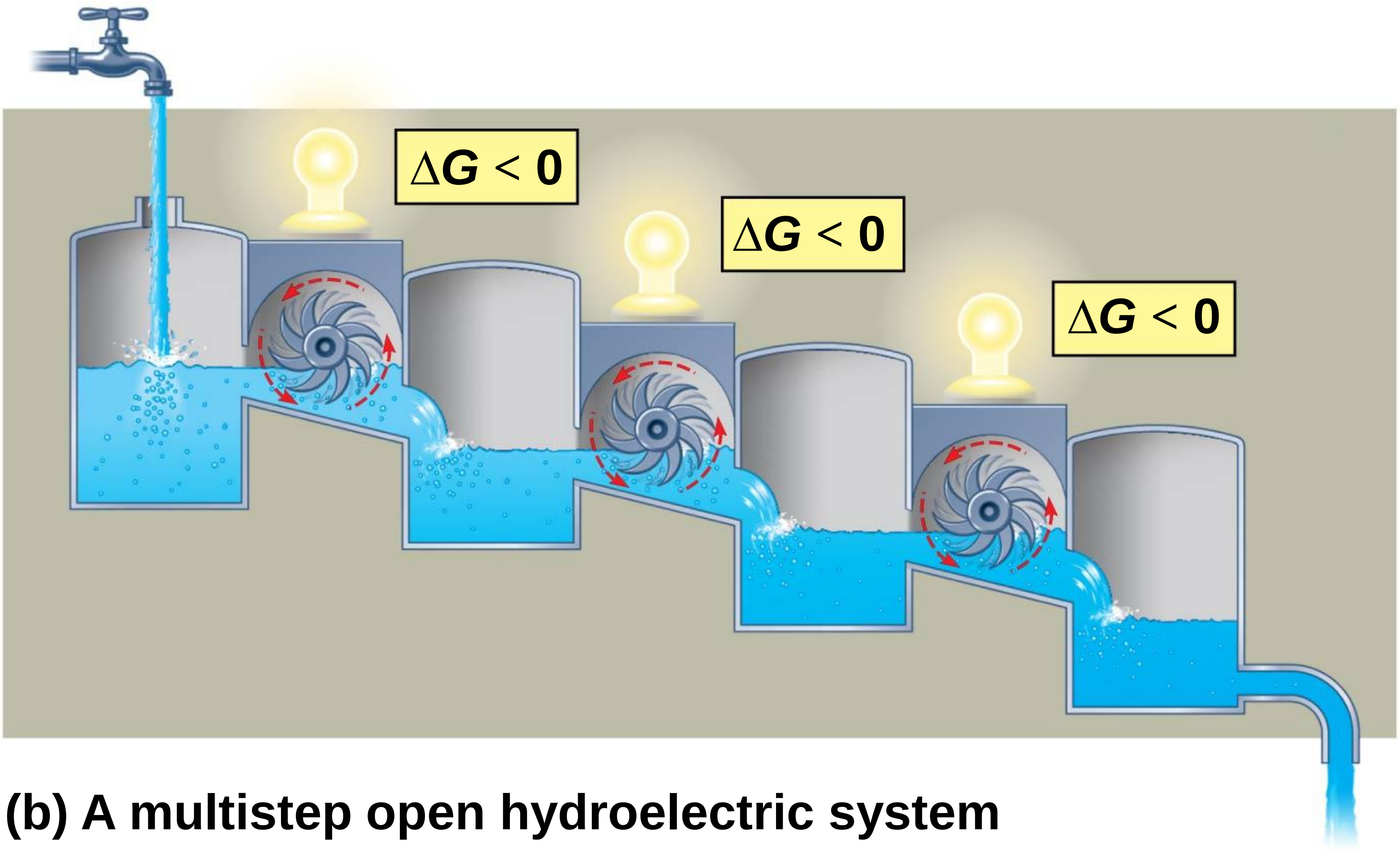
Figure 6.8a



(a) An open hydroelectric system

© 2018 Pearson Education Ltd.

Figure 6.8b



(b) A multistep open hydroelectric system

© 2018 Pearson Education Ltd.

Concept 6.3: ATP powers cellular work by coupling exergonic reactions to endergonic reactions

- A cell does three main kinds of work:
  - Chemical work—pushing endergonic reactions
  - Transport work—pumping substances against the direction of spontaneous movement
  - Mechanical work—such as contraction of muscle cells

© 2018 Pearson Education Ltd.

- To do work, cells manage energy resources by **energy coupling**, the use of an exergonic process to drive an endergonic one
- Most energy coupling in cells is mediated by ATP

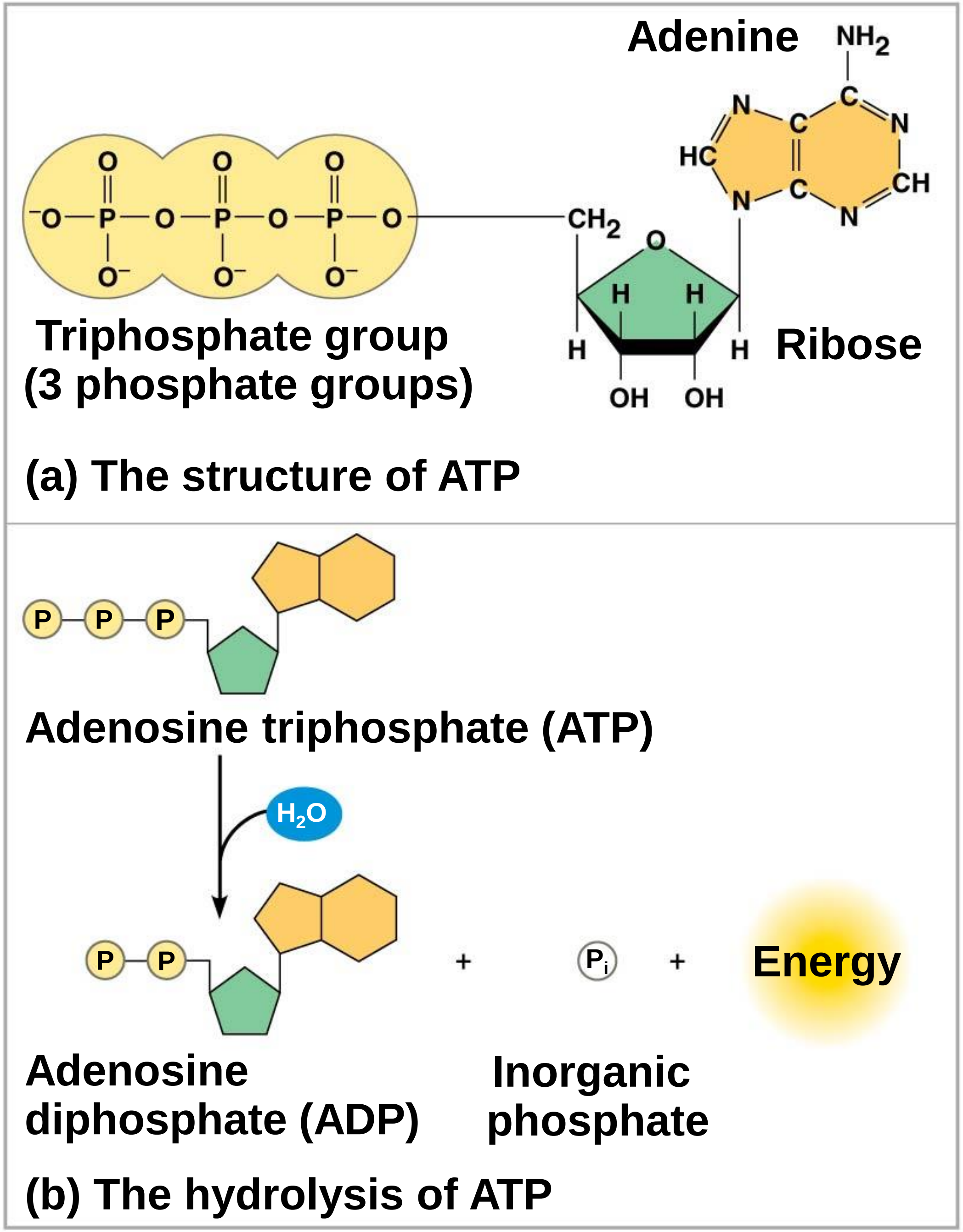
© 2018 Pearson Education Ltd.

The Structure and Hydrolysis of ATP

- **ATP (adenosine triphosphate)** is the cell's energy shuttle
- ATP is composed of ribose (a sugar), adenine (a nitrogenous base), and three phosphate groups

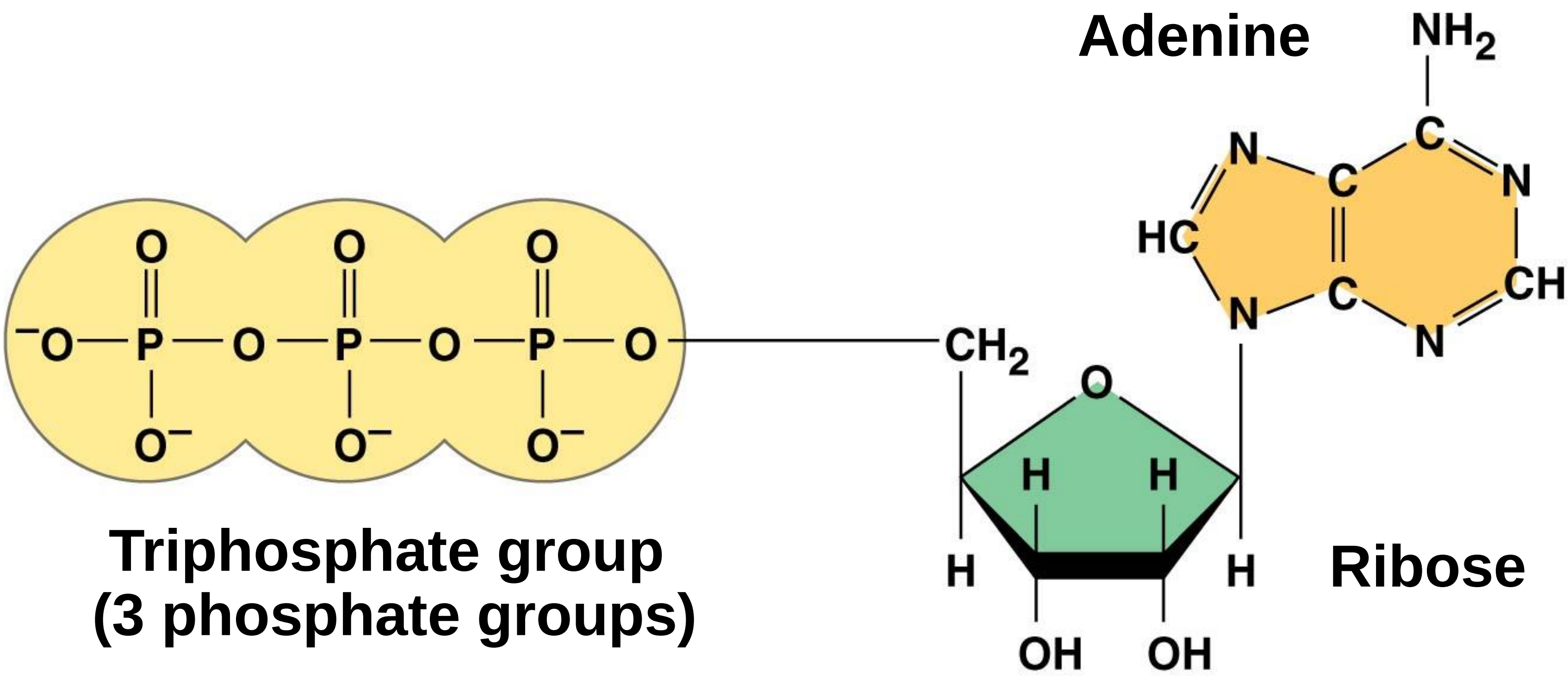
© 2018 Pearson Education Ltd.

Figure 6.9



© 2018 Pearson Education Ltd.

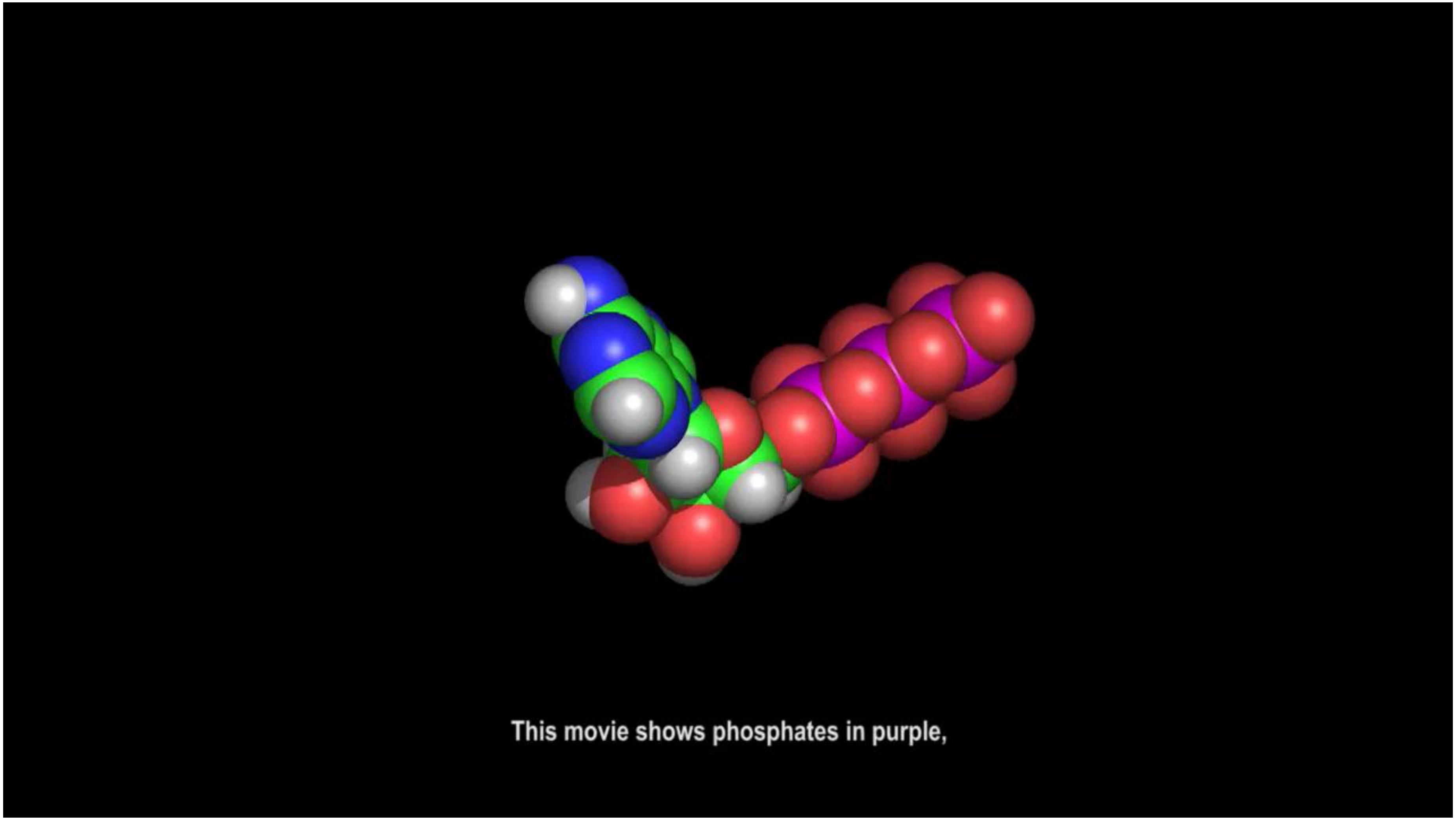
Figure 6.9a



(a) The structure of ATP

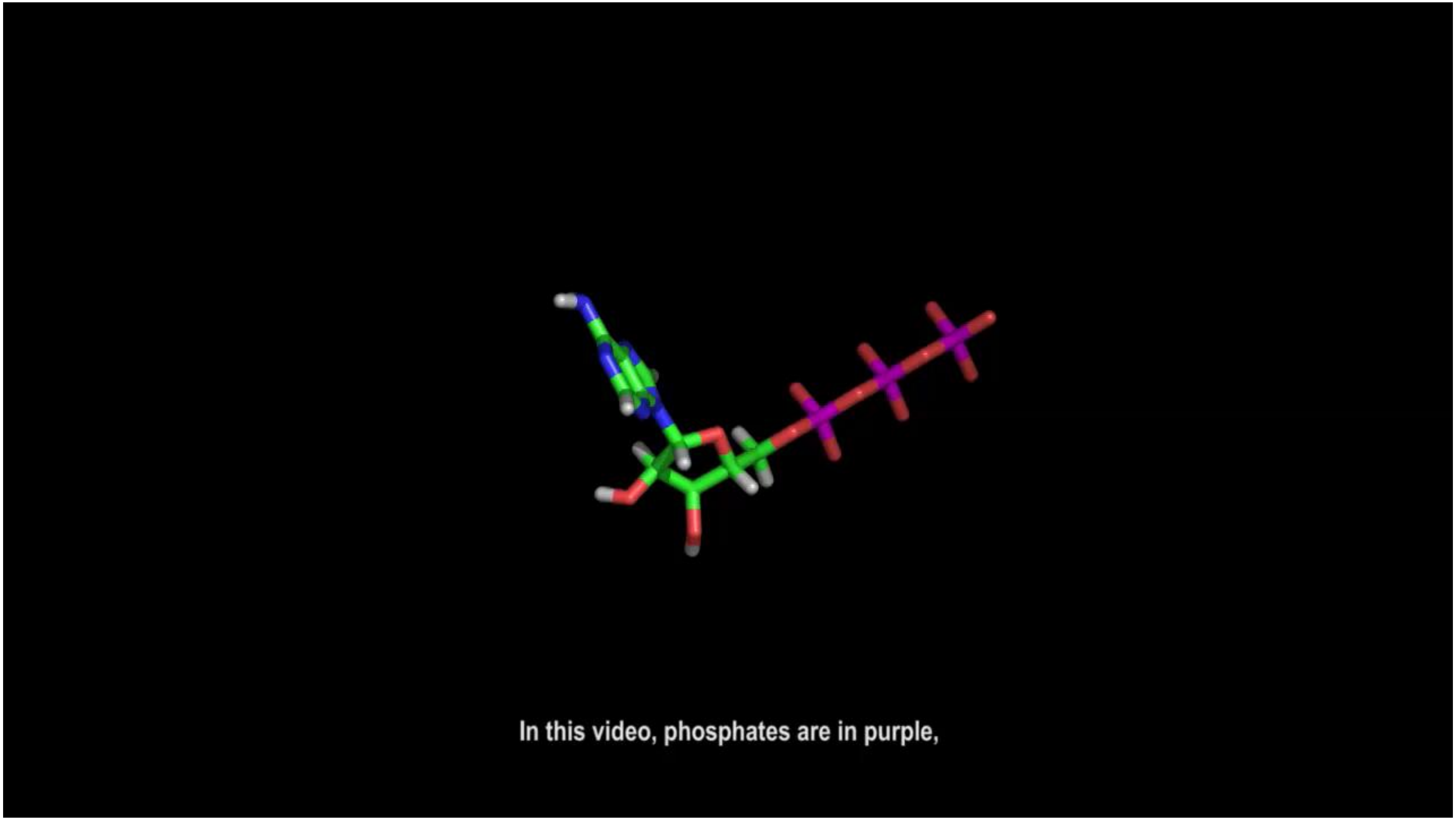
© 2018 Pearson Education Ltd.

Video: Space-Filling Model of ATP



© 2018 Pearson Education Ltd.

Video: Stick Model of ATP

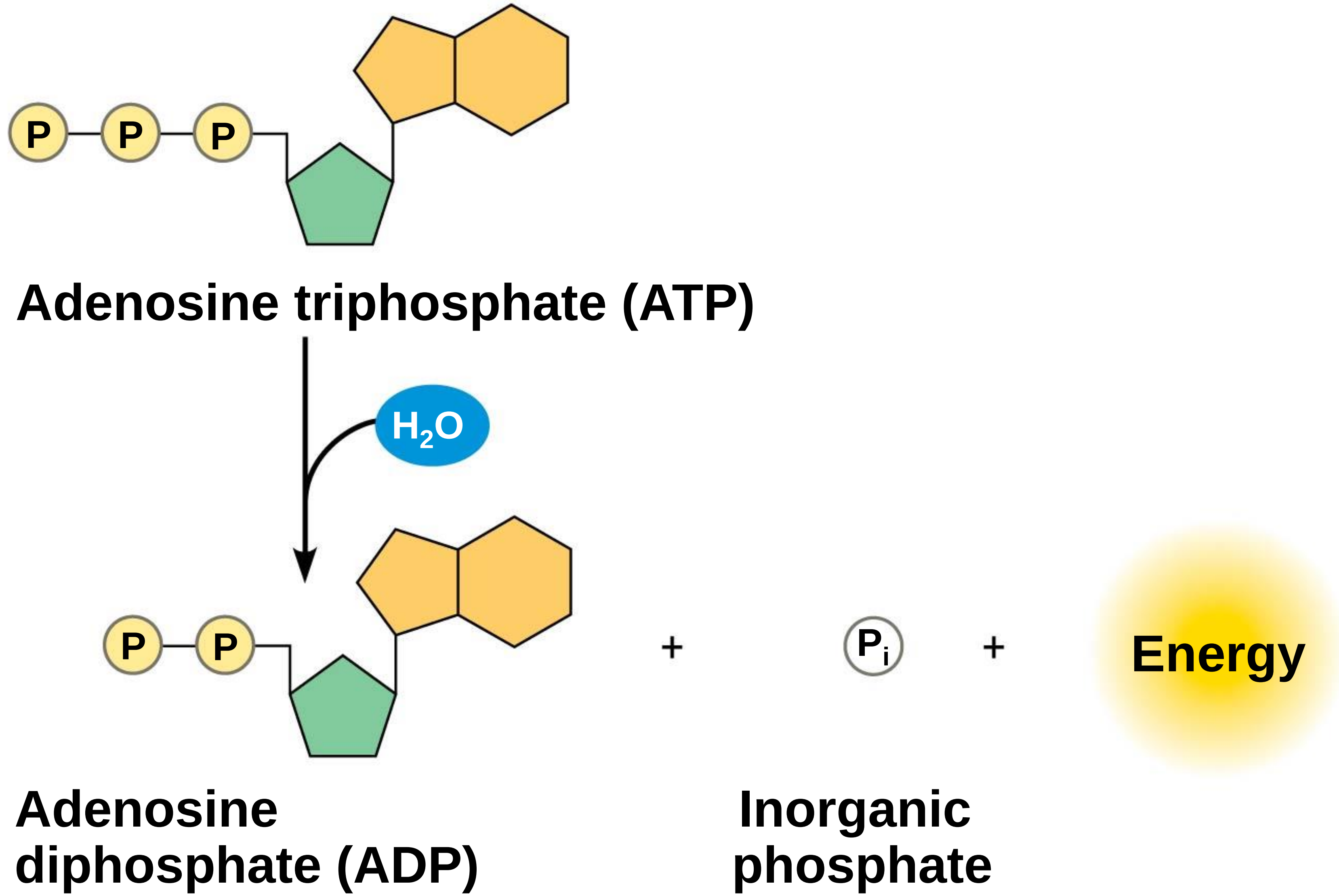


© 2018 Pearson Education Ltd.

- The bonds between the phosphate groups of ATP's tail can be broken by hydrolysis
- Energy is released from ATP when the terminal phosphate bond is broken
- This release of energy comes from the chemical change to a state of lower free energy, not from the phosphate bonds themselves

© 2018 Pearson Education Ltd.

Figure 6.9b



(b) The hydrolysis of ATP

© 2018 Pearson Education Ltd.

How the Hydrolysis of ATP Performs Work

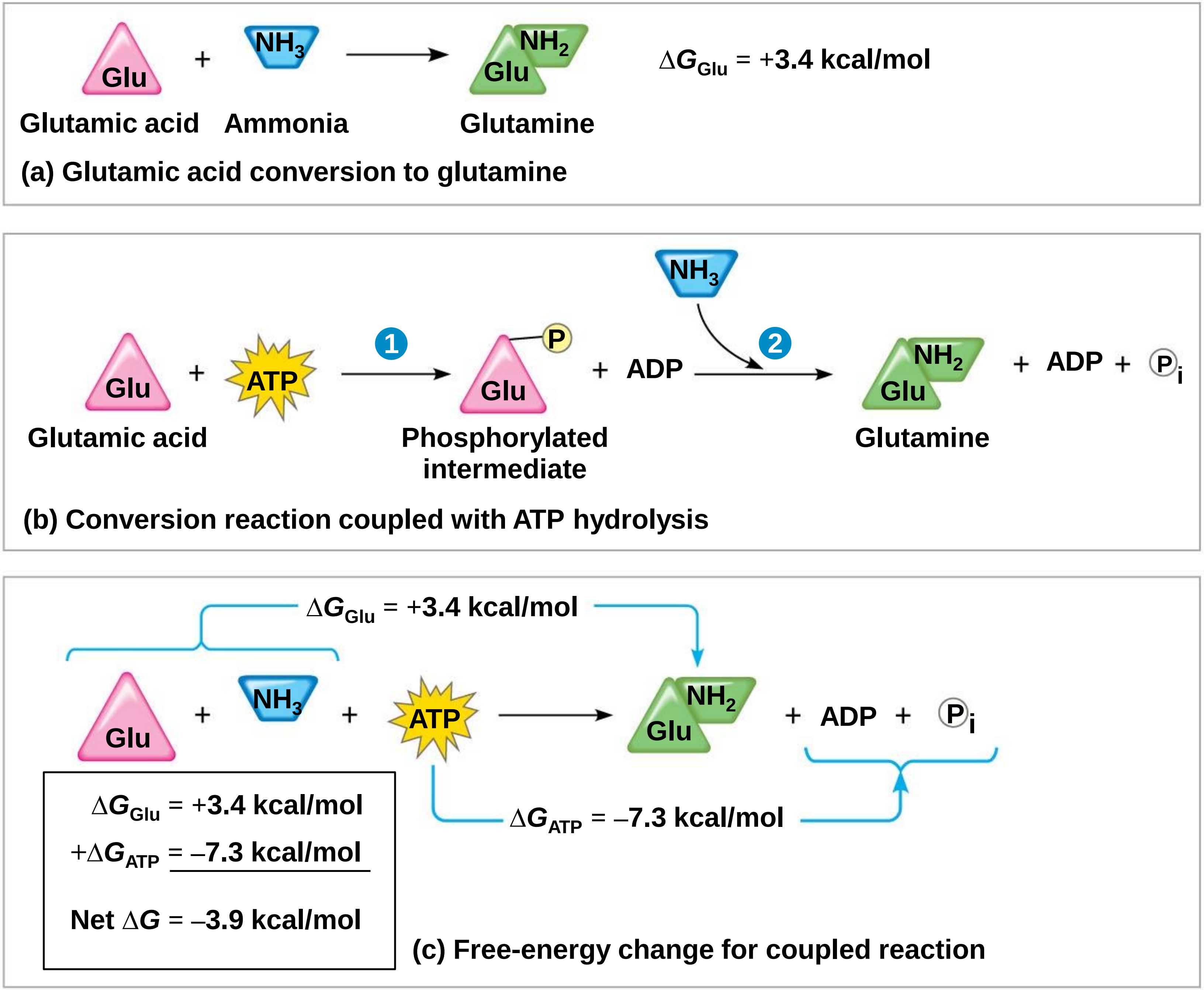
- The three types of cellular work (mechanical, transport, and chemical) are powered by the hydrolysis of ATP
- In the cell, the energy from the exergonic reaction of ATP hydrolysis can be used to drive an endergonic reaction
- Overall, the coupled reactions are exergonic

© 2018 Pearson Education Ltd.

- ATP drives endergonic reactions by phosphorylation, transferring a phosphate group to some other molecule, such as a reactant
- The recipient molecule is now called a **phosphorylated intermediate**

© 2018 Pearson Education Ltd.

Figure 6.10



© 2018 Pearson Education Ltd.

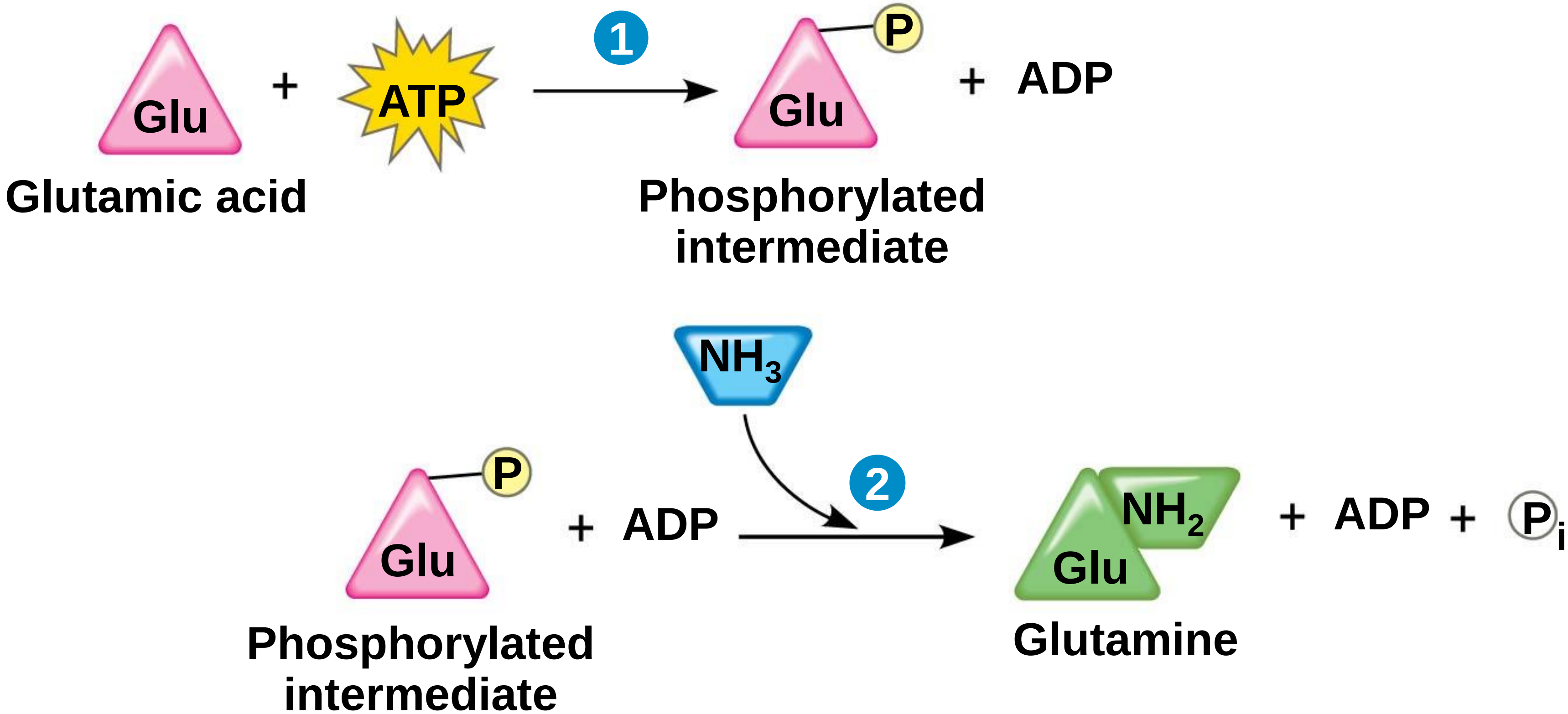
Glutamic acid Ammonia Glutamine

ΔG_{Glu} = +3.4 kcal/mol

(a) Glutamic acid conversion to glutamine

© 2018 Pearson Education Ltd.

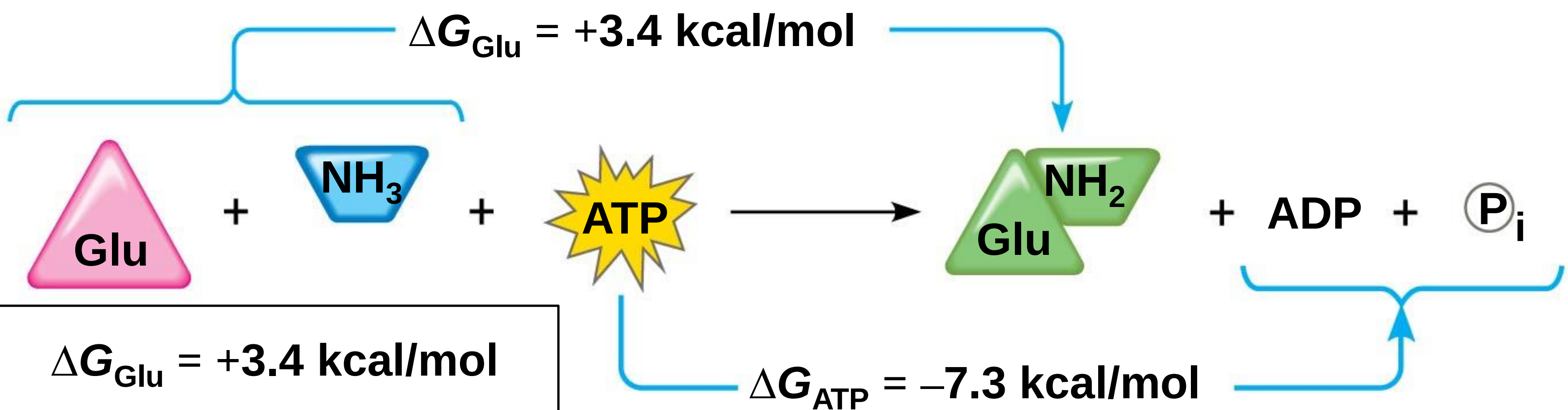
Figure 6.10b



(b) Conversion reaction coupled with ATP hydrolysis

© 2018 Pearson Education Ltd.

Figure 6.10c



$$\Delta G_{Glu} = +3.4 \text{ kcal/mol}$$

$$+\Delta G_{ATP} = -7.3 \text{ kcal/mol}$$

$$\text{Net } \Delta G = -3.9 \text{ kcal/mol}$$

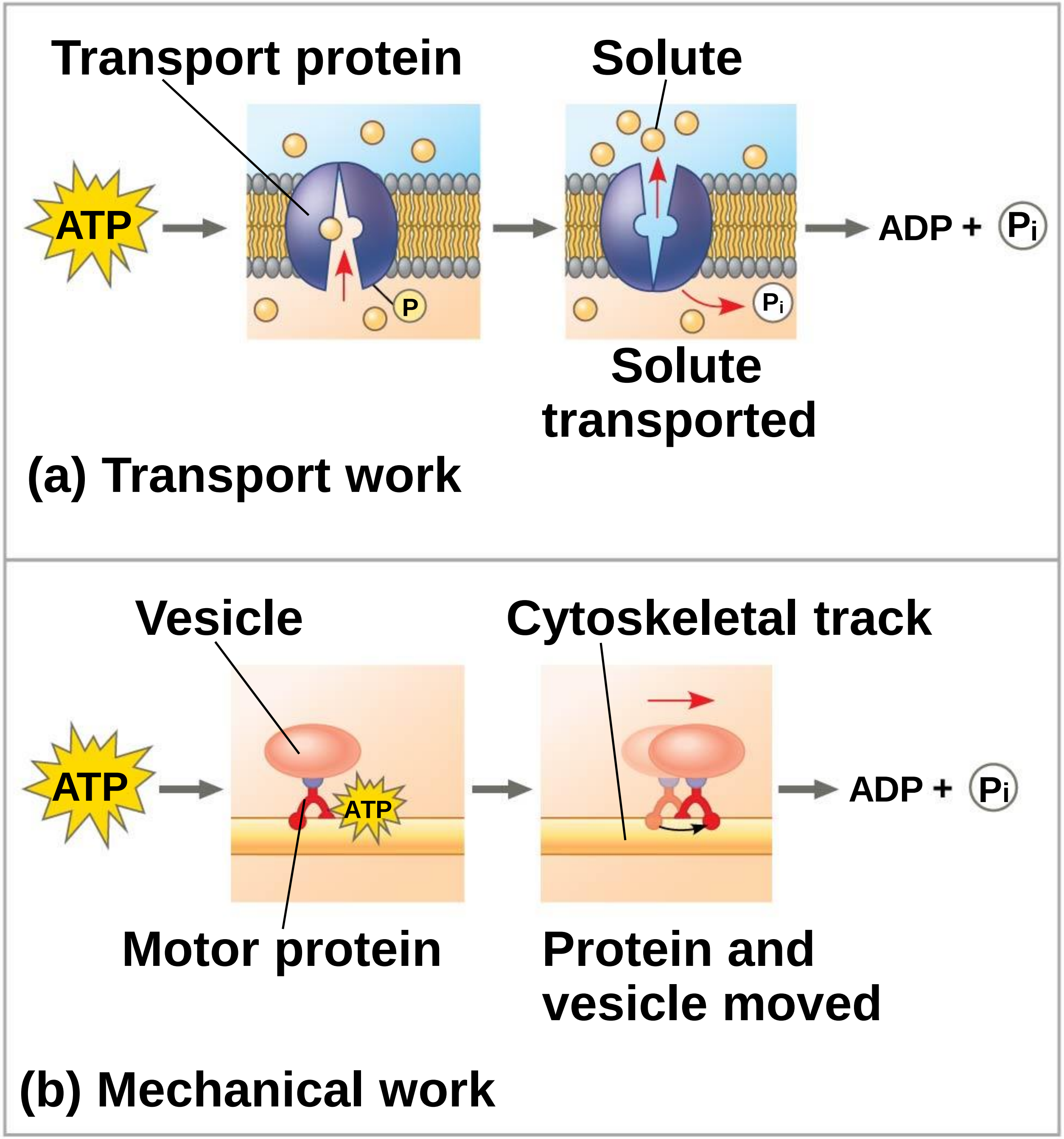
(c) Free-energy change for coupled reaction

© 2018 Pearson Education Ltd.

- Transport and mechanical work in the cell are also powered by ATP hydrolysis
- ATP hydrolysis leads to a change in protein shape and binding ability

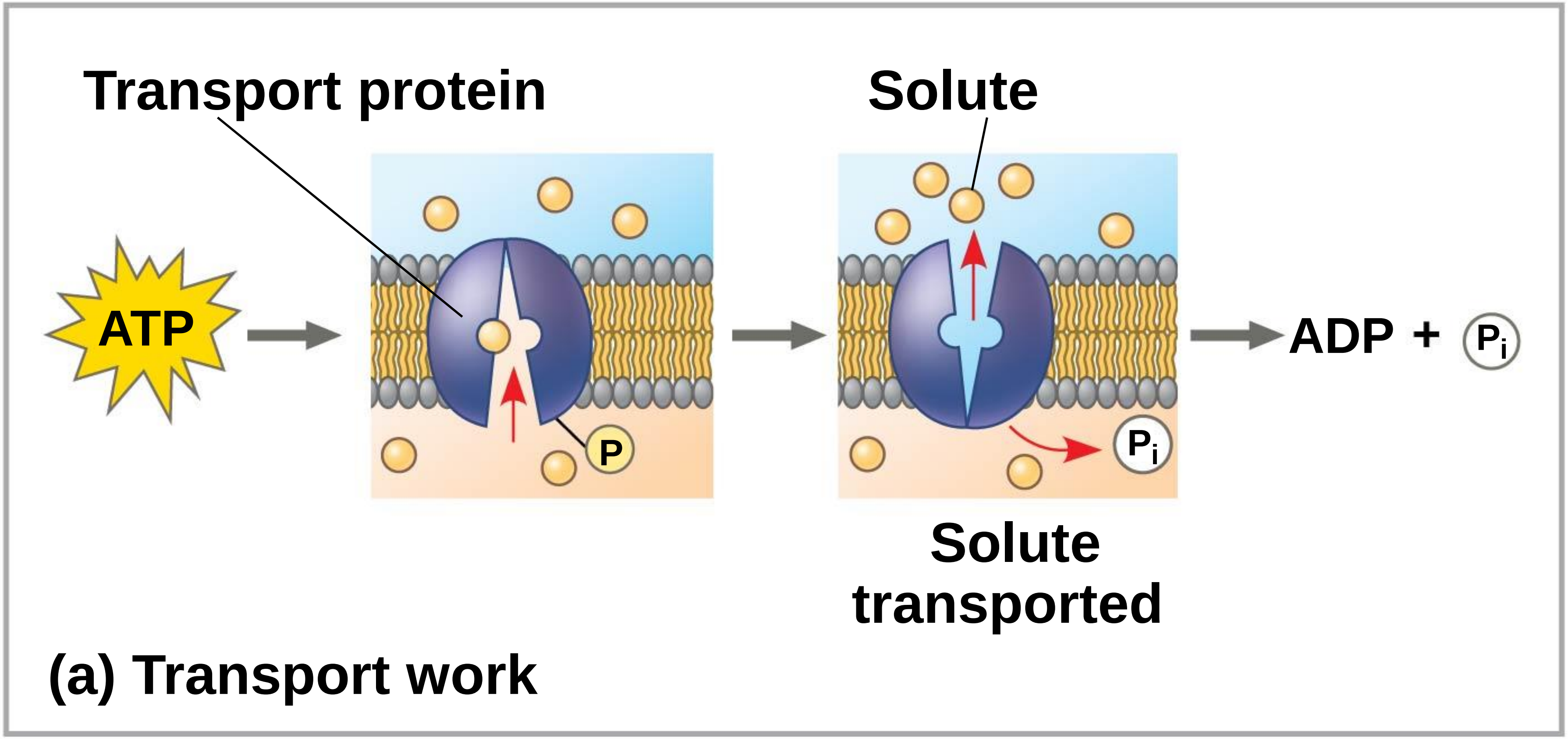
© 2018 Pearson Education Ltd.

Figure 6.11



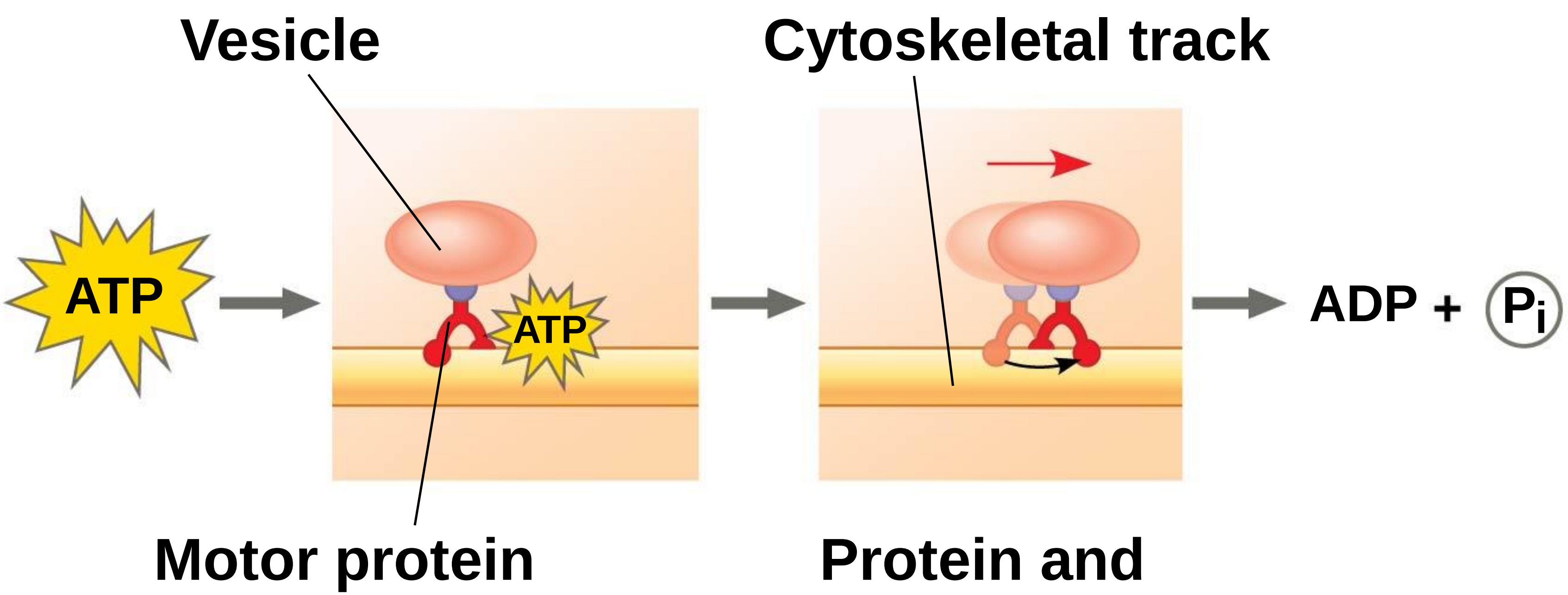
© 2018 Pearson Education Ltd.

Figure 6.11a



© 2018 Pearson Education Ltd.

Figure 6.11b



(b) Mechanical work

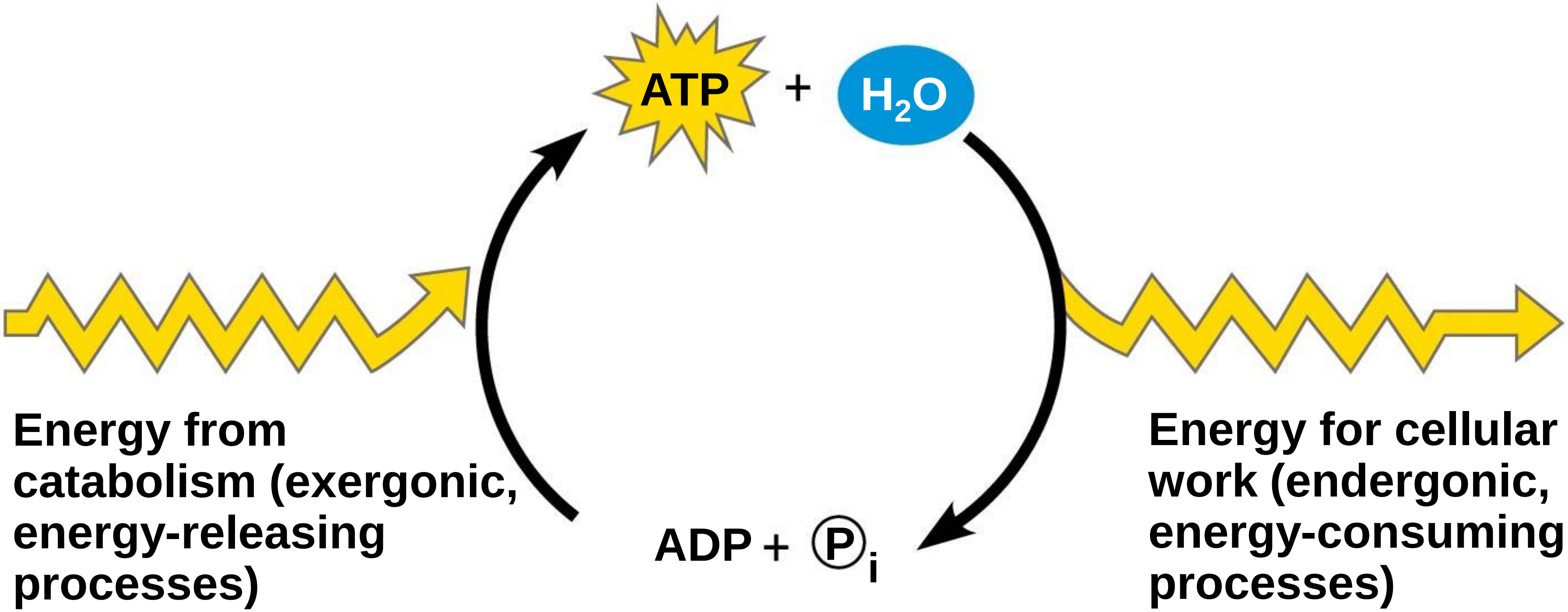
© 2018 Pearson Education Ltd.

The Regeneration of ATP

- ATP is a renewable resource that is regenerated by addition of a phosphate group to adenosine diphosphate (ADP)
- The energy to phosphorylate ADP comes from catabolic reactions in the cell
- The ATP cycle is a revolving door through which energy passes during its transfer from catabolic to anabolic pathways

© 2018 Pearson Education Ltd.

Figure 6.12



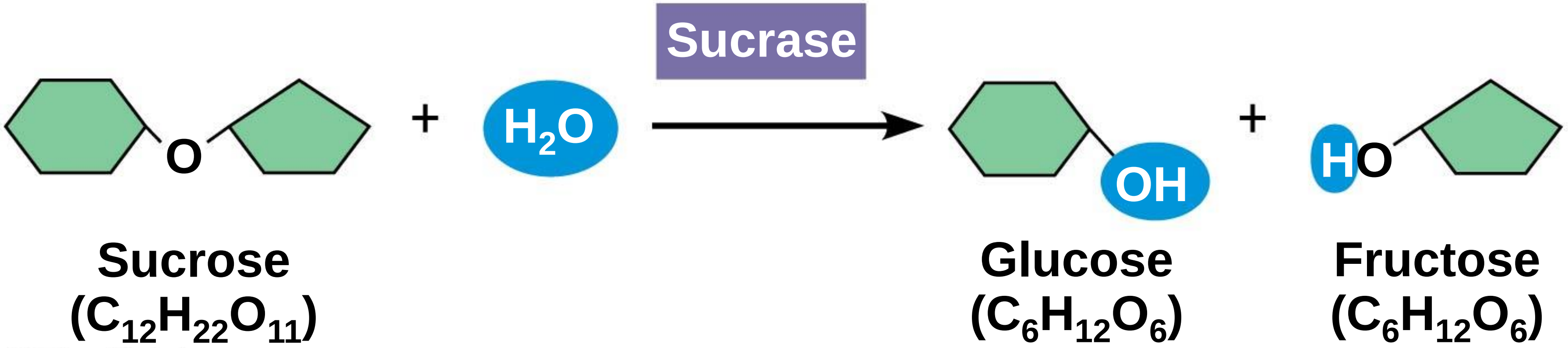
© 2018 Pearson Education Ltd.

Concept 6.4: Enzymes speed up metabolic reactions by lowering energy barriers

- A **catalyst** is a chemical agent that speeds up a reaction without being consumed by the reaction
- An **enzyme** is a catalytic protein
  - For example, sucrase is an enzyme that catalyzes the hydrolysis of sucrose

© 2018 Pearson Education Ltd.

Figure 6.UN02



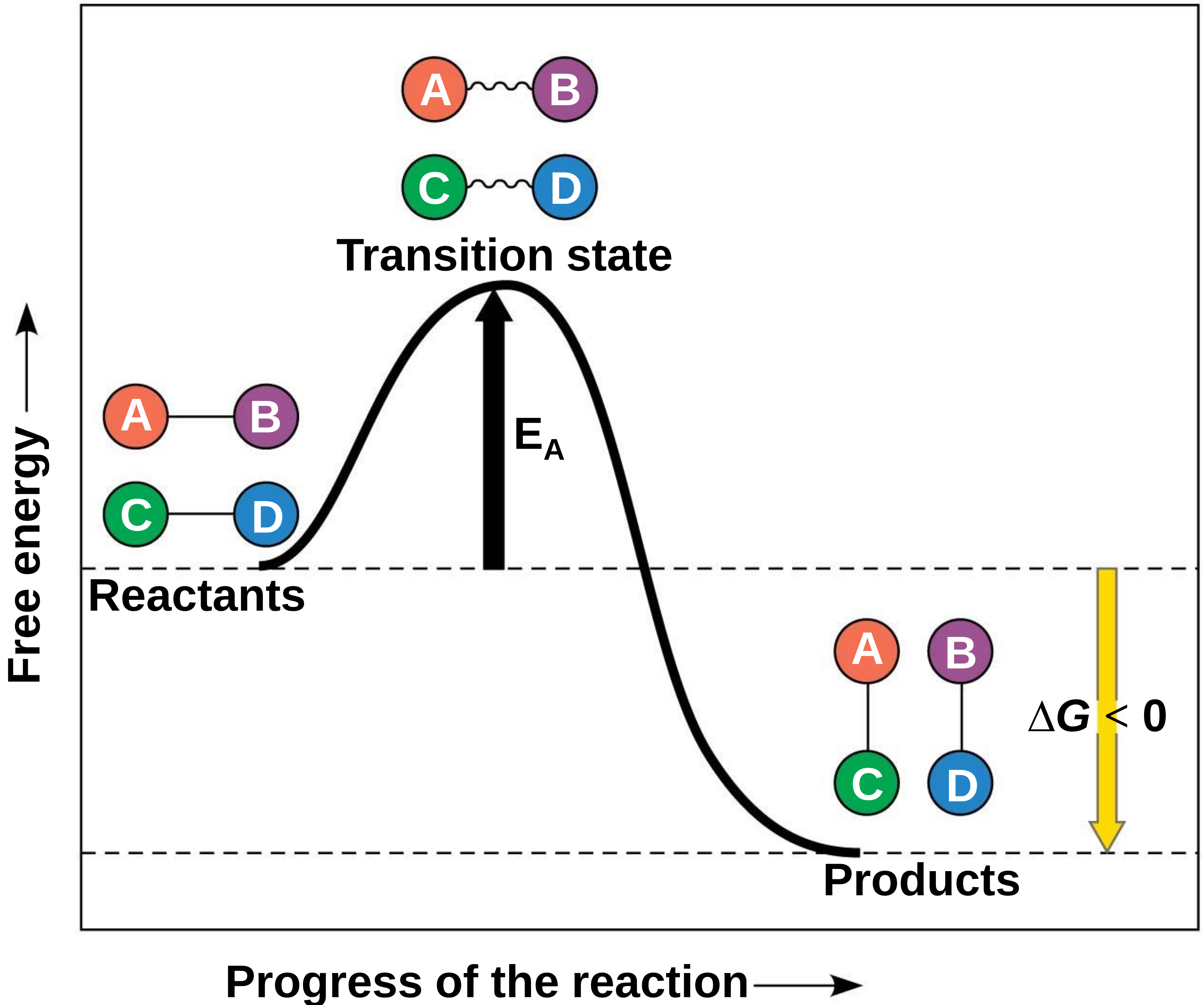
© 2018 Pearson Education Ltd.

The Activation Energy Barrier

- Every chemical reaction between molecules involves bond breaking and bond forming
- The initial energy needed to start a chemical reaction is called the free energy of activation, or **activation energy** (E_A)
- Activation energy is often supplied in the form of thermal energy that the reactant molecules absorb from their surroundings

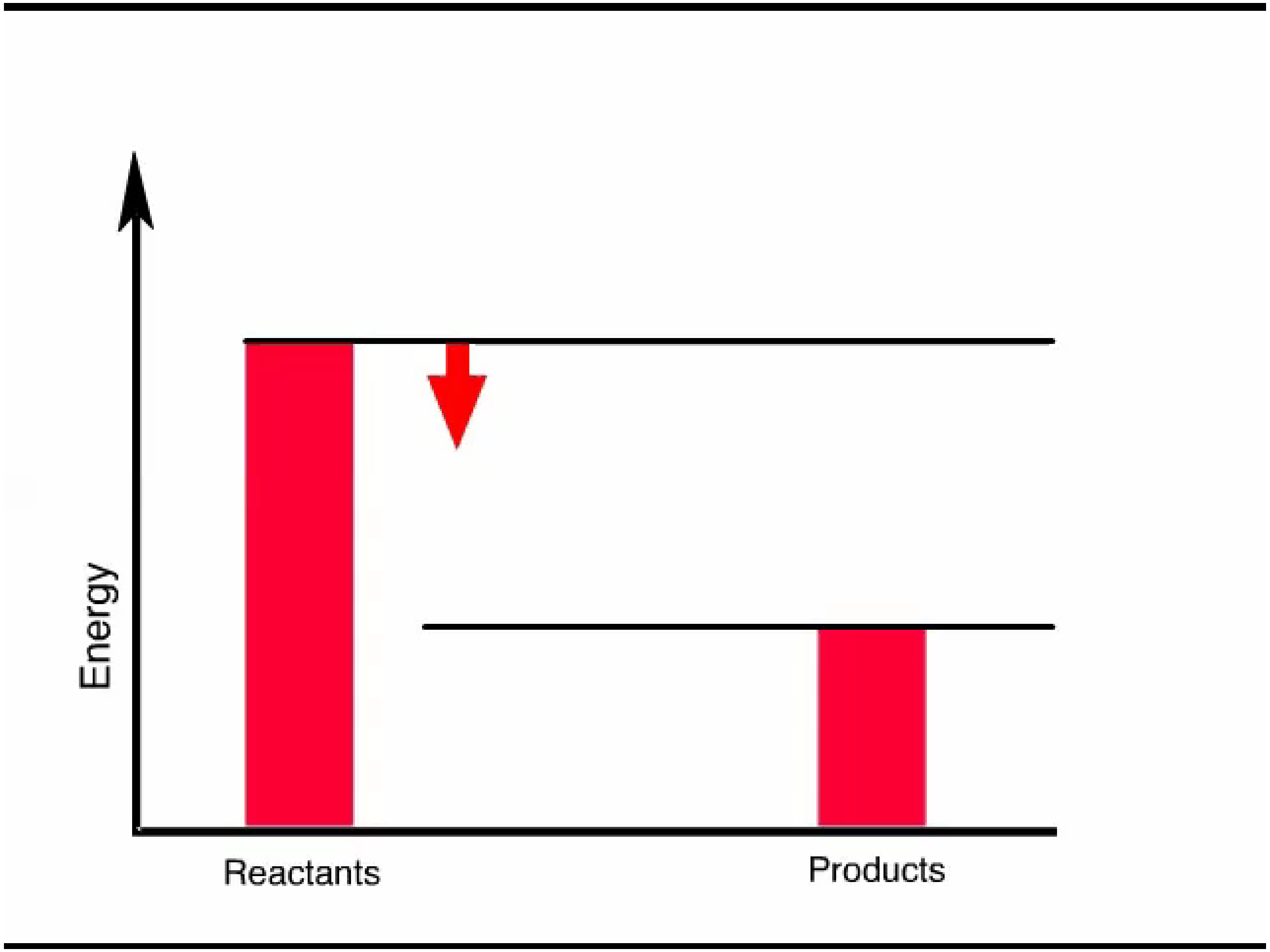
© 2018 Pearson Education Ltd.

Figure 6.13



© 2018 Pearson Education Ltd.

Animation: How Enzymes Work



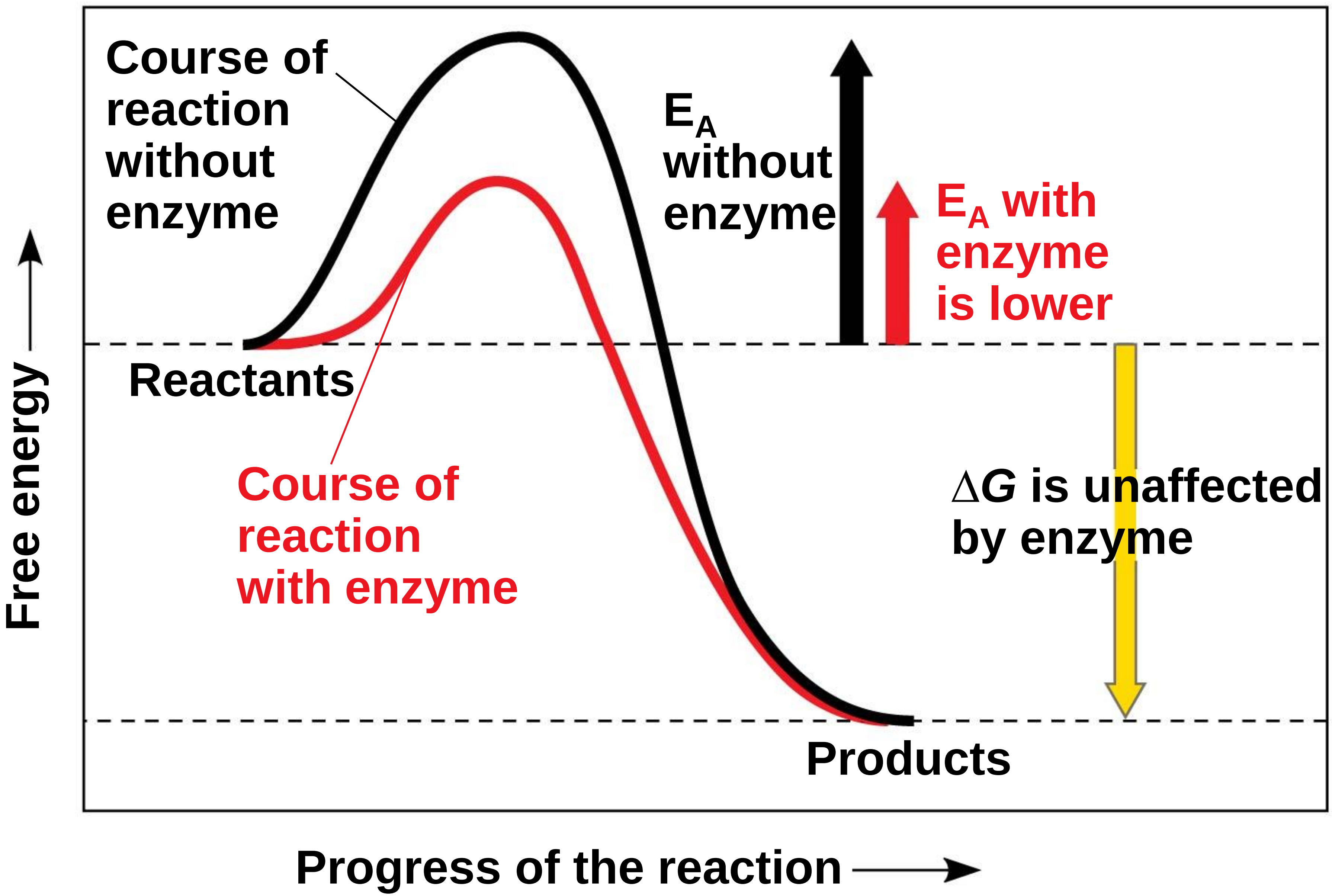
© 2018 Pearson Education Ltd.

How Enzymes Speed Up Reactions

- In **catalysis**, enzymes or other catalysts speed up specific reactions by lowering the E_A barrier
- Enzymes do not affect the change in free energy (ΔG); instead, they hasten reactions that would occur eventually

© 2018 Pearson Education Ltd.

Figure 6.14



© 2018 Pearson Education Ltd.

Substrate Specificity of Enzymes

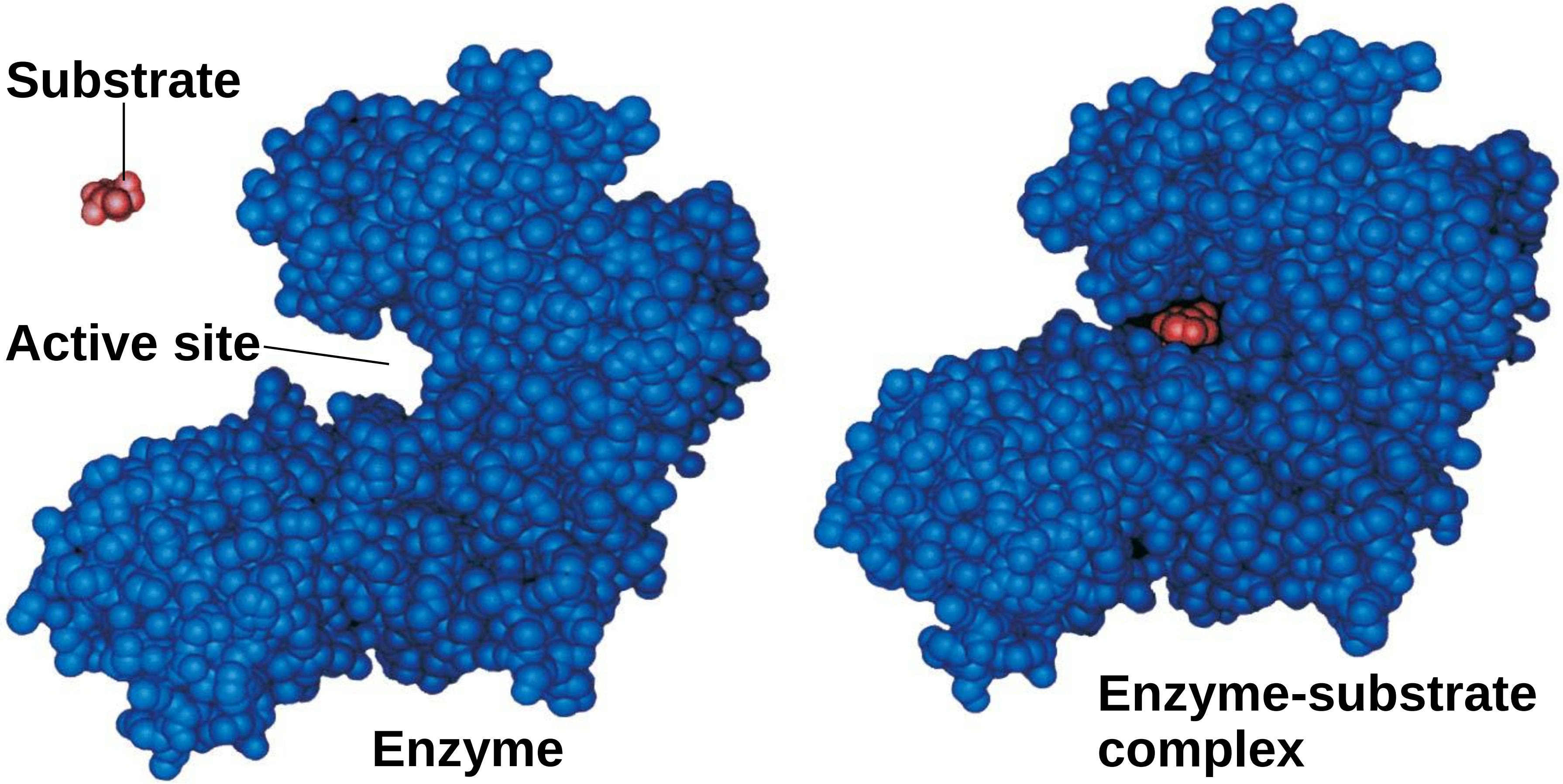
- The reactant that an enzyme acts on is called the enzyme's **substrate**
- The enzyme binds to its substrate, forming an **enzyme-substrate complex**
- While bound, the activity of the enzyme converts substrate to product

© 2018 Pearson Education Ltd.

- The reaction catalyzed by each enzyme is very specific
- The **active site** is the region on the enzyme where the substrate binds
- **Induced fit** of a substrate brings chemical groups of the active site into positions that enhance their ability to catalyze the reaction

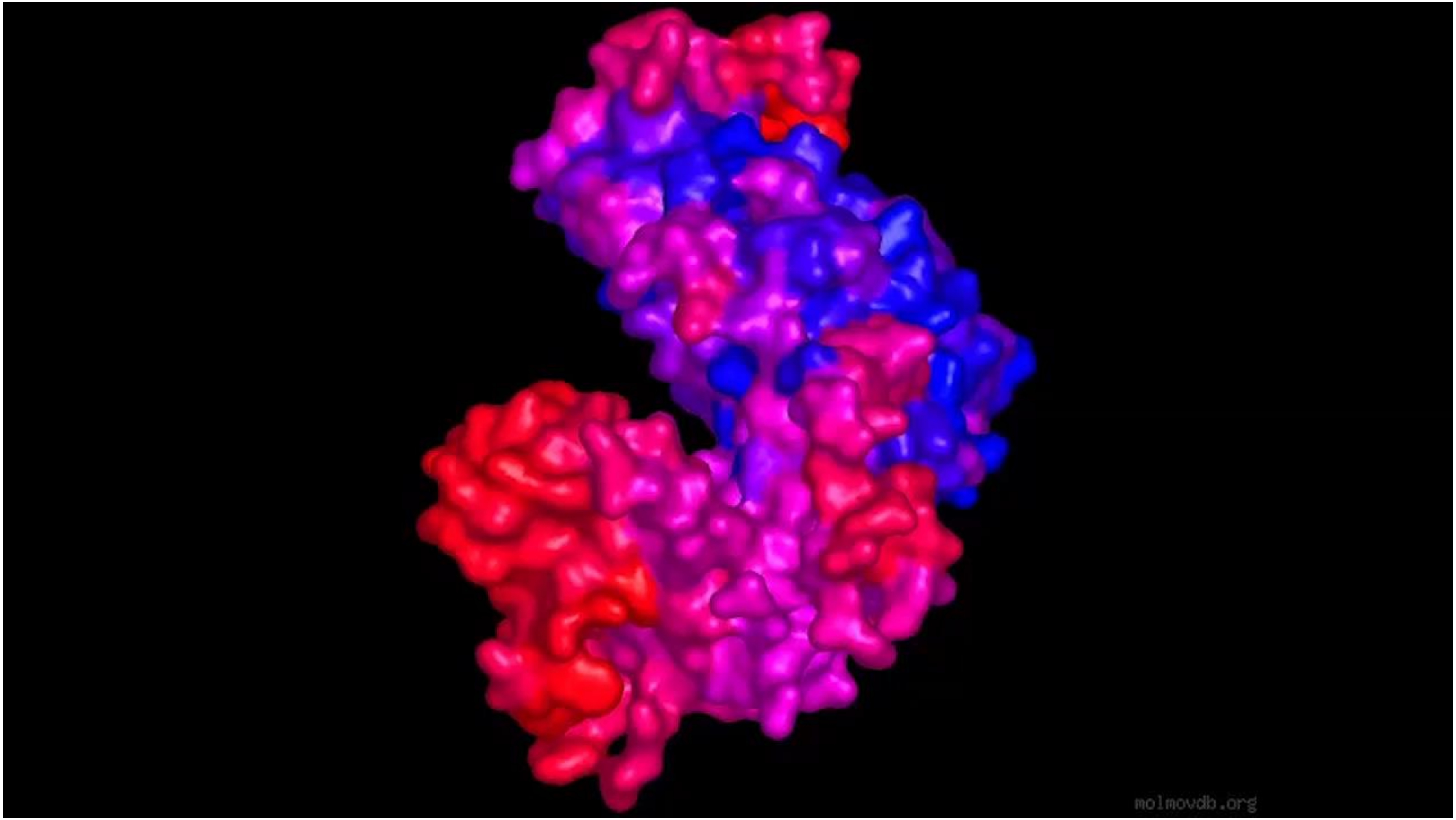
© 2018 Pearson Education Ltd.

Figure 6.15



© 2018 Pearson Education Ltd.

Video: Closure of Hexokinase Via Induced Fit



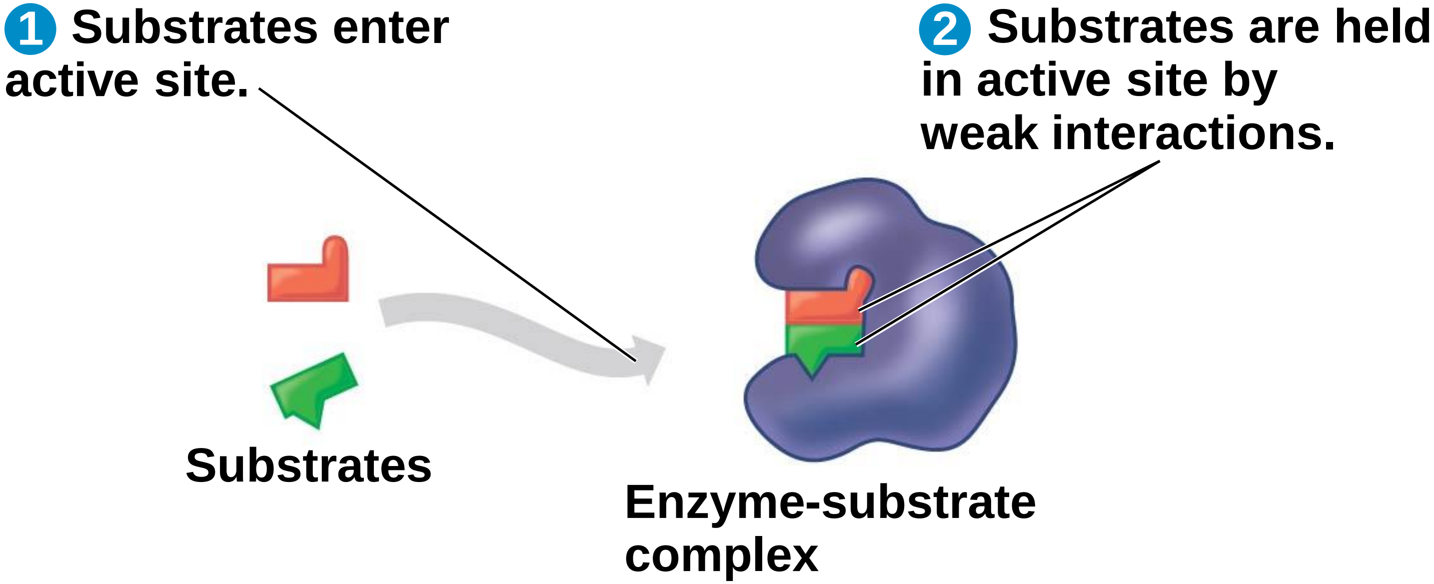
© 2018 Pearson Education Ltd.

Catalysis in the Enzyme's Active Site

- In an enzymatic reaction, the substrate binds to the active site of the enzyme
- Enzymes are extremely fast acting and emerge from reactions in their original form
- Very small amounts of enzyme can have huge metabolic effects because they are used repeatedly in catalytic cycles

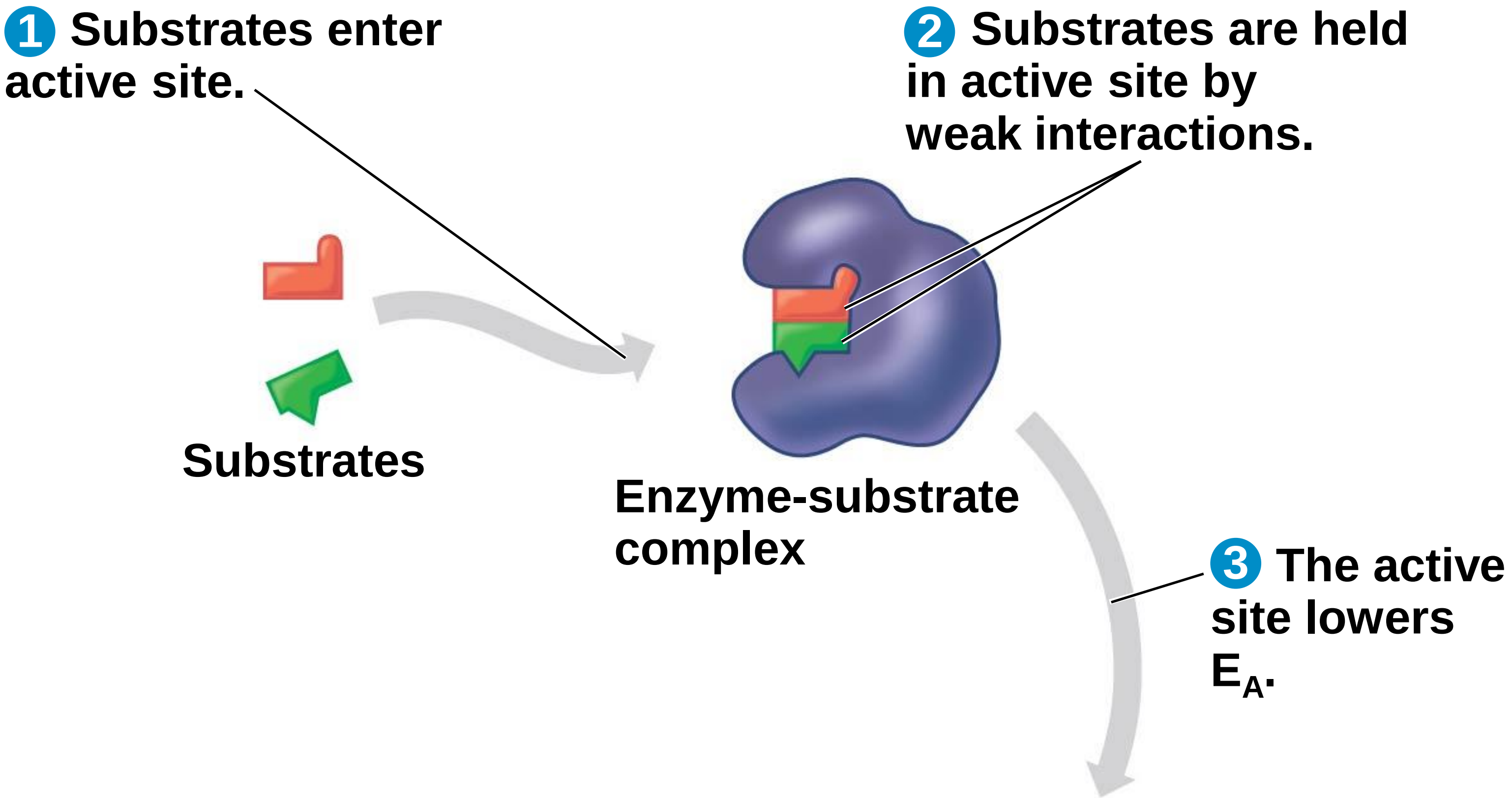
© 2018 Pearson Education Ltd.

Figure 6.16_1



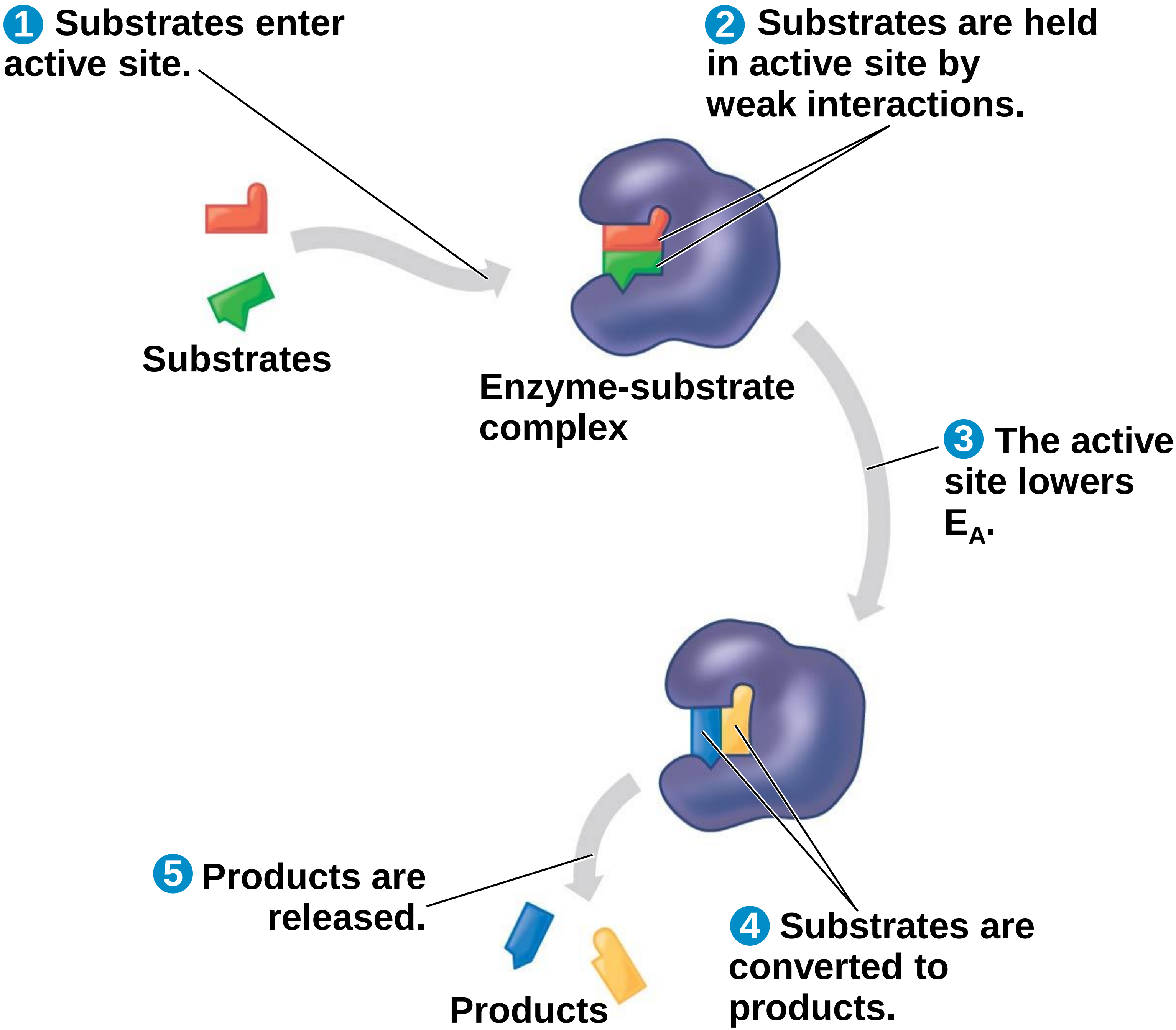
© 2018 Pearson Education Ltd.

Figure 6.16_2



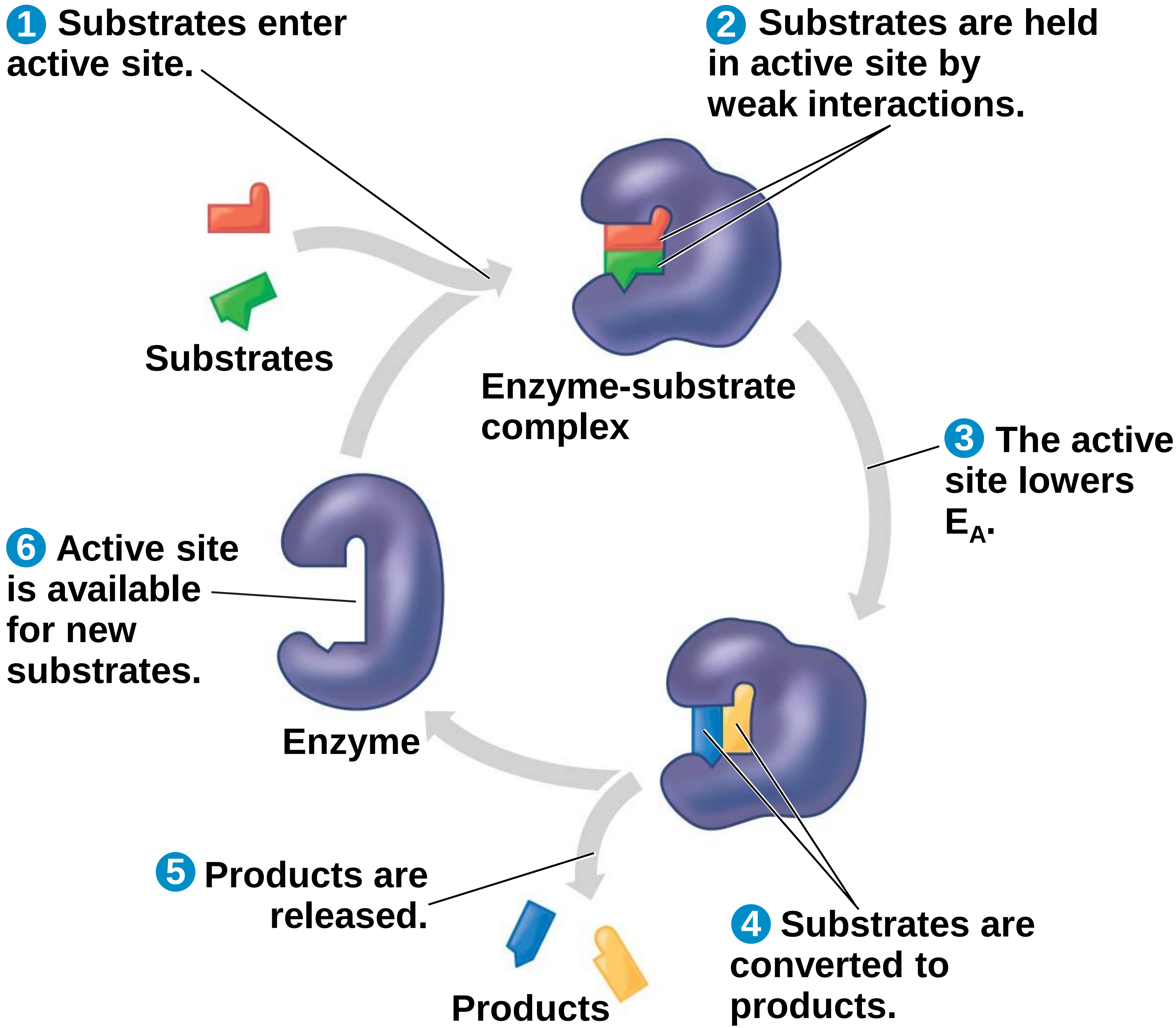
© 2018 Pearson Education Ltd.

Figure 6.16_3



© 2018 Pearson Education Ltd.

Figure 6.16_4



© 2018 Pearson Education Ltd.

- The active site can lower an E_A barrier by
  - orienting substrates correctly
  - straining substrate bonds
  - providing a favorable microenvironment
  - covalently bonding to the substrate

© 2018 Pearson Education Ltd.

- The rate of an enzyme-catalyzed reaction can be sped up by increasing substrate concentration
- When all enzyme molecules have their active sites engaged, the enzyme is saturated
- If the enzyme is saturated, the reaction rate can only be sped up by adding more enzyme

© 2018 Pearson Education Ltd.

Effects of Local Conditions on Enzyme Activity

- An enzyme’s activity can be affected by
  - general environmental factors, such as temperature and pH
  - chemicals that specifically influence the enzyme

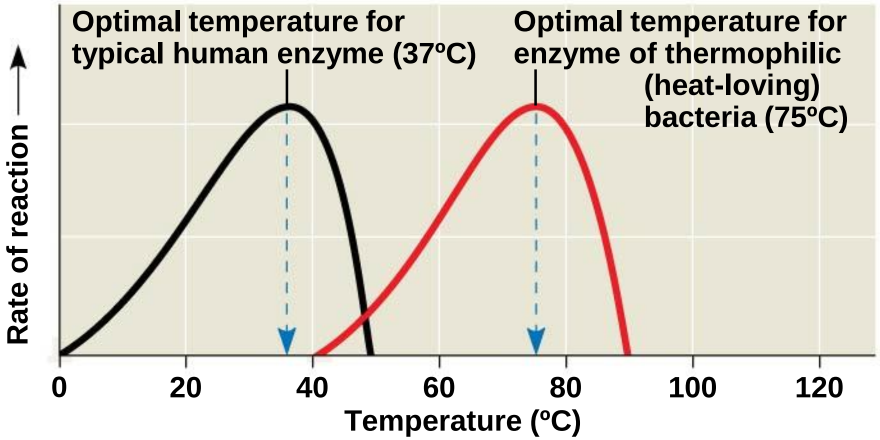
© 2018 Pearson Education Ltd.

Effects of Temperature and pH

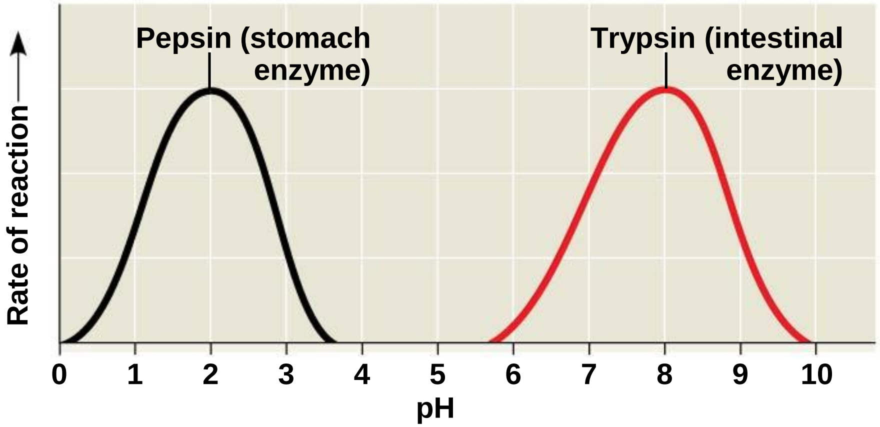
- Each enzyme has an optimal temperature in which it can function
- Each enzyme has an optimal pH in which it can function
- Optimal conditions favor the most active shape for the enzyme molecule

© 2018 Pearson Education Ltd.

Figure 6.17



(a) Optimal temperature for two enzymes



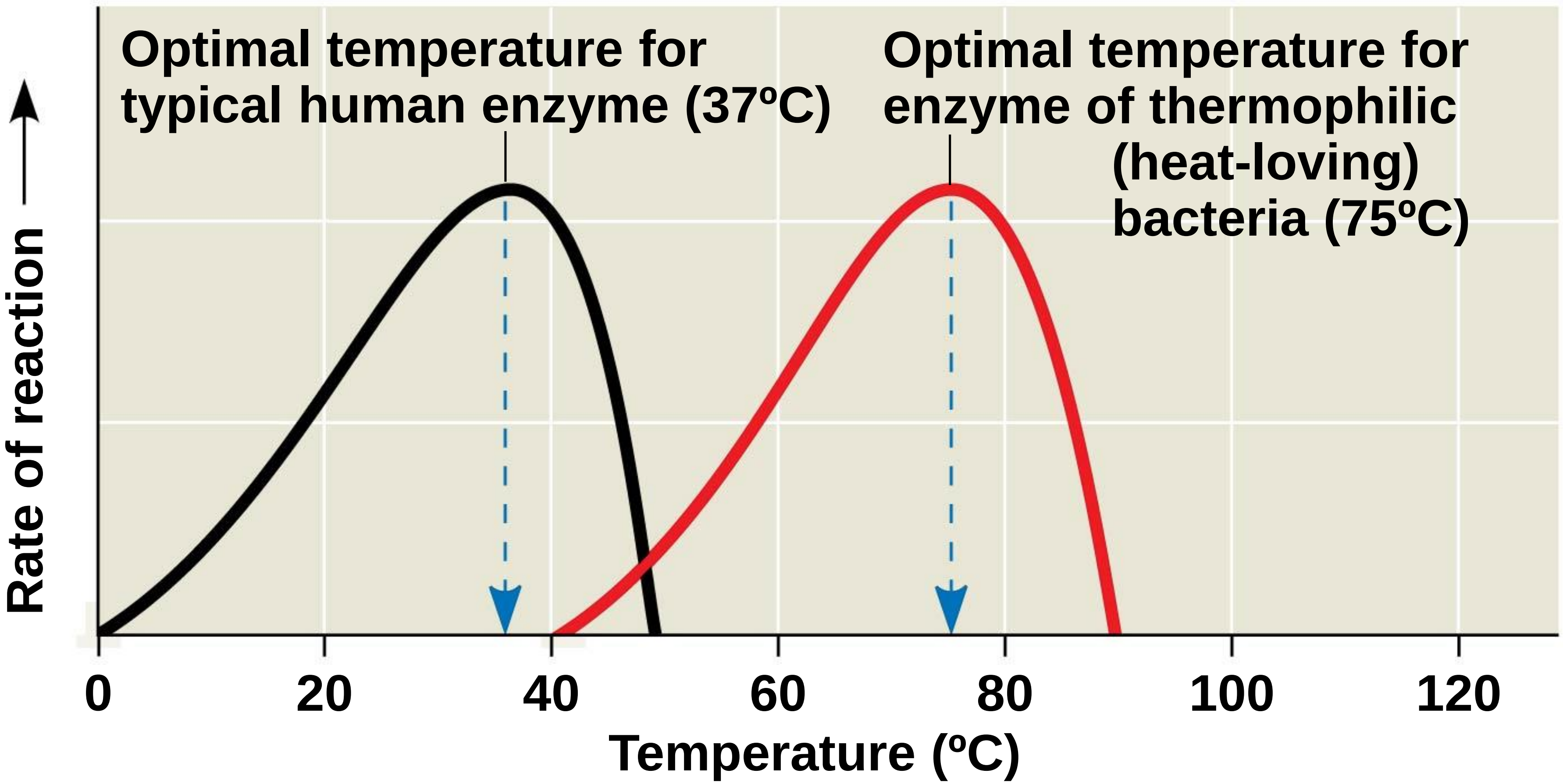
(b) Optimal pH for two enzymes

© 2018 Pearson Education Ltd.

Figure 6.17a

© 2018 Pearson Education Ltd.

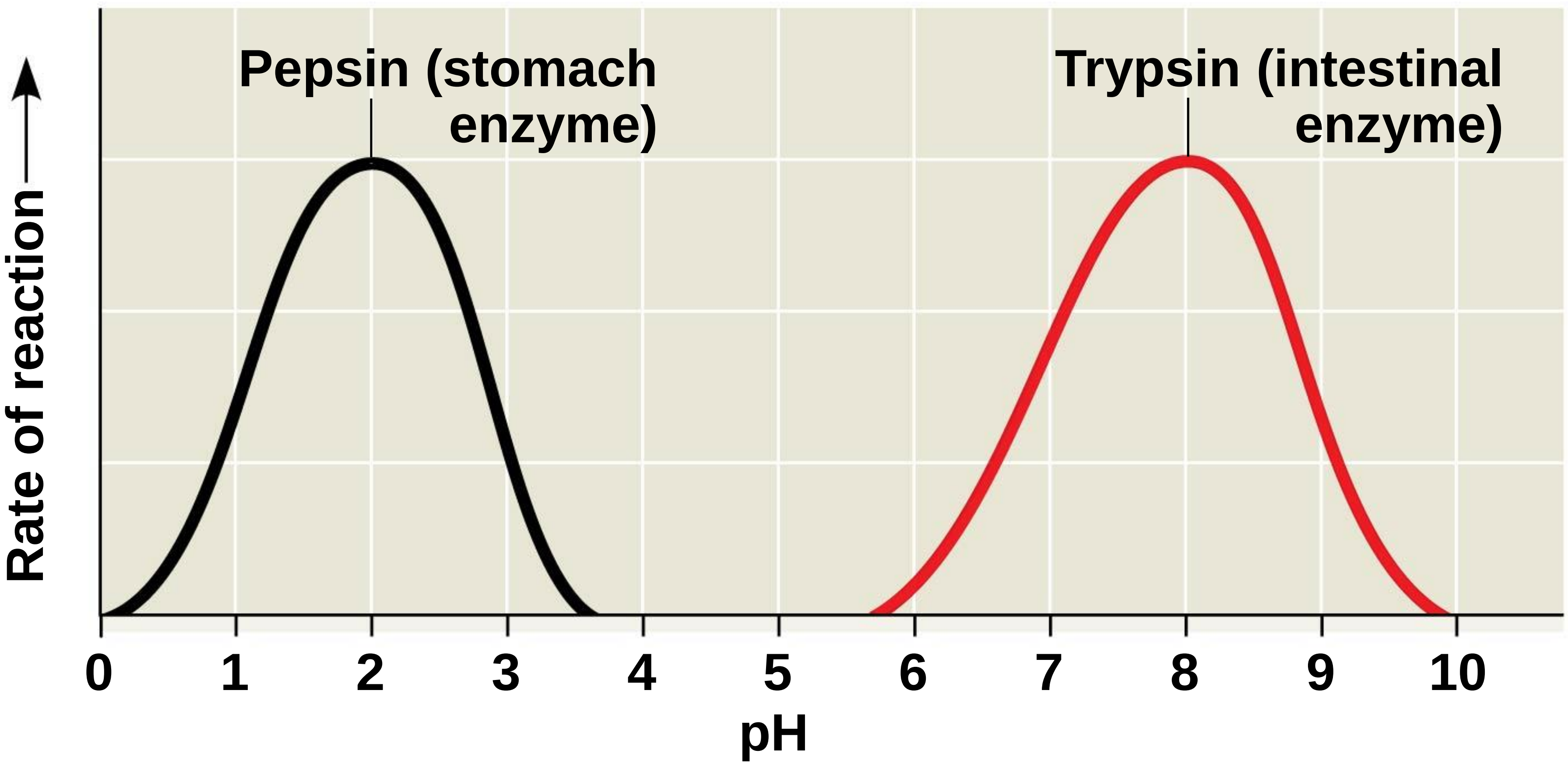
Figure 6.17b



(a) Optimal temperature for two enzymes

© 2018 Pearson Education Ltd.

Figure 6.17c



(b) Optimal pH for two enzymes

© 2018 Pearson Education Ltd.

Cofactors

- **Cofactors** are nonprotein enzyme helpers
- Cofactors may be inorganic (such as a metal in ionic form) or organic
- An organic cofactor is called a **coenzyme**
- Coenzymes include vitamins

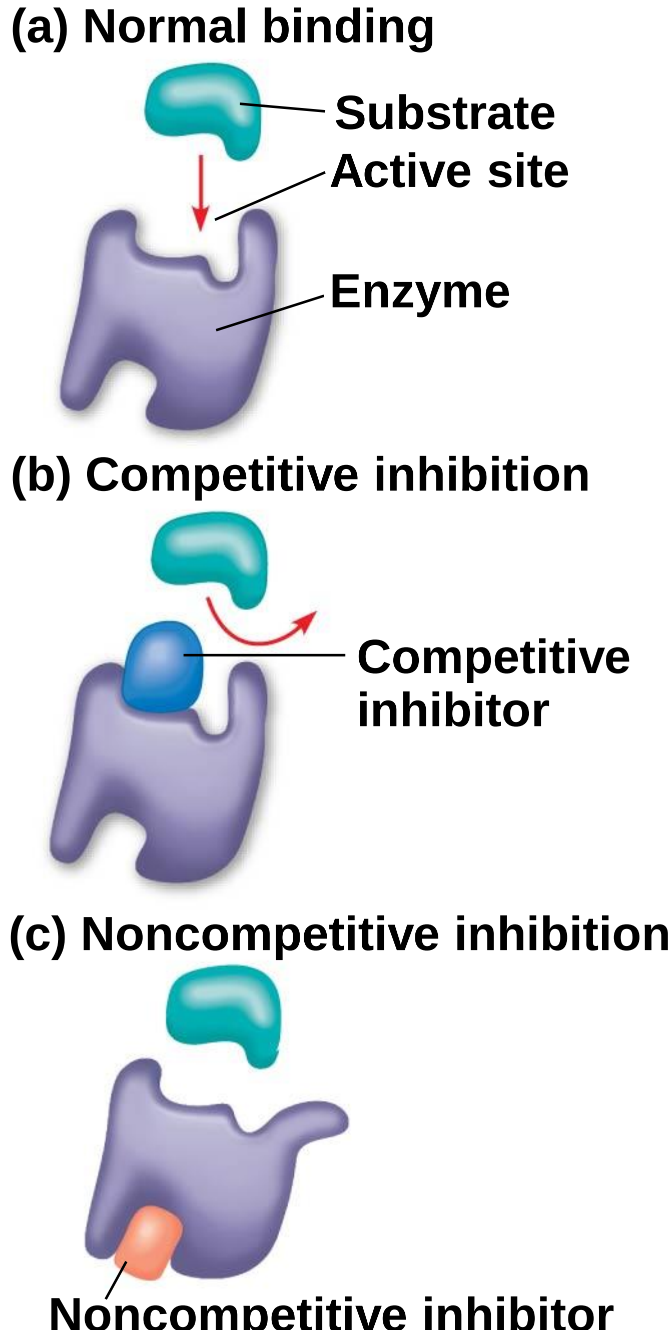
© 2018 Pearson Education Ltd.

Enzyme Inhibitors

- **Competitive inhibitors** bind to the active site of an enzyme, competing with the substrate
- **Noncompetitive inhibitors** bind to another part of an enzyme, causing the enzyme to change shape and making the active site less effective
- Some examples of inhibitors are toxins, poisons, pesticides, and antibiotics

© 2018 Pearson Education Ltd.

Figure 6.18



© 2018 Pearson Education Ltd.

The Evolution of Enzymes

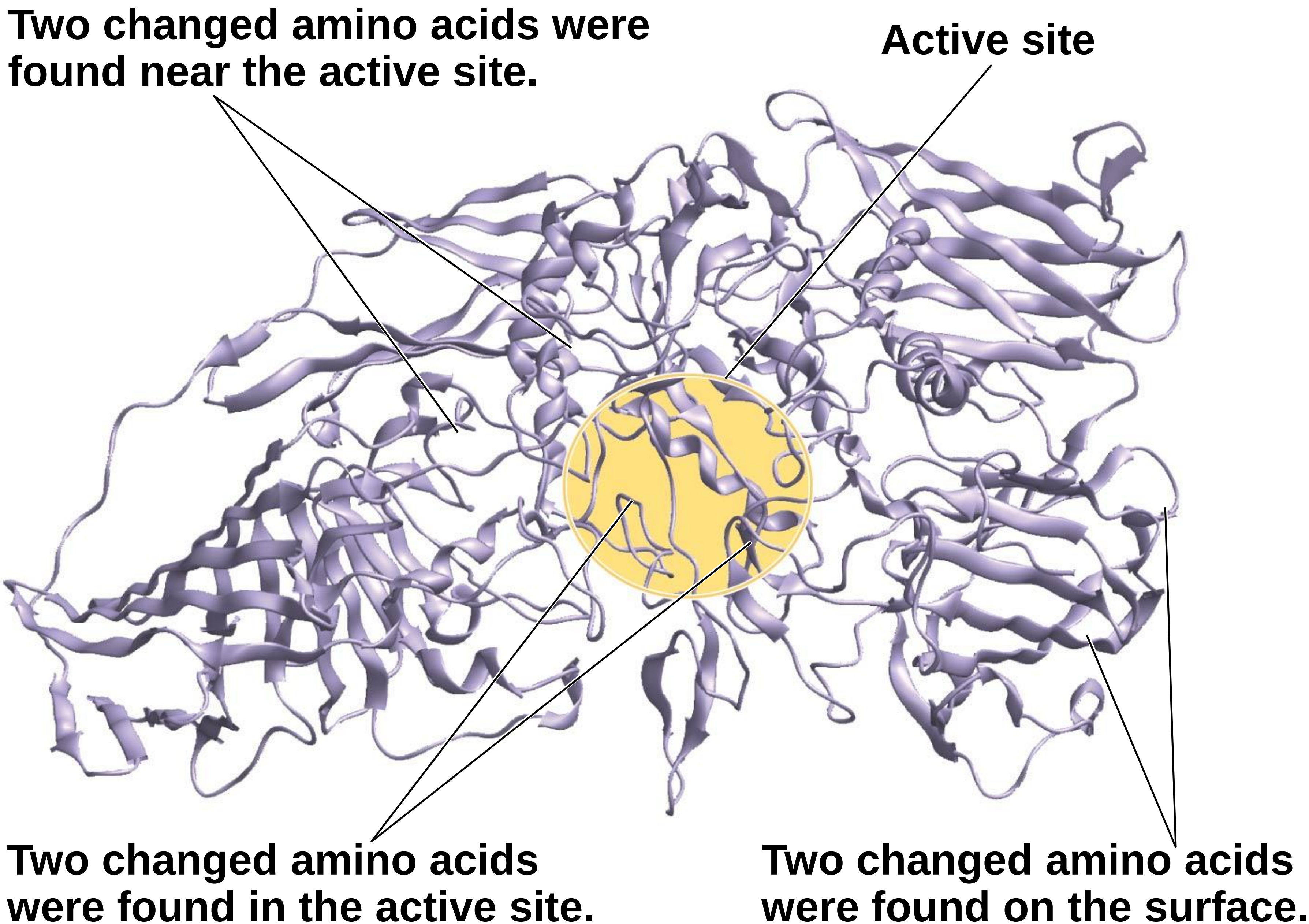
- Enzymes are proteins encoded by genes
- Changes (mutations) in genes lead to changes in amino acid composition of an enzyme
- Altered amino acids, particularly at the active site, can result in novel enzyme activity or altered substrate specificity

© 2018 Pearson Education Ltd.

- Under environmental conditions where the new function is beneficial, natural selection would favor the mutated allele
  - For example, repeated mutation and selection on the β-galactosidase enzyme in *E. coli* resulted in a change of sugar substrate under lab conditions

© 2018 Pearson Education Ltd.

Figure 6.19



© 2018 Pearson Education Ltd.

Concept 6.5: Regulation of enzyme activity helps control metabolism

- Chemical chaos would result if a cell's metabolic pathways were not tightly regulated
- A cell does this by switching on or off the genes that encode specific enzymes or by regulating the activity of enzymes

© 2018 Pearson Education Ltd.

Allosteric Regulation of Enzymes

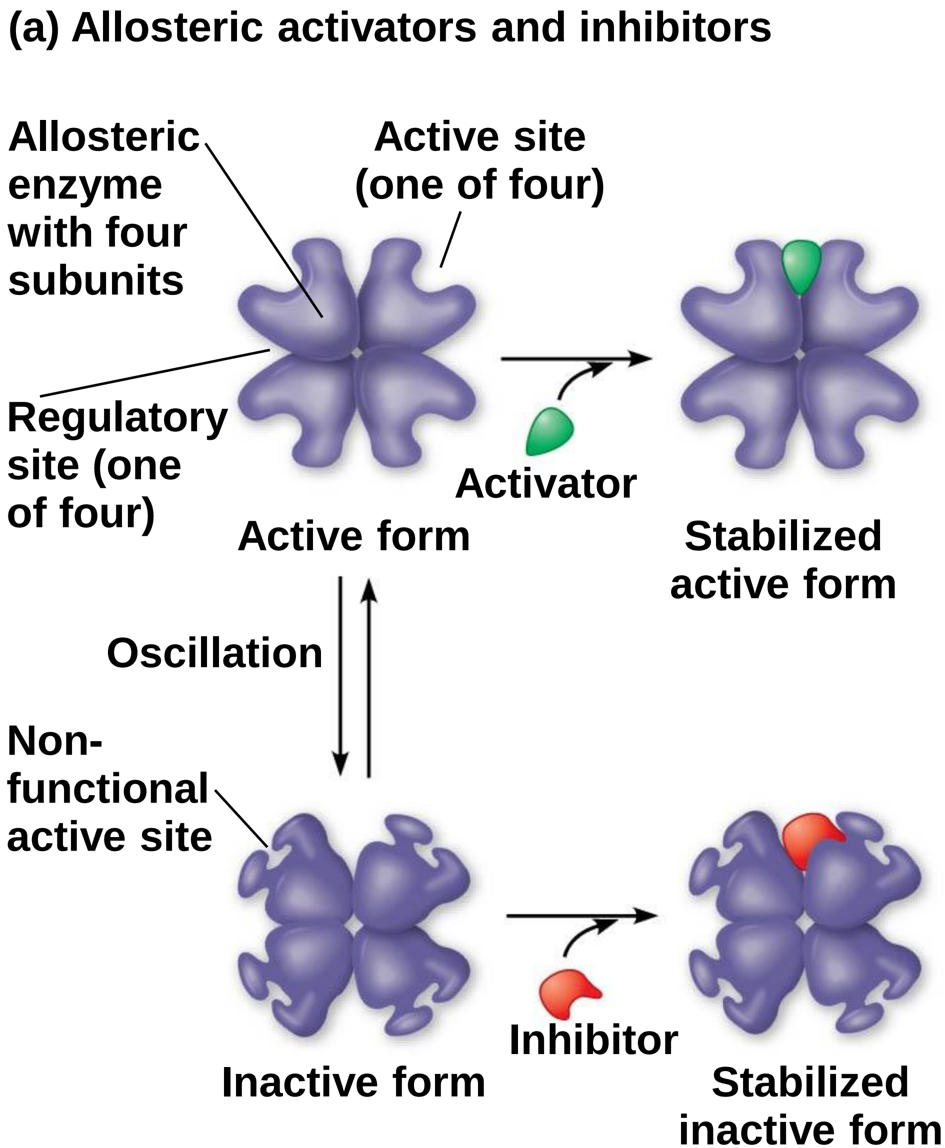
- **Allosteric regulation** may either inhibit or stimulate an enzyme's activity
- Allosteric regulation occurs when a regulatory molecule binds to a protein at one site and affects the protein's function at another site

© 2018 Pearson Education Ltd.

Allosteric Activation and Inhibition

- Most allosterically regulated enzymes are made from polypeptide subunits, each with its own active site
- The enzyme complex has active and inactive forms
- The binding of an activator stabilizes the active form of the enzyme
- The binding of an inhibitor stabilizes the inactive form of the enzyme

© 2018 Pearson Education Ltd.

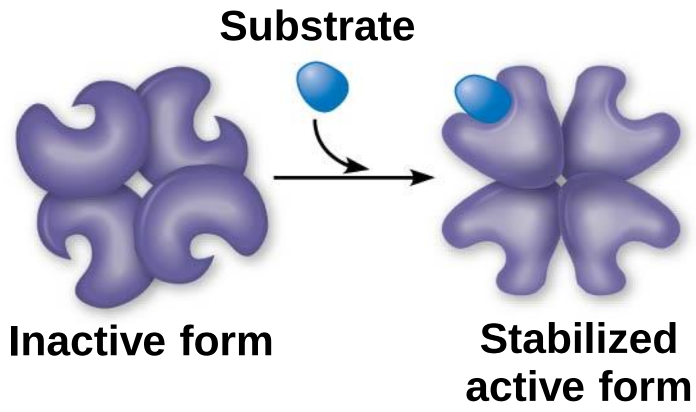


© 2018 Pearson Education Ltd.

- **Cooperativity** is a form of allosteric regulation that can amplify enzyme activity
- One substrate molecule primes an enzyme to act on additional substrate molecules more readily
- Cooperativity is allosteric because binding by a substrate to one active site affects catalysis in a different active site

© 2018 Pearson Education Ltd.

(b) Cooperativity: another type of allosteric activation



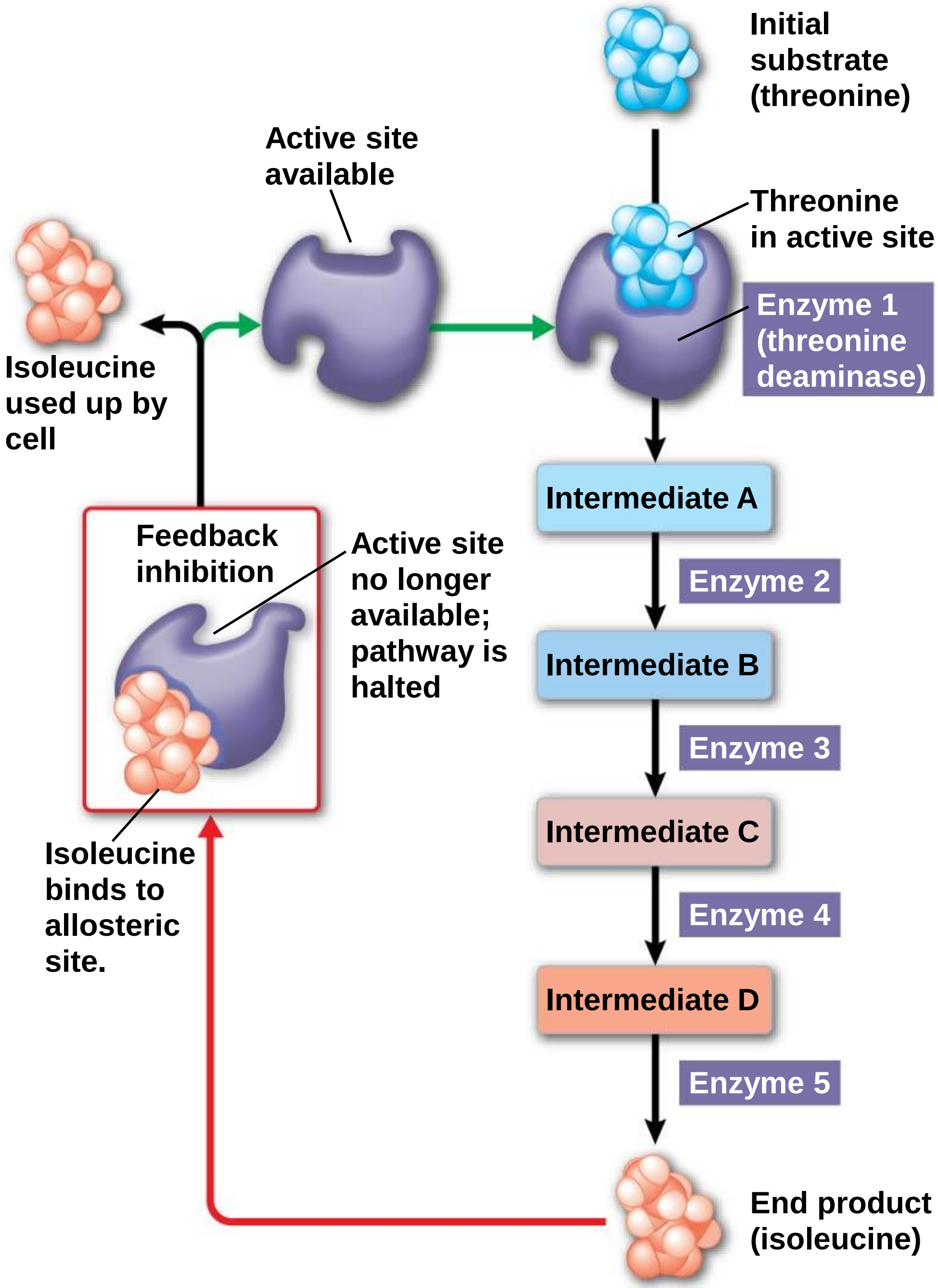
© 2018 Pearson Education Ltd.

Feedback Inhibition

- In **feedback inhibition**, the end product of a metabolic pathway shuts down the pathway
- Feedback inhibition prevents a cell from wasting chemical resources by synthesizing more product than is needed

© 2018 Pearson Education Ltd.

Figure 6.21



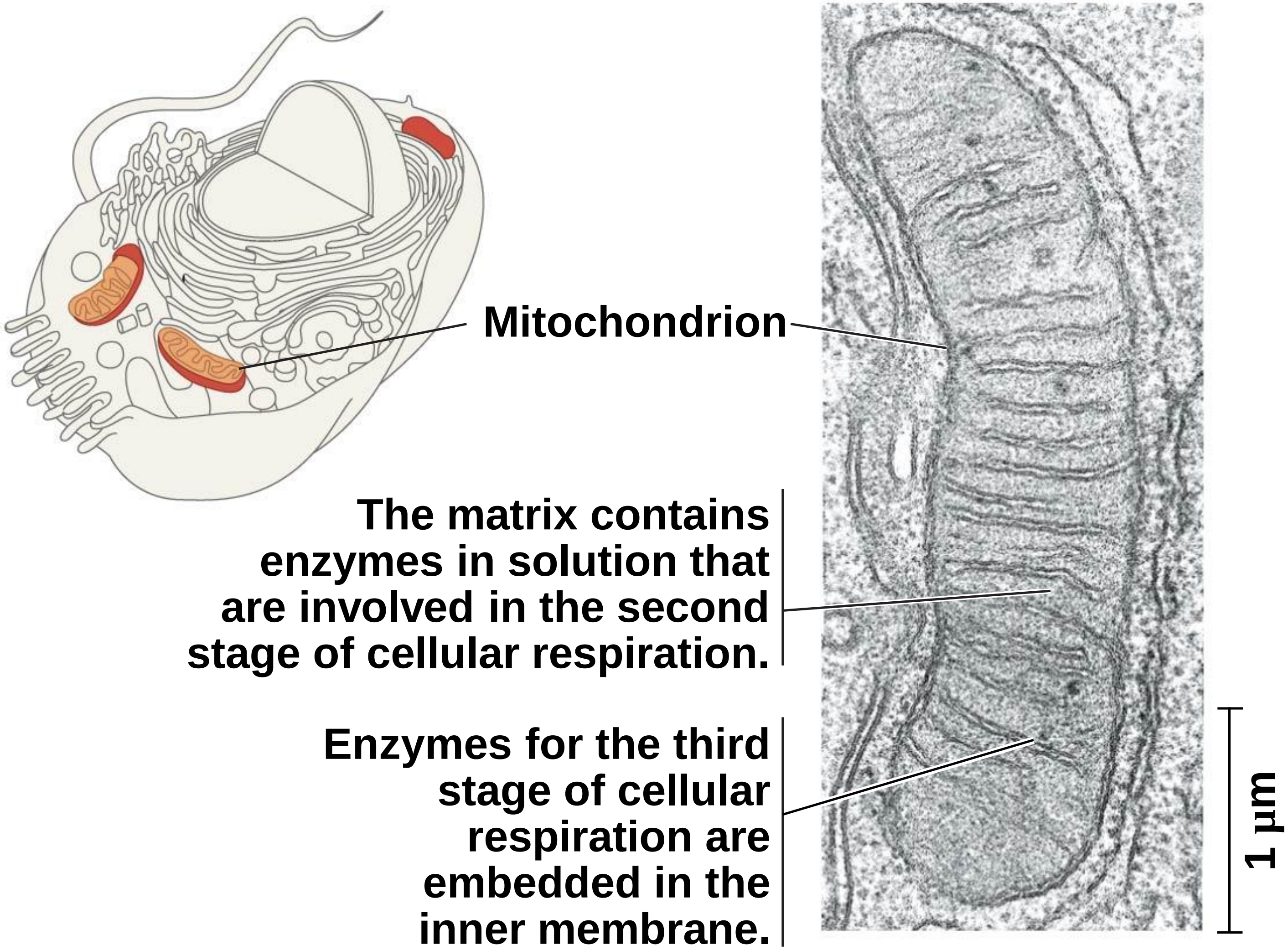
© 2018 Pearson Education Ltd.

Localization of Enzymes Within the Cell

- Structures within the cell help bring order to metabolic pathways
- Some enzymes act as structural components of membranes
- In eukaryotic cells, some enzymes reside in specific organelles; for example, enzymes for cellular respiration are located in mitochondria

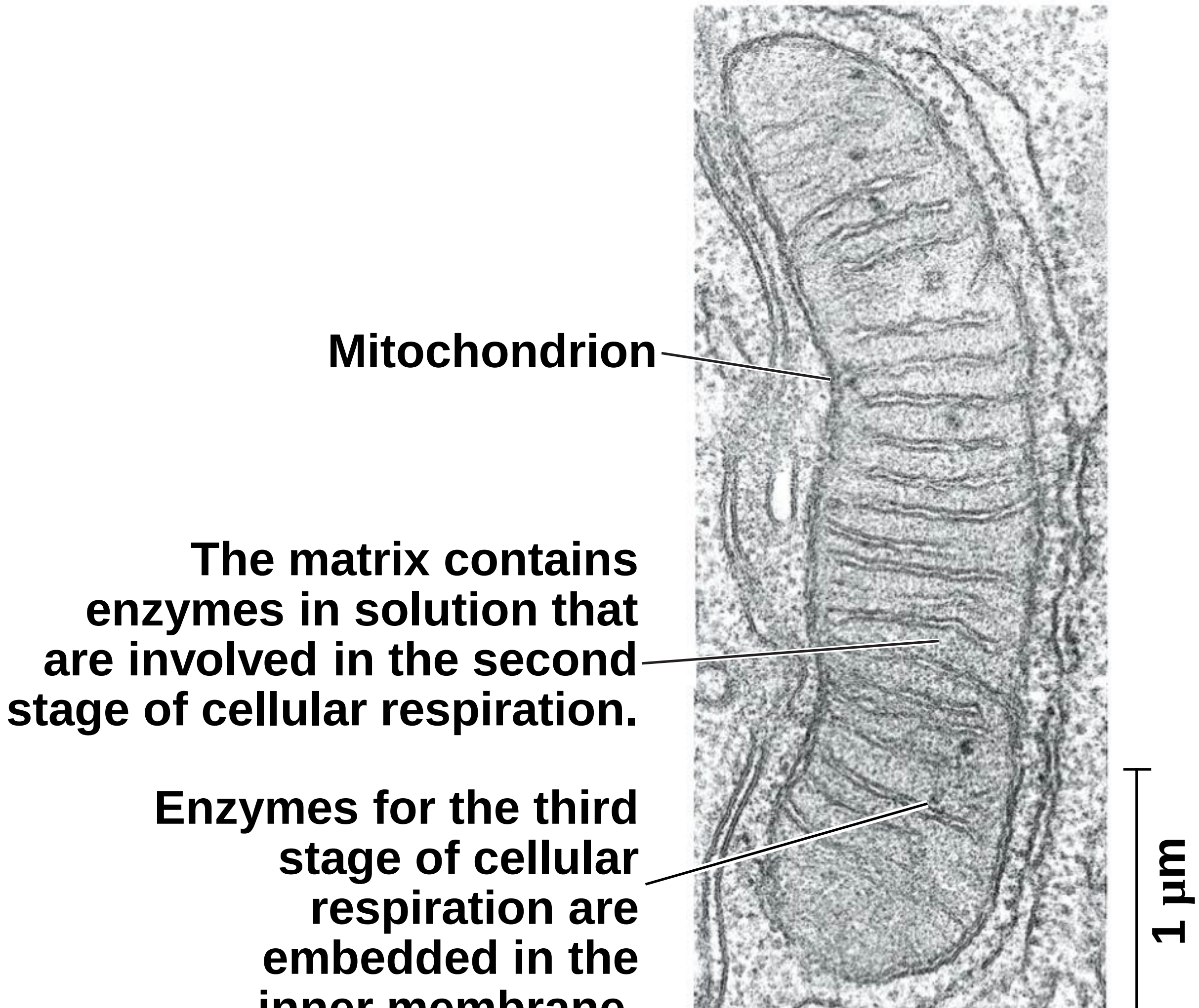
© 2018 Pearson Education Ltd.

Figure 6.22



© 2018 Pearson Education Ltd.

Figure 6.22a



© 2018 Pearson Education Ltd.

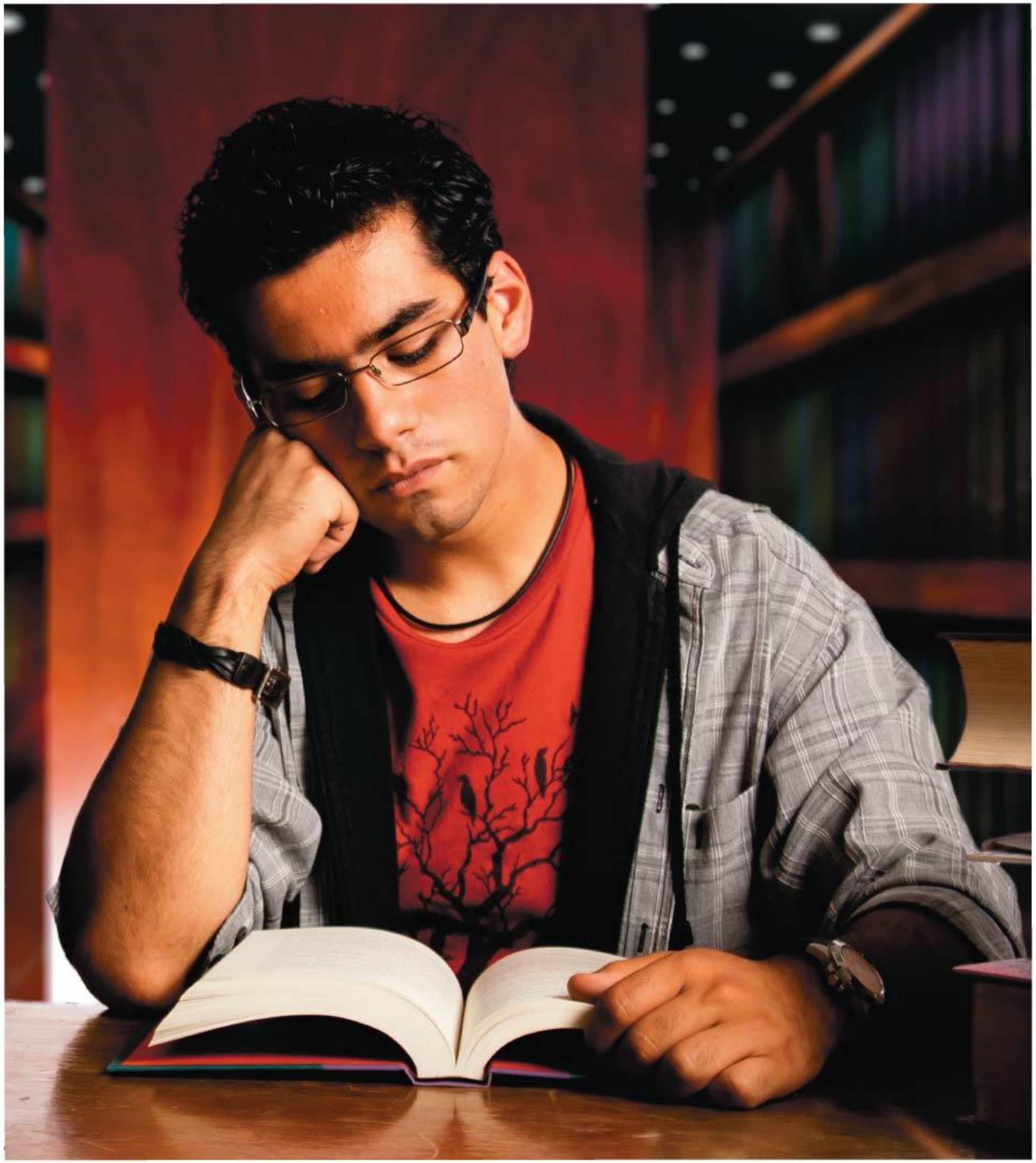
Figure 6.UN03a

Time (min)	Concentration of Ⓟ$_i$ (μmol/mL)
0	0
5	10
10	90
15	180
20	270
25	330
30	355
35	355
40	355

Data from S. R. Commerford et al., Diets enriched in sucrose or fat increase gluconeogenesis and G-6-Pase but not basal glucose production in rats, *American Journal of Physiology - Endocrinology and Metabolism* 283:E545–E555 (2002).

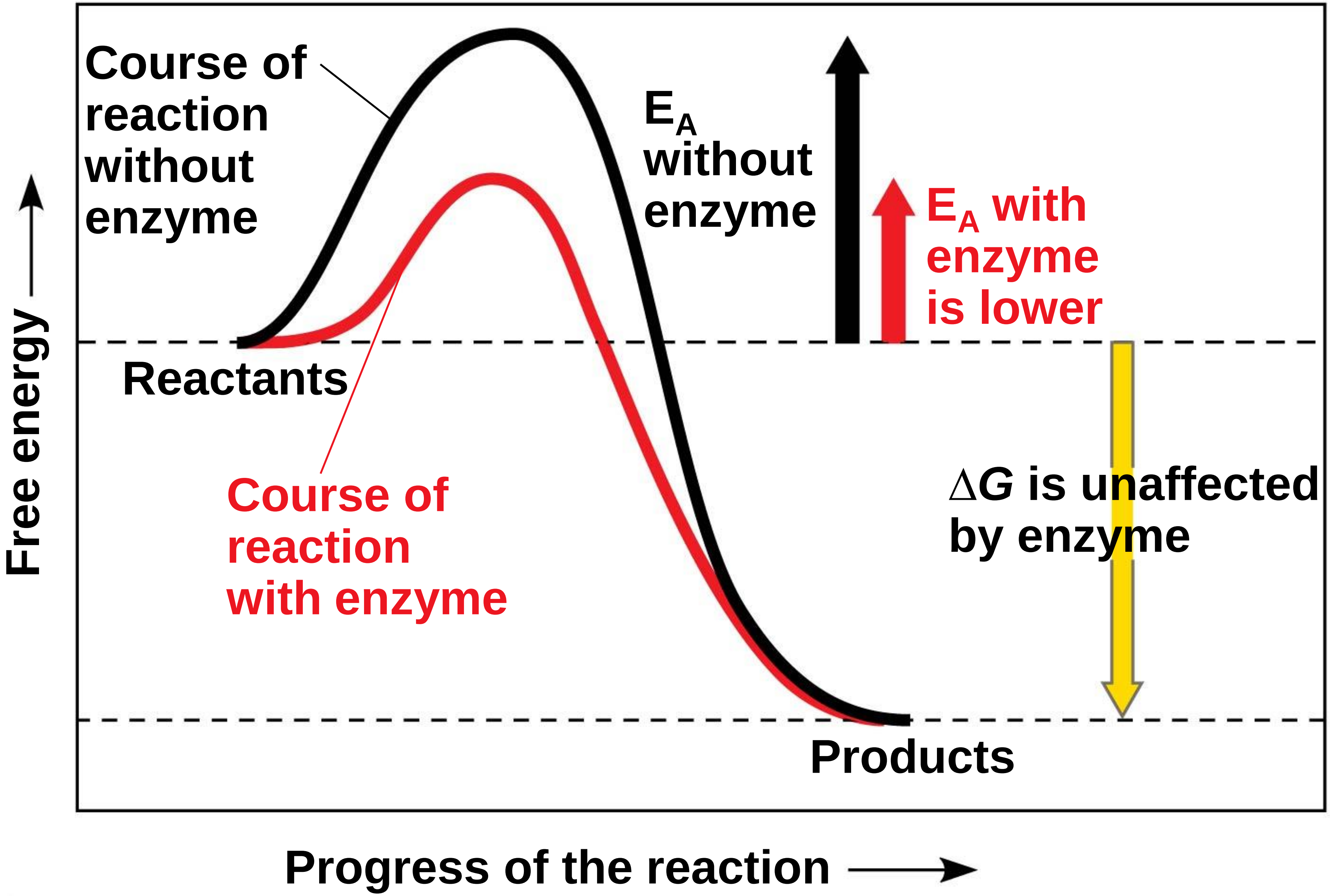
© 2018 Pearson Education Ltd.

Figure 6.UN03b



© 2018 Pearson Education Ltd.

Figure 6.UN04



© 2018 Pearson Education Ltd.

Figure 6.UN05

© 2018 Pearson Education Ltd.