

# Chapter 8

## An Introduction to Metabolism

PowerPoint® Lecture Presentations for

### **Biology**

*Eighth Edition*

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

# Overview: The Energy of Life

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- The living cell is a miniature chemical factory where thousands of reactions occur
- The cell extracts energy and applies energy to perform work
- Some organisms even convert energy to light, as in bioluminescence

Fig. 8-1



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

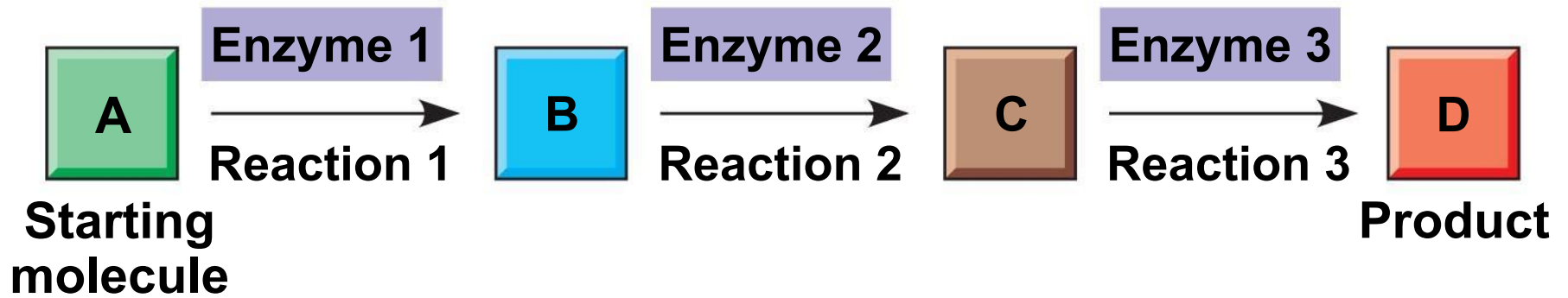
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- **Metabolism** is the totality of an organism's chemical reactions
- Metabolism is an emergent property of life that arises from interactions between molecules within the cell

# Organization of the Chemistry of Life into Metabolic Pathways

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



- 
- **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

- 
- **Anabolic pathways** consume energy to build complex molecules from simpler ones
  - The synthesis of protein from amino acids is an example of anabolism
  - **Bioenergetics** is the study of how organisms manage their energy resources



# Forms of Energy

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

- 
- **Kinetic energy** is energy associated with motion
  - **Heat (thermal energy)** is kinetic energy associated with random movement of atoms or molecules
  - **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

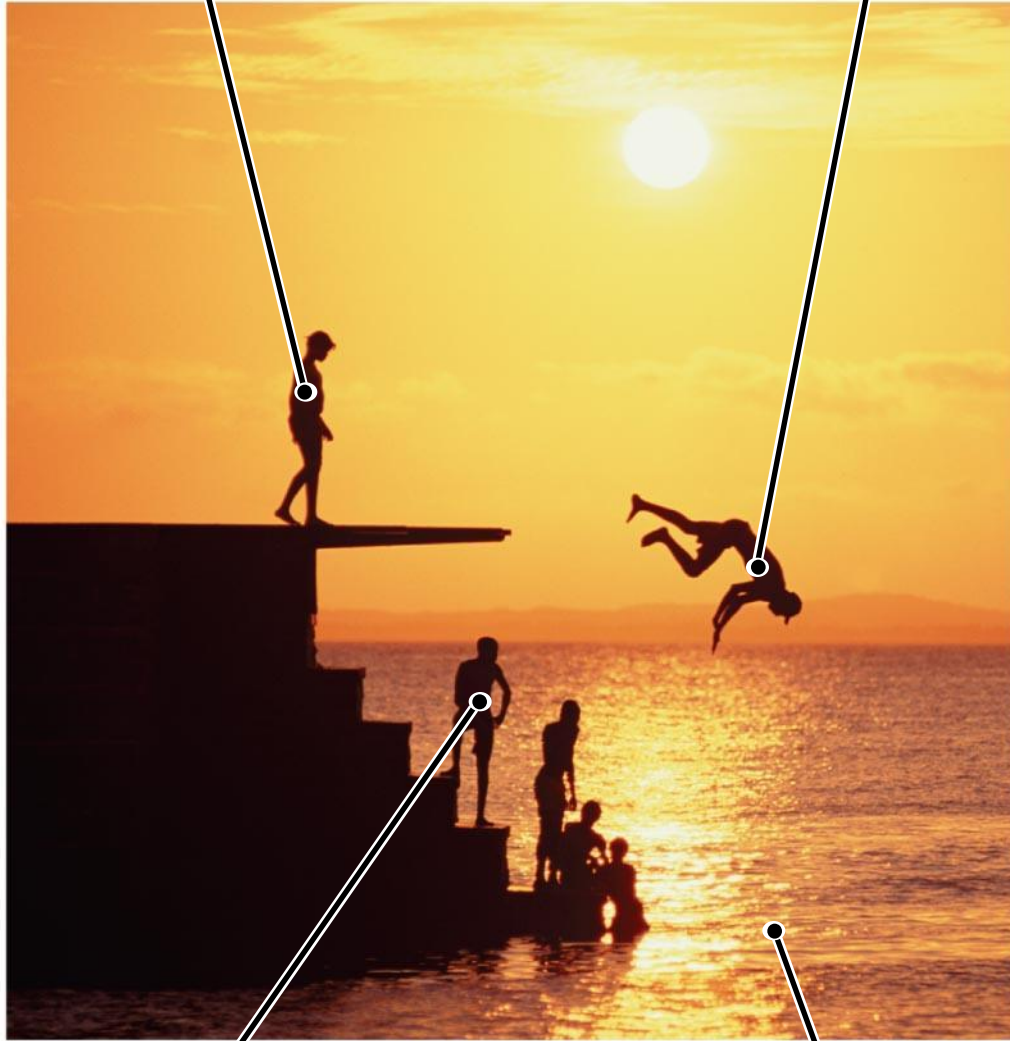
**PLAY**

Animation: Energy Concepts

Fig. 8-2

**A diver has more potential energy on the platform than in the water.**

**Diving converts potential energy to kinetic energy.**



**Climbing up converts the kinetic energy of muscle movement to potential energy.**

**A diver has less potential energy in the water than on the platform.**

# The Laws of Energy Transformation

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- **Thermodynamics** is the study of energy transformations
- A closed system, such as that approximated by liquid in a thermos, is isolated from its surroundings
- In an open system, energy and matter can be transferred between the system and its surroundings
- Organisms are open systems

# *The First Law of Thermodynamics*

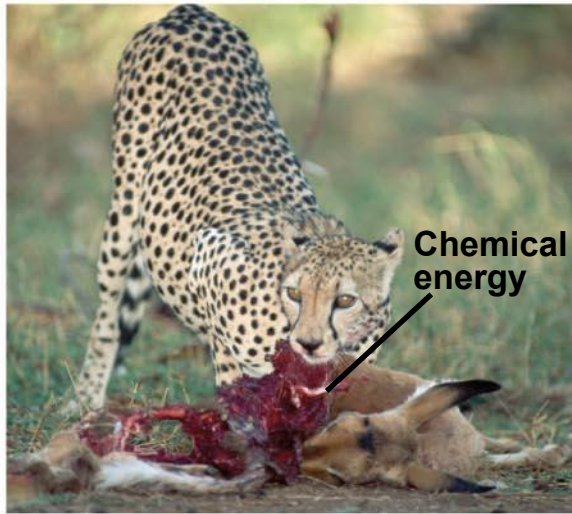
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- According to the **first law of thermodynamics**, the energy of the universe is constant:
  - *Energy can be transferred and transformed, but it cannot be created or destroyed*
- The first law is also called the principle of conservation of energy

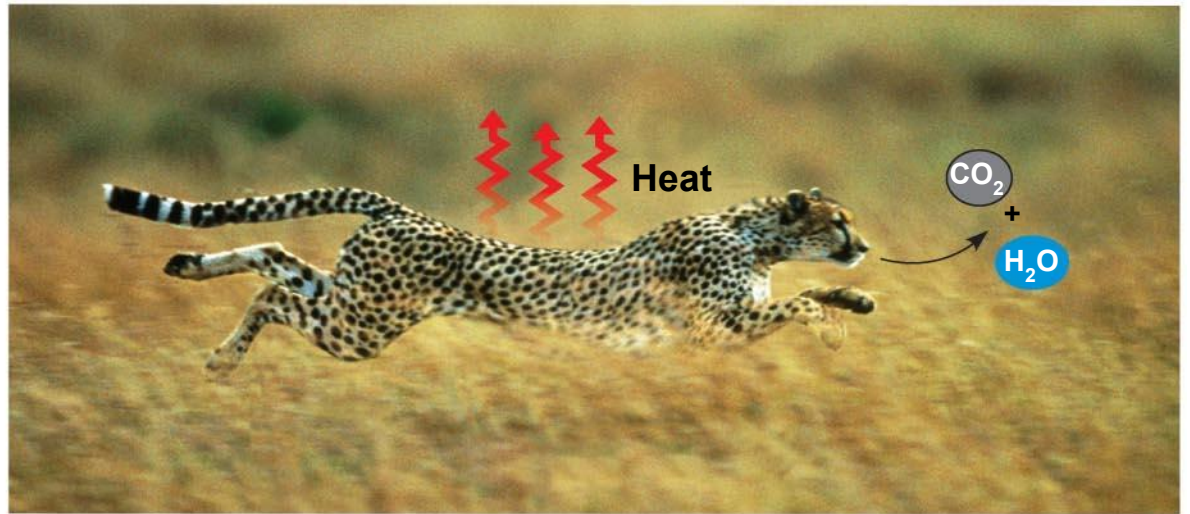
# *The Second Law of Thermodynamics*

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- 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** (disorder) of the universe*



**(a) First law of thermodynamics**



**(b) Second law of thermodynamics**

- 
- Living cells unavoidably convert organized forms of energy to heat
  - Spontaneous processes occur without energy input; they can happen quickly or slowly
  - For a process to occur without energy input, it must increase the entropy of the universe

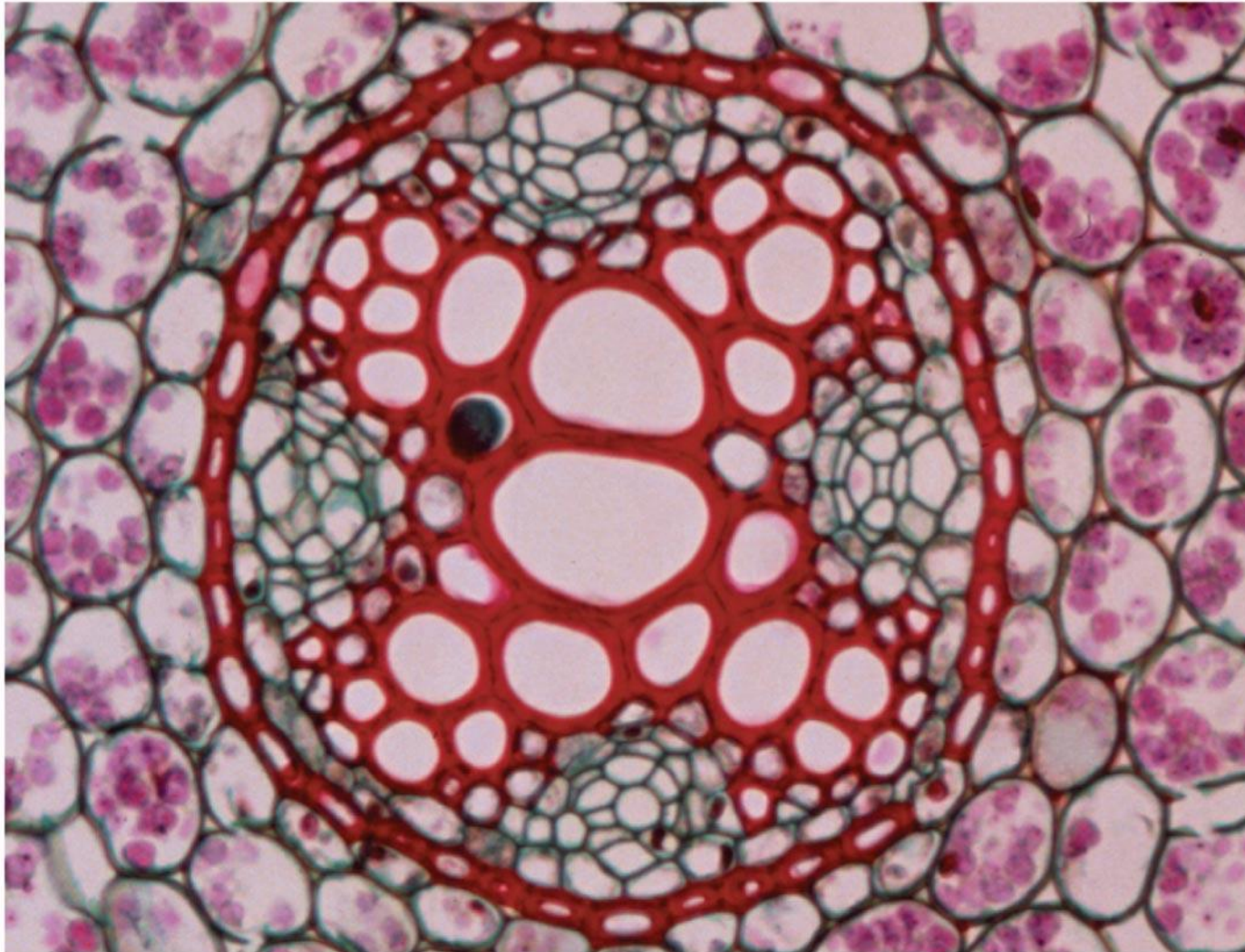


# *Biological Order and Disorder*

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- Cells create ordered structures from less ordered materials
- Organisms also replace ordered forms of matter and energy with less ordered forms
- Energy flows into an ecosystem in the form of light and exits in the form of heat

Fig. 8-4



50  
μm

- 
- The evolution of more complex organisms does not violate the second law of thermodynamics
  - Entropy (disorder) may decrease in an organism, but the universe's total entropy increases

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

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

# Free-Energy Change, $\Delta G$

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

- 
- The change in free energy ( $\Delta G$ ) during a process is related to the change in enthalpy, or change in total energy ( $\Delta H$ ), change in entropy ( $\Delta S$ ), and temperature in Kelvin ( $T$ ):

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

- Only processes with a negative  $\Delta G$  are spontaneous
- Spontaneous processes can be harnessed to perform work

# Free Energy, Stability, and Equilibrium

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- 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

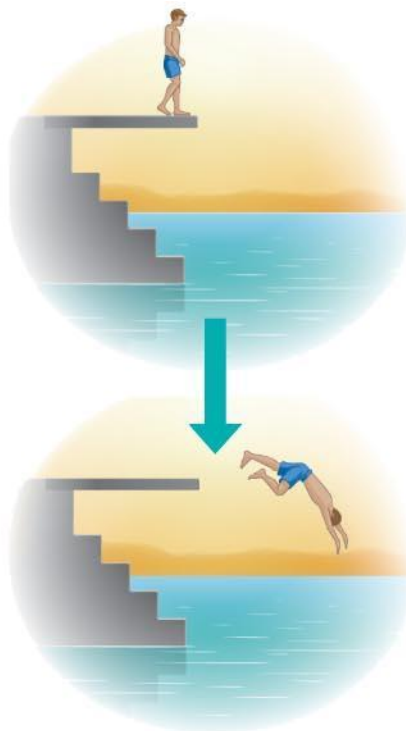
Fig. 8-5

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

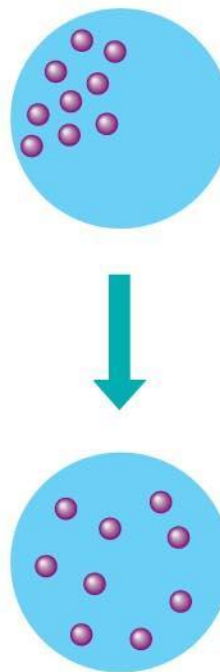
In a spontaneous change

- 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

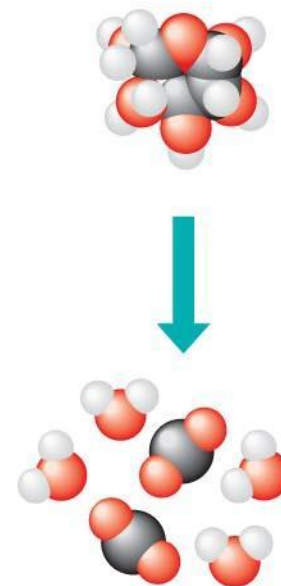
- Less free energy (lower  $G$ )
- More stable
- Less work capacity



(a) Gravitational motion



(b) Diffusion



(c) Chemical reaction



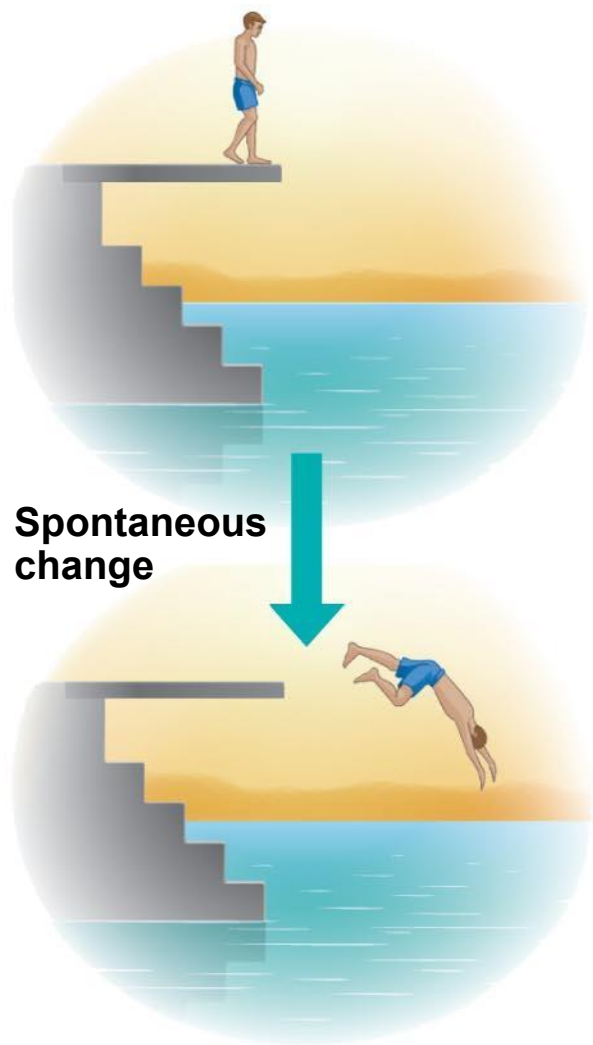
- **More free energy (higher  $G$ )**
- **Less stable**
- **Greater work capacity**

**In a spontaneous change**

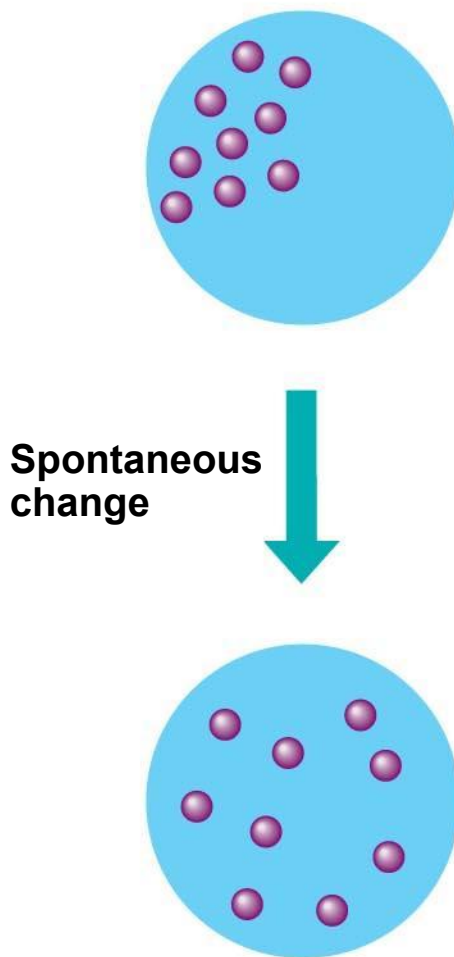
- **The free energy of the system decreases ( $\Delta G < 0$ )**
- **The system becomes more stable**
- **The released free energy can be harnessed to do work**

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

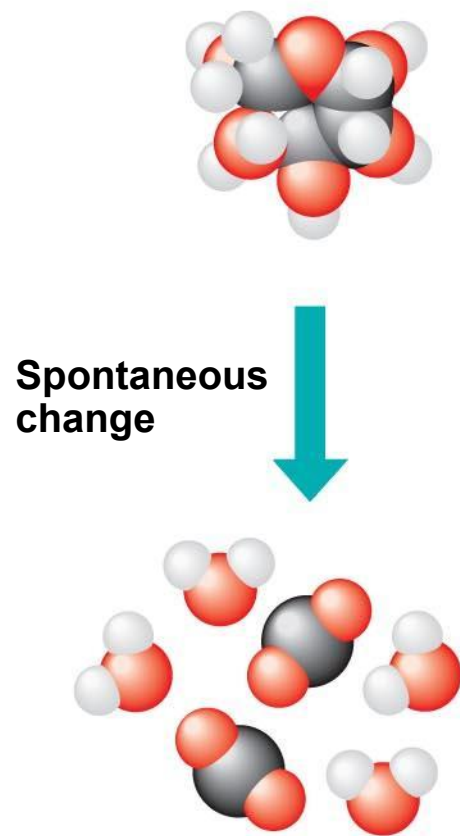
Fig. 8-5b



**(a) Gravitational motion**



**(b) Diffusion**



**(c) Chemical reaction**

# Free Energy and Metabolism

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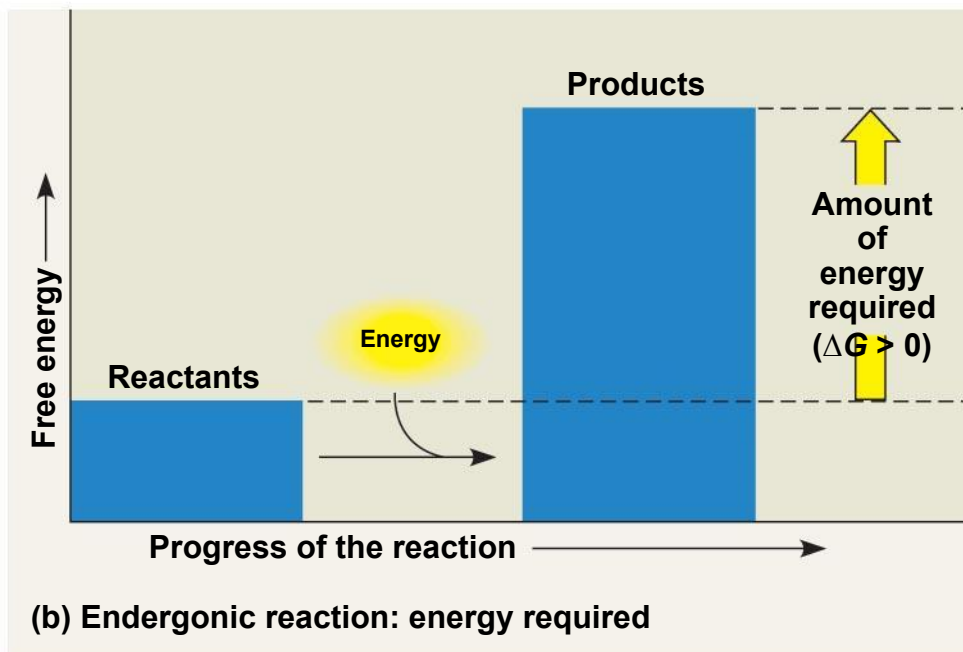
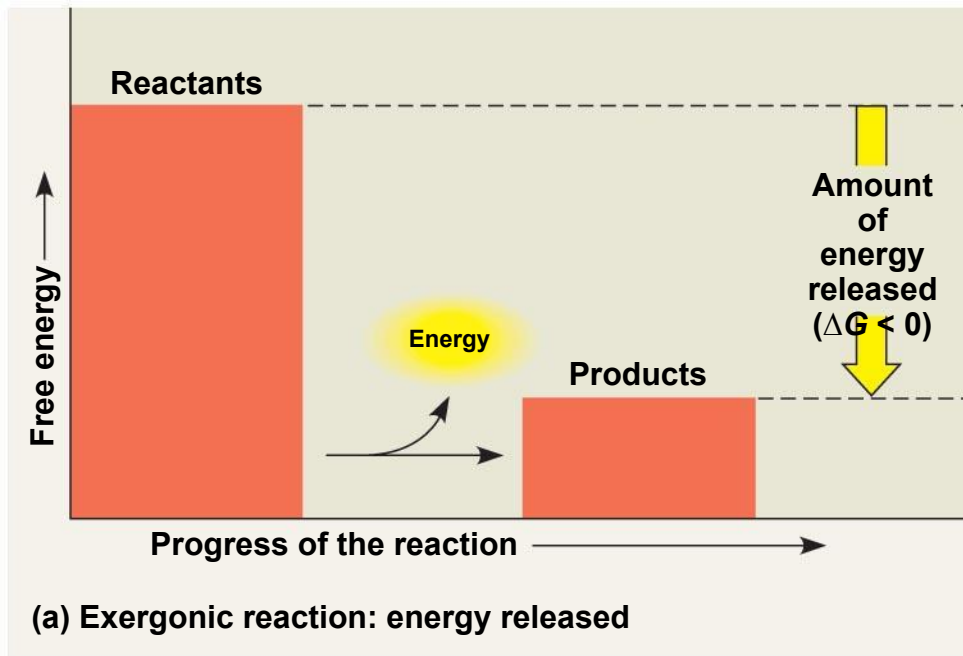
- The concept of free energy can be applied to the chemistry of life's processes

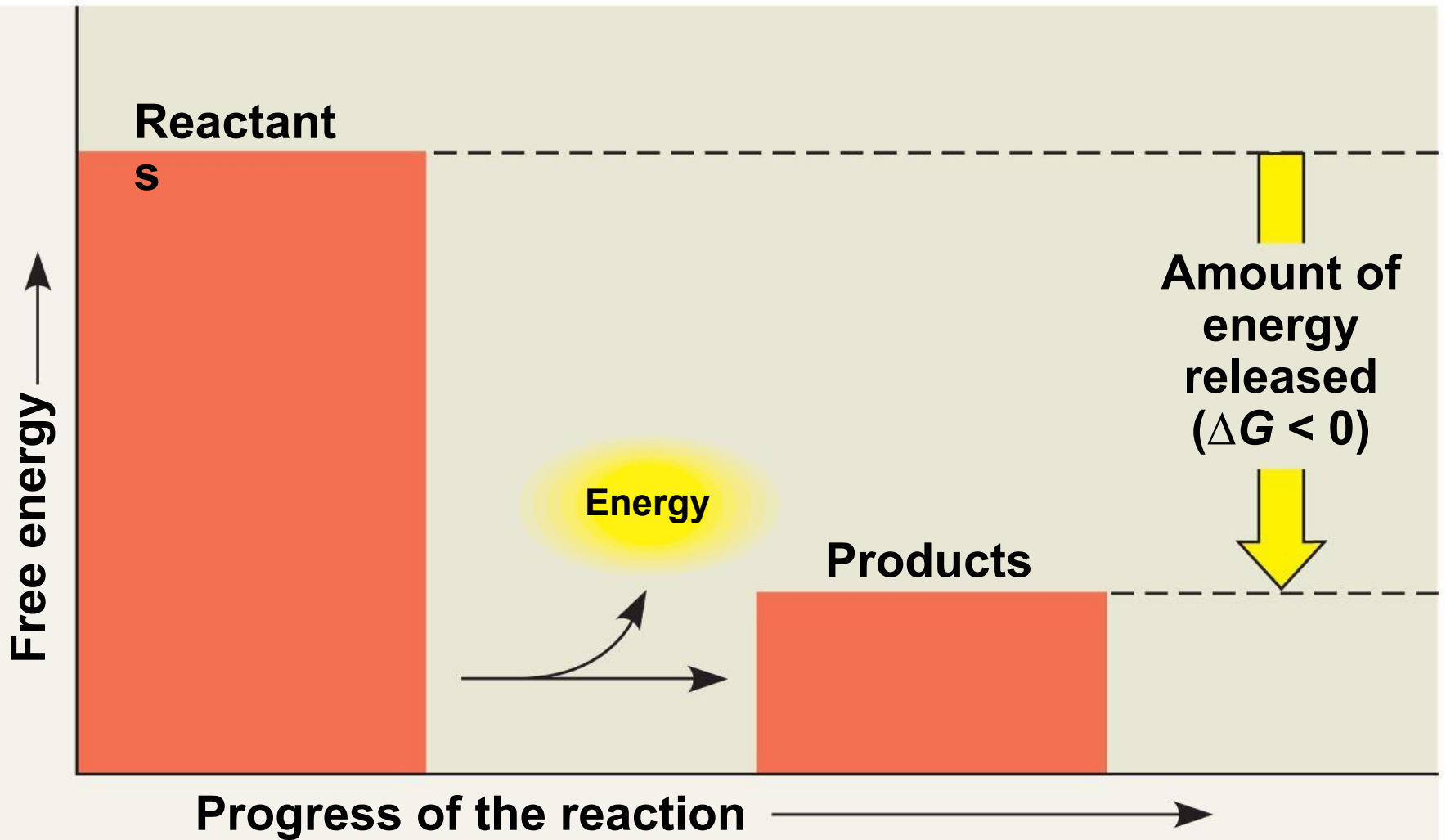
# *Exergonic and Endergonic Reactions in Metabolism*

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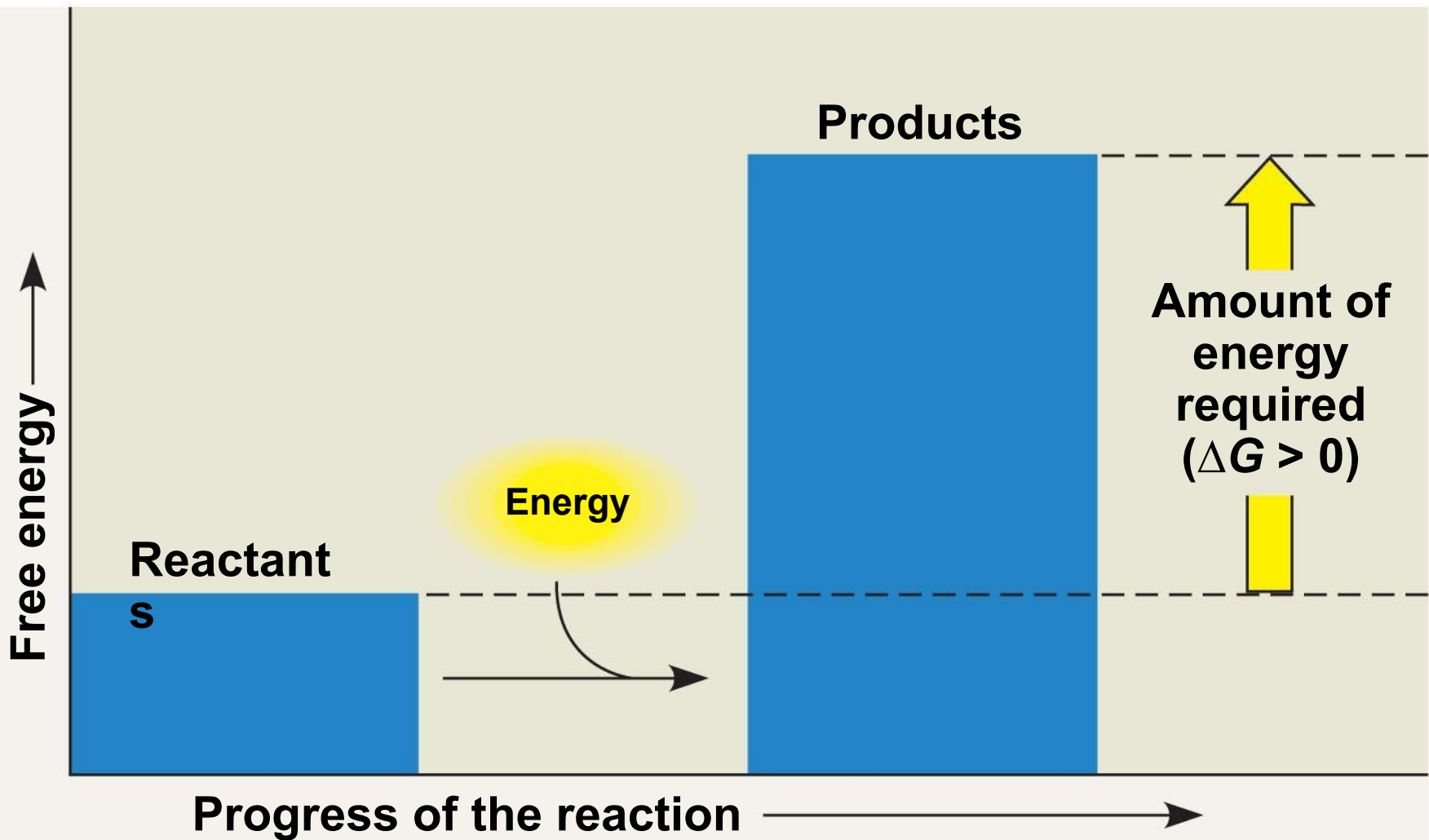
- An **exergonic reaction** proceeds with a net release of free energy and is spontaneous
- An **endergonic reaction** absorbs free energy from its surroundings and is nonspontaneous

Fig. 8-6





**(a) Exergonic reaction: energy released**



**(b) Endergonic reaction: energy required**

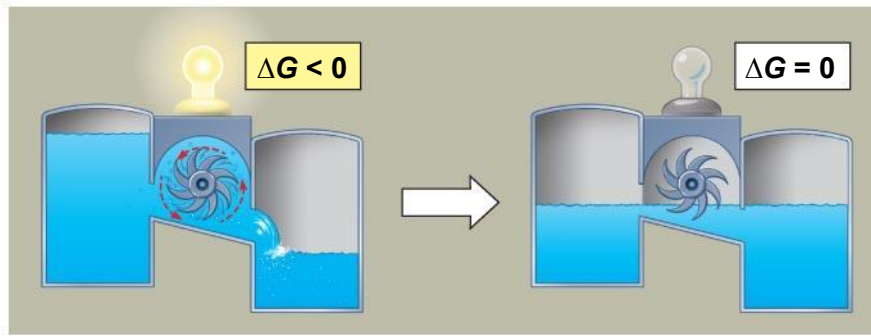
# *Equilibrium and Metabolism*

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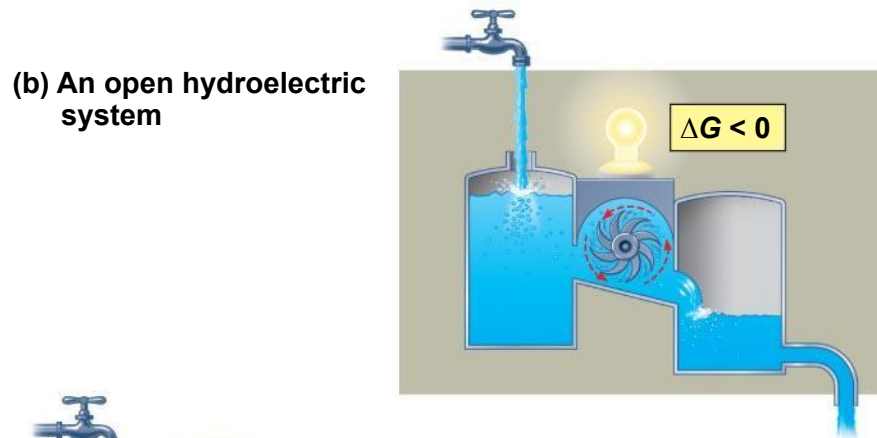
- Reactions in a closed system eventually reach equilibrium and then do no work
- Cells are not in equilibrium; they are open systems experiencing a constant flow of materials
- A defining feature of life is that metabolism is never at equilibrium
- A catabolic pathway in a cell releases free energy in a series of reactions
- Closed and open hydroelectric systems can serve as analogies



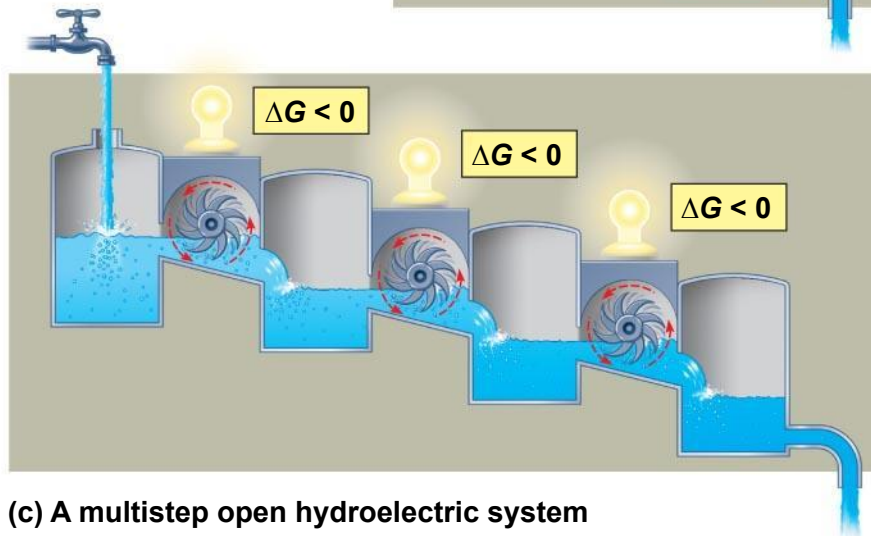
Fig. 8-7



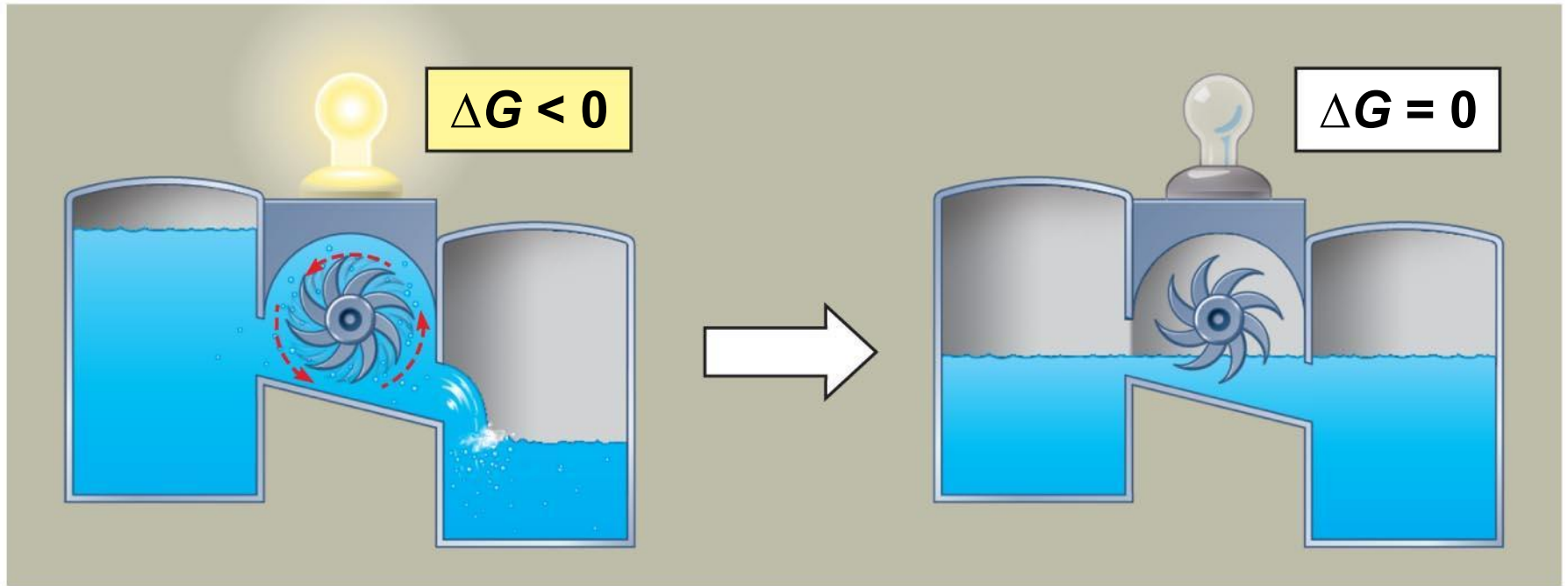
(a) An isolated hydroelectric system



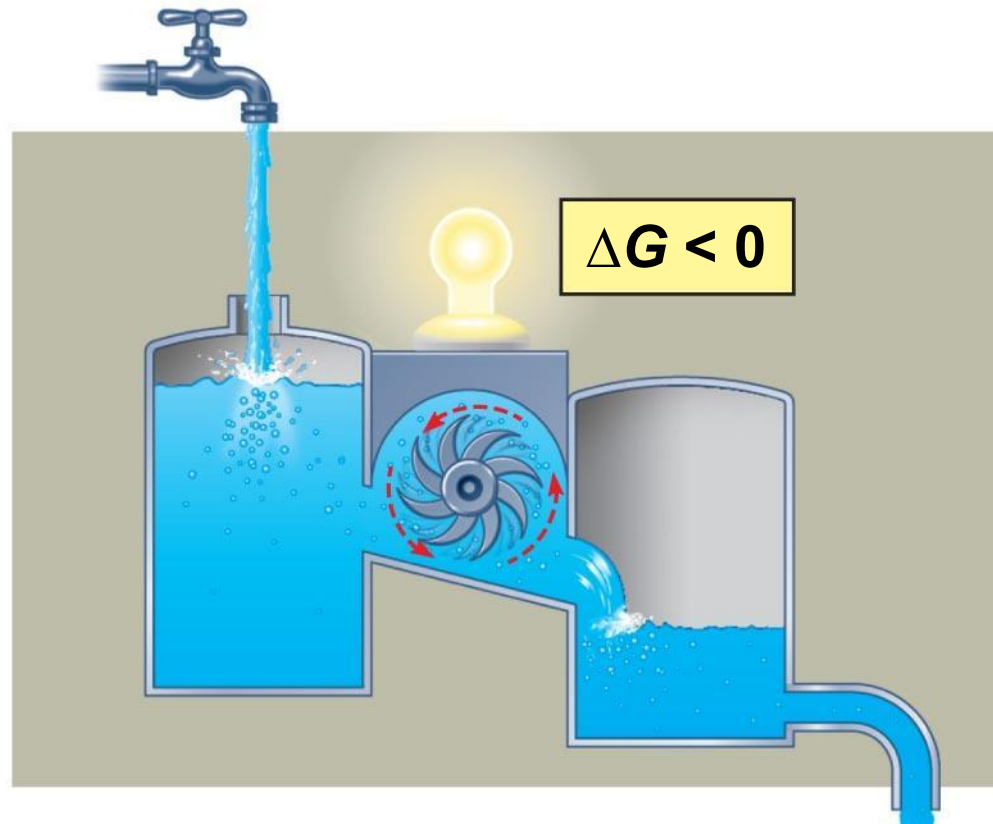
(b) An open hydroelectric system



(c) A multistep open hydroelectric system



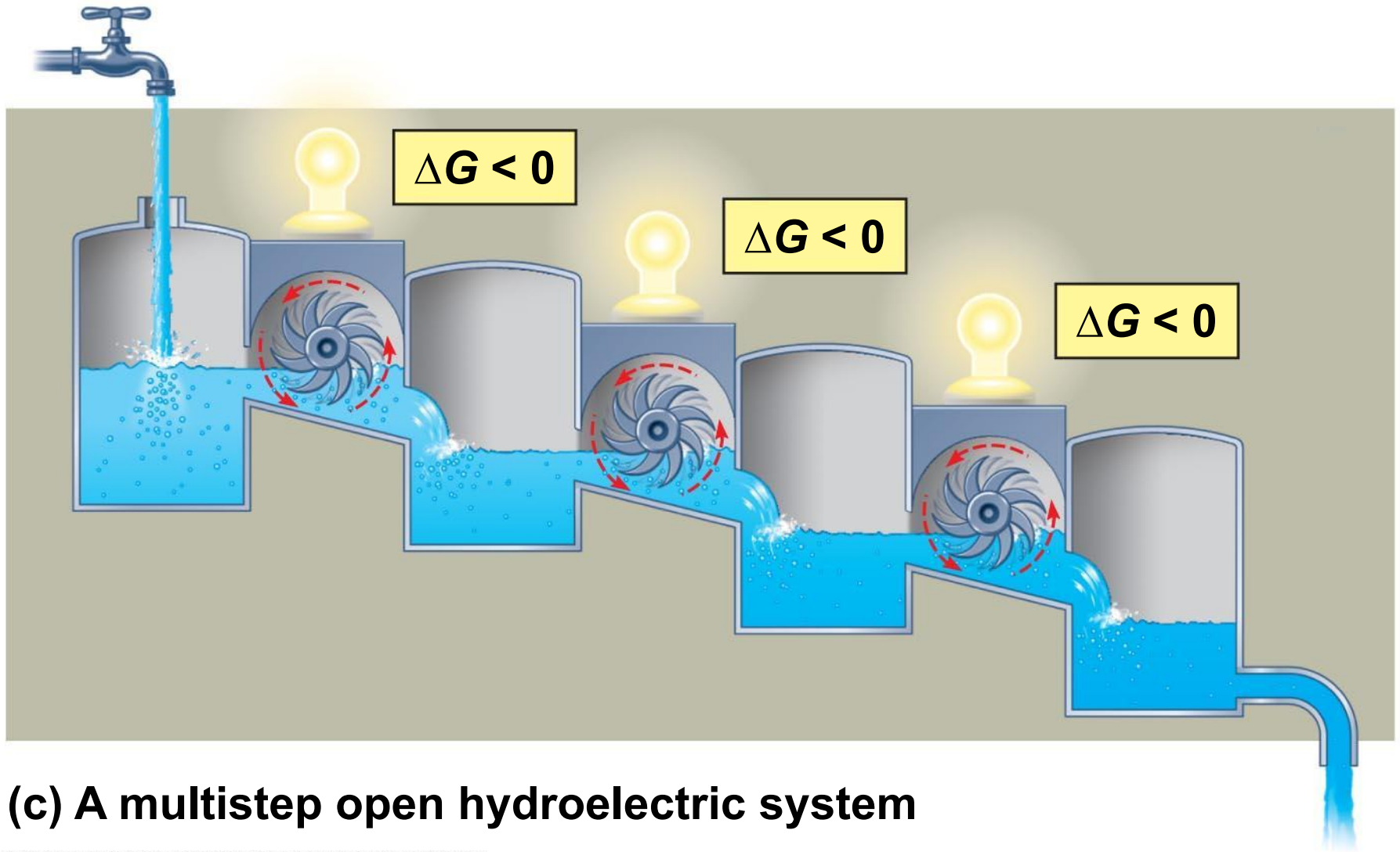
**(a) An isolated hydroelectric system**



**(b) An open hydroelectric system**

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Fig. 8-7c



**(c) A multistep open hydroelectric system**

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

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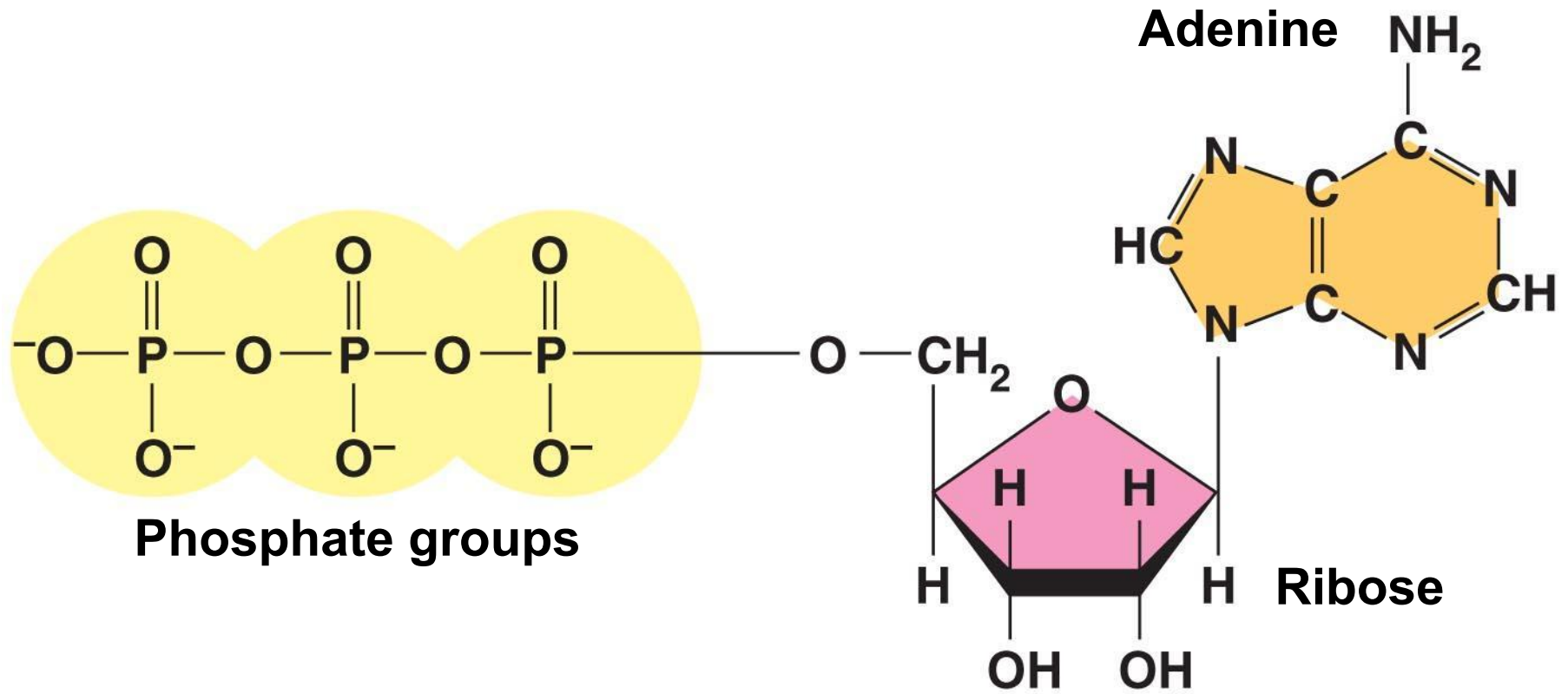
- A cell does three main kinds of work:
  - Chemical
  - Transport
  - Mechanical
- To do work, cells manage energy resources by **energy coupling**, the use of an exergonic process to drive an endergonic one
- Most energy coupling in cells is mediated by ATP

# The Structure and Hydrolysis of ATP

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

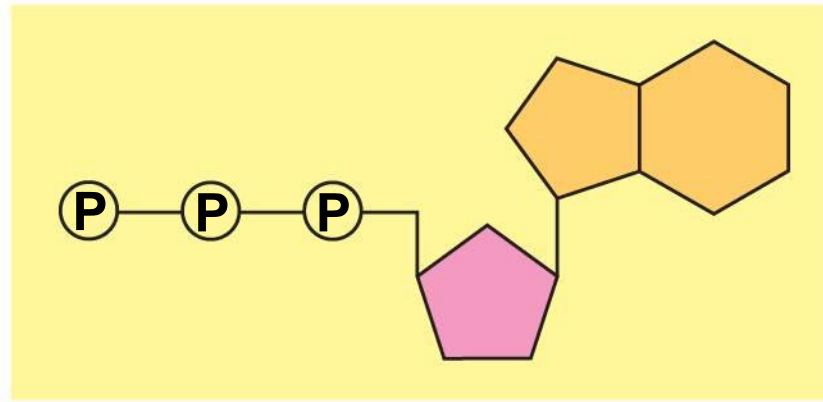
Fig. 8-8



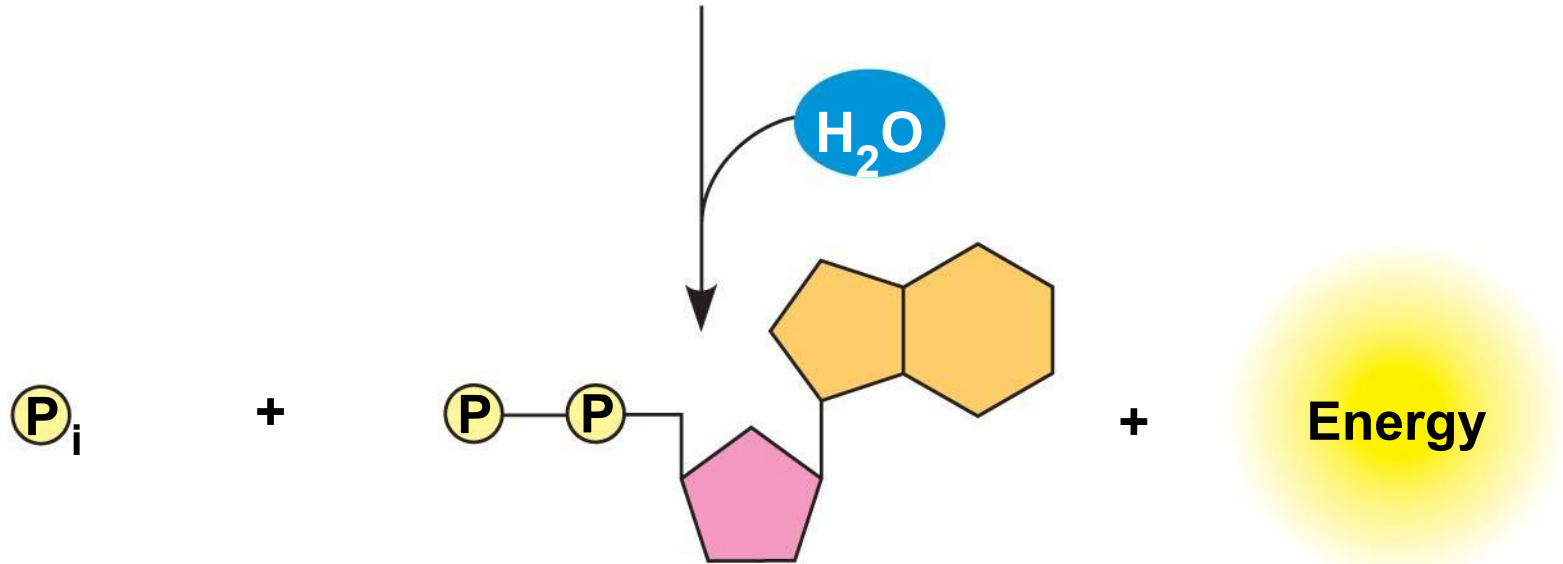
- 
- The bonds between the phosphate groups of ATP's tail can be broken by hydrolysis
  - Energy is released from ATP when the terminal phosphate bond is broken
  - This release of energy comes from the chemical change to a state of lower free energy, not from the phosphate bonds themselves



Fig. 8-9



**Adenosine triphosphate (ATP)**



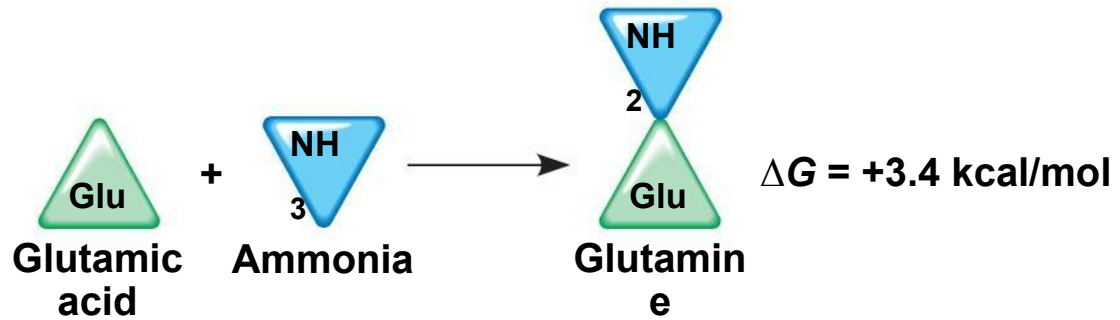
**Inorganic phosphate**

**Adenosine diphosphate (ADP)**

# How ATP Performs Work

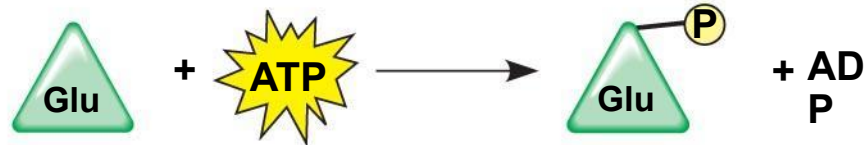
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- The three types of cellular work (mechanical, transport, and chemical) are powered by the hydrolysis of ATP
- In the cell, the energy from the exergonic reaction of ATP hydrolysis can be used to drive an endergonic reaction
- Overall, the coupled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

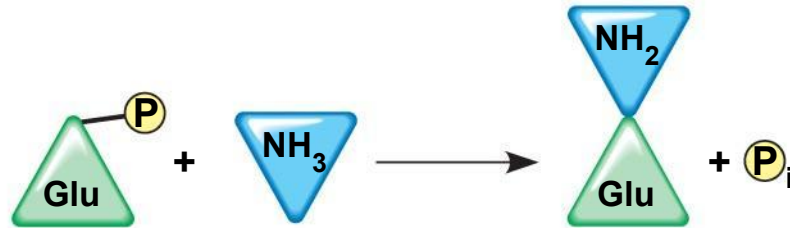


(a) Endergonic reaction

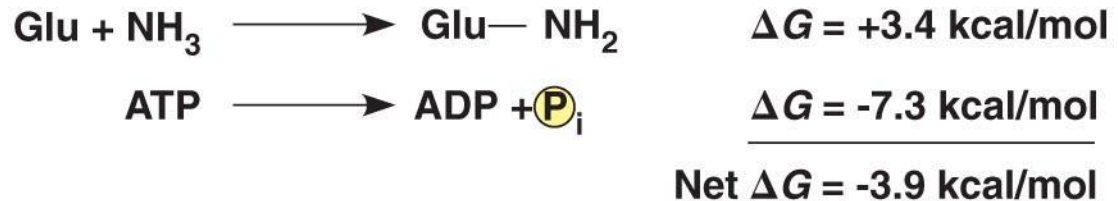
1 ATP phosphorylates glutamic acid, making the amino acid less stable.



2 Ammonia displaces the phosphate group, forming glutamine.

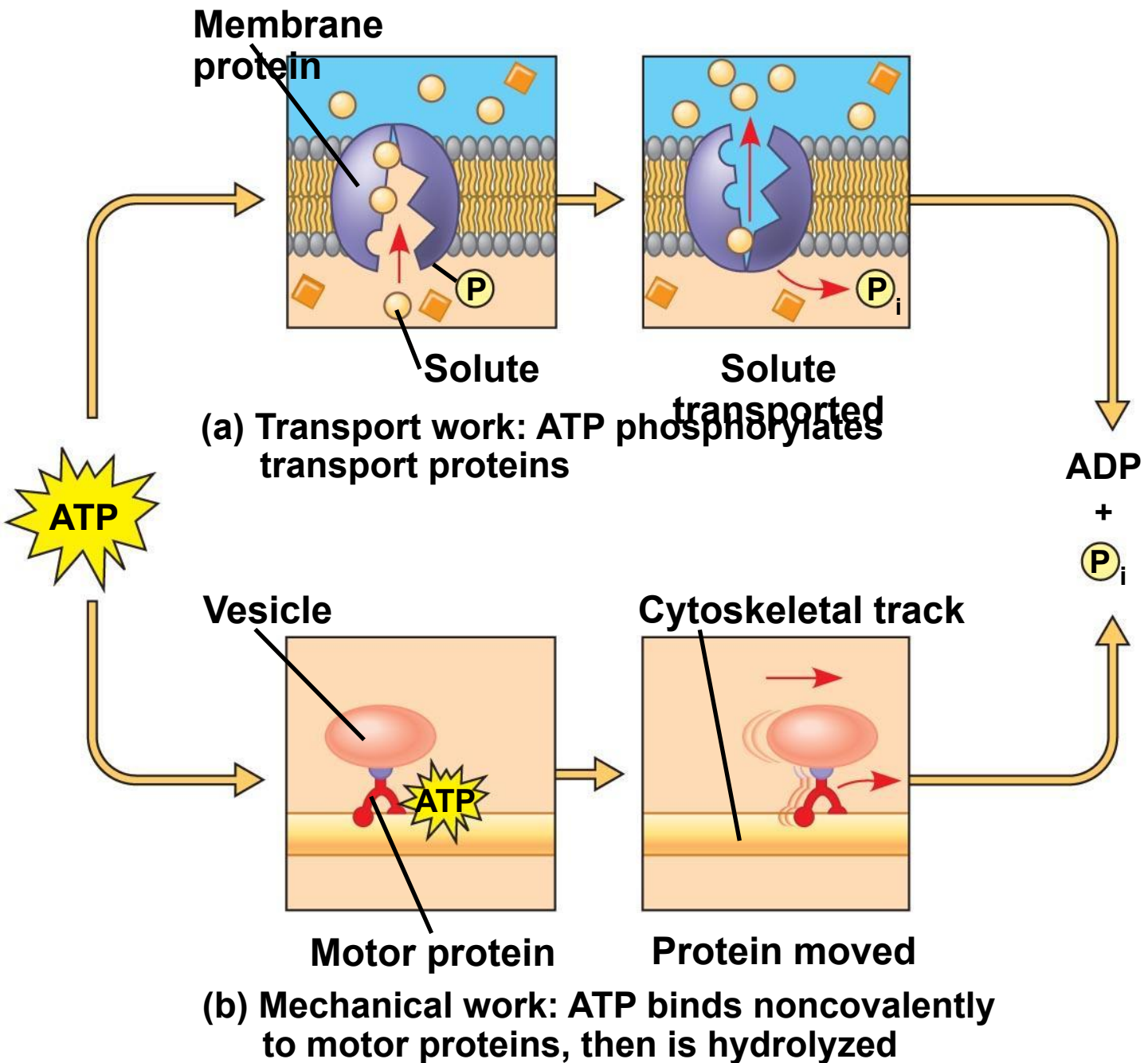


(b) Coupled with ATP hydrolysis, an exergonic reaction



(c) Overall free-energy change

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

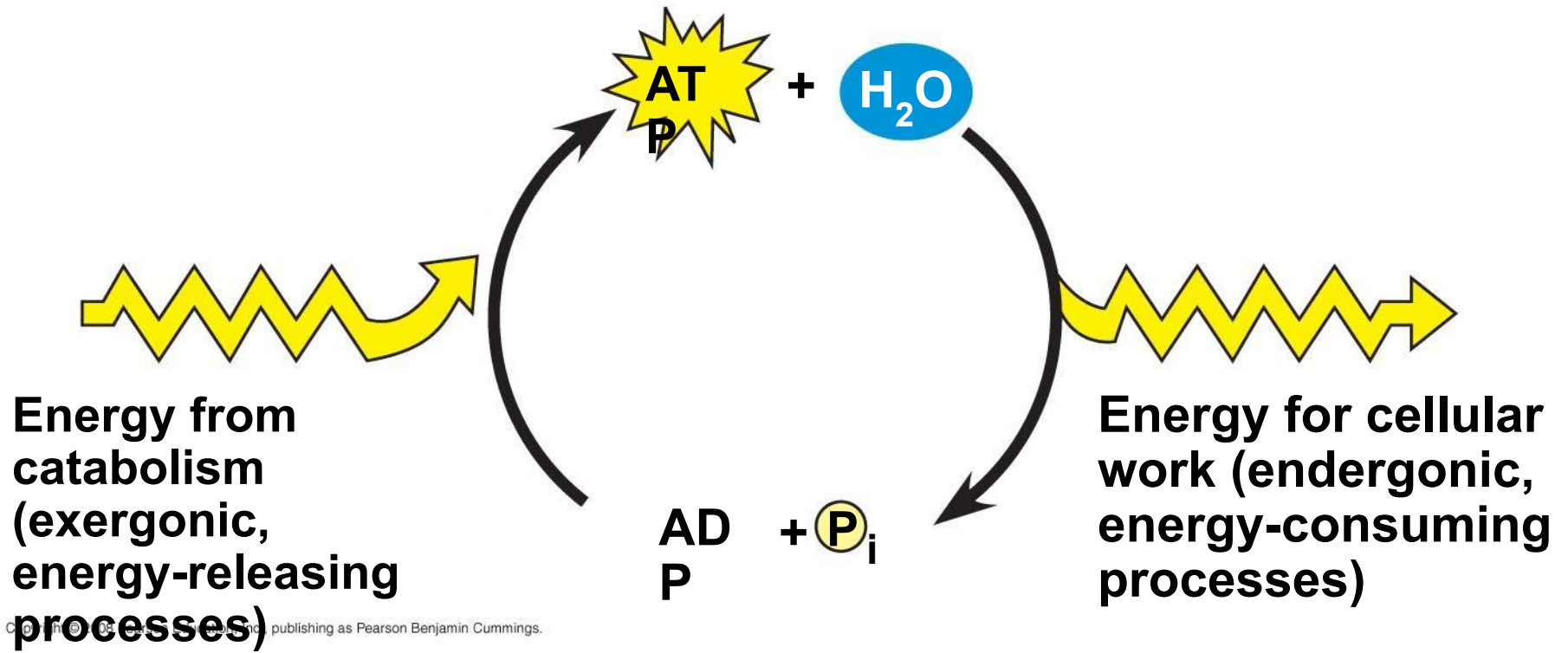


# The Regeneration of ATP

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- 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 chemical potential energy temporarily stored in ATP drives most cellular work

Fig. 8-12



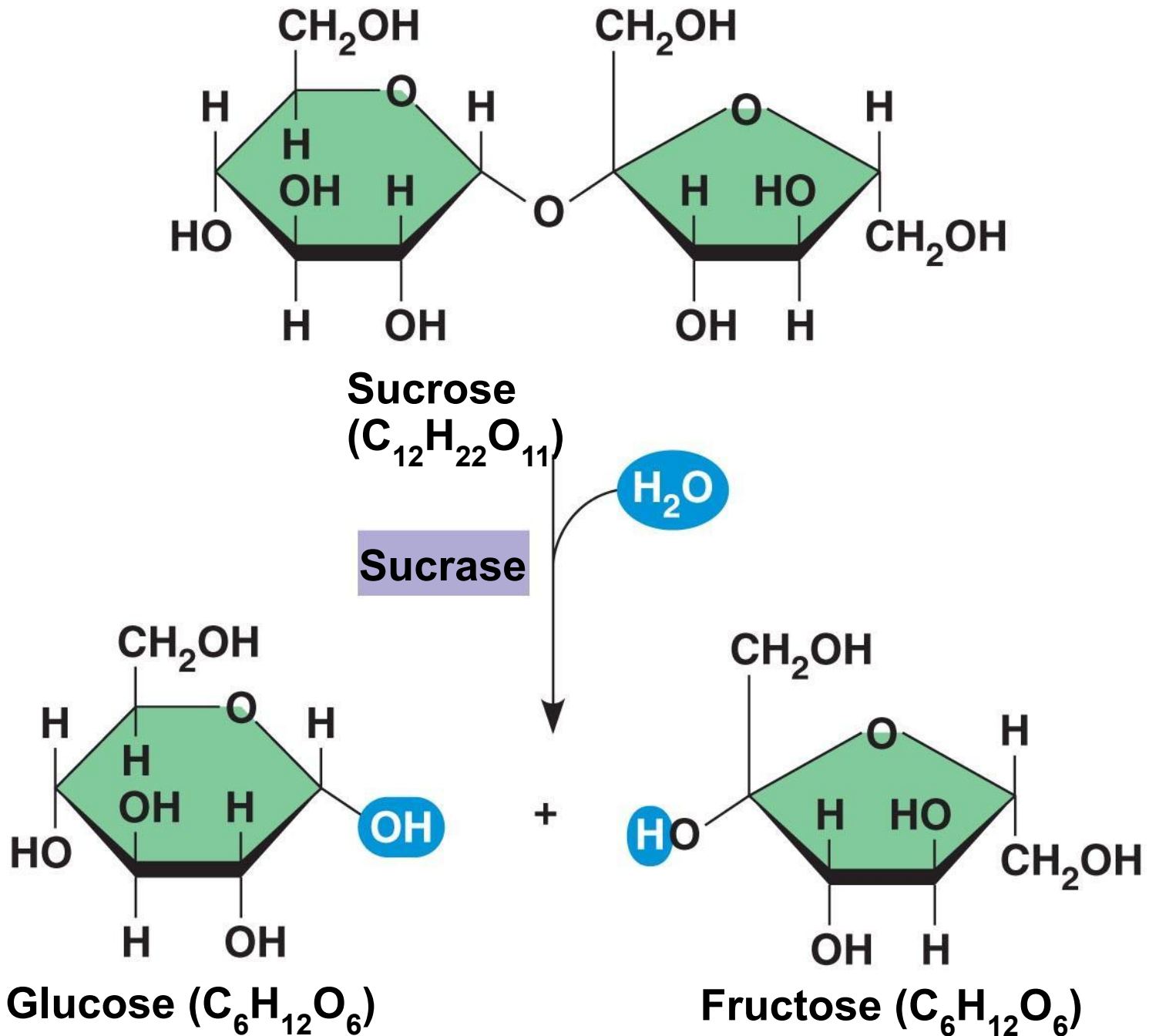
## Concept 8.4: Enzymes speed up metabolic reactions by lowering energy barriers

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



Fig. 8-13

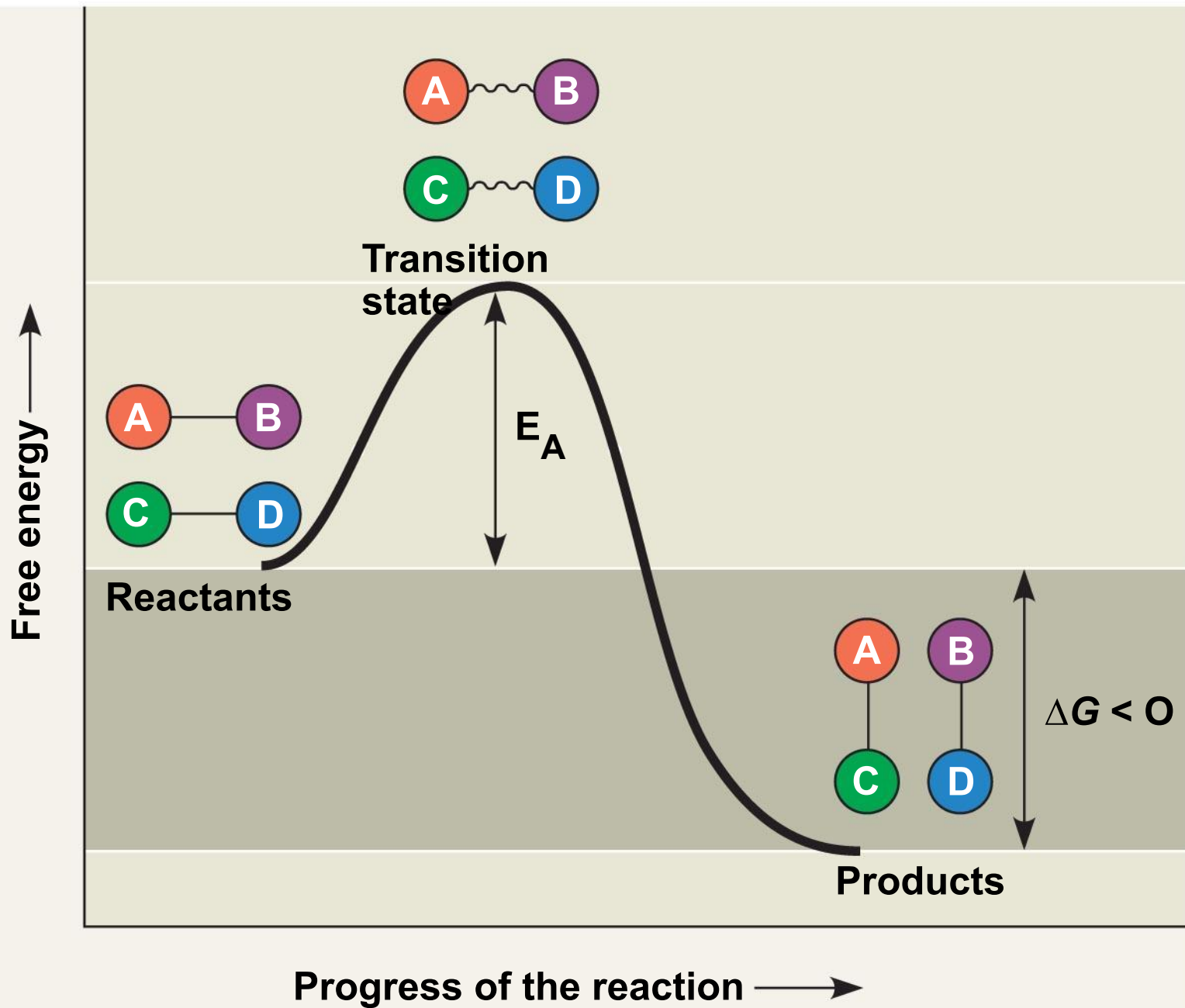


# The Activation Energy Barrier

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- 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 heat from the surroundings

Fig. 8-14



# How Enzymes Lower the $E_A$ Barrier

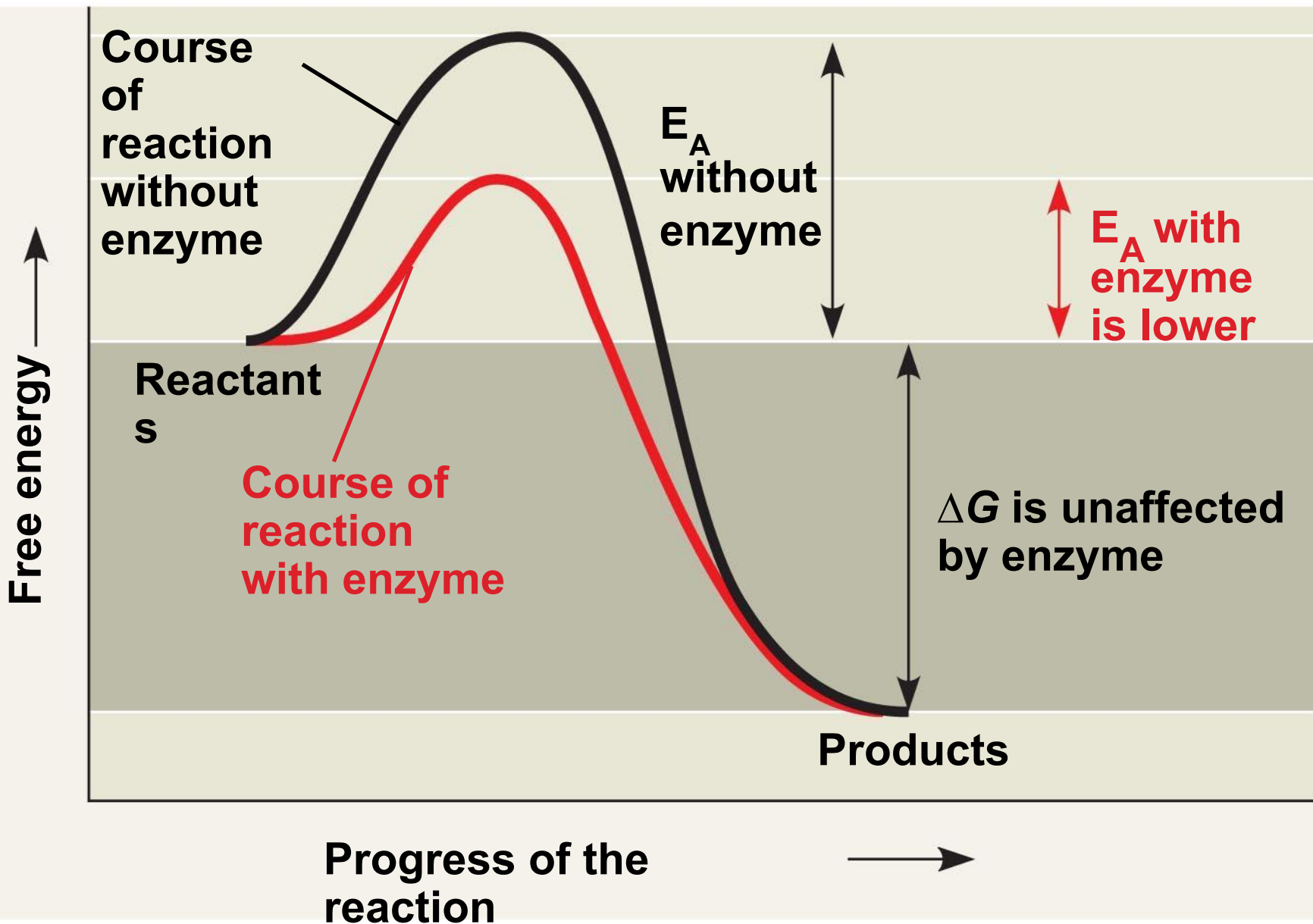
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- Enzymes catalyze reactions by lowering the  $E_A$  barrier
- Enzymes do not affect the change in free energy ( $\Delta G$ ); instead, they hasten reactions that would occur eventually

**PLAY**

Animation: How Enzymes Work

Fig. 8-15

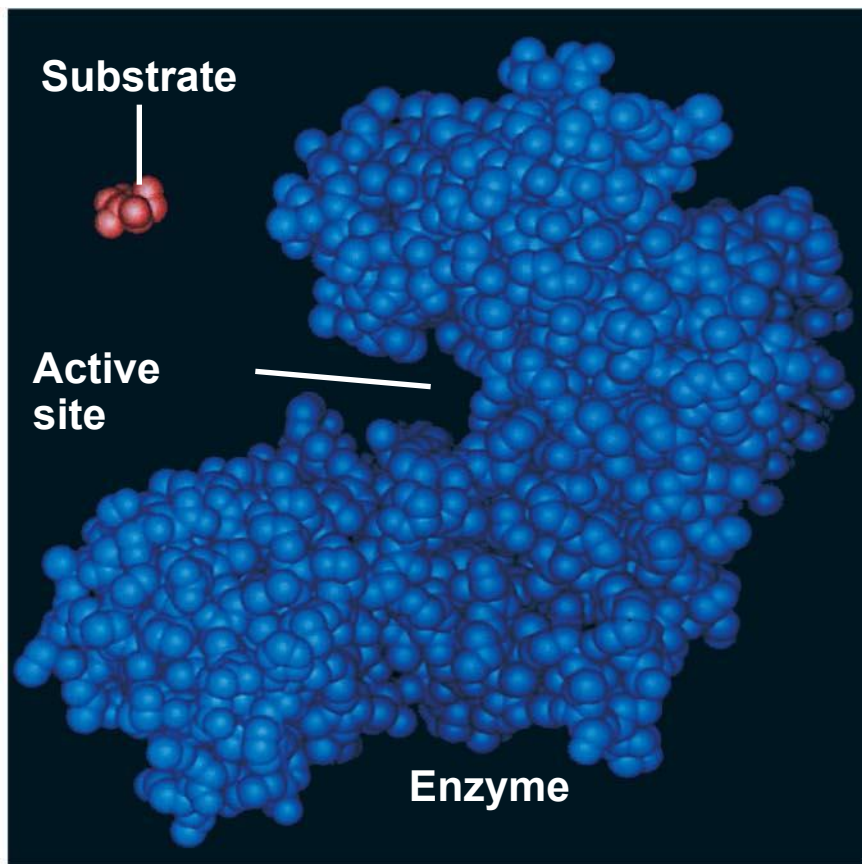


# Substrate Specificity of Enzymes

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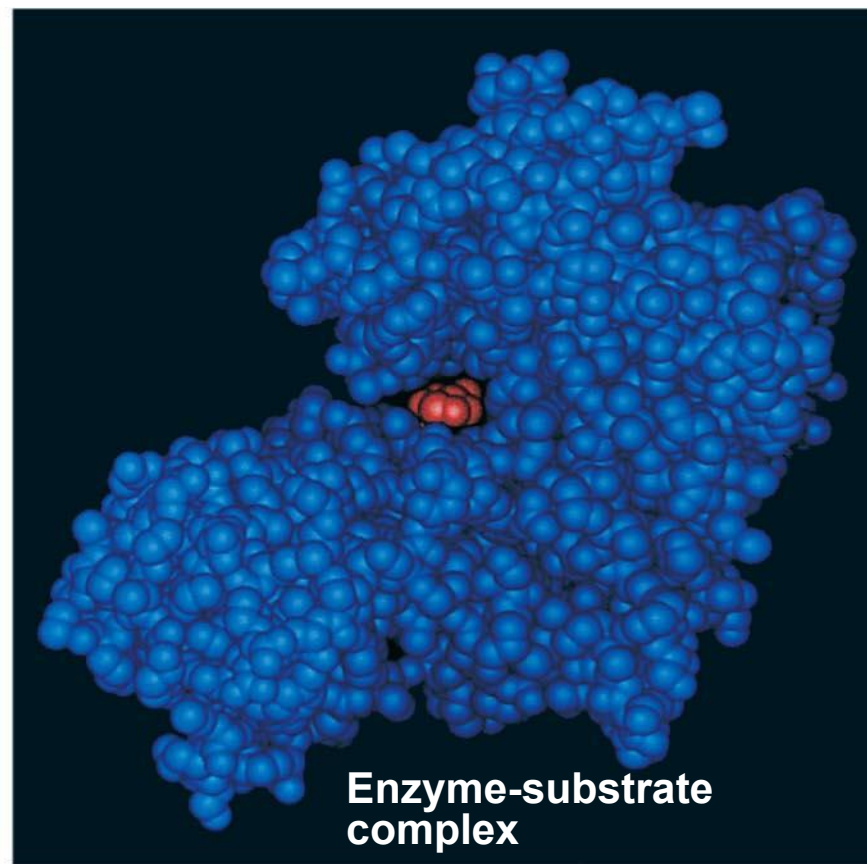
- The reactant that an enzyme acts on is called the enzyme's **substrate**
- The enzyme binds to its substrate, forming an **enzyme-substrate complex**
- The **active site** is the region on the enzyme where the substrate binds
- **Induced fit** of a substrate brings chemical groups of the active site into positions that enhance their ability to catalyze the reaction

Fig. 8-16



(a)

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(b)

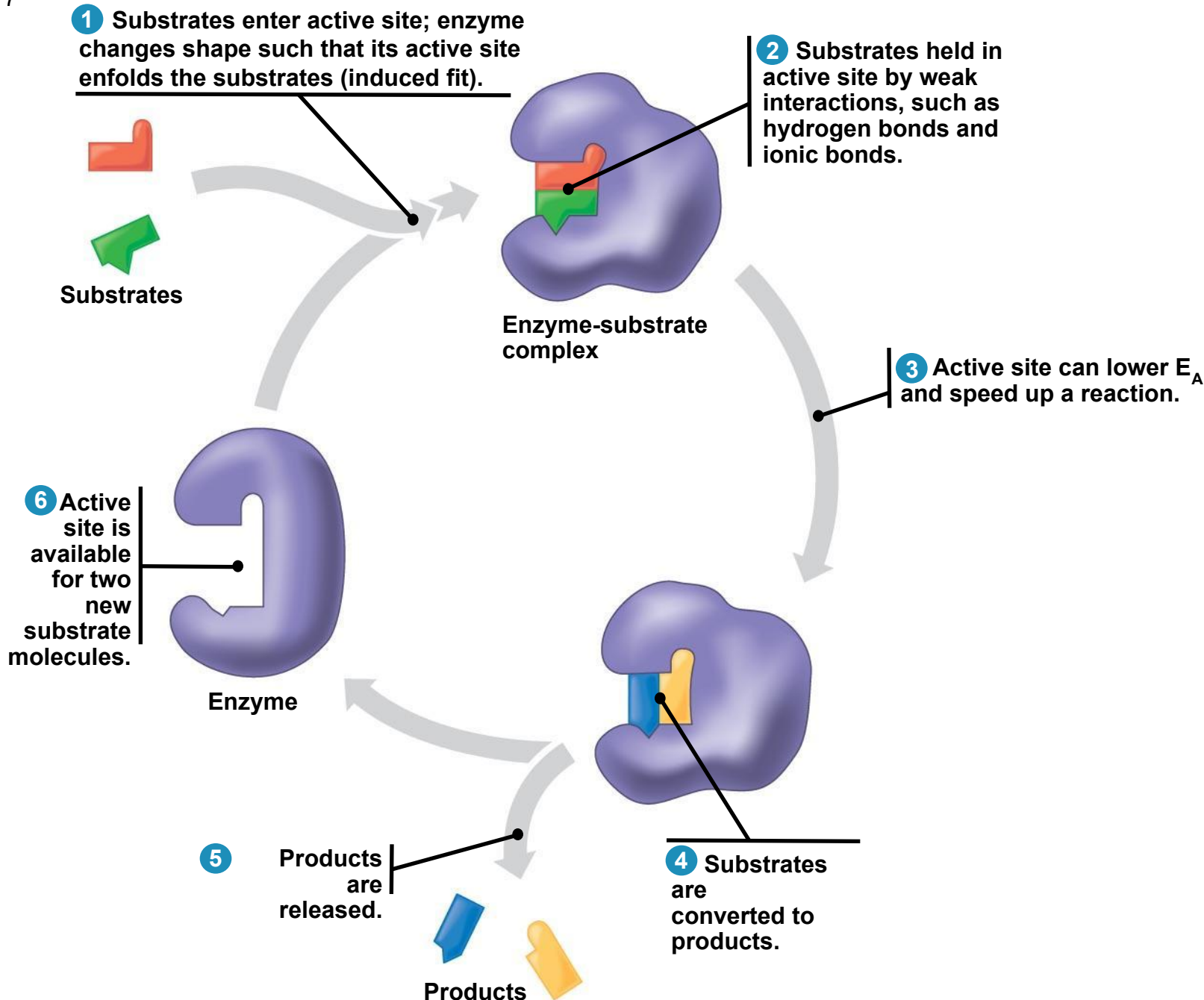
# Catalysis in the Enzyme's Active Site

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- In an enzymatic reaction, the substrate binds to the active site of the enzyme
- 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



Fig. 8-17



# Effects of Local Conditions on Enzyme Activity

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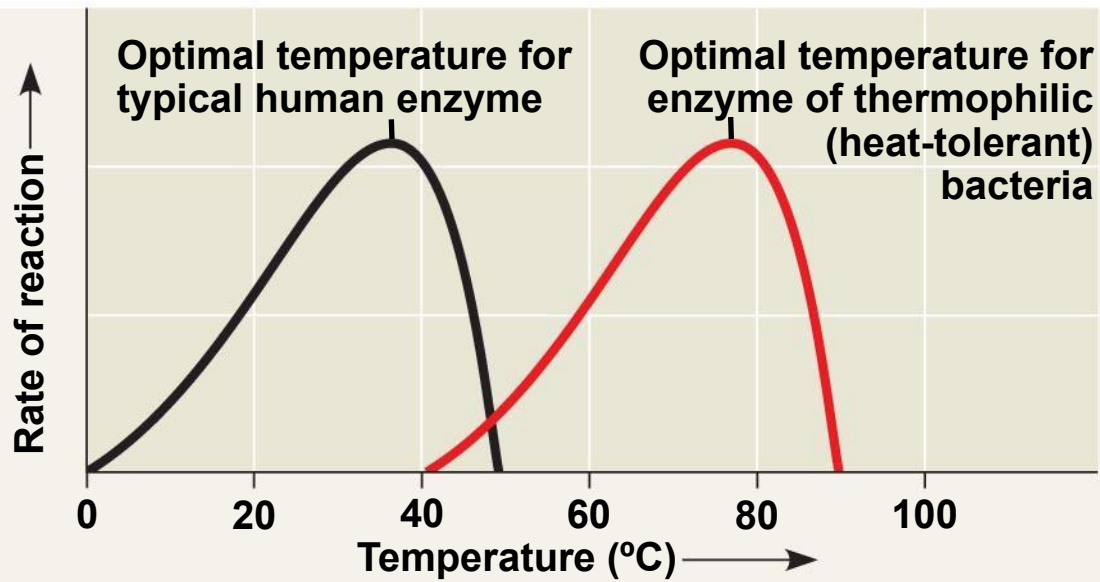
- An enzyme's activity can be affected by
  - General environmental factors, such as temperature and pH
  - Chemicals that specifically influence the enzyme

# *Effects of Temperature and pH*

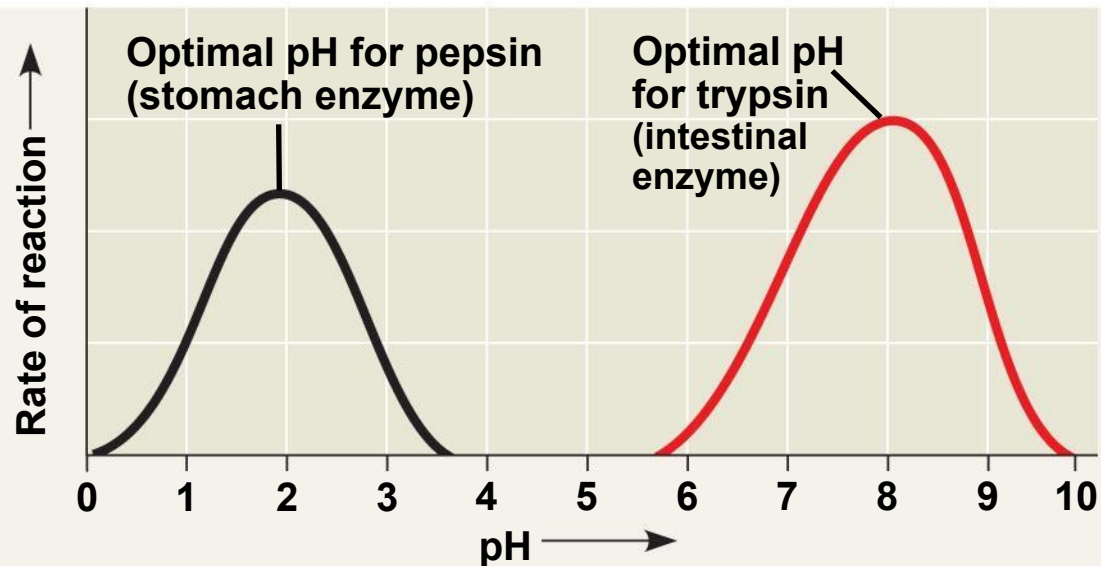
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- Each enzyme has an optimal temperature in which it can function
- Each enzyme has an optimal pH in which it can function

Fig. 8-18



(a) Optimal temperature for two enzymes



(b) Optimal pH for two enzymes

# *Cofactors*

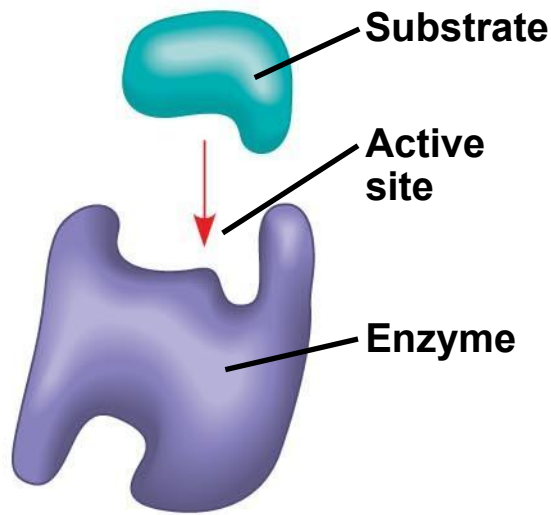
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- **Cofactors** are nonprotein enzyme helpers
- Cofactors may be inorganic (such as a metal in ionic form) or organic
- An organic cofactor is called a **coenzyme**
- Coenzymes include vitamins

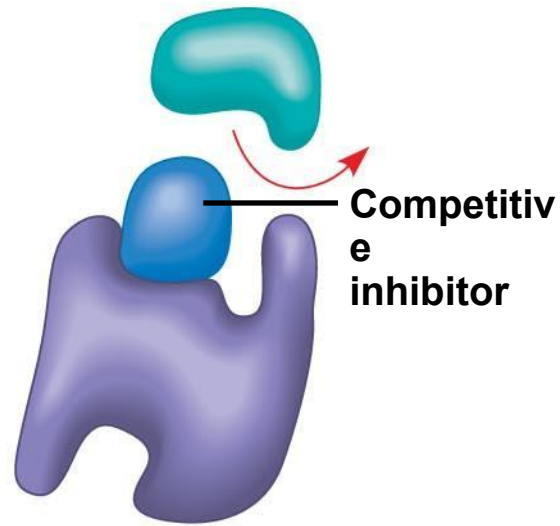
# *Enzyme Inhibitors*

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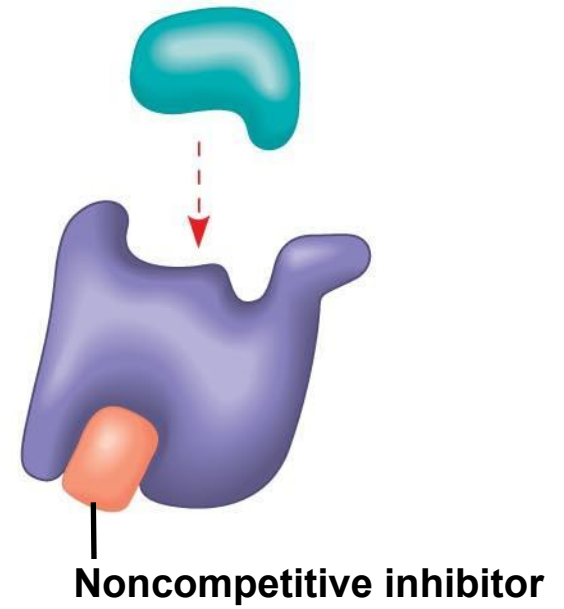
- **Competitive inhibitors** bind to the active site of an enzyme, competing with the substrate
- **Noncompetitive inhibitors** bind to another part of an enzyme, causing the enzyme to change shape and making the active site less effective
- Examples of inhibitors include toxins, poisons, pesticides,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



**(a) Normal binding**



**(b) Competitive inhibition**



**(c) Noncompetitive inhibition**

## Concept 8.5: Regulation of enzyme activity helps control metabolism

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- 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



# Allosteric Regulation of Enzymes

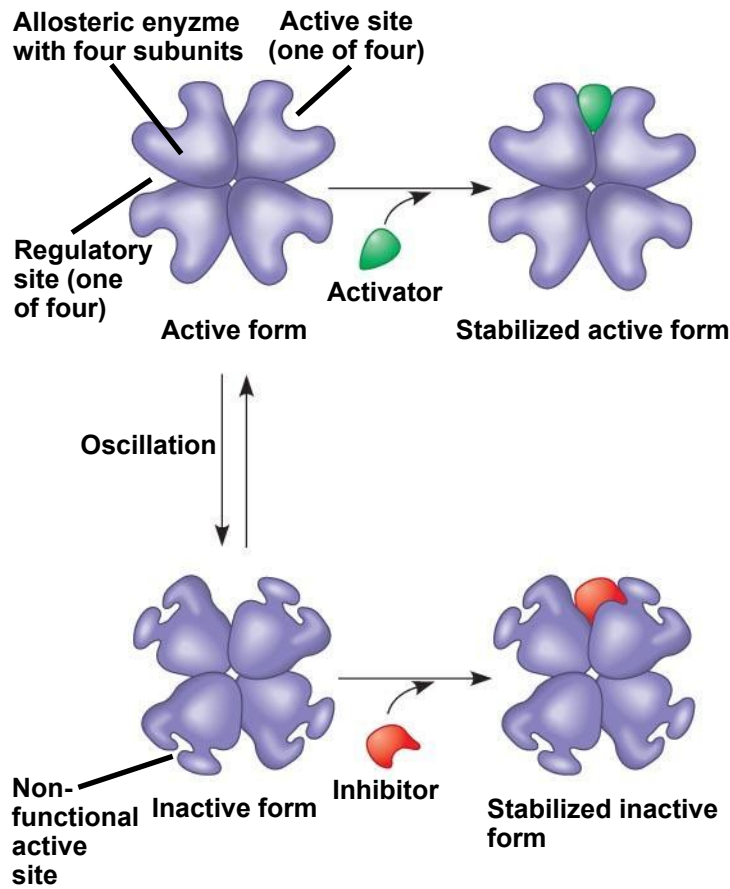
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- **Allosteric regulation** may either inhibit or stimulate an enzyme's activity
- Allosteric regulation occurs when a regulatory molecule binds to a protein at one site and affects the protein's function at another site

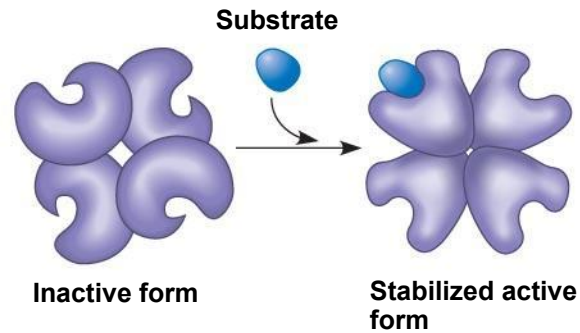
# *Allosteric Activation and Inhibition*

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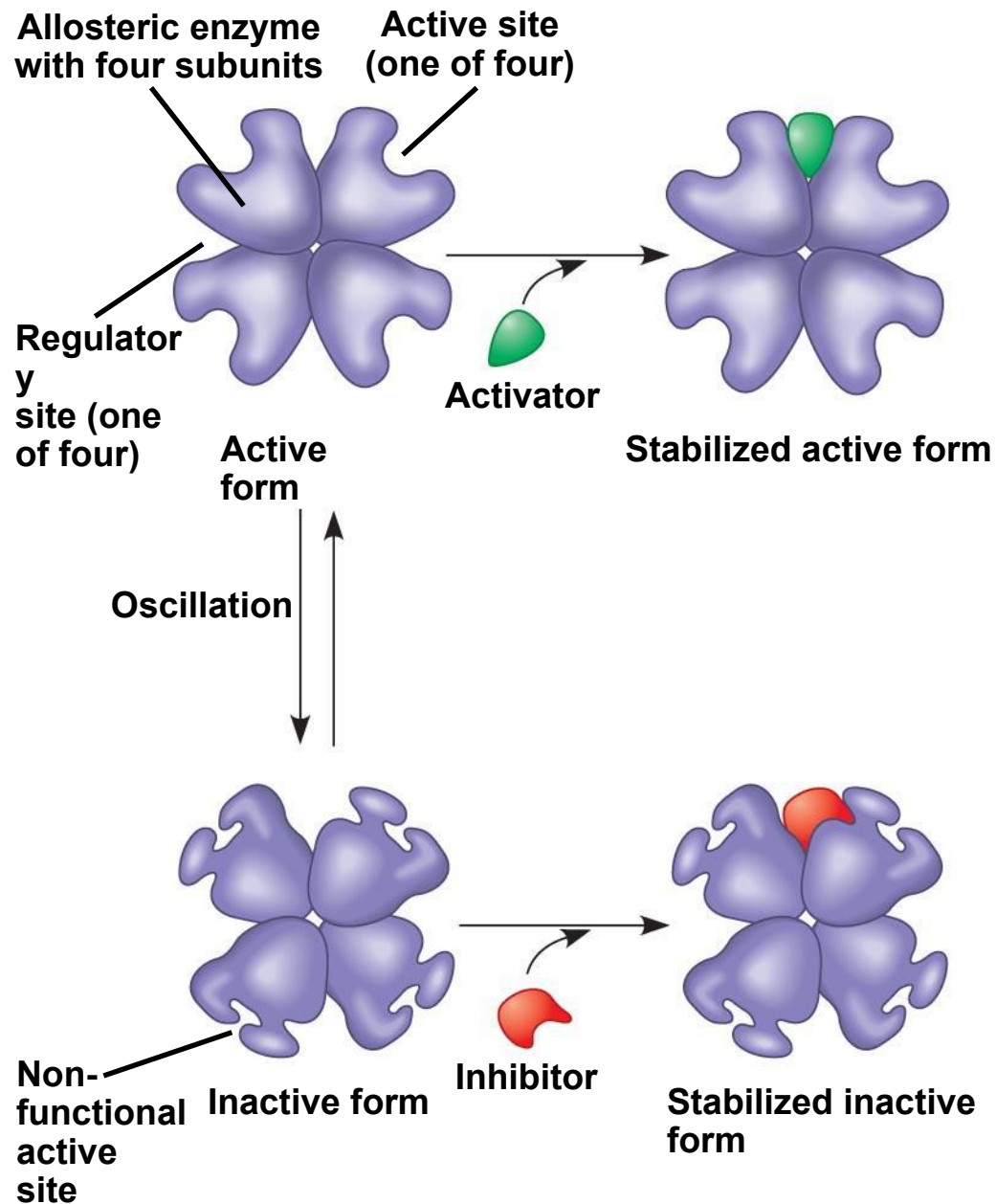
- Most allosterically regulated enzymes are made from polypeptide subunits
- Each enzyme has active and inactive forms
- The binding of an activator stabilizes the active form of the enzyme
- The binding of an inhibitor stabilizes the inactive form of the enzyme



(a) Allosteric activators and inhibitors

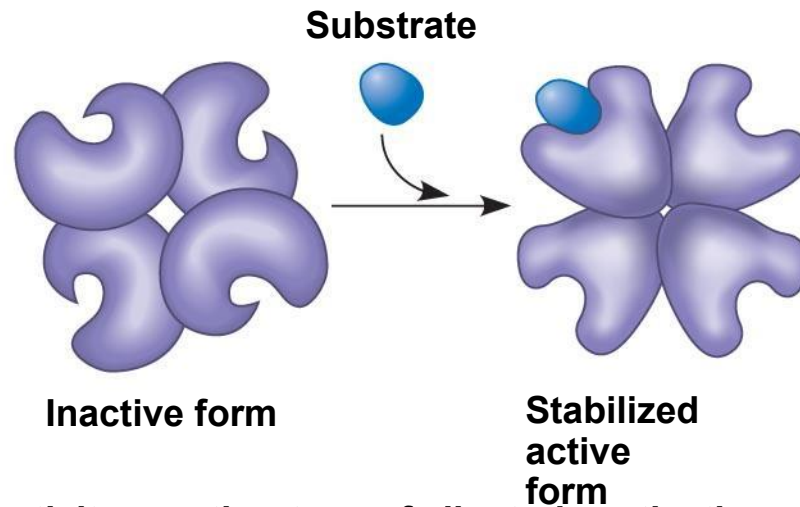


(b) Cooperativity: another type of allosteric activation



**(a) Allosteric activators and inhibitors**

- 
- **Cooperativity** is a form of allosteric regulation that can amplify enzyme activity
  - In cooperativity, binding by a substrate to one active site stabilizes favorable conformational changes at all other subunits



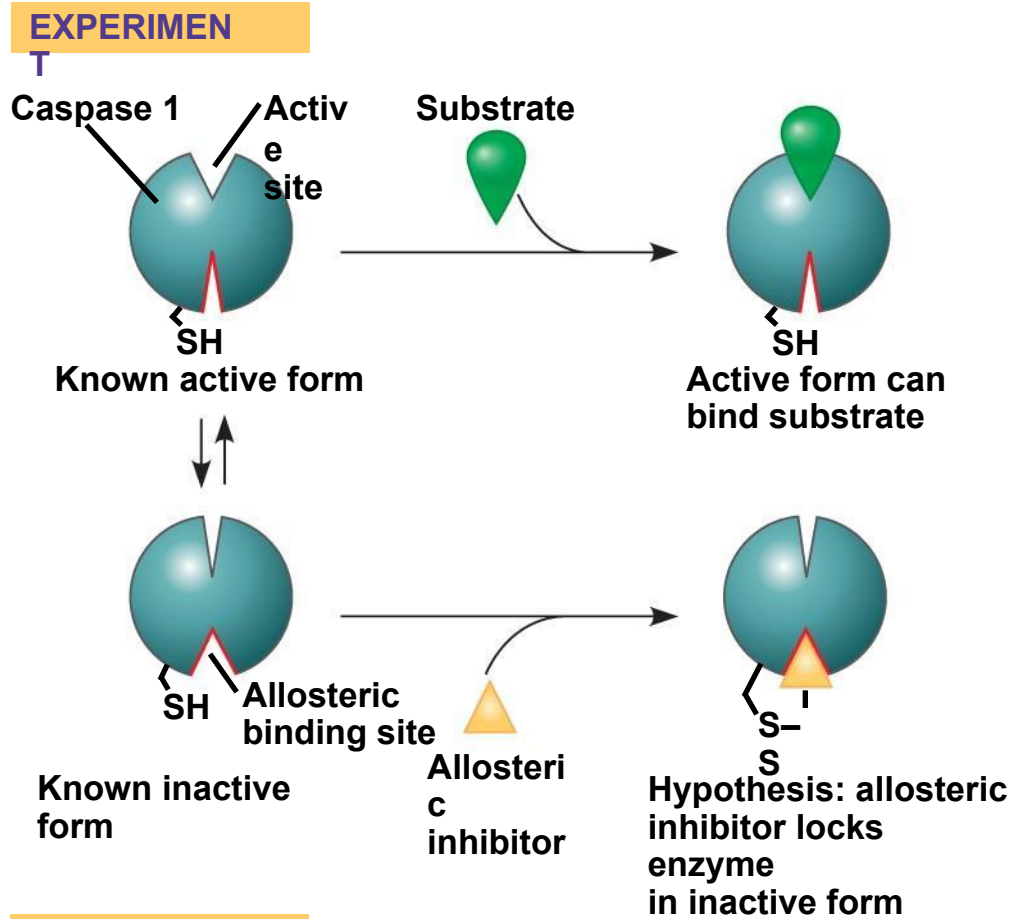
**(b) Cooperativity: another type of allosteric activation**

# *Identification of Allosteric Regulators*

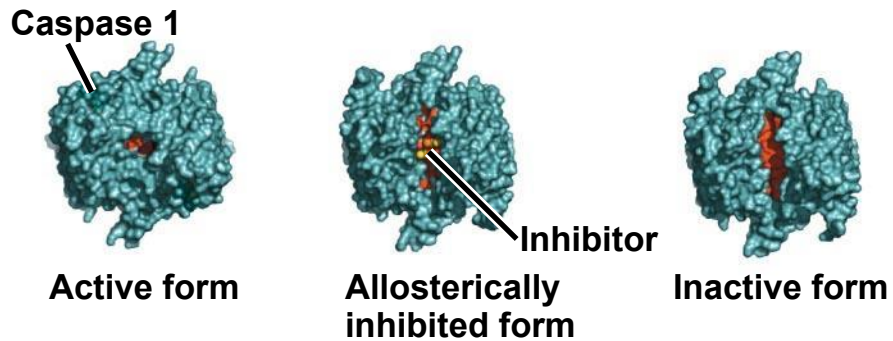
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- Allosteric regulators are attractive drug candidates for enzyme regulation
- Inhibition of proteolytic enzymes called caspases may help management of inappropriate inflammatory responses

Fig. 8-21

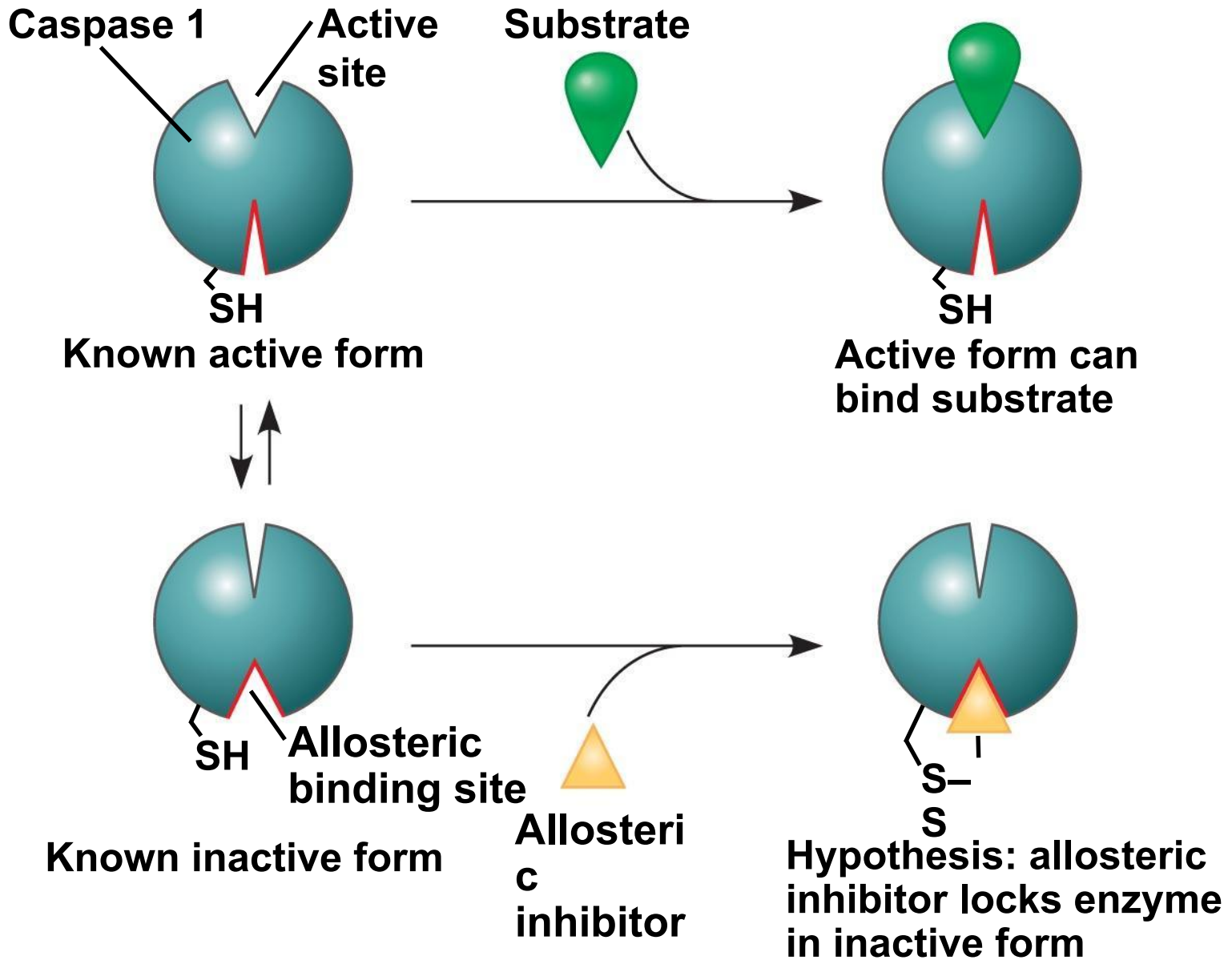


**RESULTS**



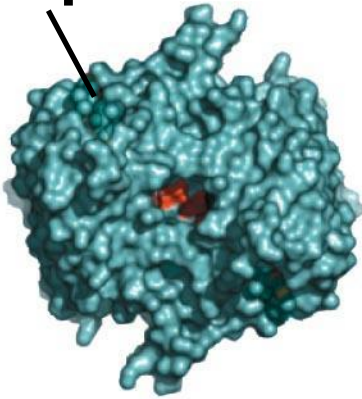


# EXPERIMENT

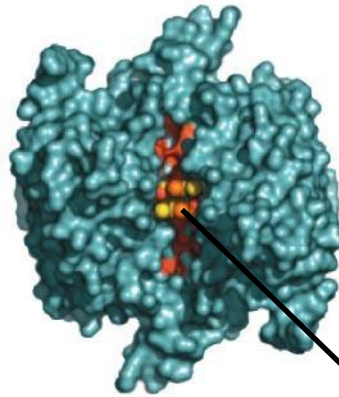


## RESULTS

**Caspase 1**

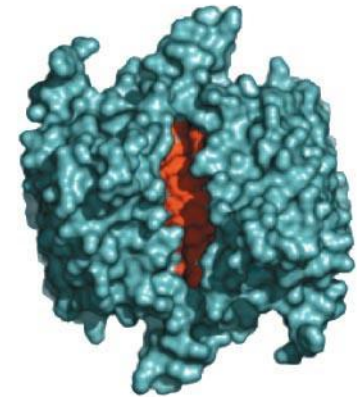


**Active form**



**Inhibitor**

**Allosterically inhibited form**



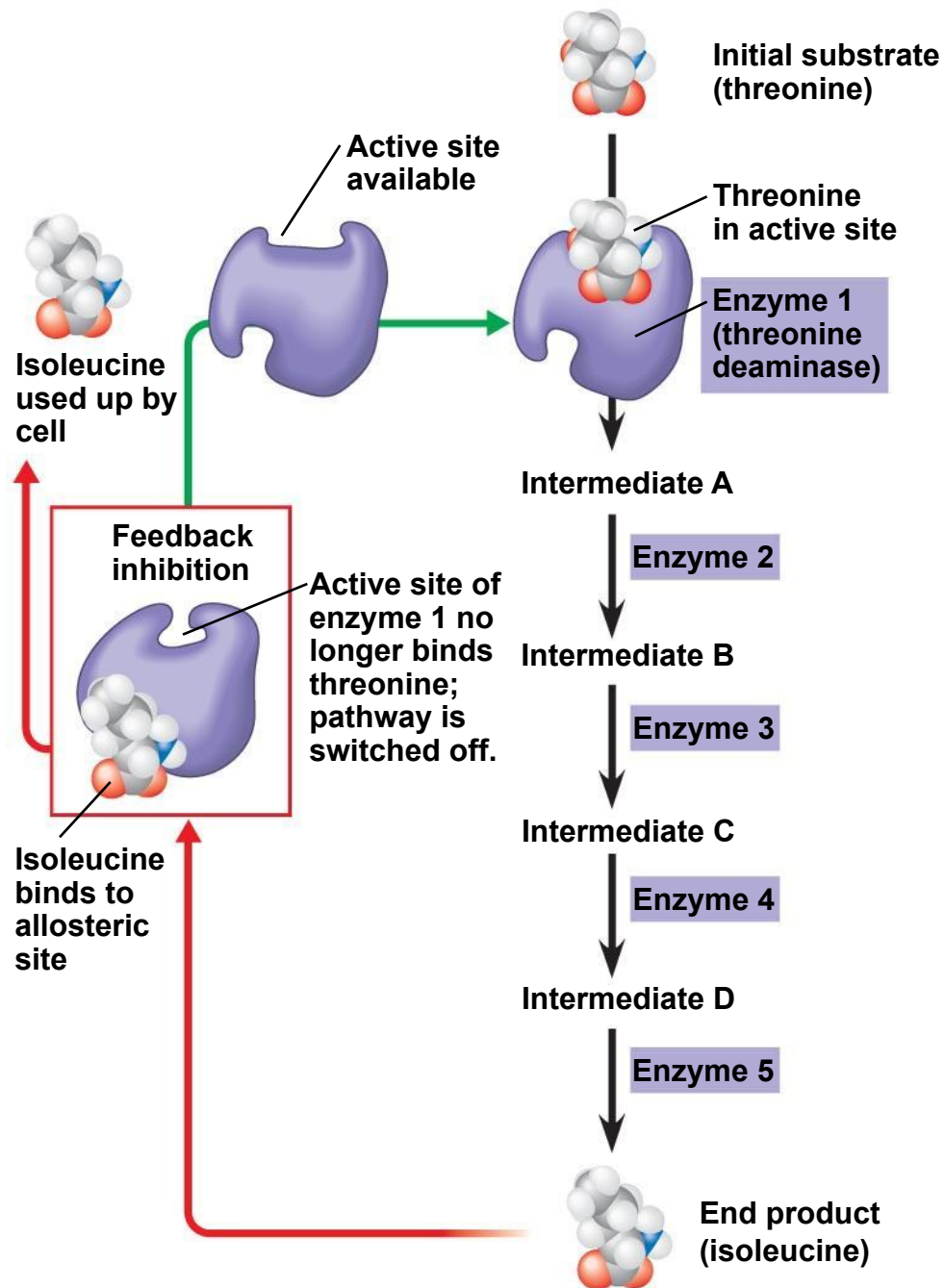
**Inactive form**

# *Feedback Inhibition*

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- 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

Fig. 8-22

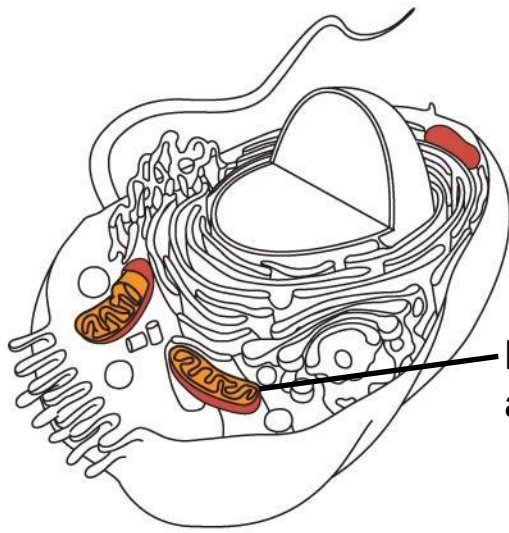


# Specific Localization of Enzymes Within the Cell

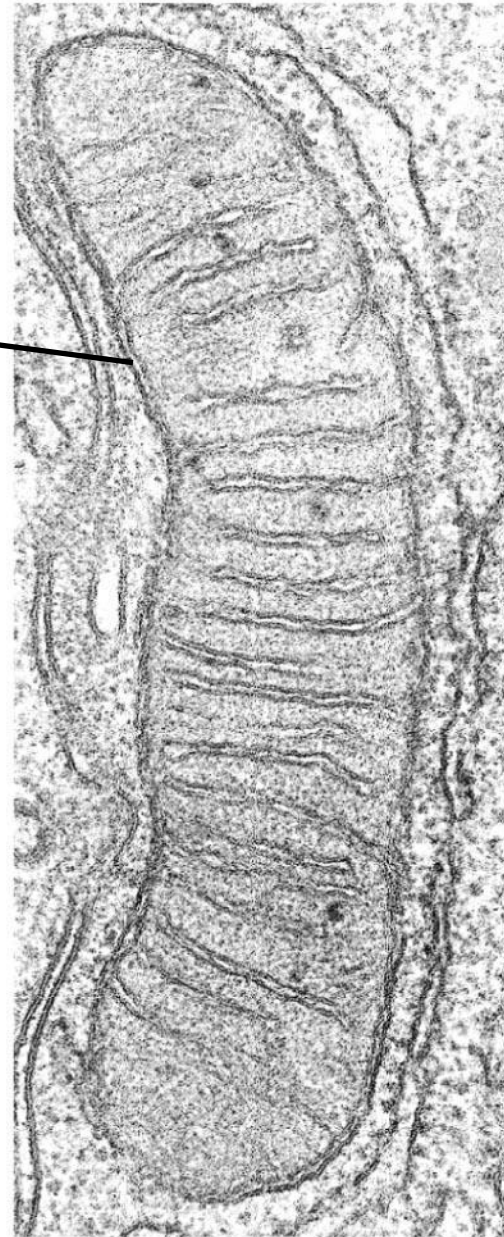
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- Structures within the cell help bring order to metabolic pathways
- Some enzymes act as structural components of membranes
- In eukaryotic cells, some enzymes reside in specific organelles; for example, enzymes for cellular respiration are located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

Fig. 8-23



**Mitochondria**  
**a**



1  $\mu$ m

Fig. 8-UN2

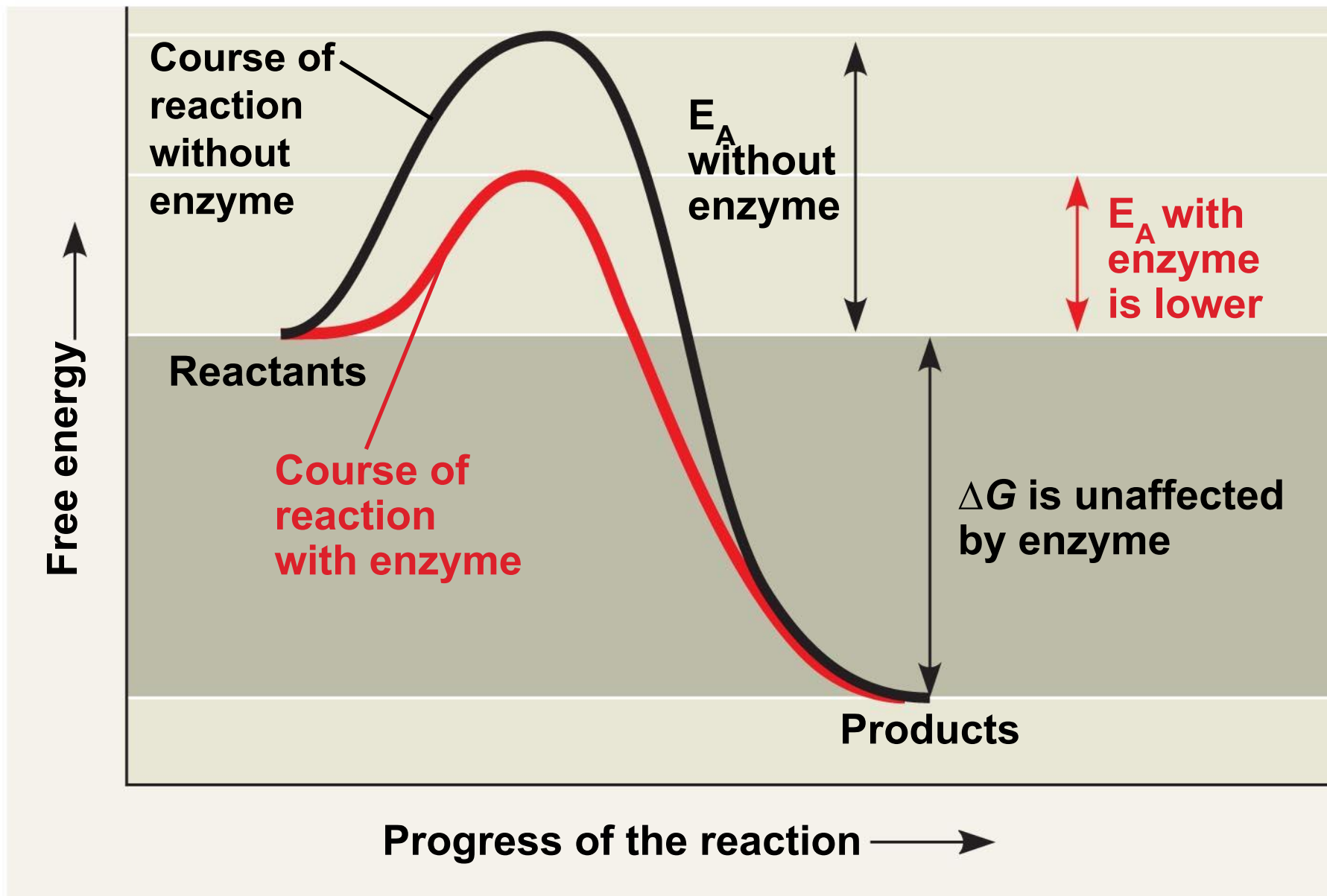


Fig. 8-UN3

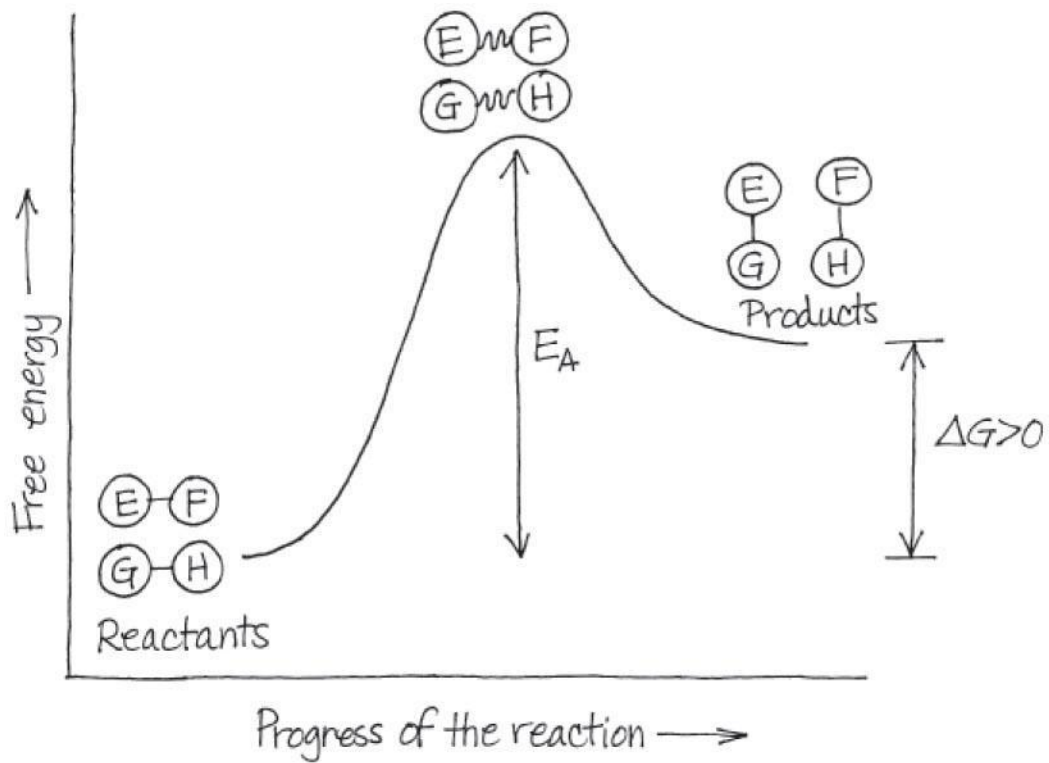
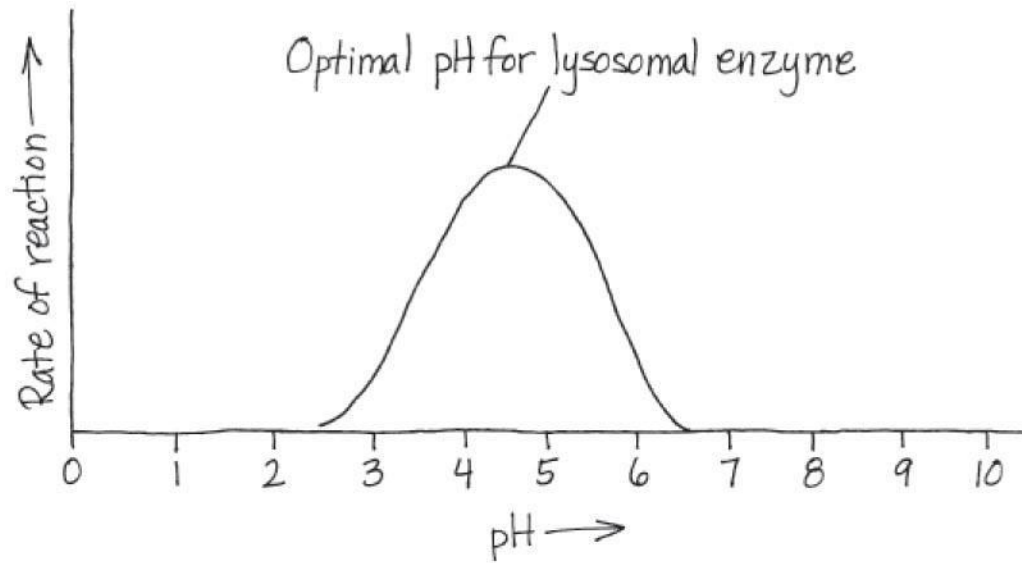


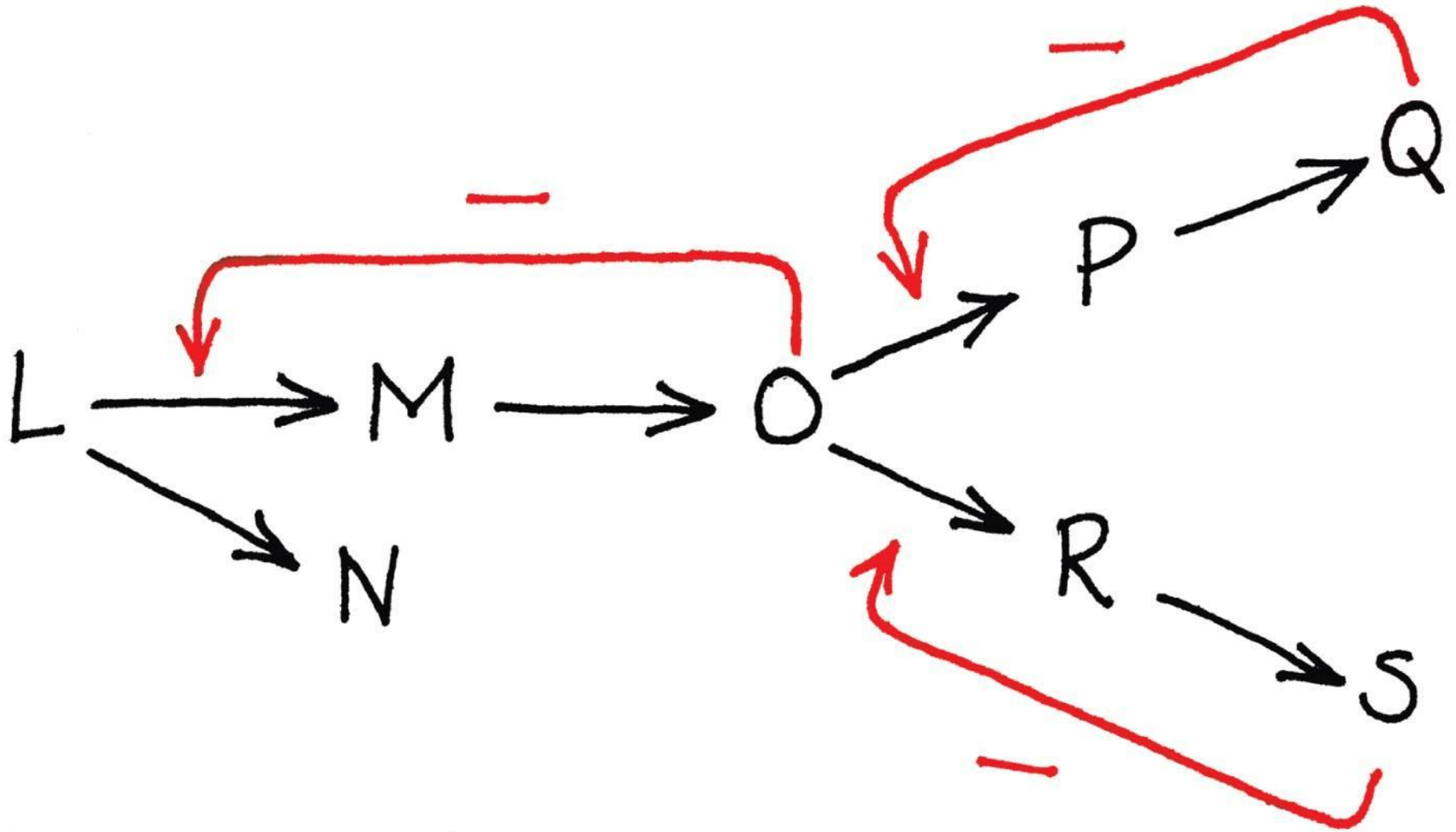


Fig. 8-UN4



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Fig. 8-UN5



## You should now be able to:

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1. Distinguish between the following pairs of terms: catabolic and anabolic pathways; kinetic and potential energy; open and closed systems; exergonic and endergonic reactions
2. In your own words, explain the second law of thermodynamics and explain why it is not violated by living organisms
3. Explain in general terms how cells obtain the energy to do cellular work

- 
4. Explain how ATP performs cellular work
  5. Explain why an investment of activation energy is necessary to initiate a spontaneous reaction
  6. Describe the mechanisms by which enzymes lower activation energy
  7. Describe how allosteric regulators may inhibit or stimulate the activity of an enzyme