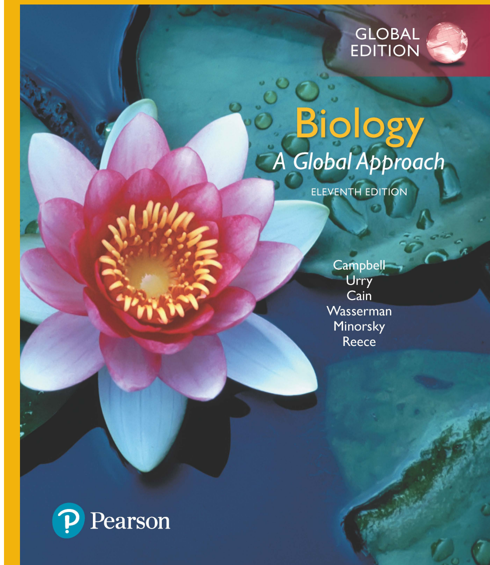


Chapter 6

Energy and Life

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

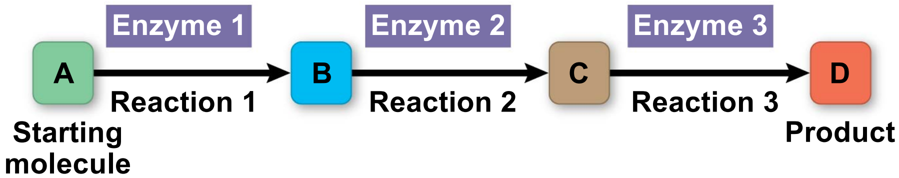
Concept 6.1: An organism's metabolism transforms matter and energy, subject to the laws of thermodynamics

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

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

Figure 6.UN01



- **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
  - For example, the synthesis of protein from amino acids is an anabolic pathway
- **Bioenergetics** is the study of how energy flows through living organisms

Forms of Energy

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

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

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

- The change in free energy:

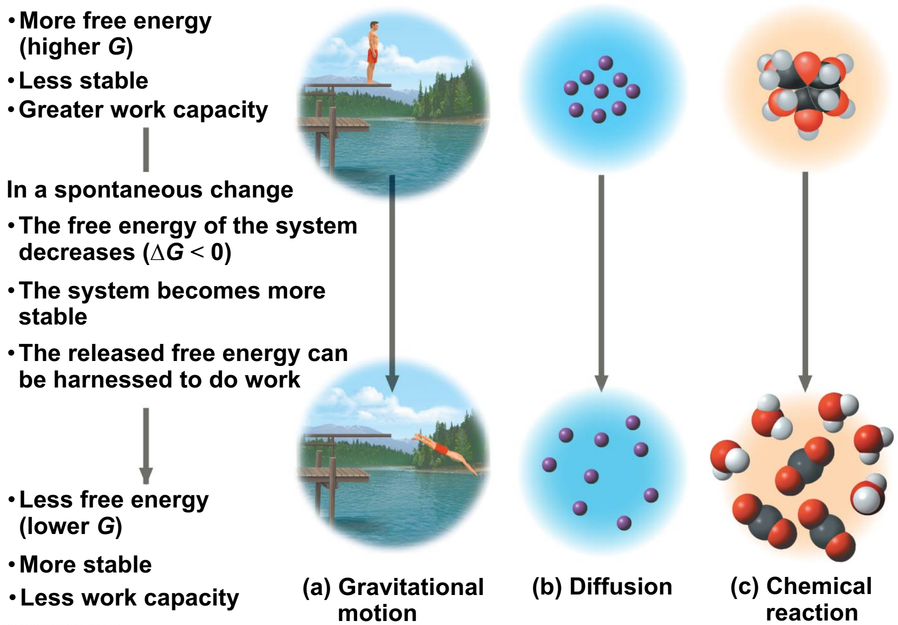
Δ*G* = G final state (products) – G initial state substrates

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

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

Figure 6.5



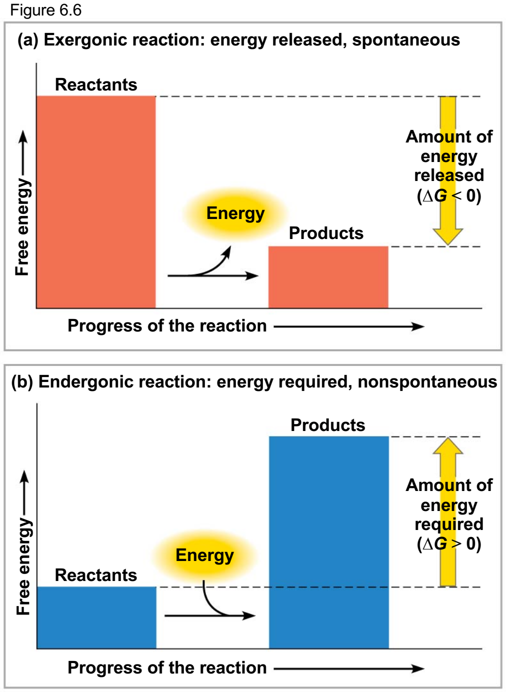
Free Energy and Metabolism

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

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

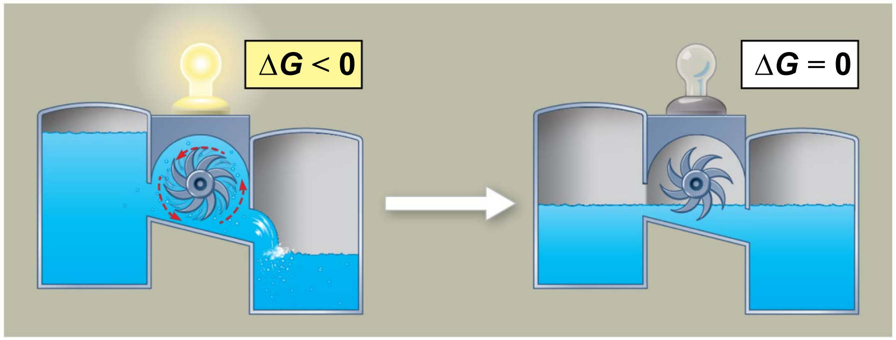
Figure 6.6



Equilibrium and Metabolism

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

Figure 6.7



- 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

Figure 6.8

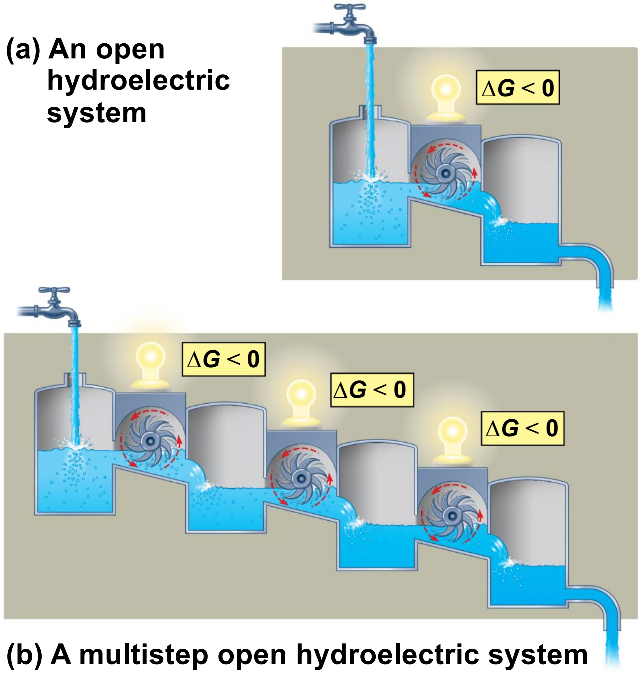
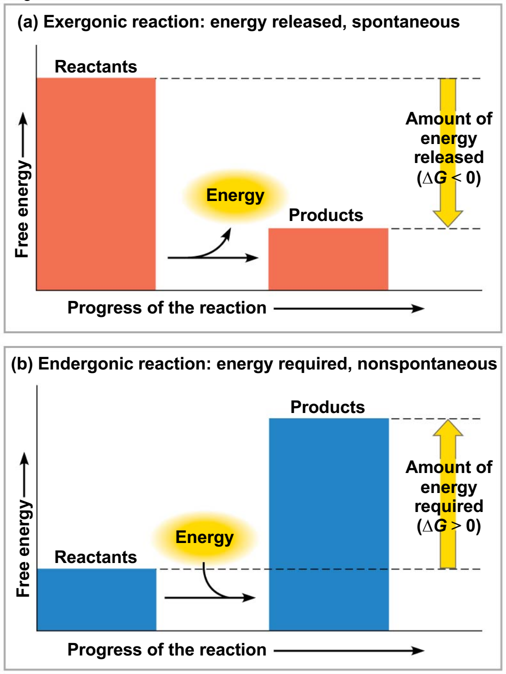
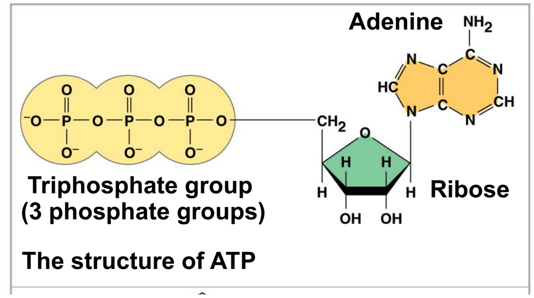


Figure 6.6



- **Catabolic pathways** release energy by breaking down complex molecules into simpler compounds
- Cellular respiration, convert potential energy stored in biomolecules (breakdown of glucose) in the presence of oxygen into available energy for cellular work
- **Anabolic pathways** consume energy to build/synthesis of complex molecules from simpler ones
- For example, the synthesis of protein from amino acids is an anabolic pathway

Figure 6.9



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

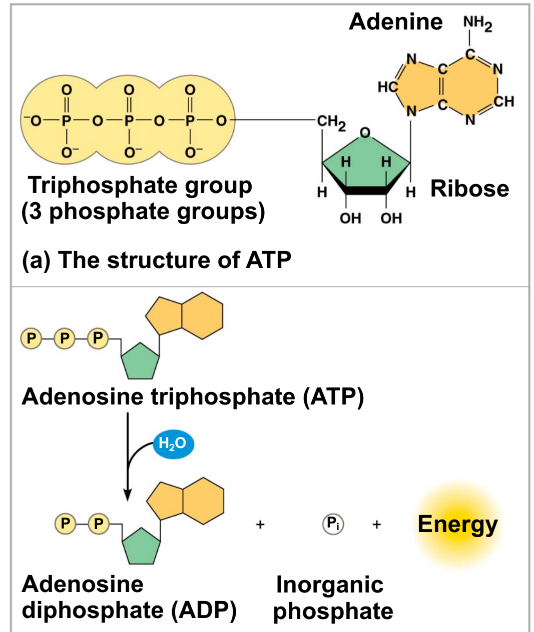
- A cell does three main kinds of work:
  - Chemical work—pushing endergonic reactions
  - Transport work—pumping substances against the direction of spontaneous movement
  - Mechanical work—such as contraction of muscle cells

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

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

Figure 6.9

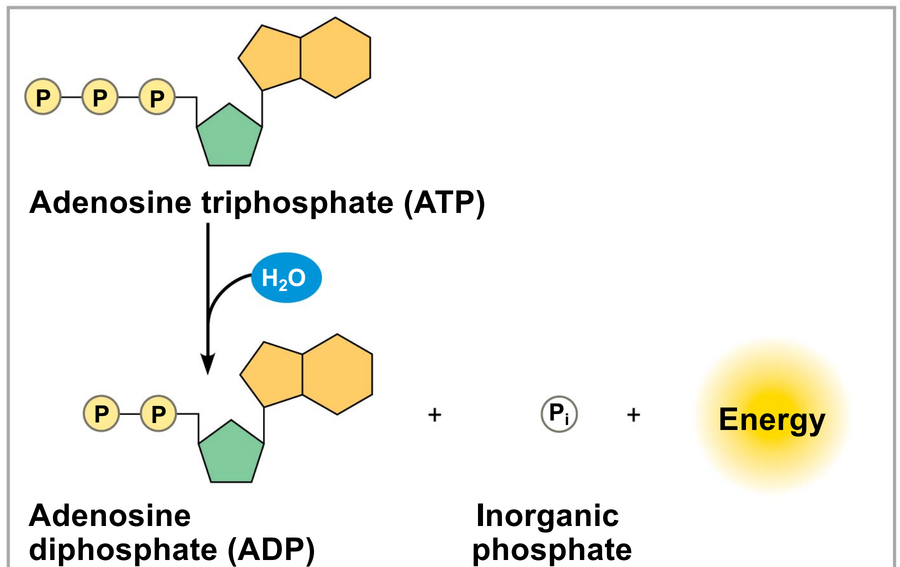


(a) The structure of ATP

(b) The hydrolysis of ATP

- 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

Figure 6.9b



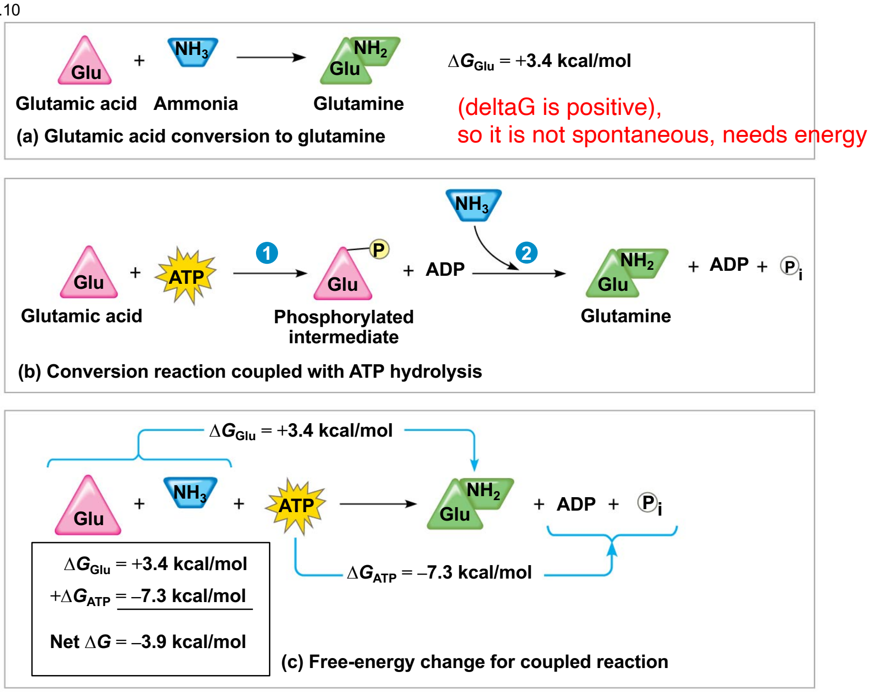
(b) The hydrolysis of ATP

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

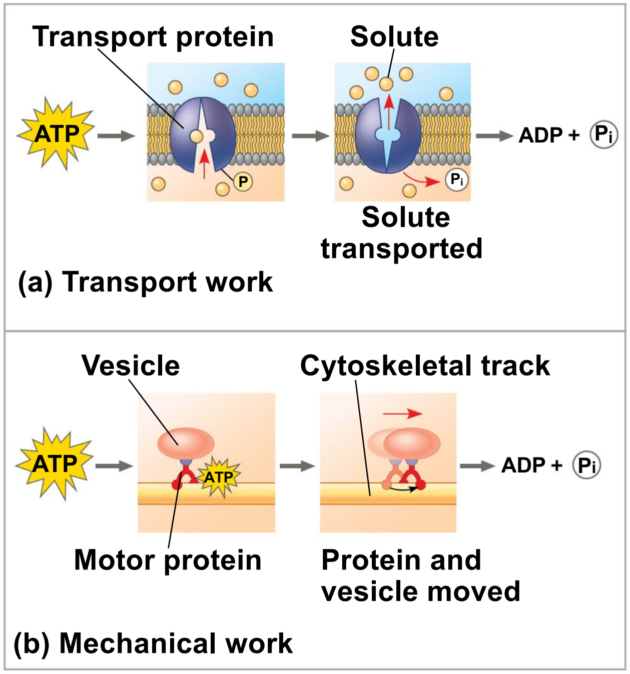
- ATP drives endergonic reactions by phosphorylation, transferring a phosphate group to some other molecule, such as a reactant
- The recipient molecule is now called a **phosphorylated intermediate**

Figure 6.10



- 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

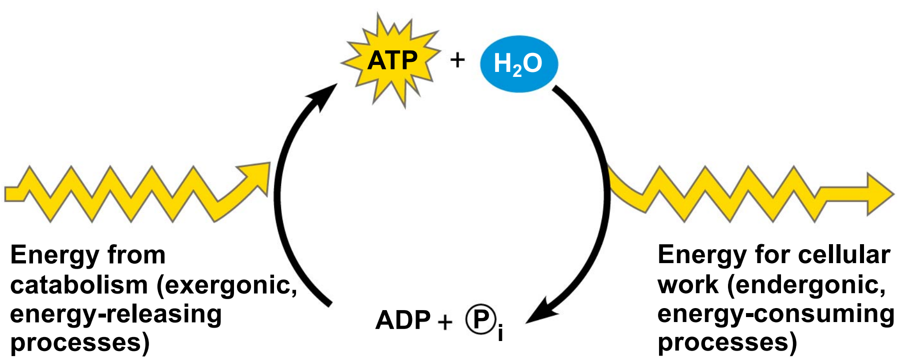
Figure 6.11



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

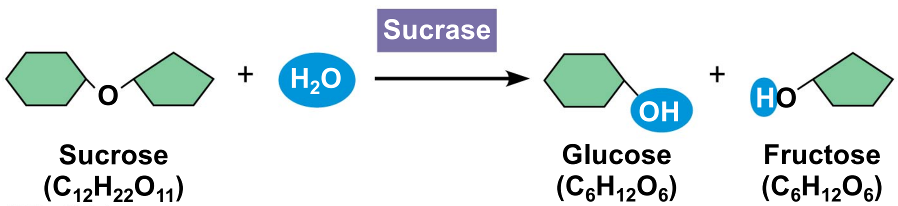
Figure 6.12



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

- Enzymes: mostly proteins
- A **catalyst** is a chemical agent that speeds up (increase rate) a reaction **without being consumed** by the reaction
- do not change the free energy change or direction of the reaction
- An **enzyme** is a catalytic protein
  - For example, sucrase is an enzyme that catalyzes the hydrolysis of sucrose

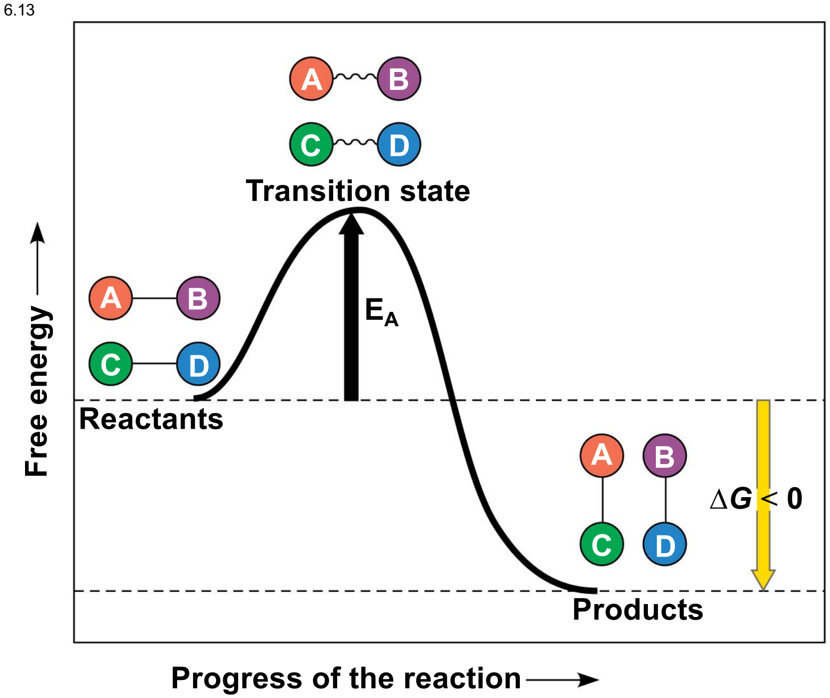
Figure 6.UN02



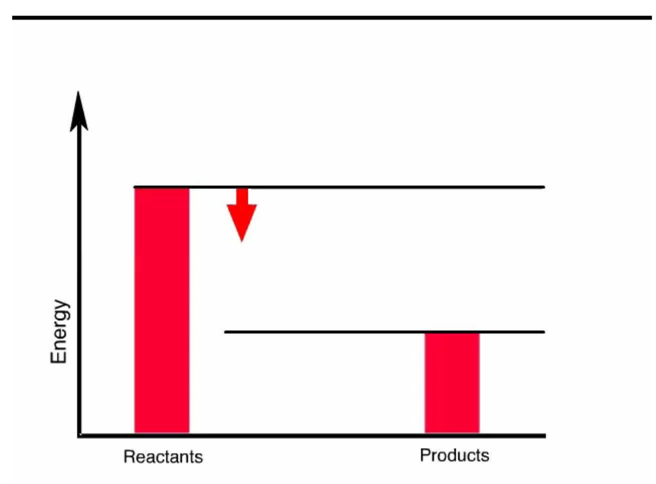
The Activation Energy Barrier

- 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

Figure 6.13



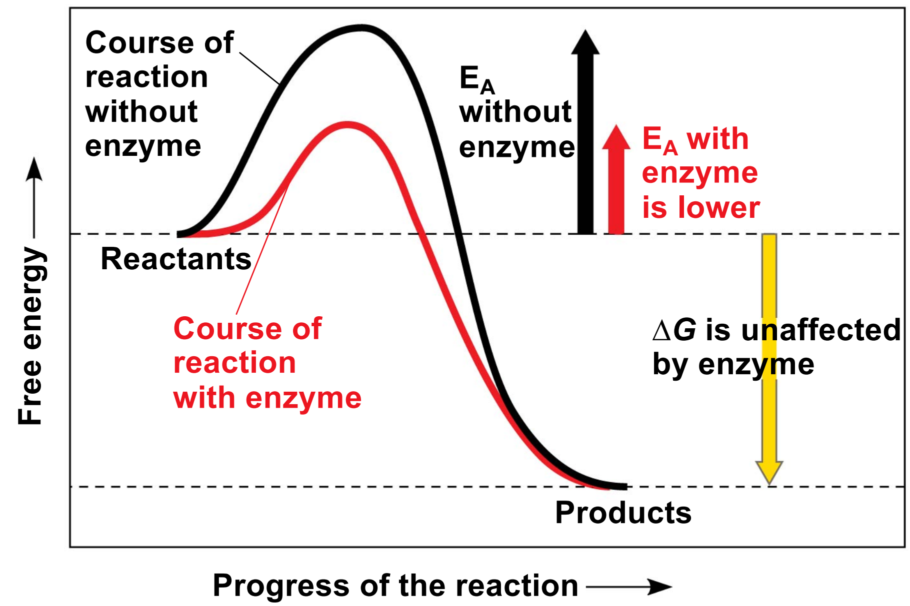
Animation: How Enzymes Work



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

Figure 6.14



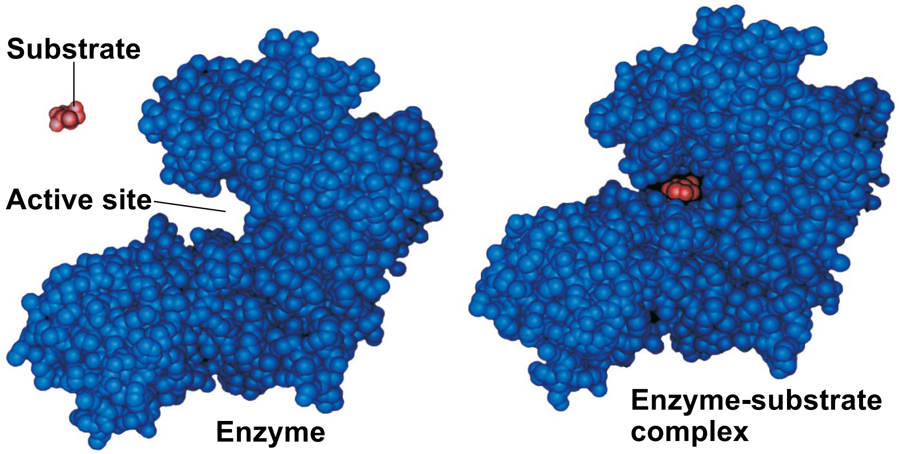
Substrate Specificity of Enzymes

- 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

- 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

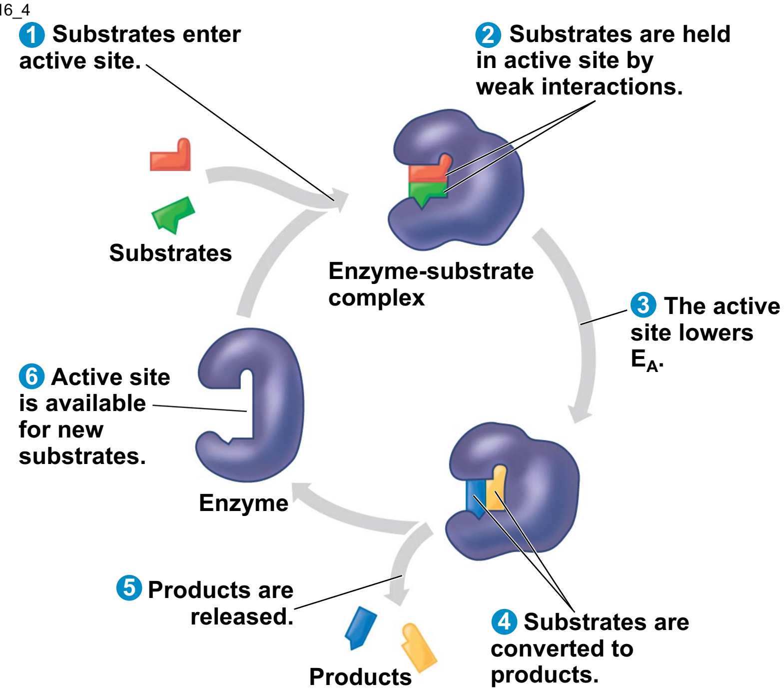
Catalysis in the Enzyme's Active Site

Figure 6.15



- 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

Figure 6.16_4



orienting substrates correctly
straining substrate bond
providing favorable microenvironment

- 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

- 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

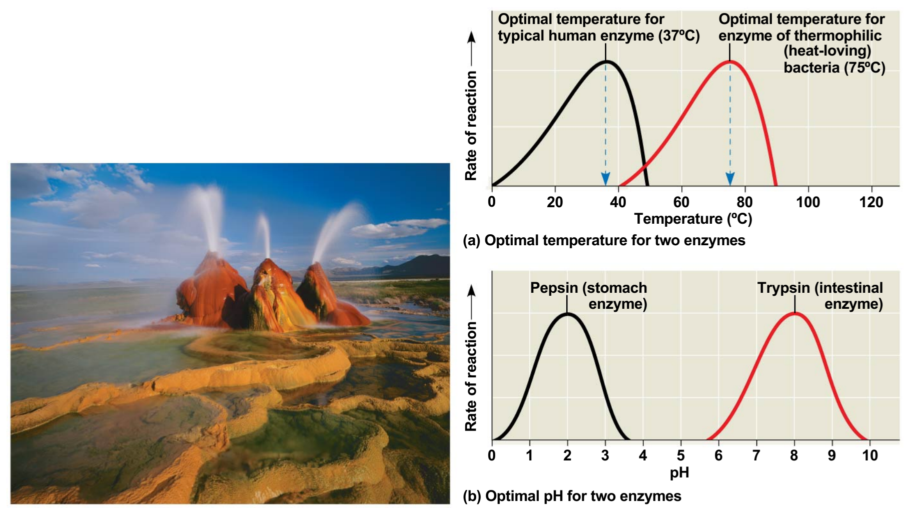
Effects of Local Conditions on Enzyme Activity

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

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

Figure 6.17



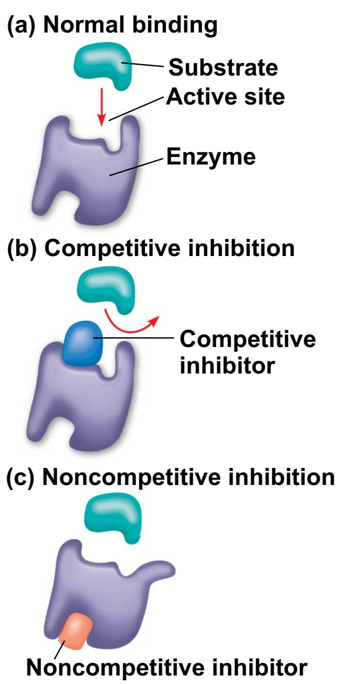
Cofactors

- **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

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

Figure 6.18



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

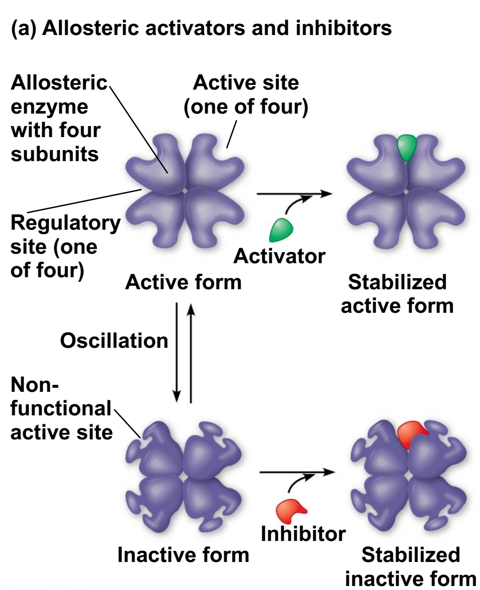
Allosteric Regulation of Enzymes

- **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

Allosteric Activation and Inhibition

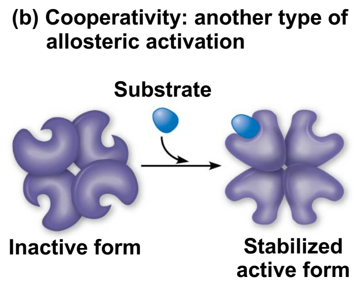
- Most allosterically regulated enzymes are made from polypeptide subunits, each with its own active site
- The enzyme complex has active and inactive forms
- The binding of an activator stabilizes the active form of the enzyme
- The binding of an inhibitor stabilizes the inactive form of the enzyme

Figure 6.20a



- **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

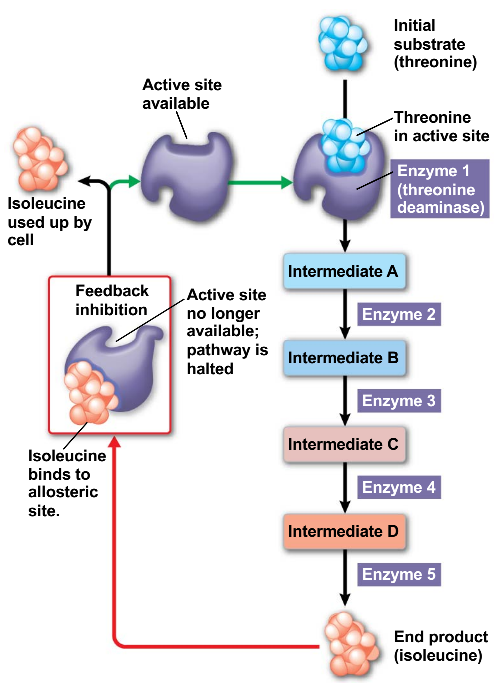
Figure 6.20b



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

Figure 6.21



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

Figure 6.22

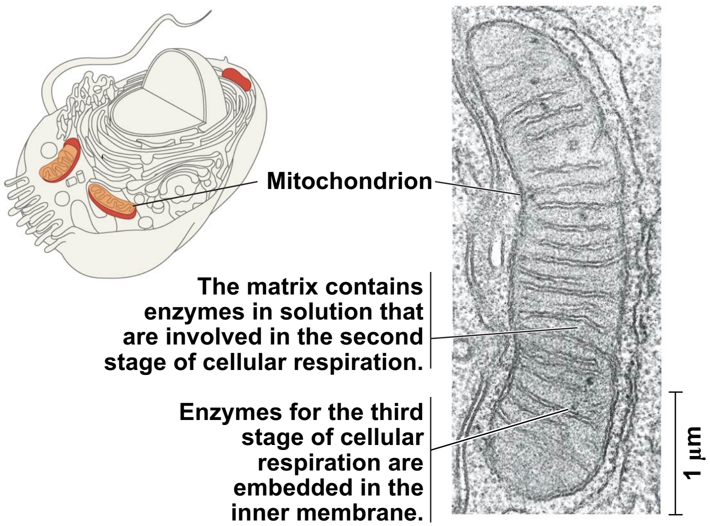


Figure 6.UN04