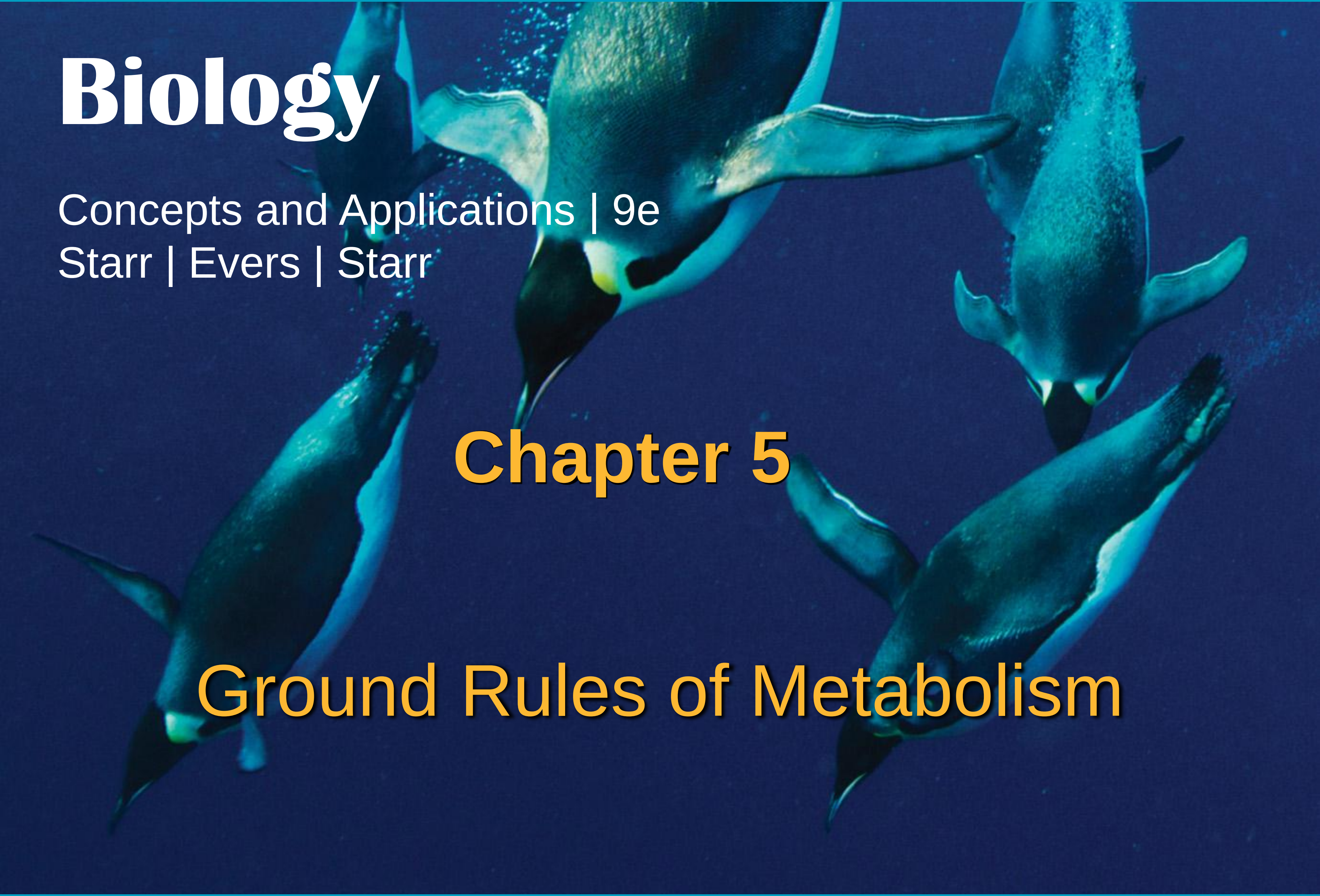

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Chapter 5

Ground Rules of Metabolism

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5.1 What Is Energy?

- Energy: the capacity to do work
- Kinetic energy: the energy of motion
- First law of thermodynamics: energy cannot be created or destroyed
- Entropy: measure of how much the energy of a system is dispersed
- Second law of thermodynamics: energy disperses spontaneously

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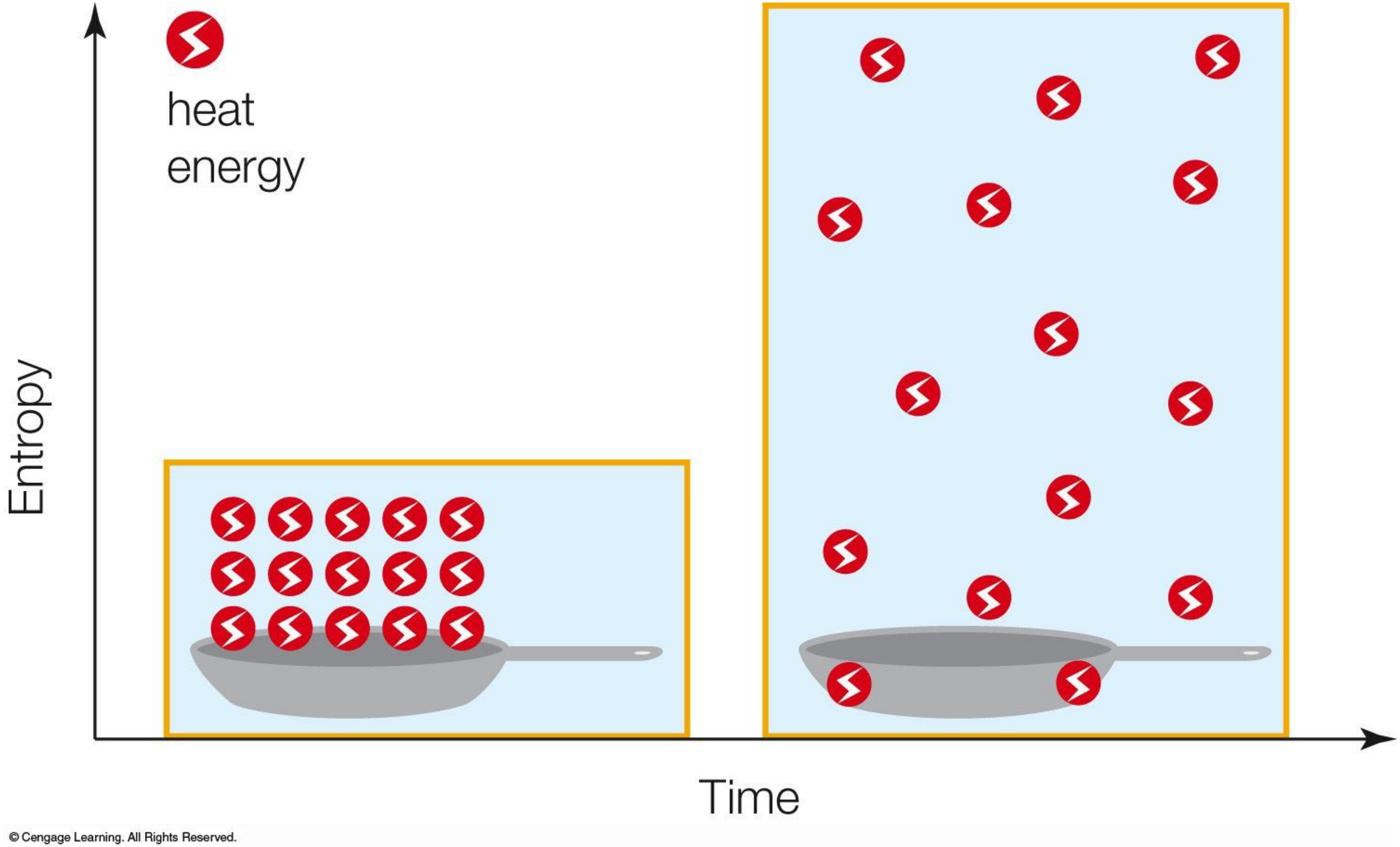
Energy Disperses (cont'd.)



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Energy's One-Way Flow

- Work occurs as a result of energy transfers
  - Energy lost from a transfer is usually in the form of heat
  - Since heat is not useful for doing work, the total amount of energy available for doing work in the universe is always decreasing
  - Lost energy must be replenished for life to continue

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Energy's One-Way Flow (cont'd.)

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Energy's One-Way Flow (cont'd.)

- The energy that fuels most life on Earth comes from the sun
  - This energy from the sun is transferred many times until it is permanently dispersed

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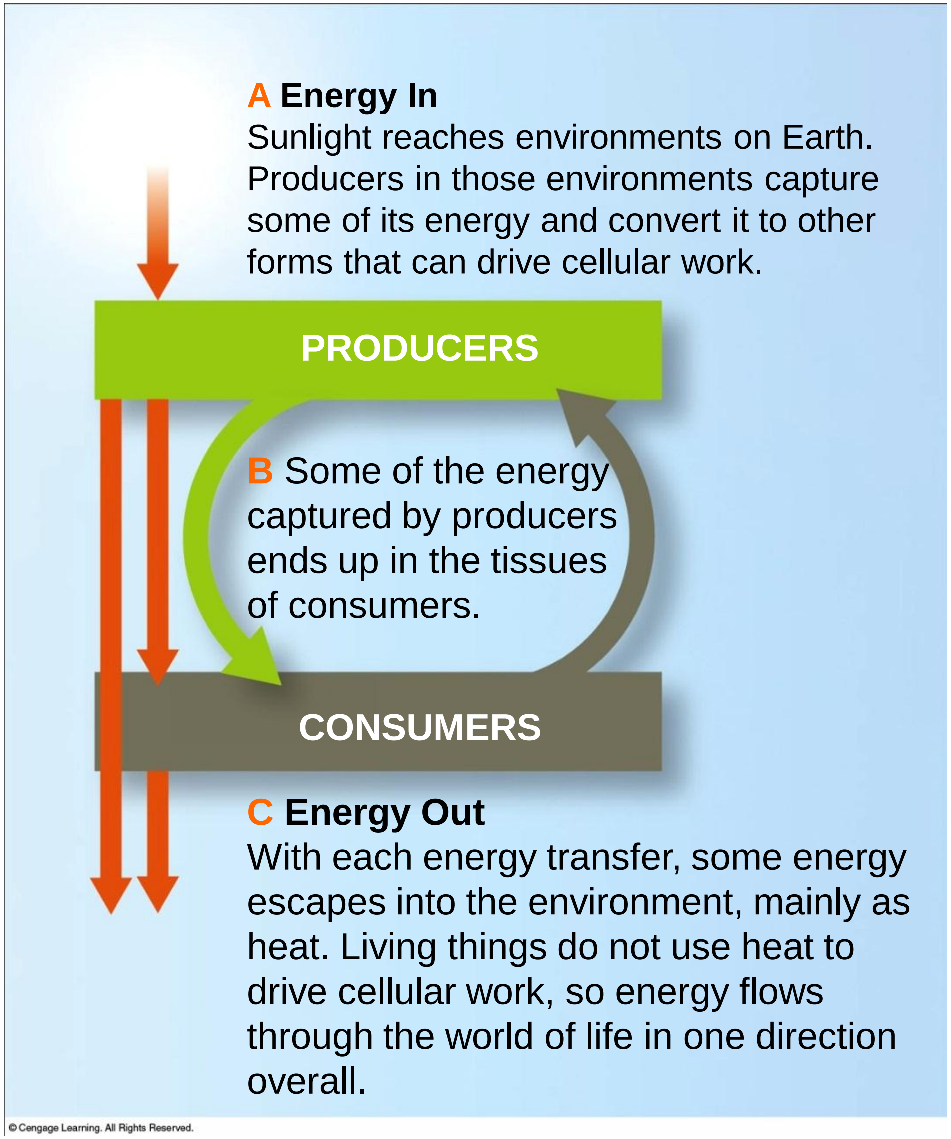
Energy’s One-Way Flow (cont’d.)



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Energy's One-Way Flow (cont'd.)

- Energy's spontaneous dispersal is resisted by chemical bonds
  - Energy in chemical bonds is a type of *potential energy* (stored energy)

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Energy's One-Way Flow (cont'd.)

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5.2 How Do Cells Use Energy?

- During a reaction, one or more *reactants* become one or more *products*
  - Reactant: molecule that enters a reaction and is changed by participating in it
  - Product: molecule that is produced by a reaction

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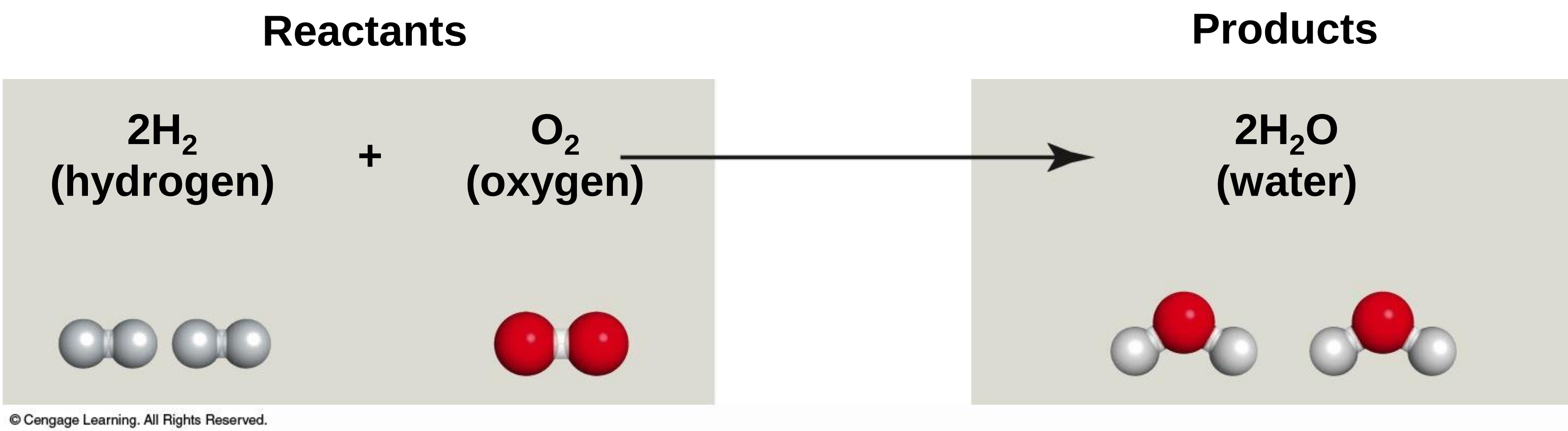
How Do Cells Use Energy? (cont'd.)



4 hydrogen atoms + 2 oxygen atoms → 4 hydrogen atoms + 2 oxygen atoms

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Chemical Bond Energy

- Bond energy and entropy both contribute to a molecule's free energy (amount of energy available to do work)
  - Endergonic: energy in; reaction that requires a net input of free energy to proceed
  - Exergonic: energy out; reaction that ends with a net release of free energy

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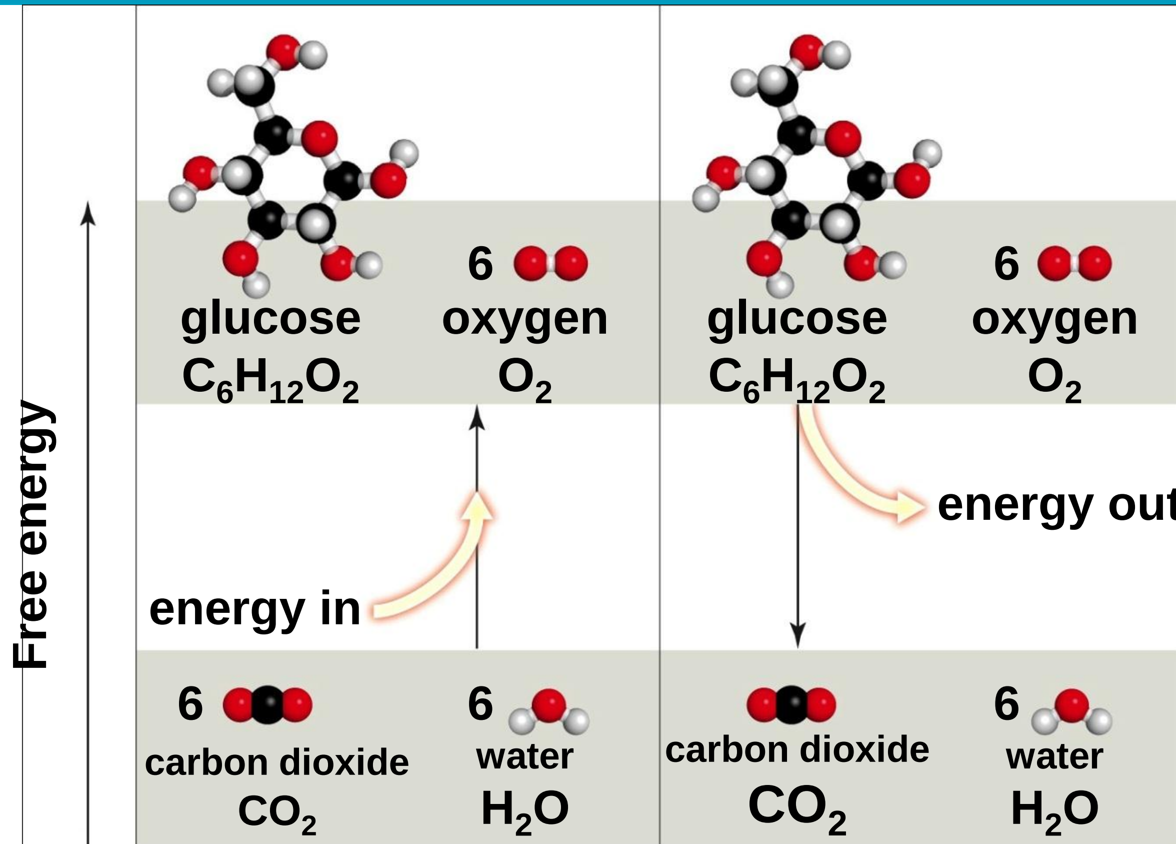
Chemical Bond Energy (cont'd.)



A Endergonic reactions convert molecules with lower free energy to molecules with higher free energy, so they require a net energy input in order to proceed.

B Exergonic reactions convert molecules with higher free energy to molecules with lower
free energy, so they end with an energy release.

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Why Earth Does Not Go Up in Flames

- The molecules of life release energy when they combine with oxygen
  - Example: a spark starts a reaction that converts cellulose (in wood) and oxygen (in air) to water and carbon dioxide
  - The reaction is highly exergonic, causing wood to continue to burn

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Why Earth Does Not Go Up in Flames (cont'd.)

- Earth is rich in oxygen – and in potential exergonic reactions
  - Why then doesn't Earth burst into flames?
- Chemical bonds do not break without at least a small input of energy
  - Activation energy: the minimum amount of energy required to get a chemical reaction started

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ANIMATED FIGURE: Activation energy

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Energy In, Energy Out

- Cells store energy by running endergonic reactions that build organic compounds
  - Example: light energy drives the overall reactions of photosynthesis, which produce sugars from carbon dioxide and water

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ANIMATION: Energy changes in chemical work

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Energy In, Energy Out (cont'd.)

- Cells harvest energy by running exergonic reactions that break the bonds of organic compounds
  - Example: aerobic respiration releases the energy of glucose by breaking the bonds between its carbon atoms

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5.3 How Do Enzymes Work?

- Metabolism requires enzymes
- In a process called *catalysis*, an enzyme makes a reaction run much faster than it would on its own

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How Do Enzymes Work? (cont'd.)

- Most enzymes are proteins
- Each kind of enzyme recognizes specific *substrates* (reactants) that are altered in specific ways
  - Active site: pocket in an enzyme where substrates bind and a reaction occurs

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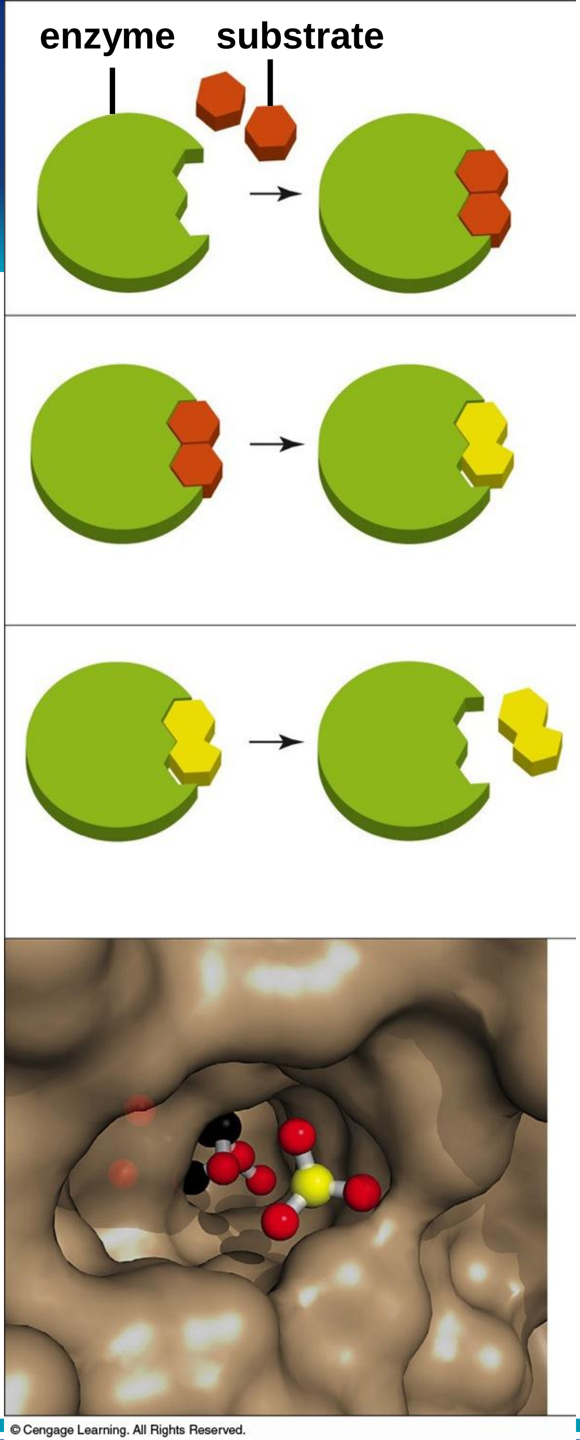
How Do Enzymes Work? (cont'd.)



A An active site binds substrates that are complementary in shape, size, polarity, and charge.

B The binding squeezes substrates together, influences their charge, or causes some change that lowers activation energy, so the reaction proceeds.

C The product leaves the active site after the reaction is finished. The enzyme is unchanged, so it can work again.

D For simplicity, enzymes are often depicted as blobs or geometric shapes. This model shows the actual contours of an active site in an enzyme (hexokinase) that adds a phosphate group to a six-carbon sugar. Both substrates are shown.

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How Do Enzymes Work? (cont'd.)

- Another way to think of activation energy:
  - Energy required to bring reactant bonds to their breaking point (transition state)
- At the transition state, the reaction can run without any additional energy input

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How Do Enzymes Work? (cont'd.)

- Enzymes help bring on the transition state by lowering activation energy via:
  - Forcing substrates together
  - Orienting substrates
  - Inducing fit
  - Shutting out water

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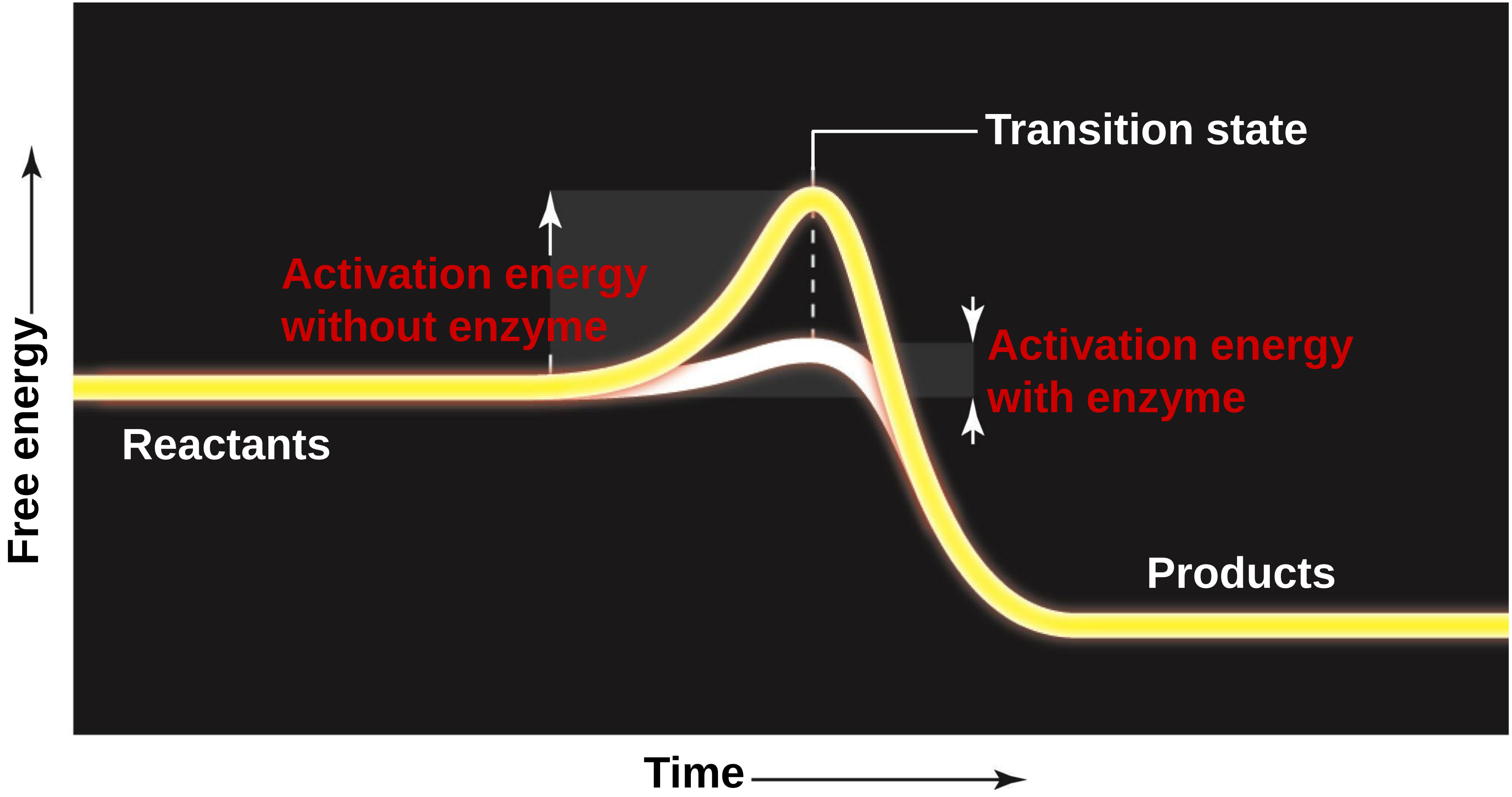
How Do Enzymes Work? (cont'd.)



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Enzyme Activity

- Environmental factors (e.g., pH, temperature, salt) influence an enzyme's shape and function
  - Each enzyme functions best in a particular range of conditions that reflect the environment in which it evolved

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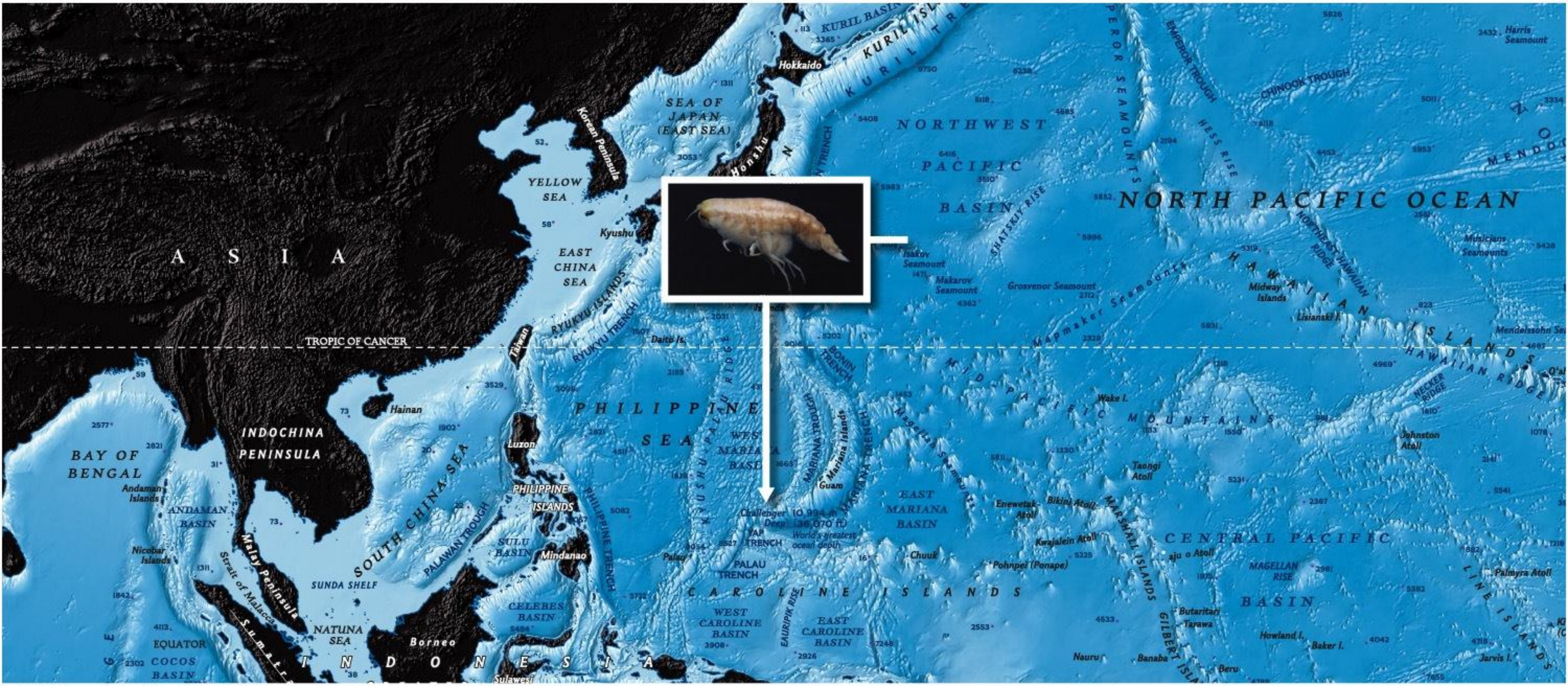
Enzyme Activity (cont'd.)



inset, JAMSTEC; map, Courtesy National Geographic Maps

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Enzyme Activity (cont'd.)

- The enzyme pepsin digests proteins in the very acidic (pH 2) stomach environment
- Pepsin denatures above pH 5.5
  - Pepsin becomes inactivated when the stomach's contents pass into the small intestine (pH 9)
- The enzyme trypsin continues protein digestion in the small intestine at the higher pH

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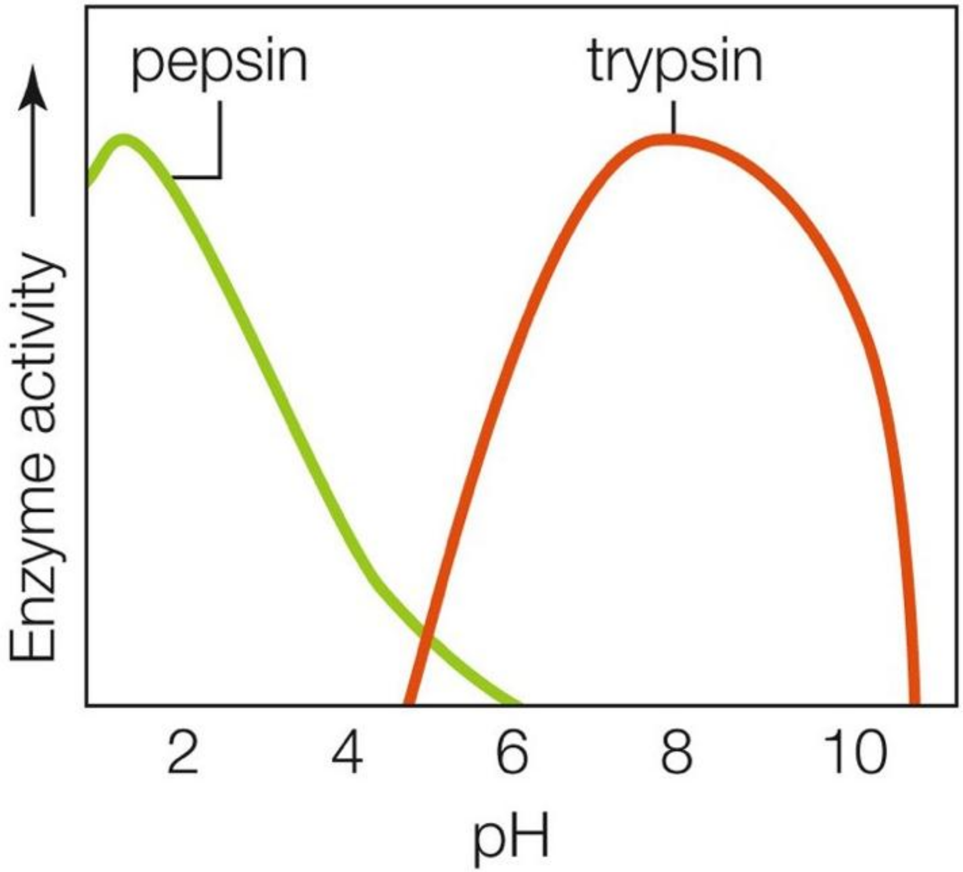
Enzyme Activity (cont'd.)



A The pH-dependent activity of two digestive enzymes, pepsin and trypsin. Pepsin acts in the stomach, where the normal pH is 2. Trypsin acts in the small intestine, where the normal pH is 9.

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Enzyme Activity (cont'd.)

- Adding heat boosts free energy, bringing reactants closer to activation energy
- The rate of an enzymatic reaction typically increases with temperature — but only up to a point
  - An enzyme denatures above a characteristic temperature, causing the reaction rate to fall sharply as the shape of the enzyme changes

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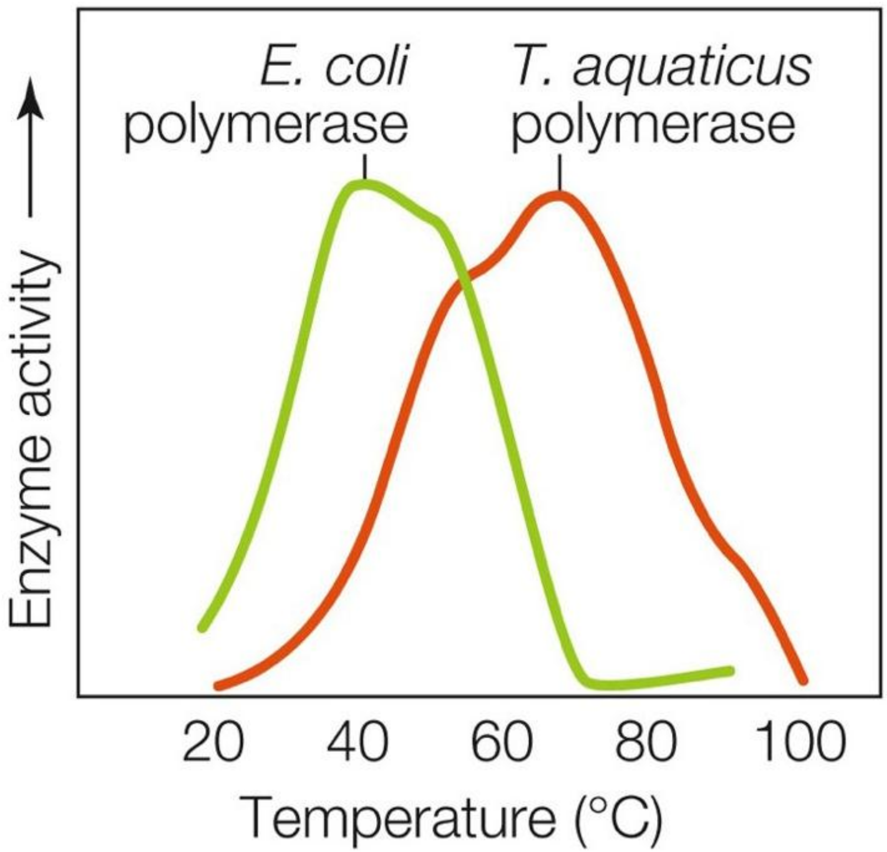
Enzyme Activity (cont'd.)



B Comparison of temperature-dependent activity of a DNA synthesis enzyme from two species of bacteria: *E. coli*, which inhabits the gut (normally 37°C); and *Thermus aquaticus*, which lives in hot springs around 70°C.

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5.4 What Is a Metabolic Pathway?

- Metabolic pathway: series of enzyme-mediated reactions by which cells build, remodel, or break down an organic molecule
  - Linear pathway: reactions run straight from reactant to product
  - Cyclic pathway: the last step regenerates a reactant for the first step

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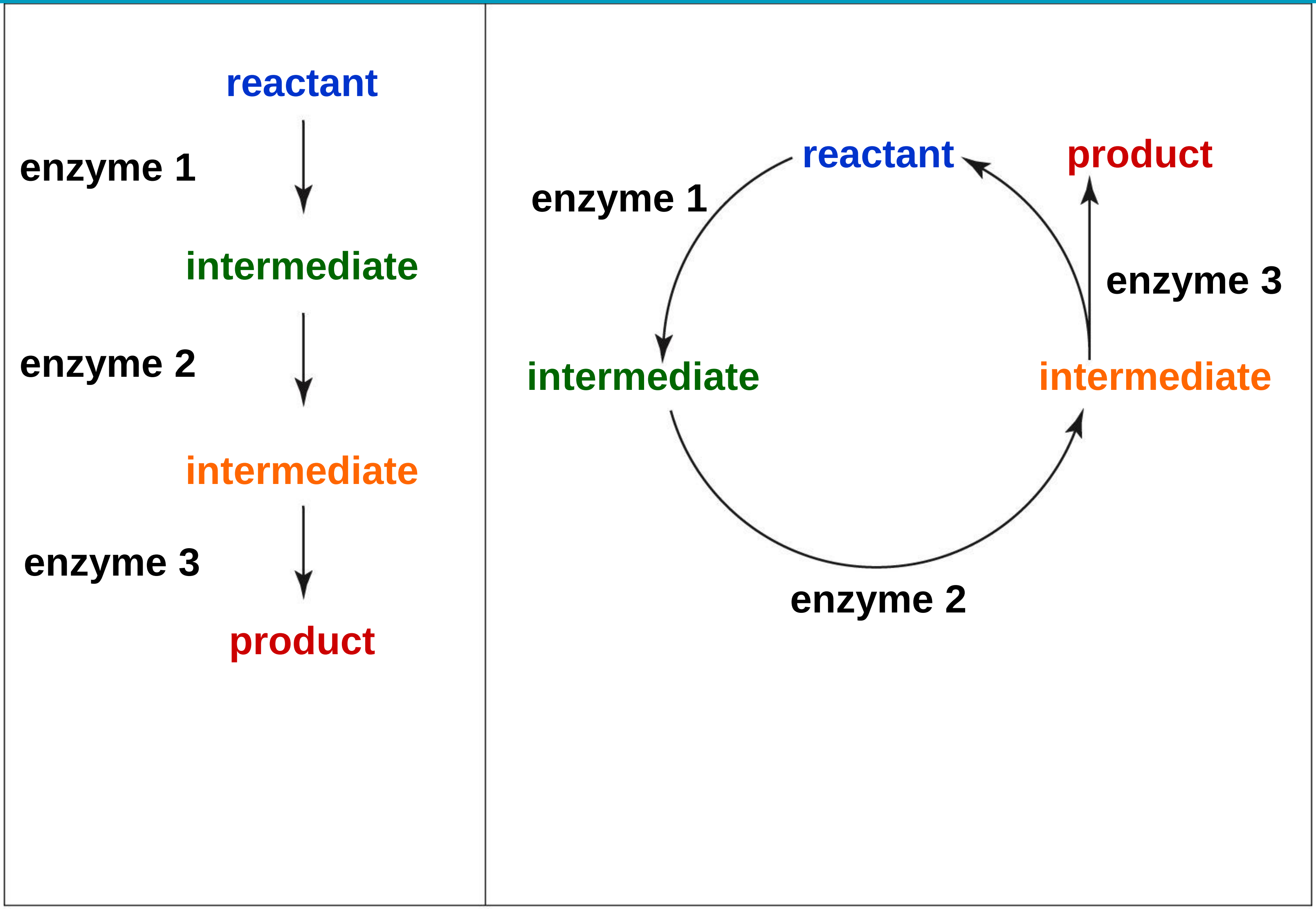
What Is a Metabolic Pathway? (cont'd.)



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Controls Over Metabolism

- What mechanisms help cells regulate the production of substances?
  - The coupling of forward and reverse reactions
  - Regulatory molecules or ions that bind directly to an enzyme’s active site
  - Binding of an allosteric regulator (outside of the active site) alters the shape of an enzyme in a way that enhances or inhibits its function

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ANIMATED FIGURE: Allosteric activation

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Controls Over Metabolism (cont'd.)

- The end product of a series of enzymatic reactions often inhibits the activity of one of the enzymes in the series
  - Feedback inhibition: regulatory mechanism; a change that occurs during a specific cellular activity supresses that activity

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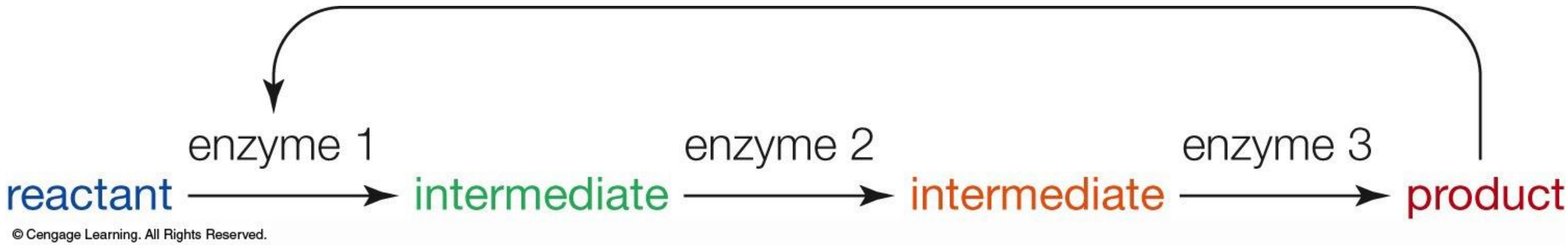
Controls Over Metabolism (cont'd.)



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Electron Transfers

- The bonds of organic molecules hold a lot of energy that can be released in a reaction with oxygen
  - Burning involves a reaction with oxygen; energy from organic molecules is released all at once—explosively

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Animation: Controlling energy release

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Electron Transfers (cont'd.)

- To facilitate burning, cells break organic molecules apart in small, manageable steps
  - Most of these steps are oxidation–reduction reactions (redox reactions; electron transfers)
  - In a typical redox reaction, one molecule accepts electrons (it becomes reduced) from another molecule (which becomes oxidized)

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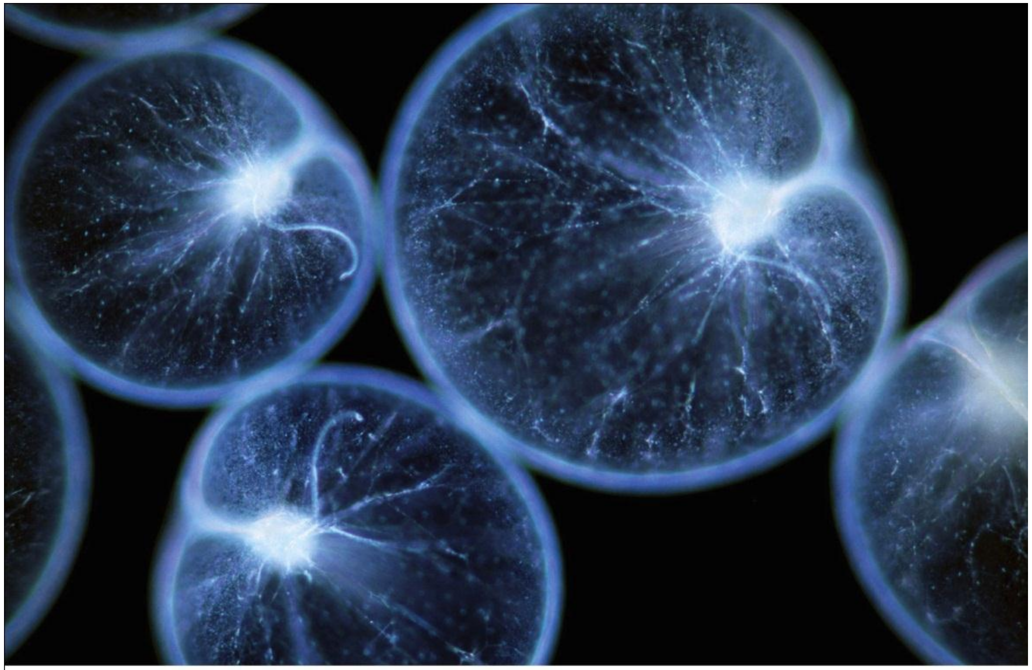
Electron Transfers (cont'd.)

$$\text{luciferin—H}_2 + O_2 \xrightarrow{\text{luciferase}} \text{luciferin=O} + H_2O + \textbf{light}$$



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Electron Transfers (cont'd.)

- Electron transfer chain: array of enzymes and other molecules that accept and give up electrons in sequence
  - The energy of the electrons is released with each step of the sequence
  - Important for photosynthesis and aerobic respiration

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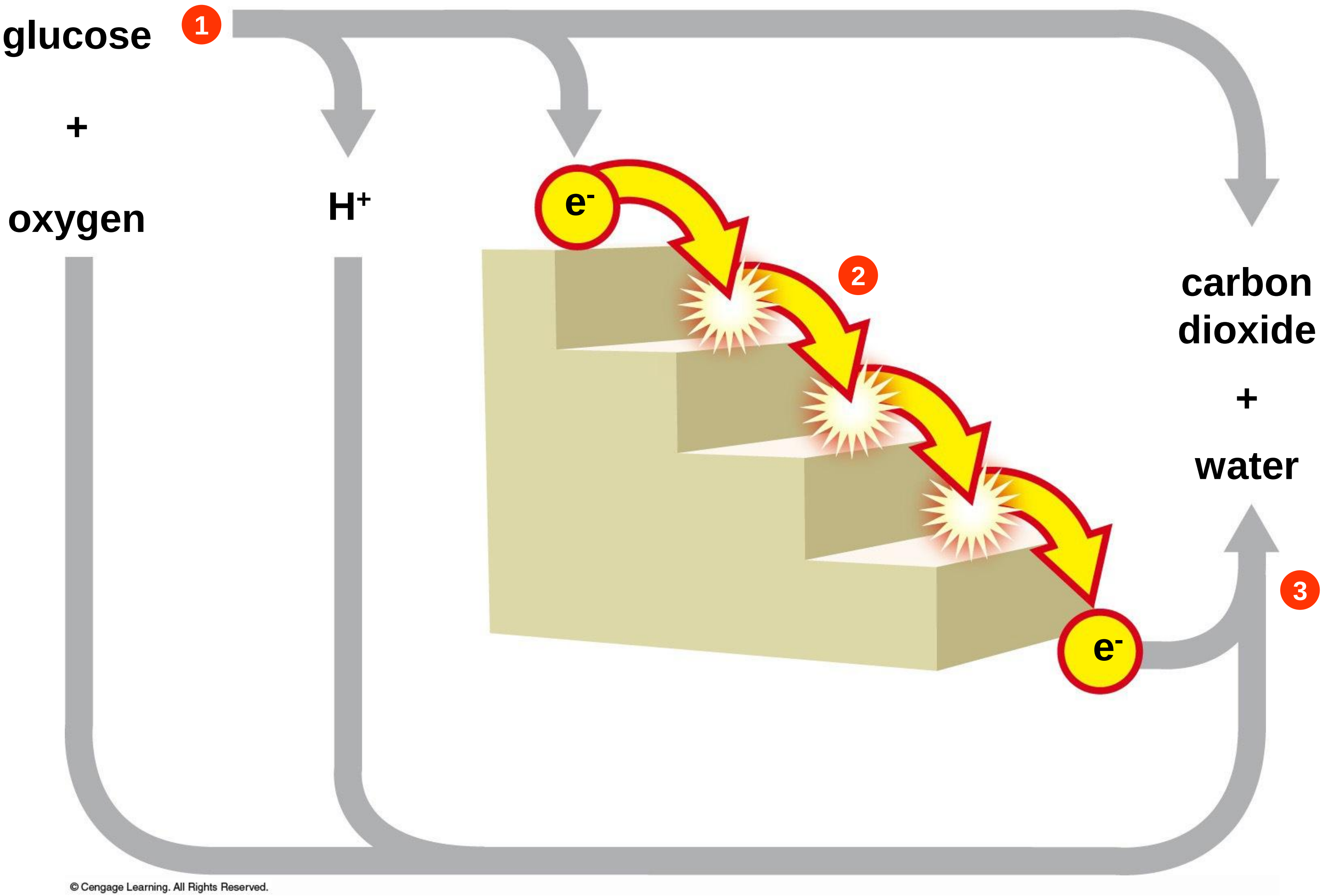
Electron Transfers (cont'd.)



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5.5 How Do Cofactors Work?

- Cofactor: metal ion or organic compound that associates with an enzyme and is necessary for that enzyme's function
  - Examples: vitamins, minerals, metal ions
- Coenzyme: an organic cofactor
  - Example: coenzyme Q10, NAD^+

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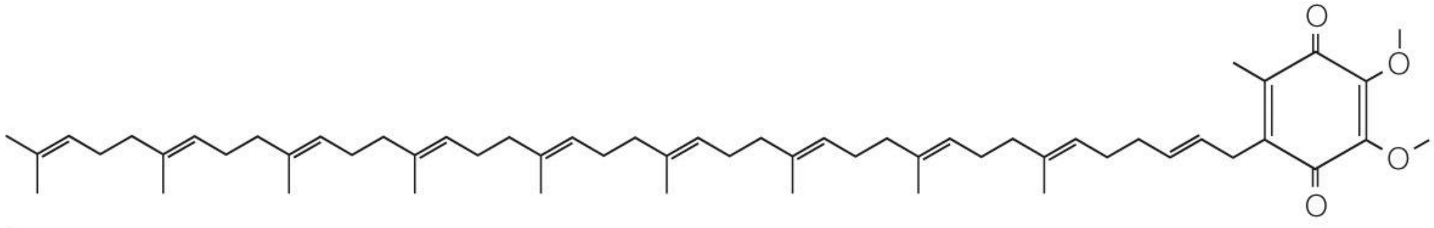
How Do Cofactors Work? (cont'd.)



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How Do Cofactors Work? (cont'd.)

TABLE 5.1

Some Common Coenzymes

Coenzyme	Example of Function
ATP	Transfers energy with a phosphate group
NAD, NAD^+	Carries electrons during glycolysis
NADP, NADPH	Carries electrons, hydrogen atoms during photosynthesis
FAD, FADH, $FADH_2$	Carries electrons during aerobic respiration
CoA	Carries acetyl group ($COCH_3$) during glycolysis
Coenzyme Q_{10}	Carries electrons in electron transfer chains of aerobic respiration
Heme	Accepts and donates electrons
Ascorbic acid	Carries electrons during peroxide breakdown (in lysosomes)
Biotin (vitamin B_7)	Carries CO_2 during fatty acid synthesis

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How Do Cofactors Work? (cont'd.)

- The enzyme catalase has four tightly bound cofactors called hemes
  - Catalase's substrate is hydrogen peroxide, a highly reactive molecule that can be dangerous
  - The heme in catalase breaks hydrogen peroxide into water
  - Catalase is an *antioxidant*: prevents oxidation of other molecules

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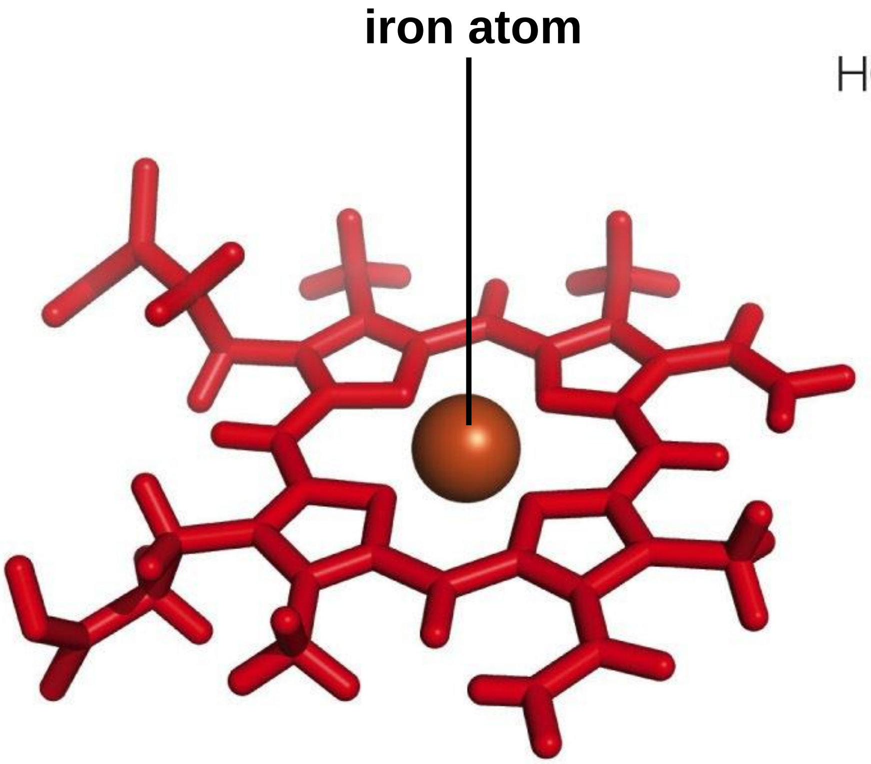
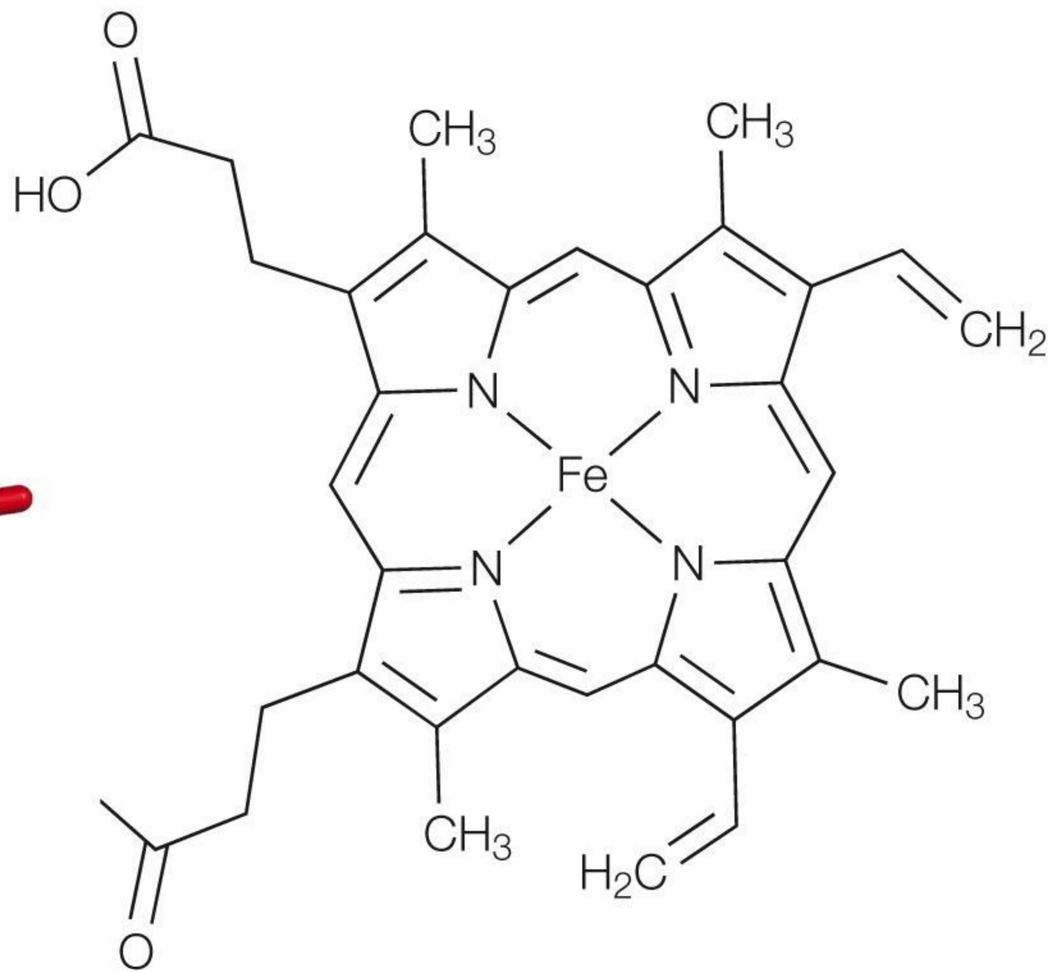
How Do Cofactors Work? (cont'd.)





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ATP — A Special Coenzyme

- ATP (adenosine triphosphate) functions as a cofactor in many reactions
  - Bonds between phosphate groups hold a lot of energy
  - When a phosphate group is transferred via the process of *phosphorylation*, energy is transferred along with it

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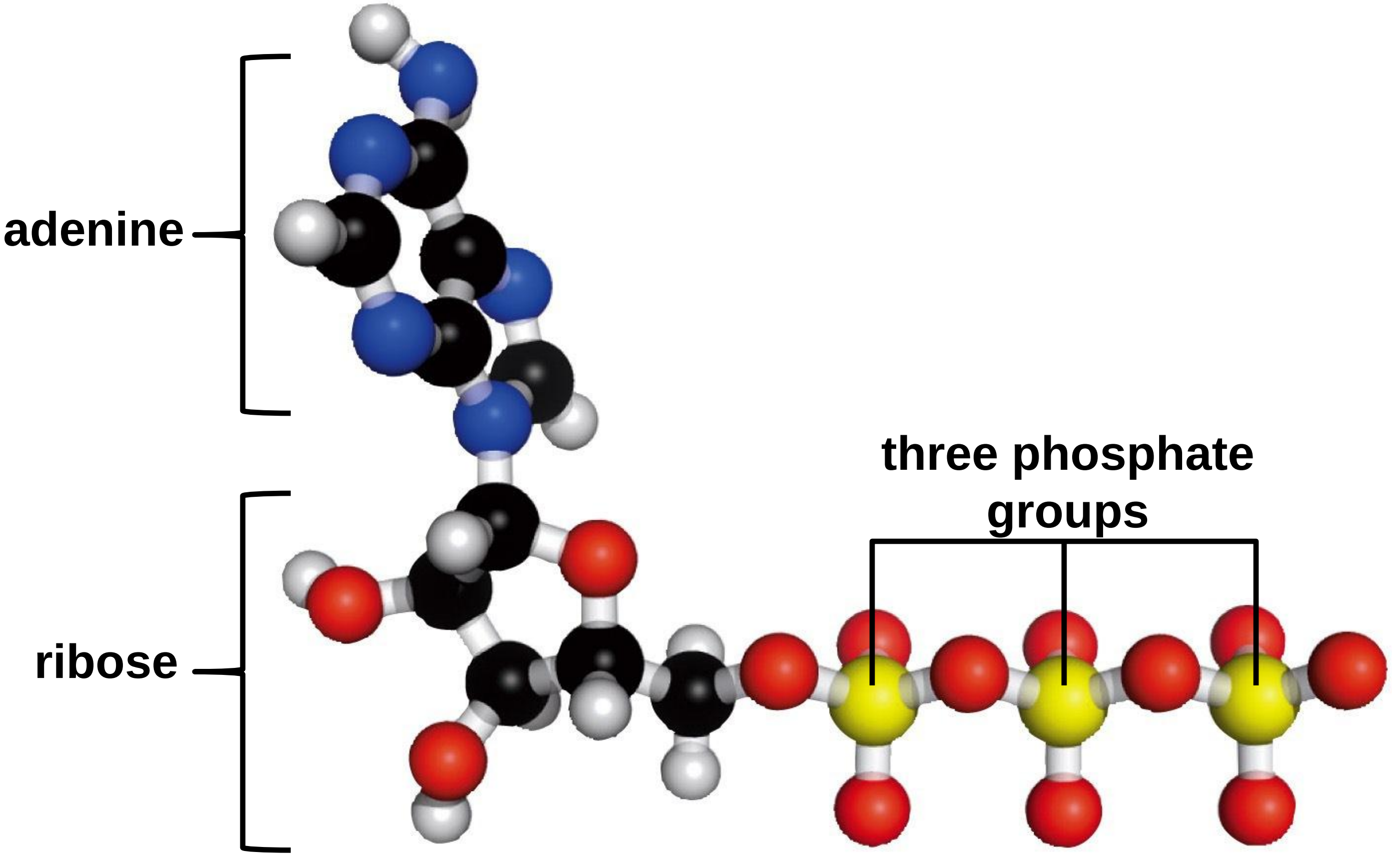
ATP — A Special Coenzyme (cont'd.)



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ATP — A Special Coenzyme (cont’d.)

- ATP/ADP cycle:
  - Process by which cells regenerate ATP
  - ADP (adenosine diphosphate) forms when a phosphate group is removed from ATP, then ATP forms again as ADP gains a phosphate group
- The ATP/ADP cycle couples endergonic reactions with exergonic ones

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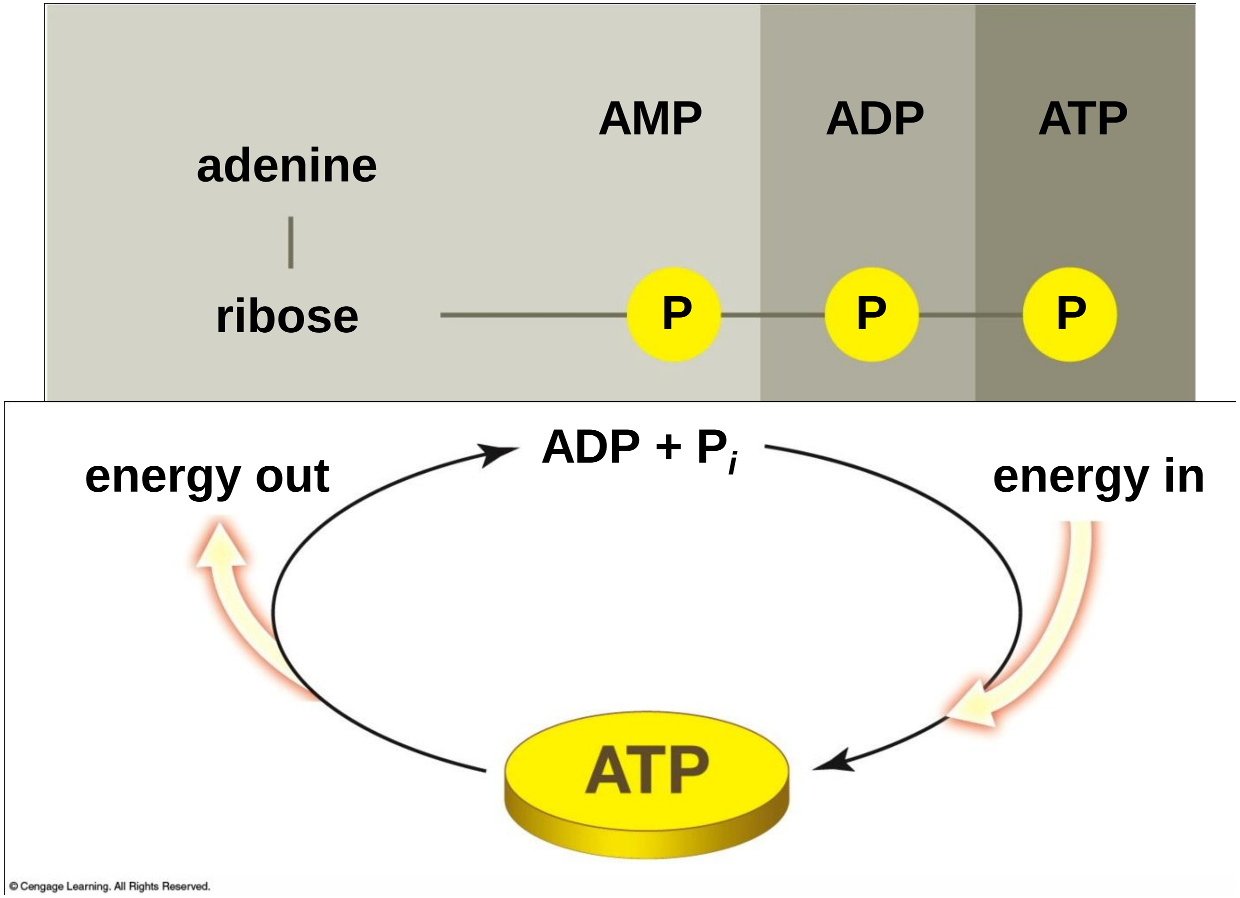
ATP — A Special Coenzyme (cont'd.)



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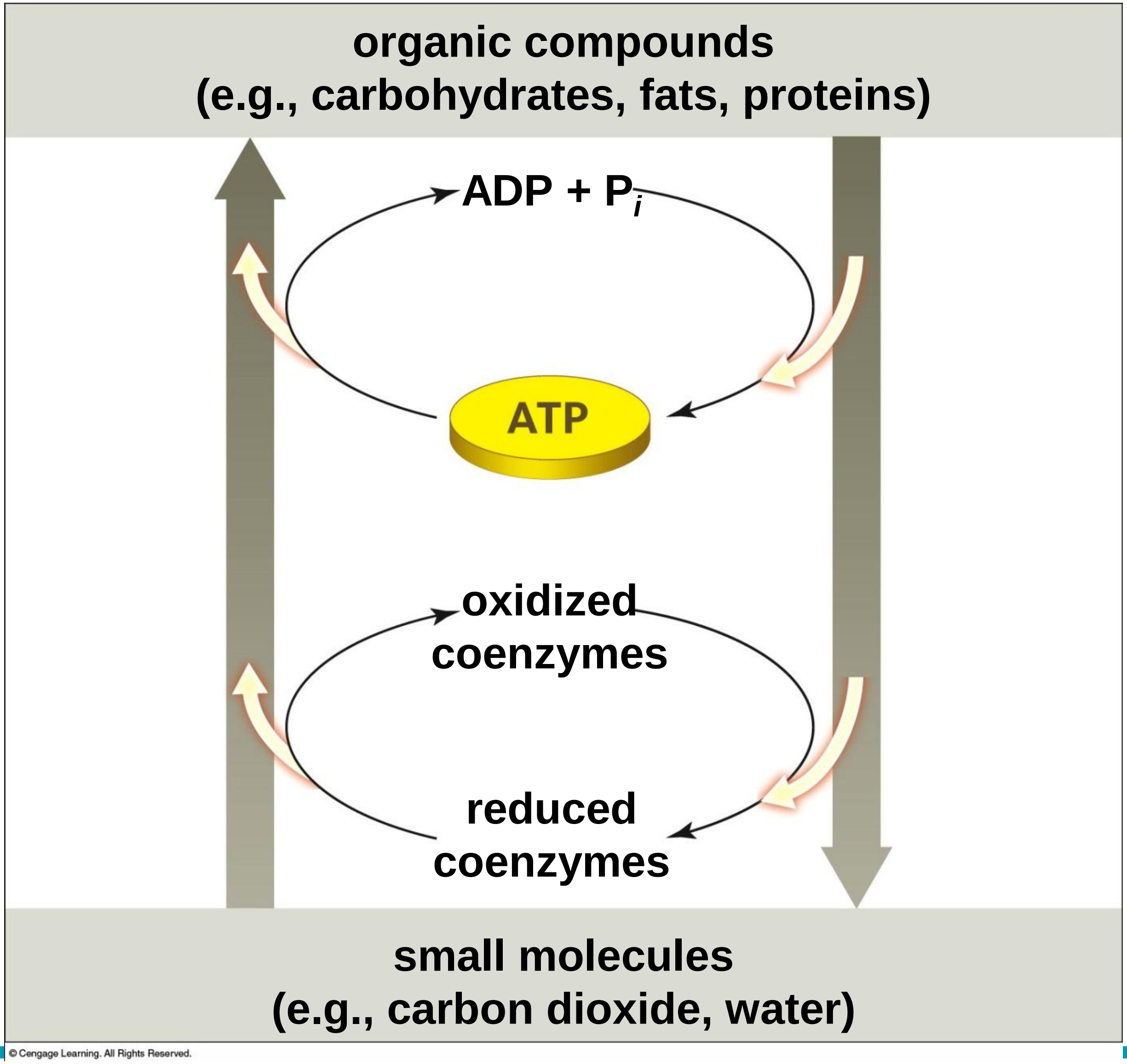
ATP — A Special Coenzyme (cont'd.)



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5.6 What Influences the Movement of Ions and Molecules?

- Diffusion: spontaneous spreading of molecules or ions
  - Essential for substances to move into, through, and out of cells
- What affects the rate of diffusion?
  - Size, temperature, concentration, charge, and pressure

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Semipermeable Membranes

- Lipid bilayers are selectively permeable
  – Water can cross, but ions and most polar molecules cannot

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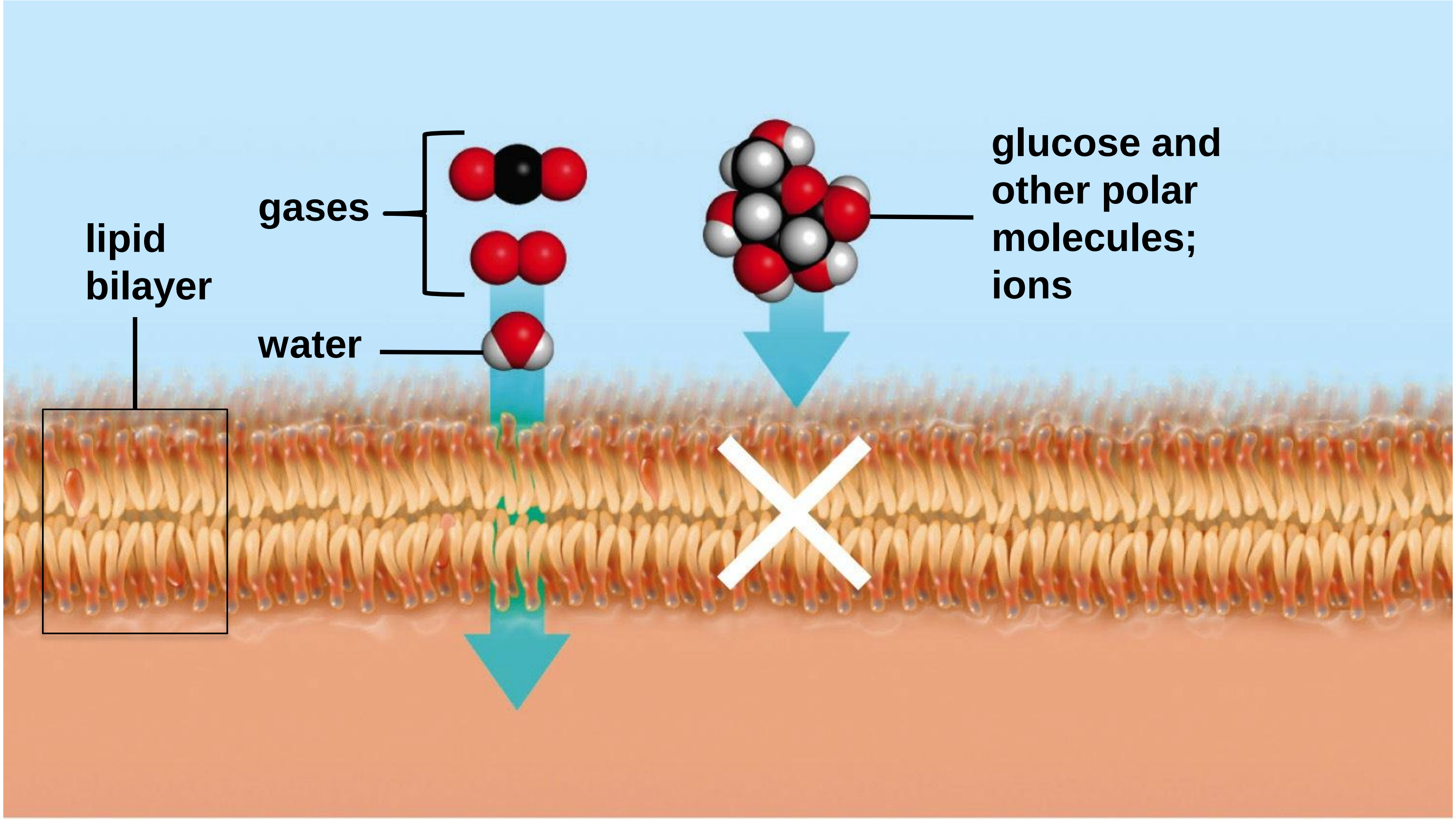
Semipermeable Membranes (cont'd.)



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Semipermeable Membranes (cont'd.)

- Osmosis: diffusion of water across a selectively permeable membrane
  - Occurs in response to a difference in solute concentration (tonicity) between the fluids on either side of the membrane
    - Isotonic: equal solute concentrations; no osmosis
    - Hypotonic: low solute relative to another fluid; water flows out of hypotonic cytoplasm
    - Hypertonic: high solute relative to another fluid; water flows into hypertonic cytoplasm

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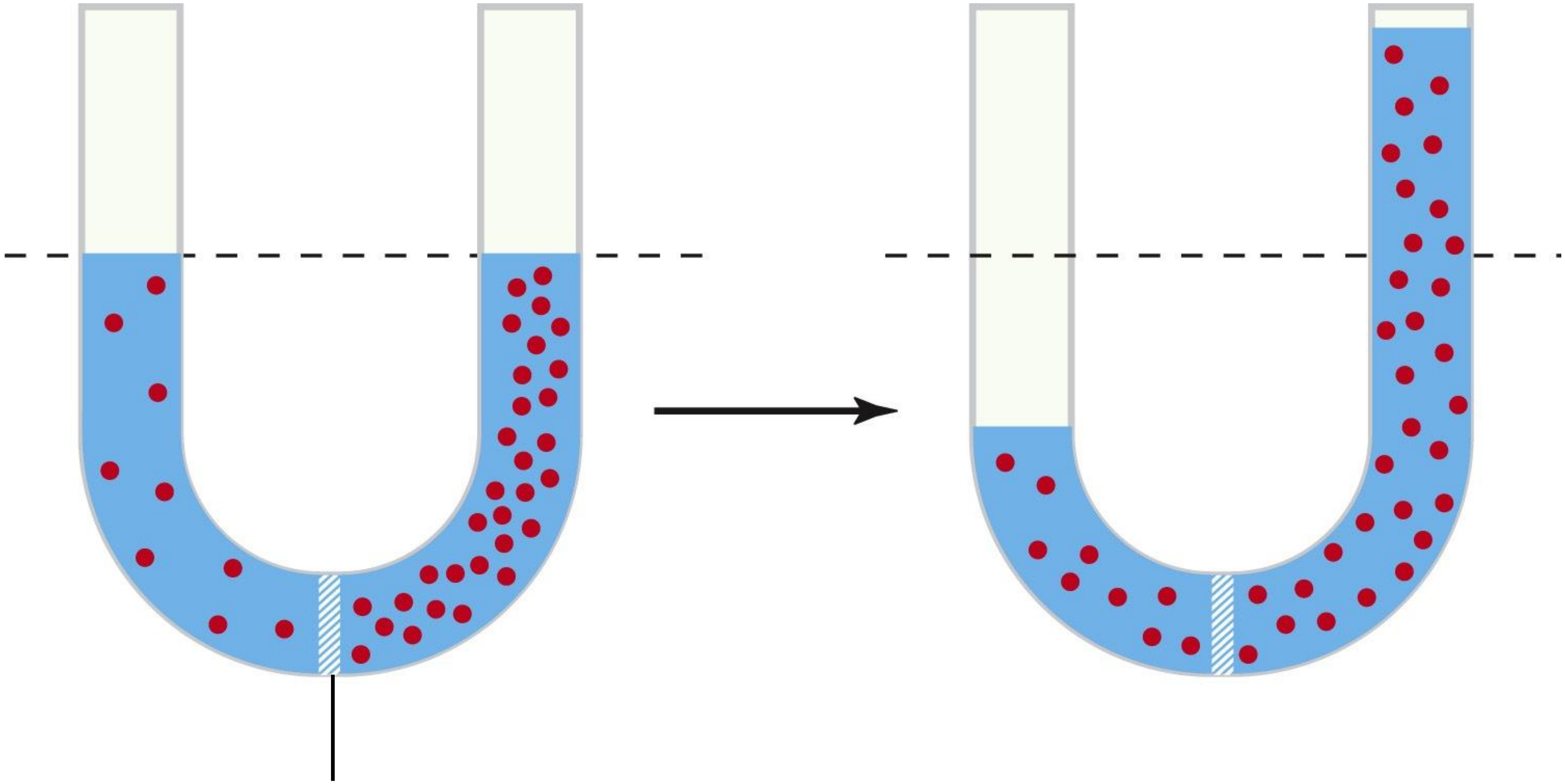
Semipermeable Membranes (cont'd.)



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Turgor

- Stiff cell walls keep plant cells from expanding very much
  - An inflow of water causes pressure to build up
  - Turgor: pressure that a fluid exerts against a structure
  - Osmotic pressure: amount of turgor that prevents osmosis into cytoplasm or other hypertonic fluid

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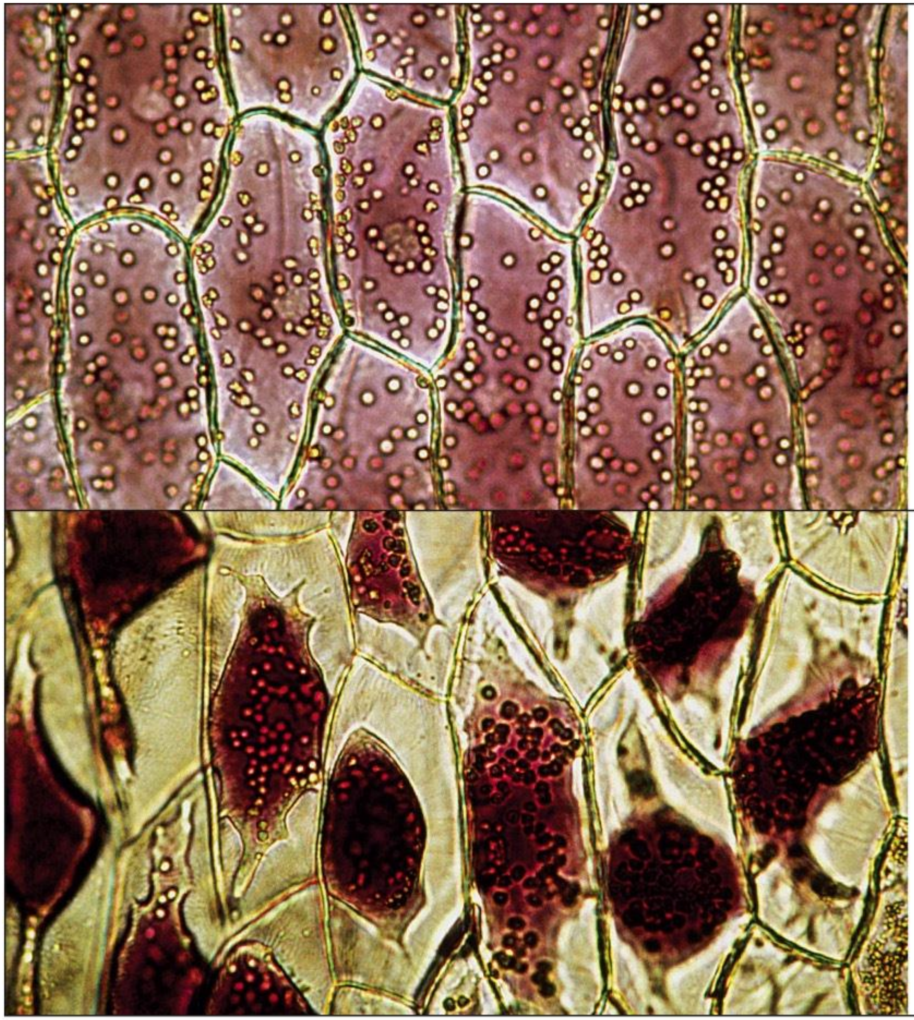
Turgor (cont’d.)



A Osmotic pressure keeps plant parts erect. These cells in an iris petal are plump with cytoplasm.

B Cells from a wilted iris petal. The cytoplasm shrank, and the plasma membrane moved away from the wall.

(25A,B) Claude Nuridsany & Marie Perennou/Science Source; (25 inset) © Evgenyi/Shutterstock.com.

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5.7 How Do Ions and Charged Molecules Cross Cell Membranes?

- Transport proteins allow only specific substance to cross the membrane
- Passive transport: solutes move through membrane; requires no energy
  - Example: facilitated diffusion - solute binds to transport protein and moves across membrane with its concentration gradient

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ANIMATION: Passive transport

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How Do Ions and Charged Molecules Cross Cell Membranes? (cont'd.)

- Active transport: transport protein pumps a solute against its concentration gradient; requires energy
  - Examples:
    - Calcium pumps
    - Sodium–potassium pumps

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ANIMATION: Active transport

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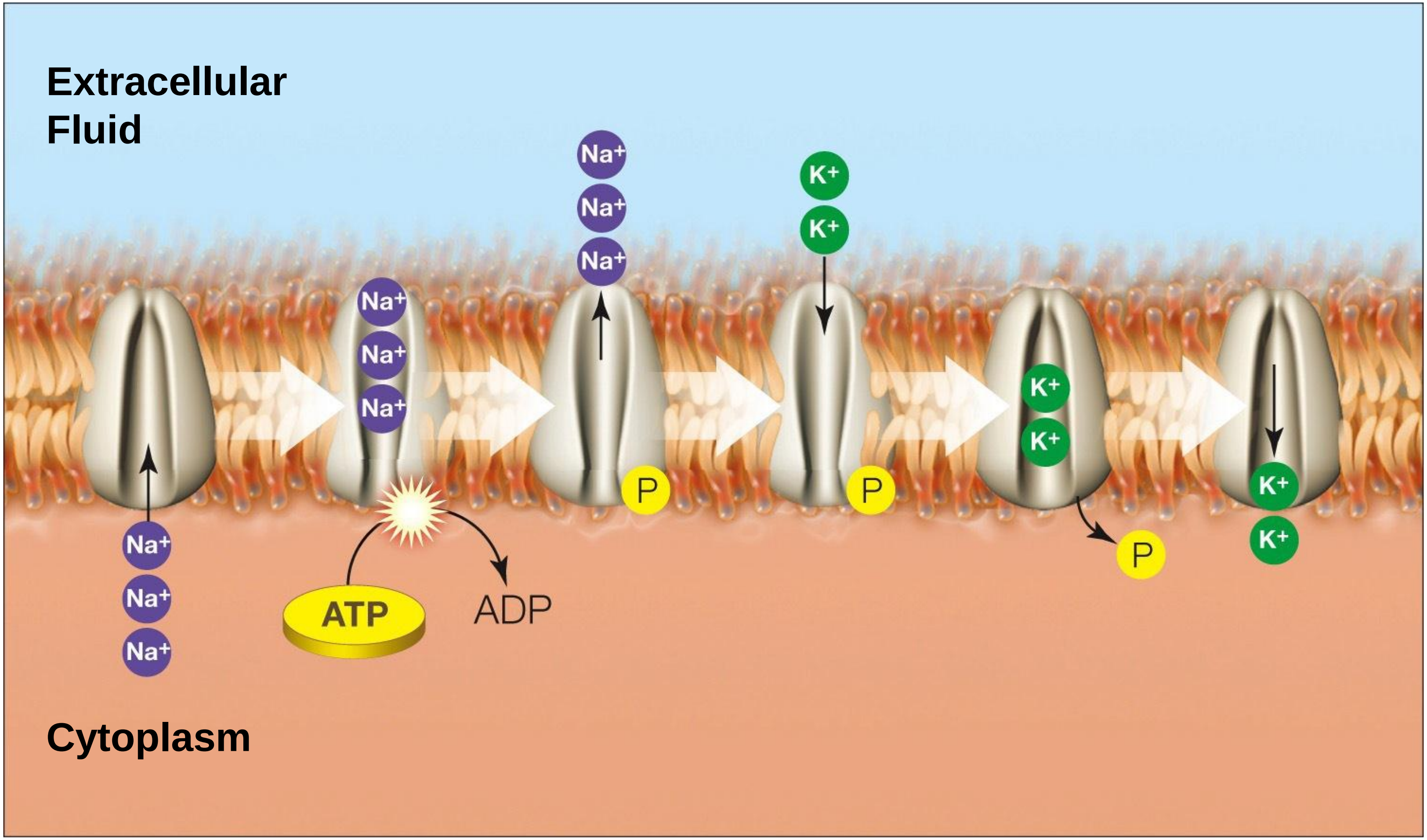
How Do Ions and Charged Molecules Cross Cell Membranes? (cont'd.)



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5.8 How Do Large Particles/Bulk Substances Move Across Membranes?

- Vesicle movement
  - Exocytosis: cell expels a vesicle's contents to extracellular fluid
  - Endocytosis: cell takes in a small amount of extracellular fluid (and its contents) by the ballooning inward of the plasma membrane
  - Phagocytosis: "Cell eating"; an endocytic pathway by which a cell engulfs particles such as microbes or cellular debris

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ANIMATION: Membrane cycling

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ANIMATION: Phagocytosis

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Membrane Trafficking

- Membrane proteins and lipids are made in the ER and move to the Golgi bodies for final modification
  - "Finalized" vesicles containing proteins and lipids move to and fuse with the plasma membrane
- Exocytosis and endocytosis continually replace and withdraw membrane patches

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