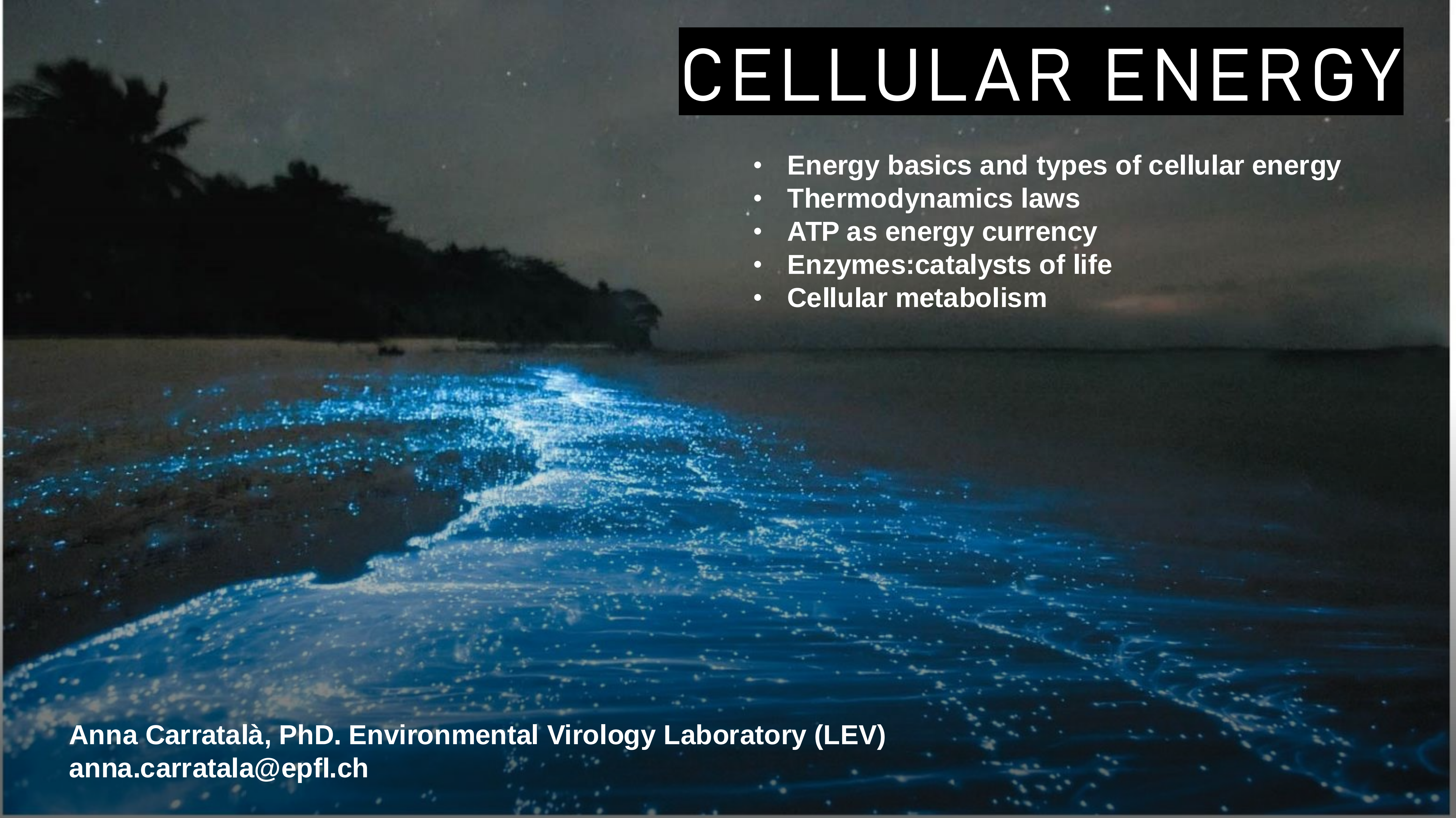

CELLULAR ENERGY

- **Energy basics and types of cellular energy**
- **Thermodynamics laws**
- **ATP as energy currency**
- **Enzymes:catalysts of life**
- **Cellular metabolism**

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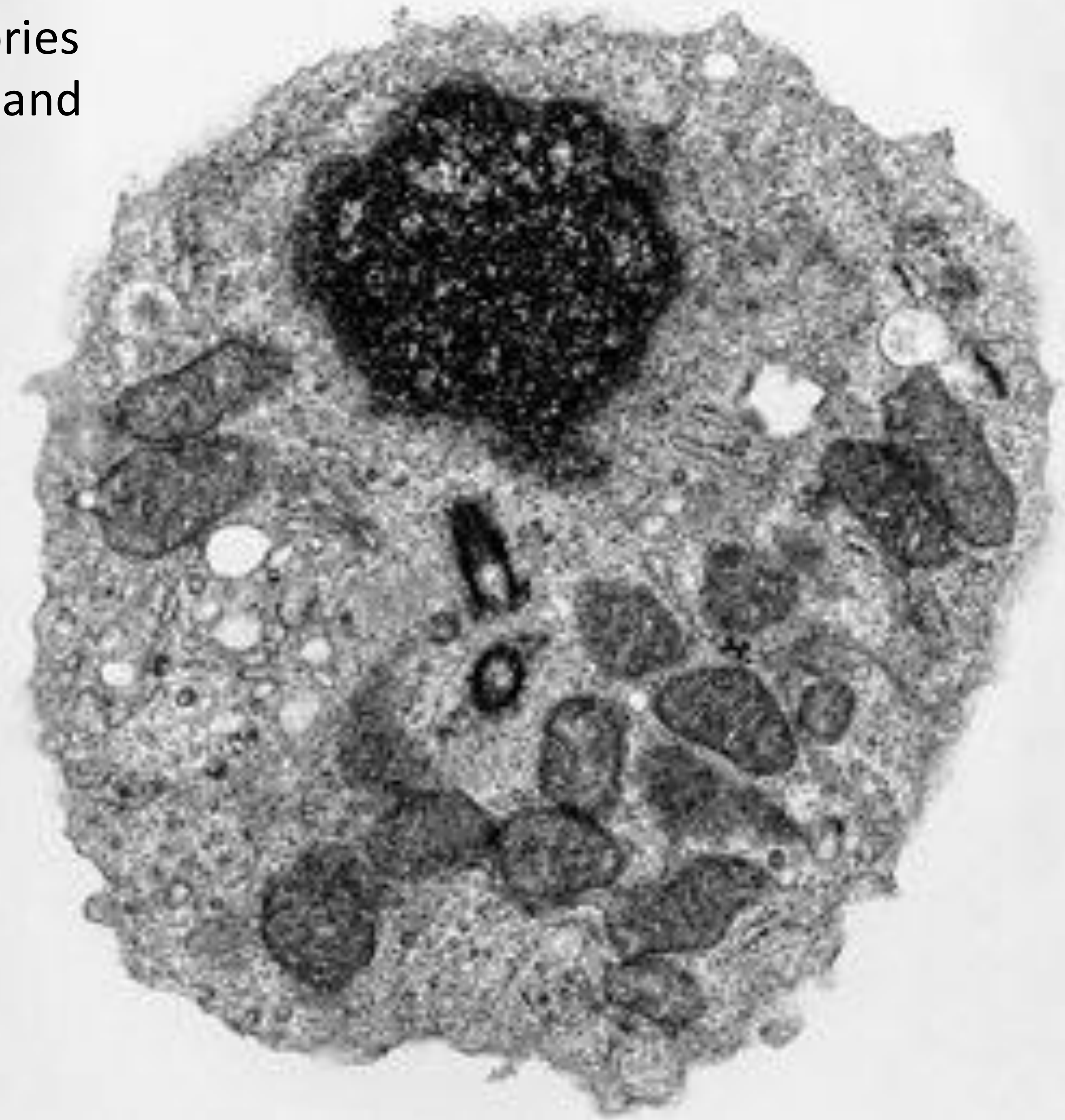
Why Should Environmental Engineering Students Care About … Cellular Energy?

- **Because you have to, there is an exam ☺ and to be wiser**
- **Foundation of Life Processes:** Cellular energy (mainly ATP) powers essential life functions, including nutrient processing, growth, and reproduction in all organisms.
- **Environmental Systems:** Microorganisms use cellular energy to break down pollutants in **bioremediation** and convert waste into renewable energy in **biogas production** (e.g., anaerobic digestion).
- **Ecosystem Sustainability:** Cellular energy underpins the **carbon and nitrogen cycles**, critical for maintaining ecosystem balance and addressing climate change.
- **Practical Engineering Applications:** Understanding cellular energy helps optimize processes in **wastewater treatment**, **biofuel production**, and **sustainable environmental solutions**.

What is energy?

Power derived from the utilization of physical or chemical resources, especially to provide light and heat or to work machines (Source: Oxford Dictionary).

Imagine cells as factories which rely on matter and energy…



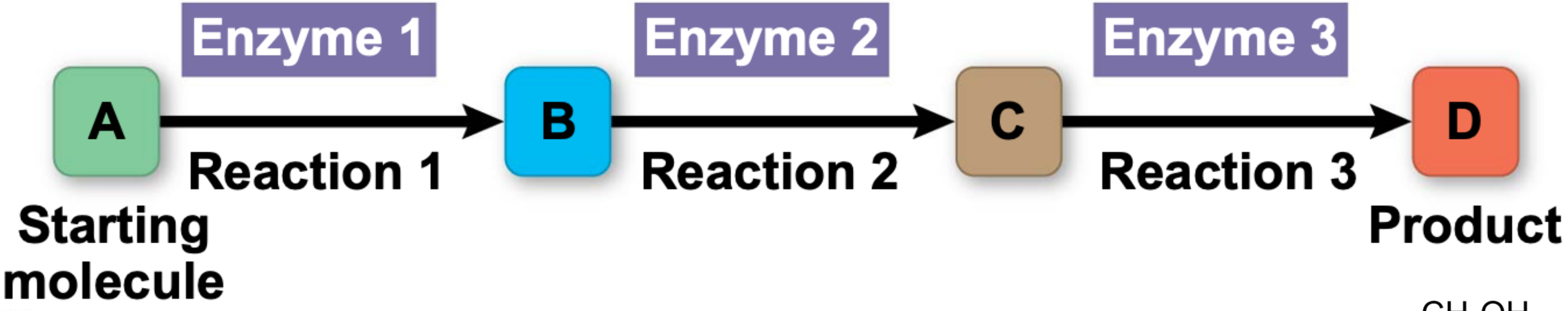
The energy of life: cellular energy

- Cells extract energy stored in sugars and other biomolecules which act as fuel to perform **work (aka: cell respiration).**

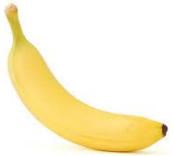
- **Examples**: some organisms even convert energy to light, as in bioluminescence, or use mechanical energy to perform muscular contractions

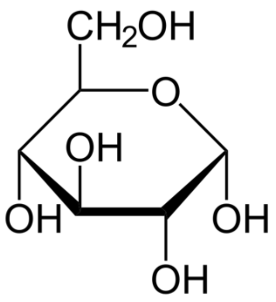
Metabolism and metabolic pathways of the cell

- **Metabolism** is the totality of an organism's chemical reactions
- **Metabolic pathways** begin with a specific molecule and ends with a product
- Each step of a metabolic pathway is catalyzed by a specific enzyme



Eg:





- **Bioenergetics** is the science which studies how energy flows through living organisms

Metabolism: Catabolism vs. Anabolism

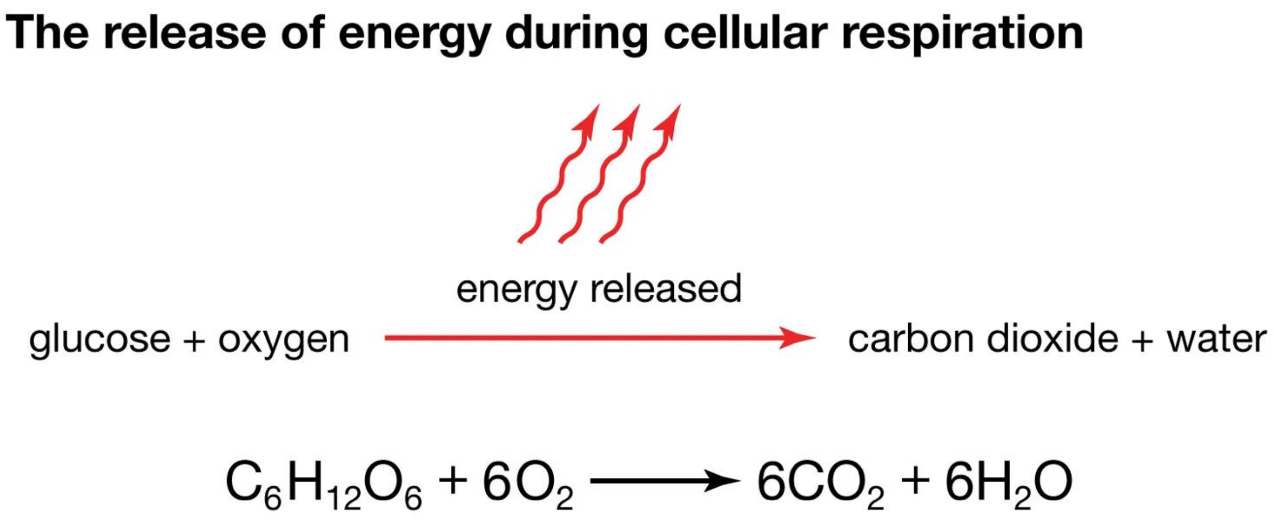
Catabolism

Anabolism

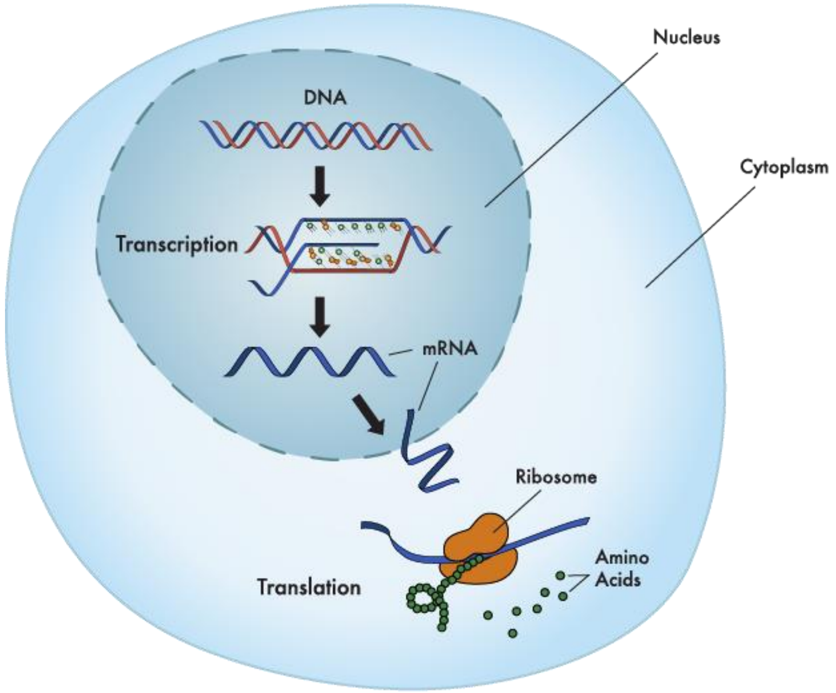
Catabolism vs. Anabolism

- **Catabolic pathways** release energy by breaking down complex molecules into simpler compounds. Eg. Cellular respiration (breakdown of glucose molecules in the presence of oxygen)
- **Anabolic pathways** consume energy to build complex molecules from simpler ones. Eg: synthesis of protein from amino acids is an anabolic pathway.

Catabolism



Anabolism



Forms of energy

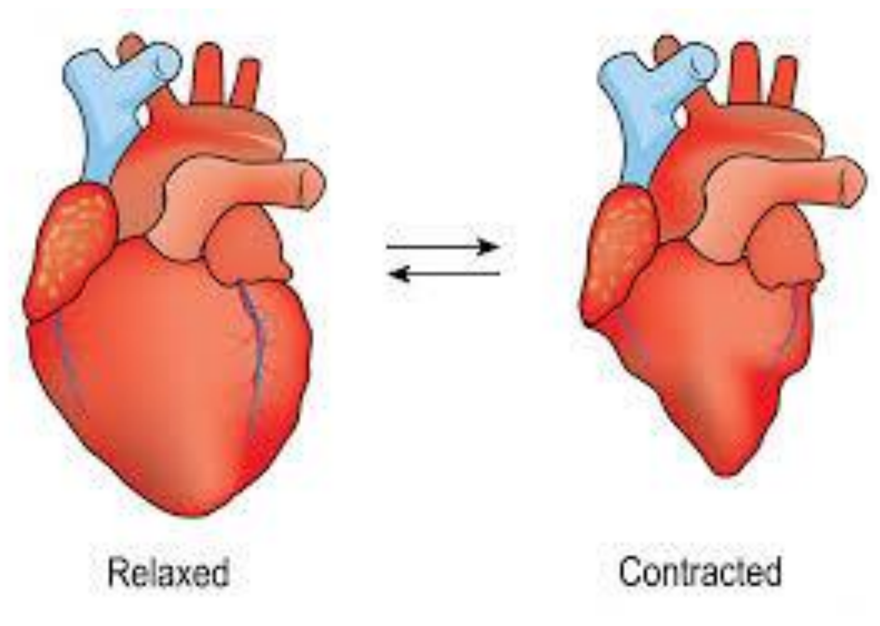
Energy enables the capacity of producing change and it exists in different forms, some of which can produce work

- **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

Some examples…

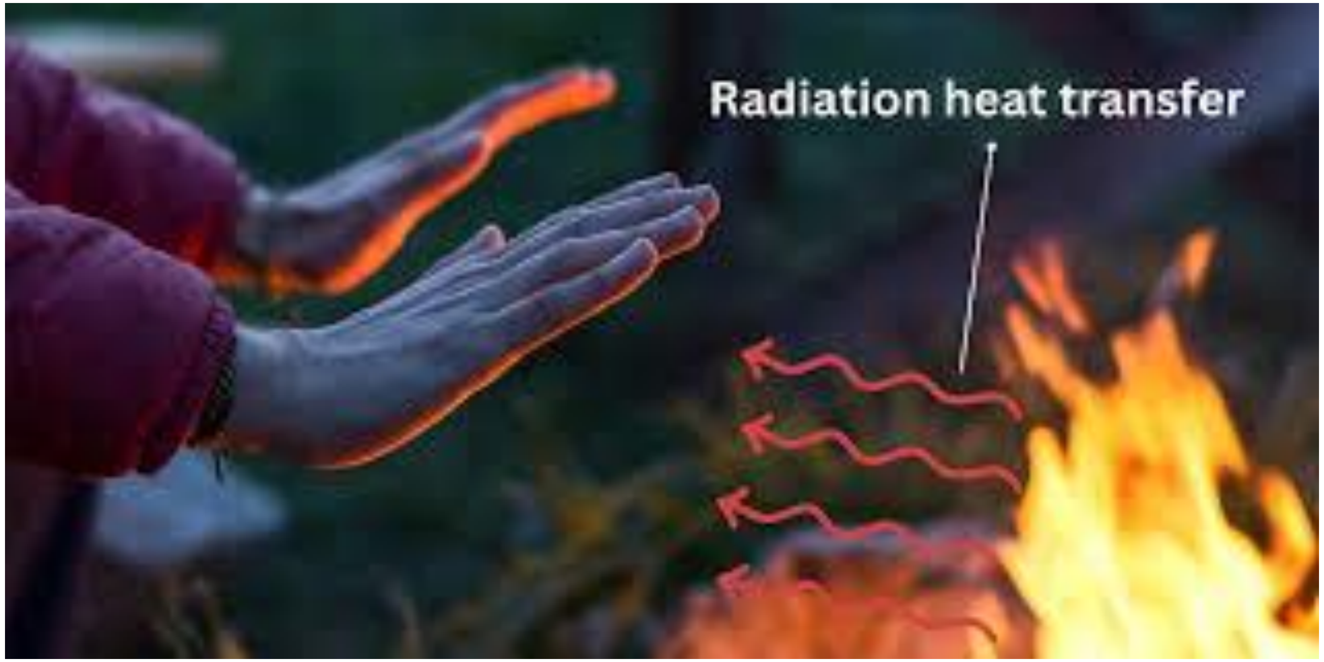
Kinetic energy is energy associated with motion

- Moving objects perform work by imparting motion to other matter. Eg:
    - For example, water gushing through a dam turns turbines
    - Muscular contractions



Forms of energy: more examples

- **Thermal energy** is the kinetic energy associated with random movement of atoms or molecules
- Thermal energy in transfer from one object to another is called **heat**
- **Light** is another type of energy that can be harnessed to do work, such as photosynthesis



- **Chemical energy** is potential energy available for release in a chemical reaction
- Complex molecules, such as glucose, are high in chemical energy because energy is released as they are broken down to simpler products

- **Potential energy** is energy that matter possesses because of its location or structure
  - For example, water behind a dam possesses energy because of its altitude above sea level
  - Molecules possess energy due to the arrangement of electrons in bonds between their atoms

Who has more potential energy?

Who has more potential energy?

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.

Thermodynamics

- **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

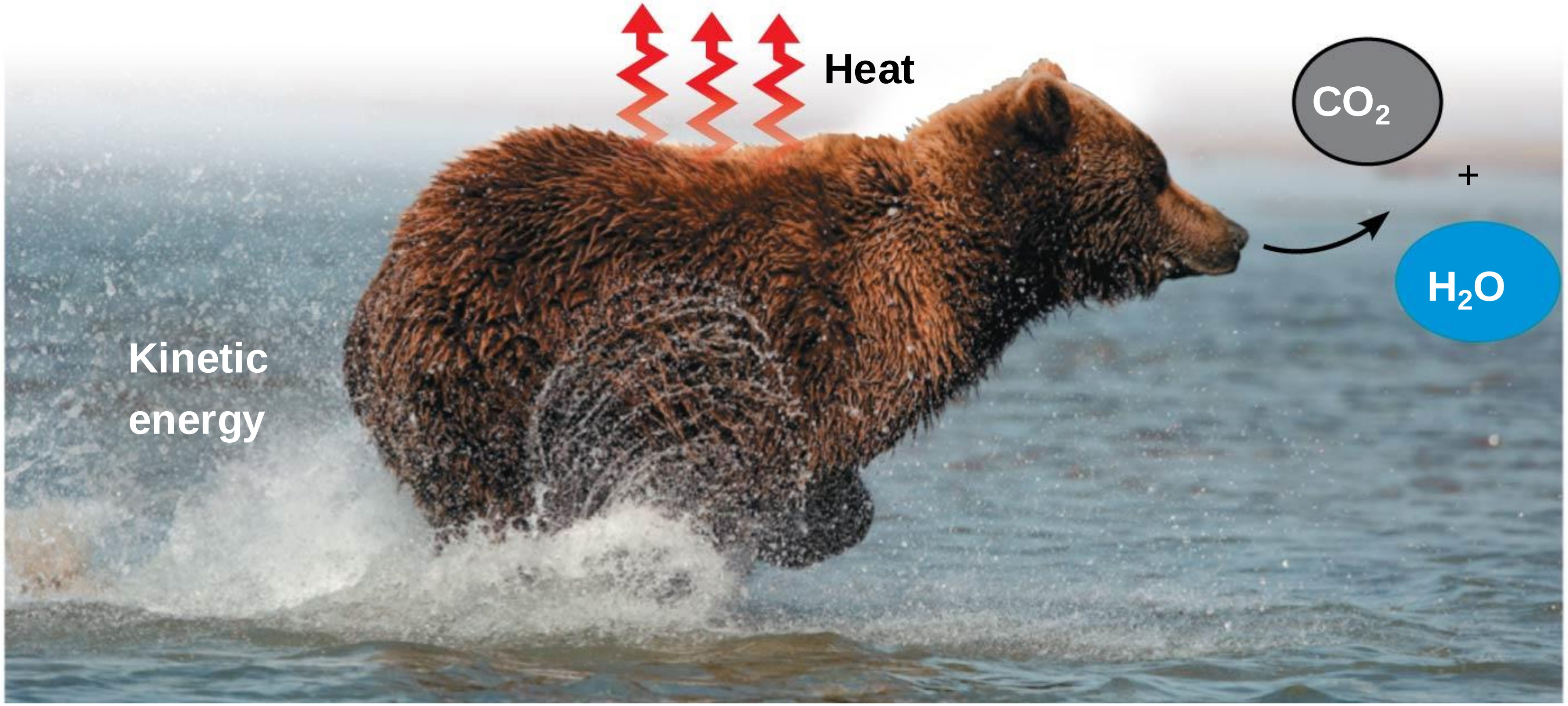
Vs.

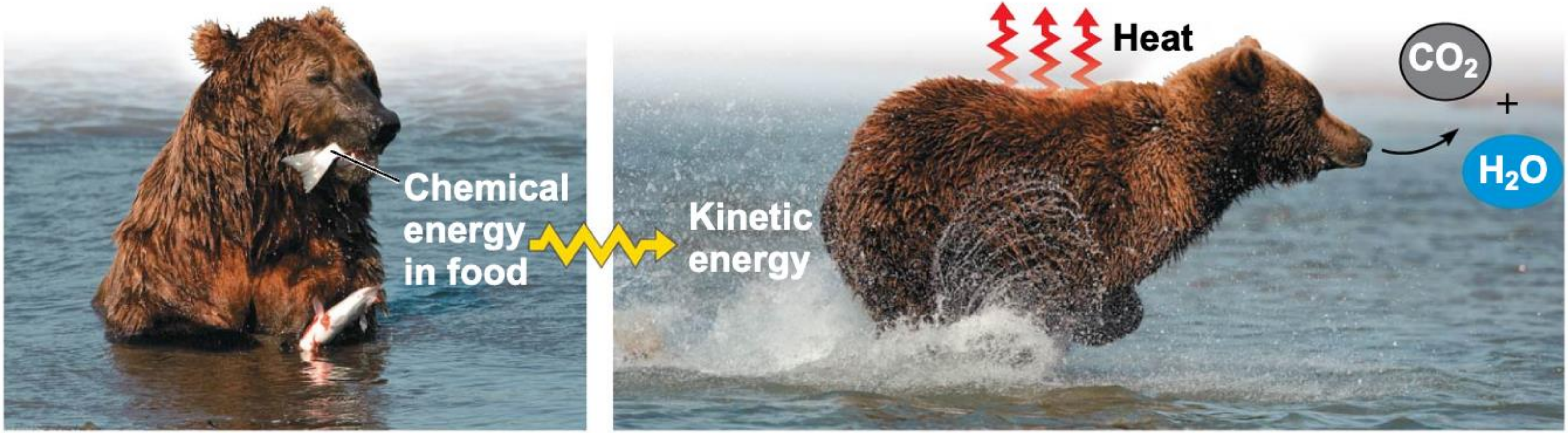
The first law of thermodynamics

- 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

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

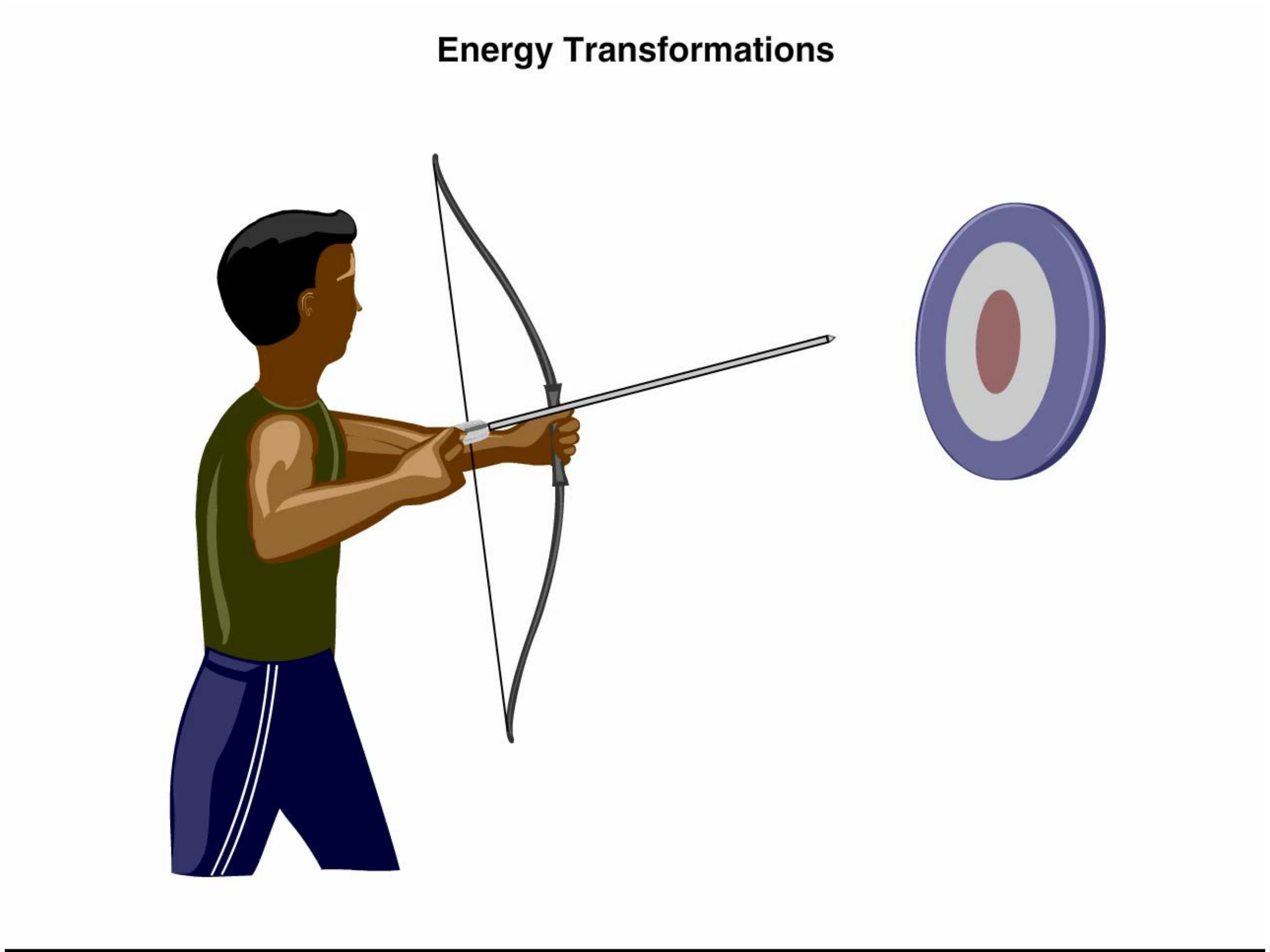




(a) First law of thermodynamics **(b) Second law of thermodynamics**

Living cells unavoidably convert organized forms of energy to **heat**, a more disordered form of energy

ANIMATION: ENERGY TRANSFORMATIONS



Thermodynamic spontaneity

- **Spontaneous processes** occur without energy input; they can happen quickly or slowly (eg. catabolic metabolism)
  - For a process to occur spontaneously, it must increase the entropy of the universe

- Processes that decrease entropy (eg. anabolic metabolism) are **nonspontaneous**; they will occur only if energy is provided

Some examples…

Nonspontaneous

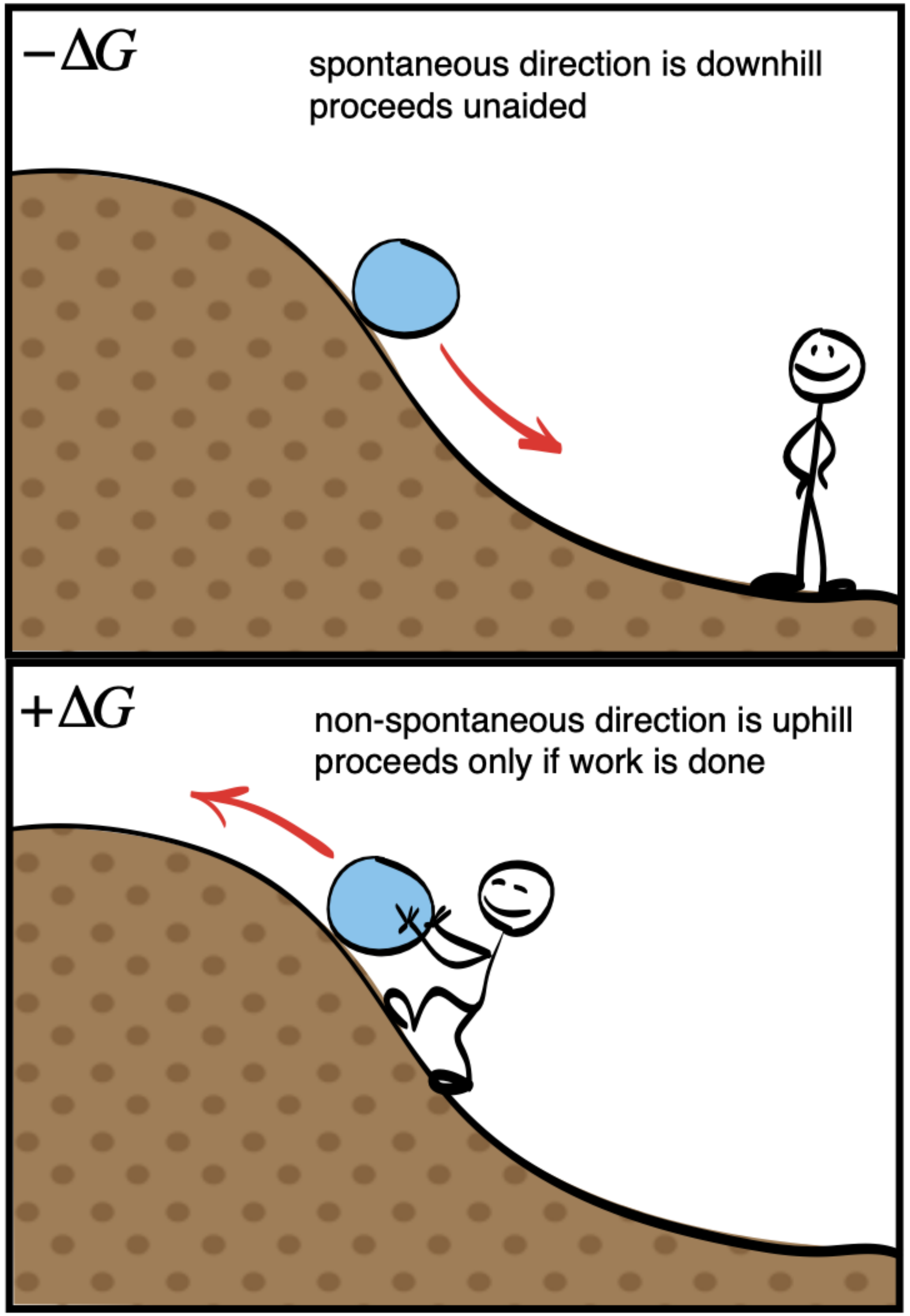
Spontaneous

Free energy change, ΔG

- Free energy change is the amount of energy available to do work during a chemical reaction. It tells us whether a reaction can happen spontaneously (on its own) or if it needs an input of energy.

- 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
- If ΔG is zero ($\Delta G = 0$), the reaction is at equilibrium, meaning there's no net change—the forward and reverse reactions happen at the same rate.

Free energy, stability and equilibrium: summary

- 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

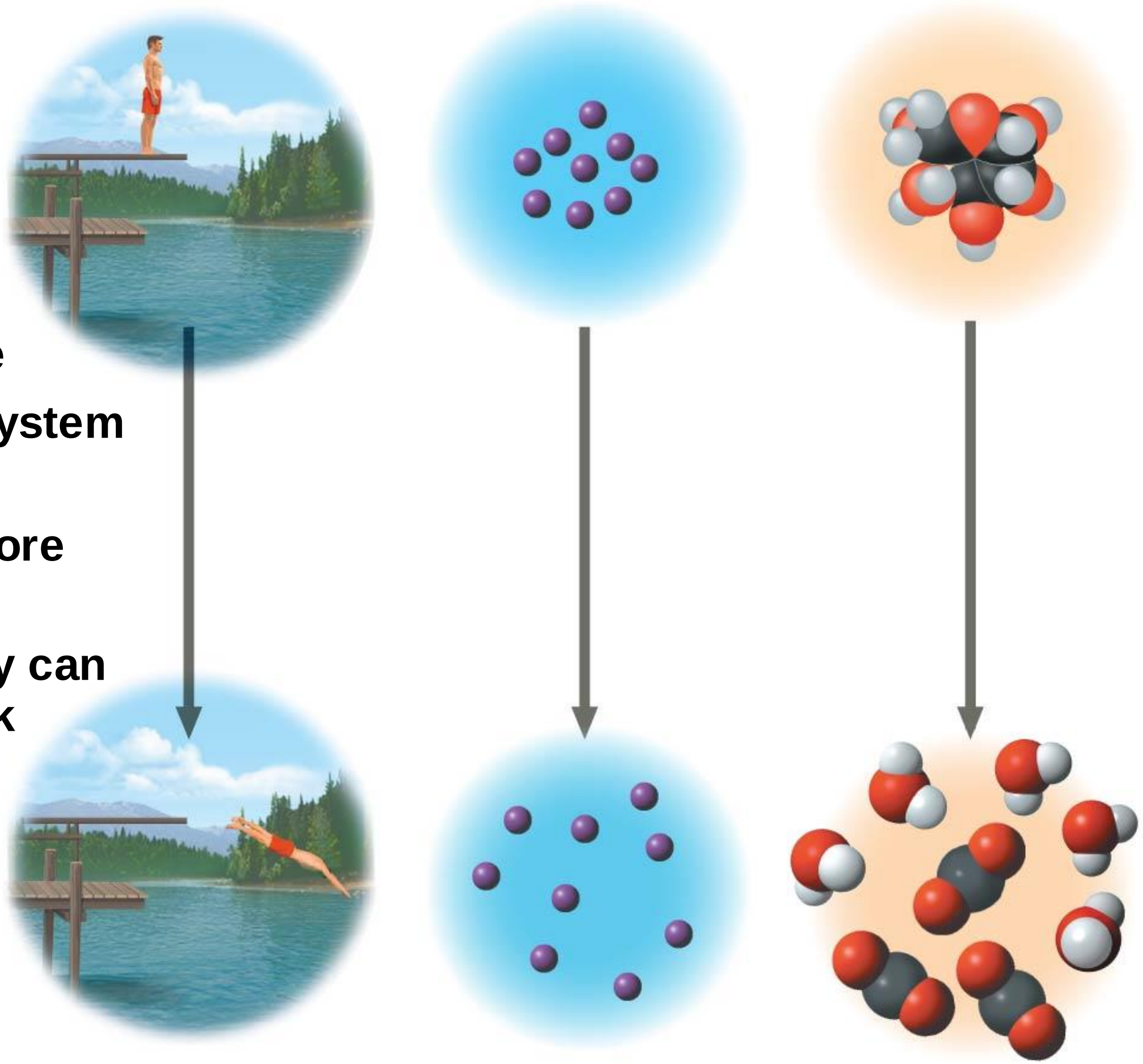
- A process is spontaneous and can perform work only when it is moving toward equilibrium

- 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

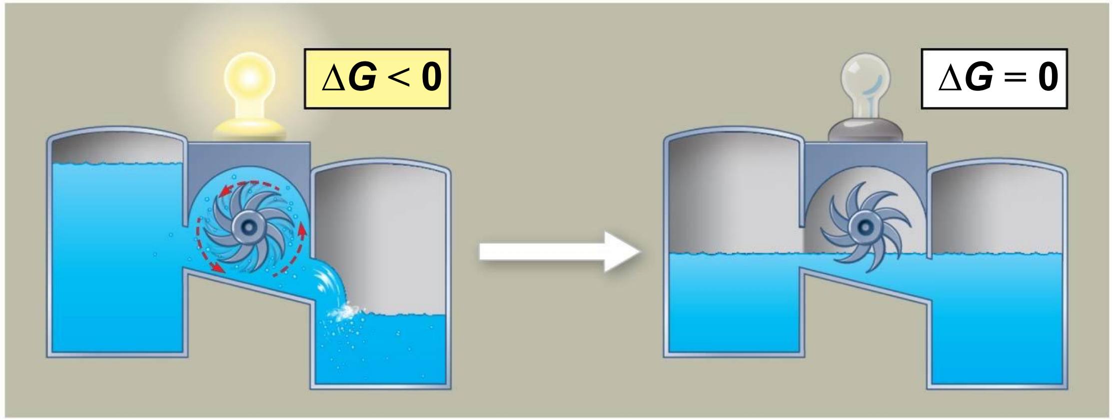
- Less free energy (lower G)
- More stable
- Less work capacity



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

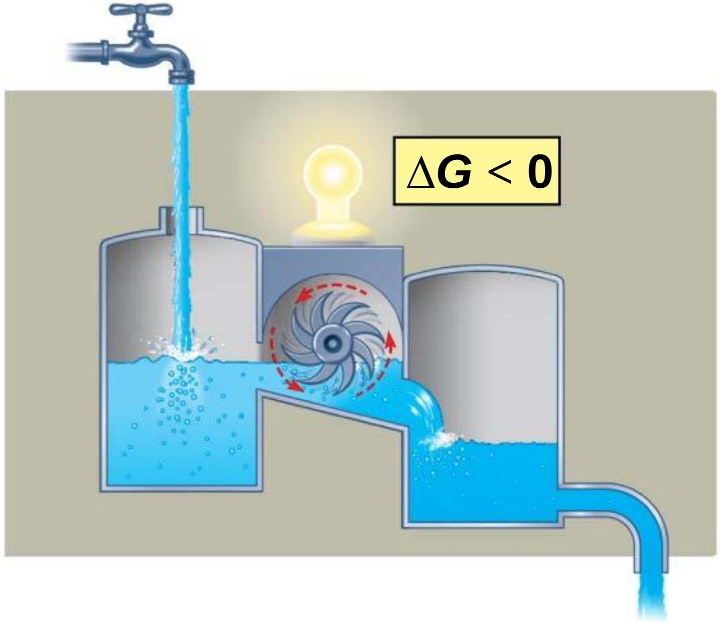
Equilibrium and metabolism

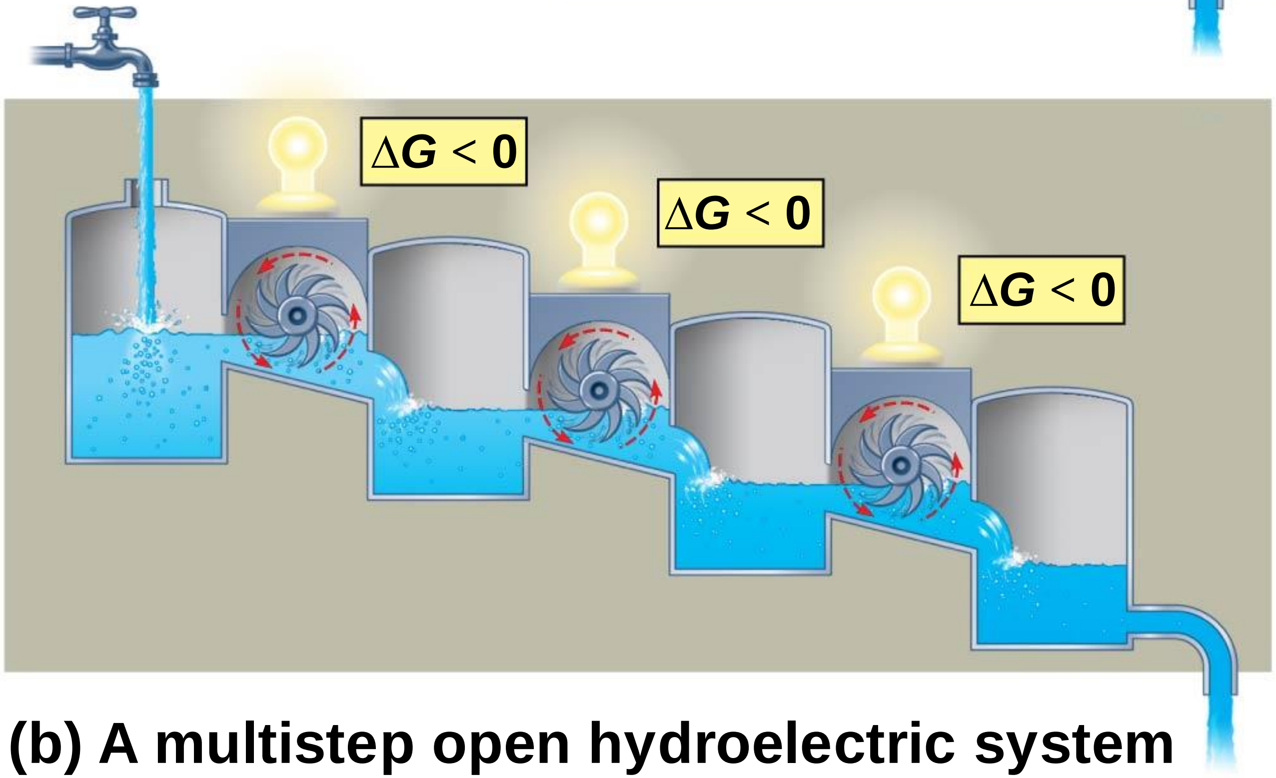
- Reactions in a closed system eventually reach equilibrium and can then do no work



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

(a) An open hydroelectric system



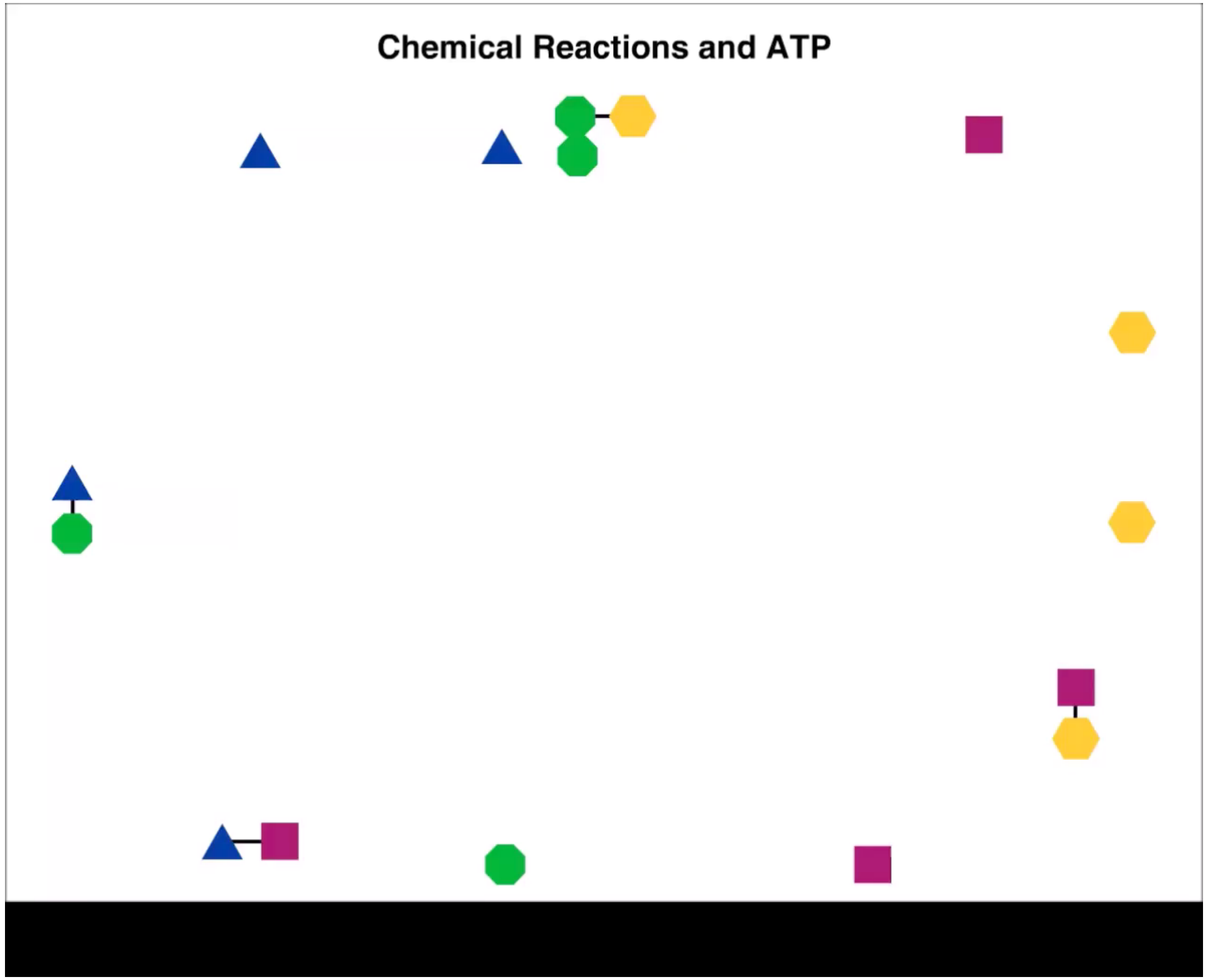


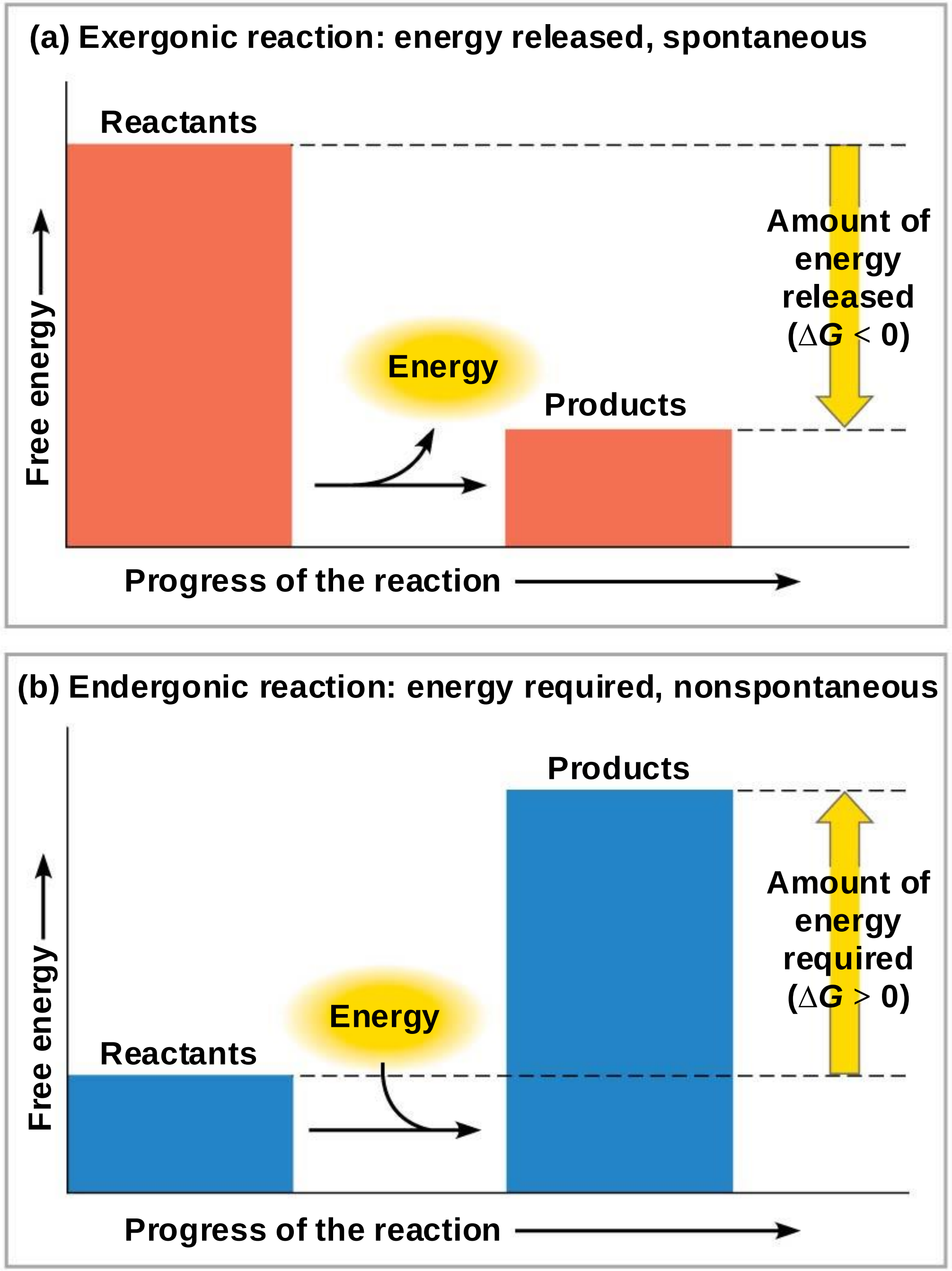
(b) A multistep open hydroelectric system

Free energy and 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

ANIMATION: EXERGONIC AND ENDERGONIC REACTIONS

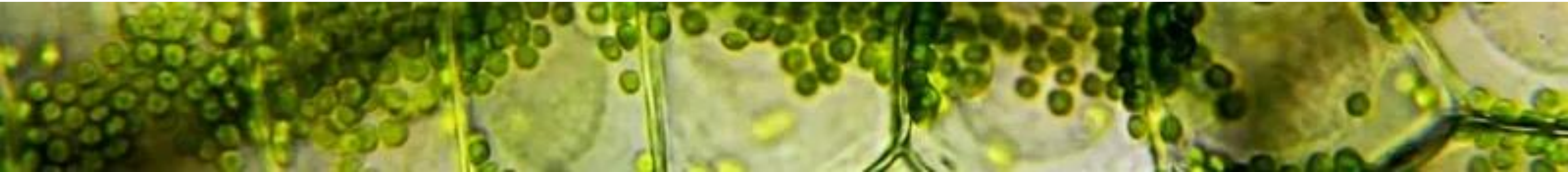




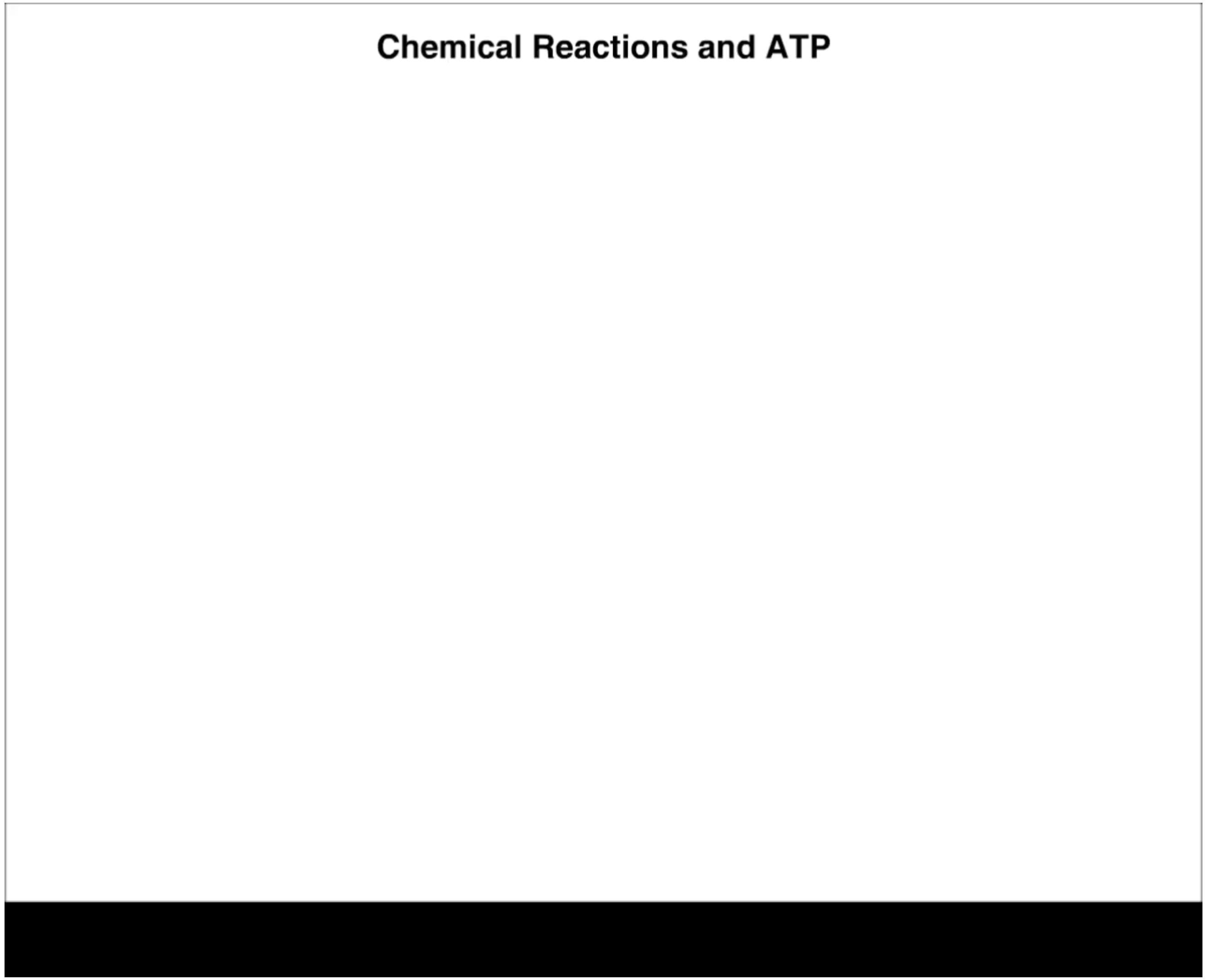
How can cells perform endergonic reactions?

- The magnitude of ΔG determines the maximum amount of work an exergonic reaction can perform
  - For example, for each mole of glucose broken down during cellular respiration, 686 kcal of energy is available for work
  - The chemical products of respiration store 686 kcal less free energy per mole than the reactants

- The magnitude of Δ*G* determines the quantity of energy required to drive an endergonic reaction
  - For example, to produce glucose and O_2 from CO_2 and H_2O requires an input of 686 kcal/mol
  - The products of photosynthesis store 686 kcal more free energy per mole than the reactants
  - This reaction is powered by converting light energy to chemical energy



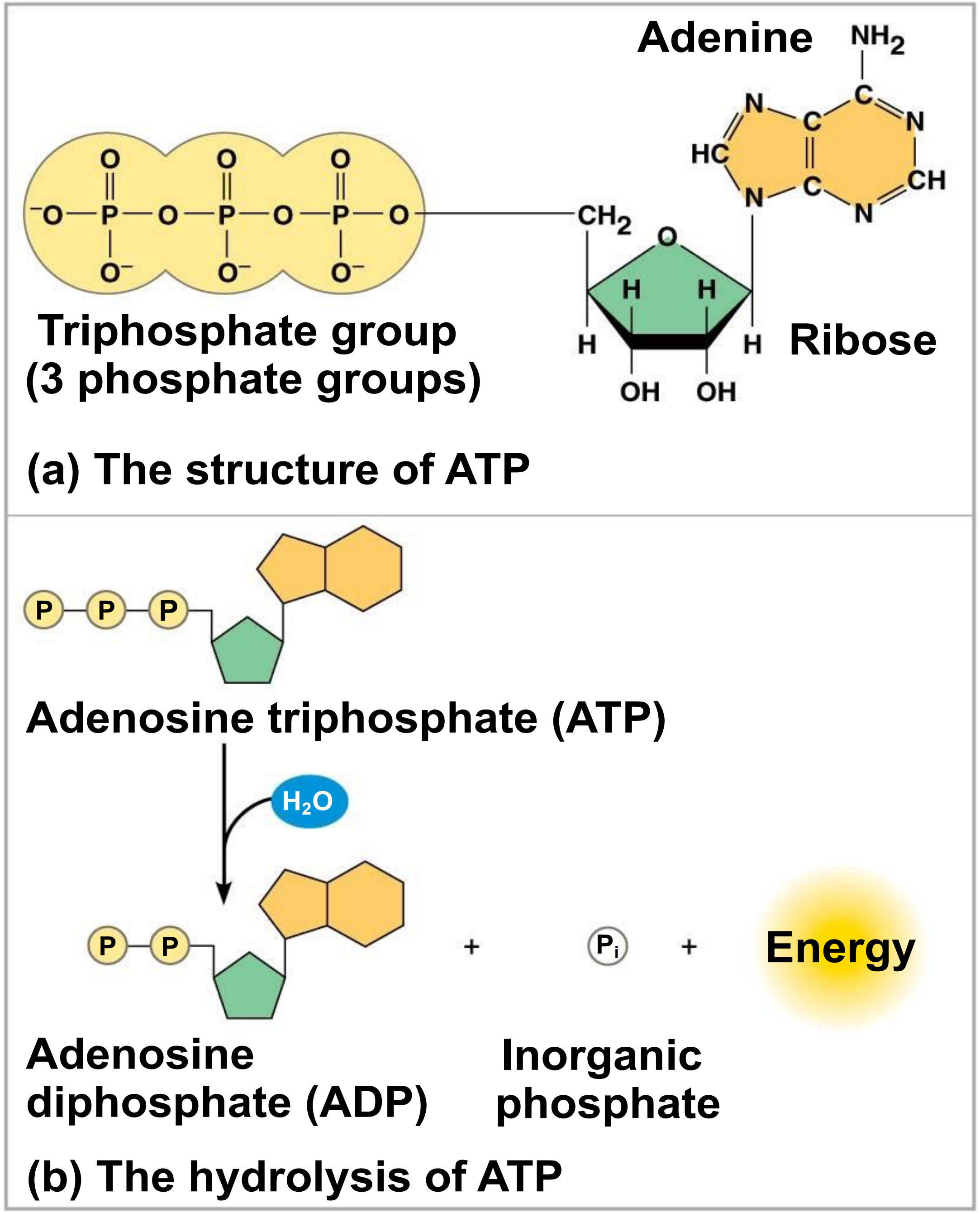
ANIMATION: ENERGY COUPLING



ATP powers cellular work by coupling exergonic reactions to endergonic reactions

Structure and hydrolysis of ATP

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



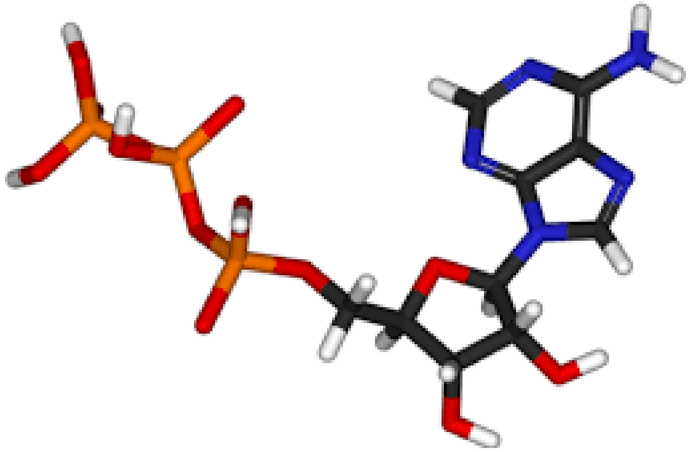
ANIMATION: THE STRUCTURE OF ATP

ATP powers cellular work by coupling exergonic reactions to endergonic reactions: energy coupling

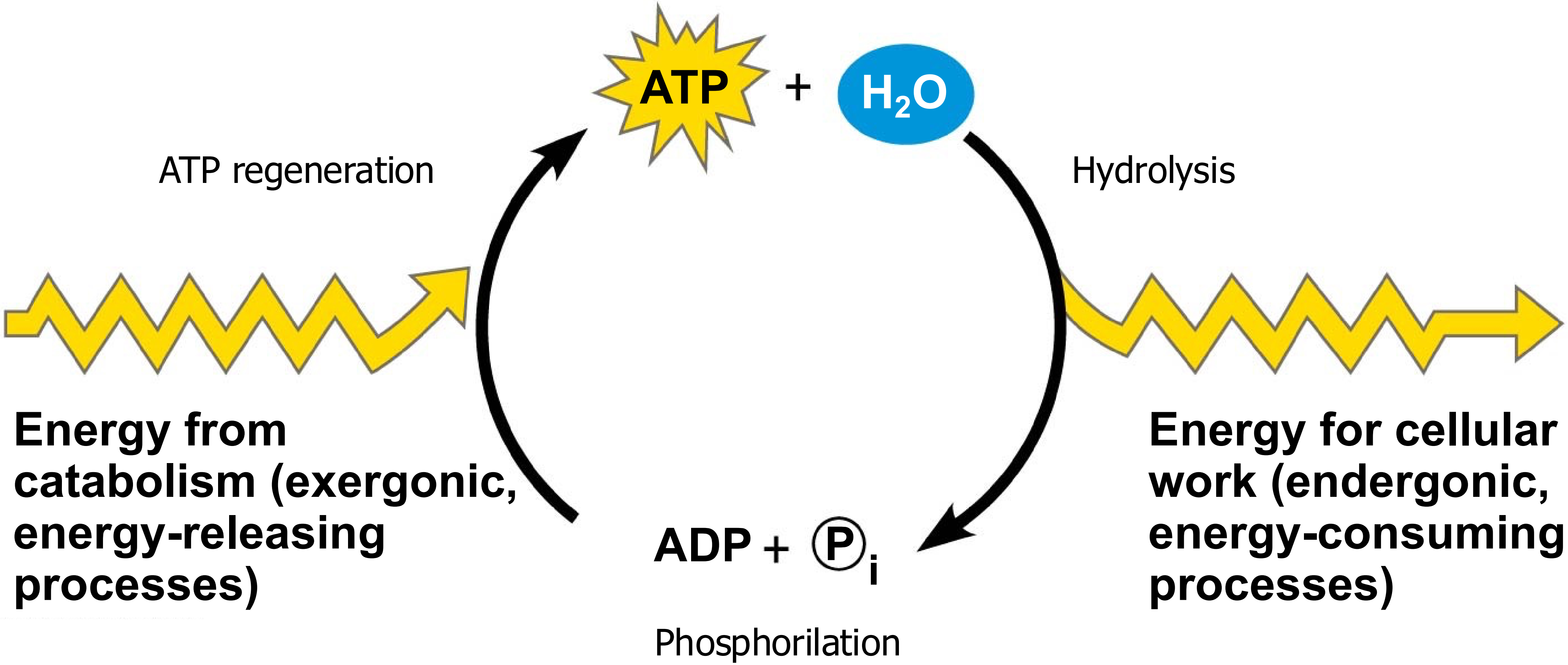
- A cell does three main kinds of work:
  - Chemical work—pushing endergonic reactions
  - Transport work—pumping substances against the direction of spontaneous movement
  - Mechanical work—such as contraction of muscle cells or flagella

ATP powers cellular work by coupling exergonic reactions to endergonic reactions: energy coupling

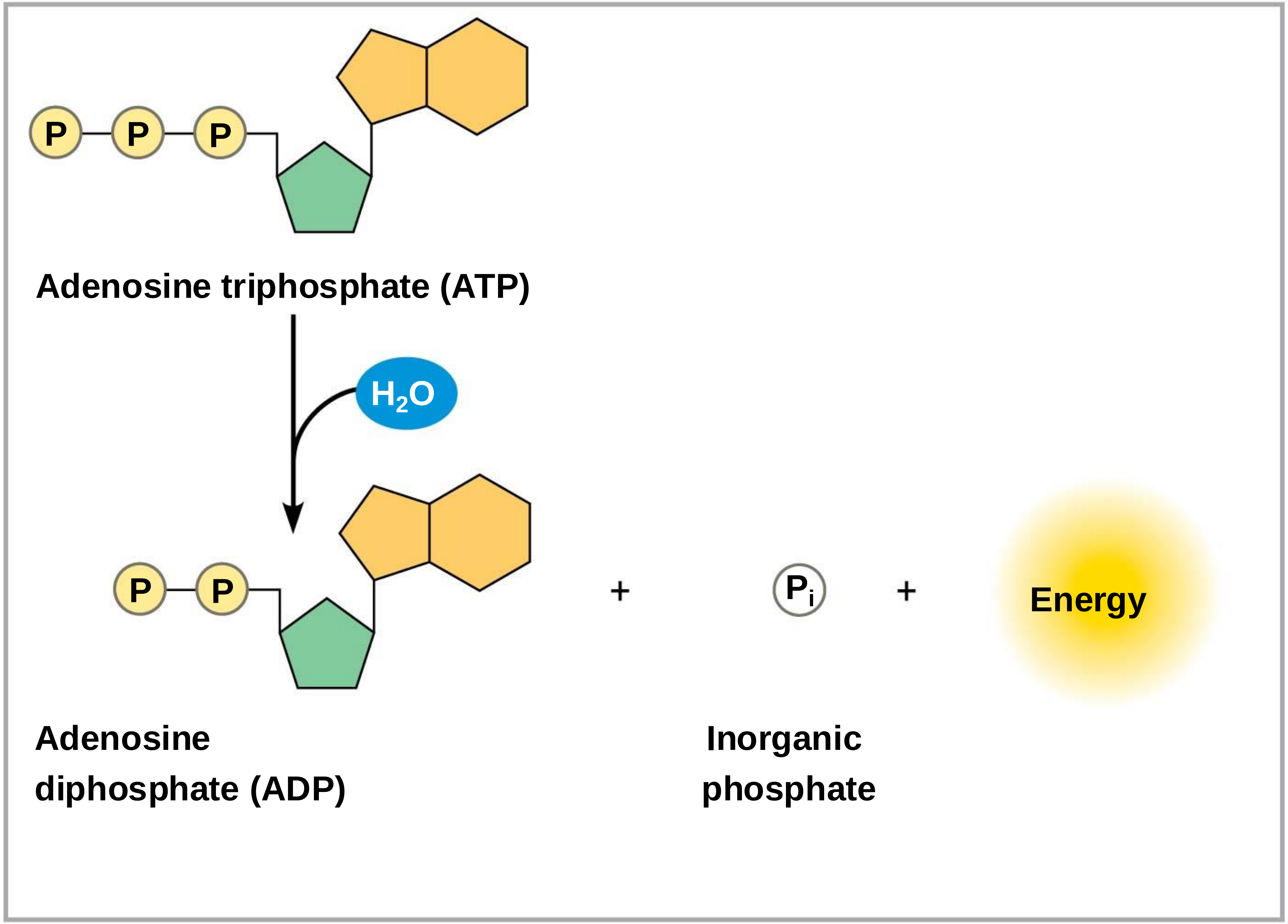
- To do work, cells manage energy resources by **energy coupling**, the **use of an exergonic process to drive an endergonic one**
- Most energy coupling in cells is mediated by ATP



ATP as the cell's energy currency



The hydrolysis of ATP



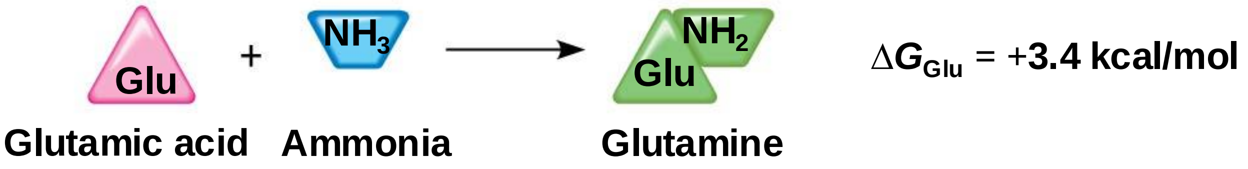
The hydrolysis of ATP

- 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

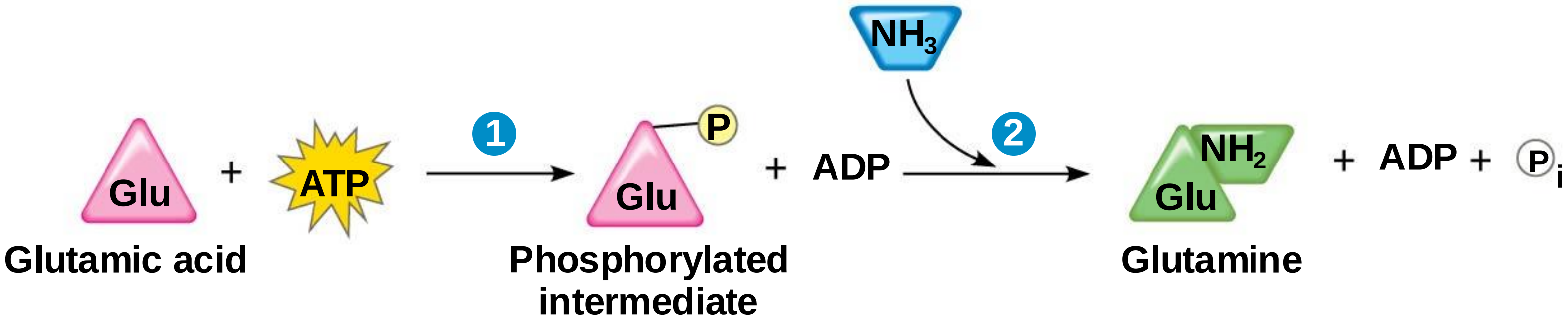
How the Hydrolysis of ATP Performs Work

- 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
- ATP hydrolysis leads to a change in protein shape and binding ability
- 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**

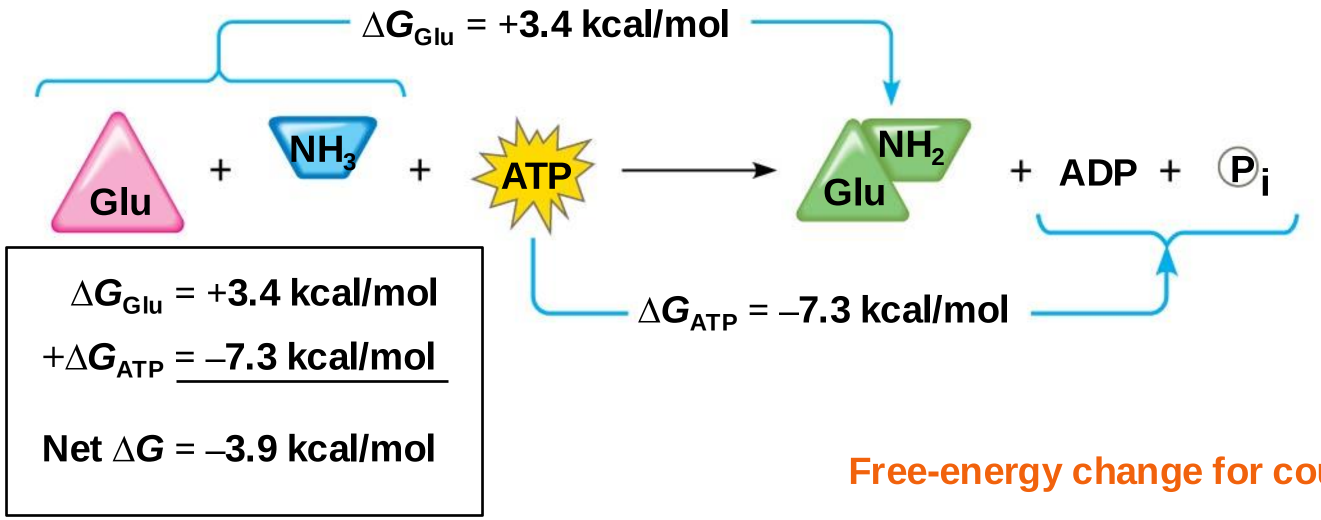
Examples:



Glutamic acid conversion to glutamine



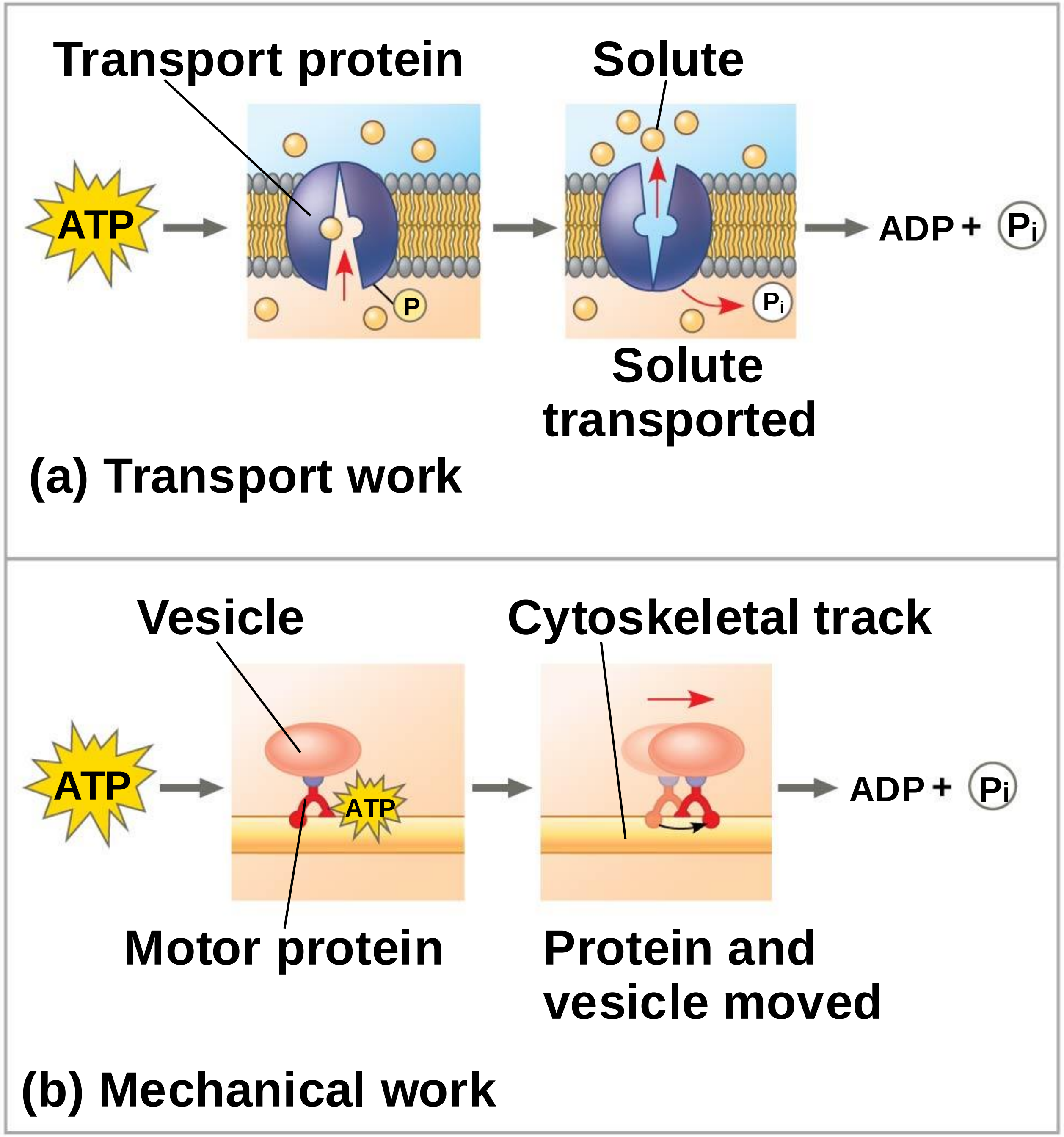
Conversion reaction coupled with ATP hydrolysis



Free-energy change for coupled reaction

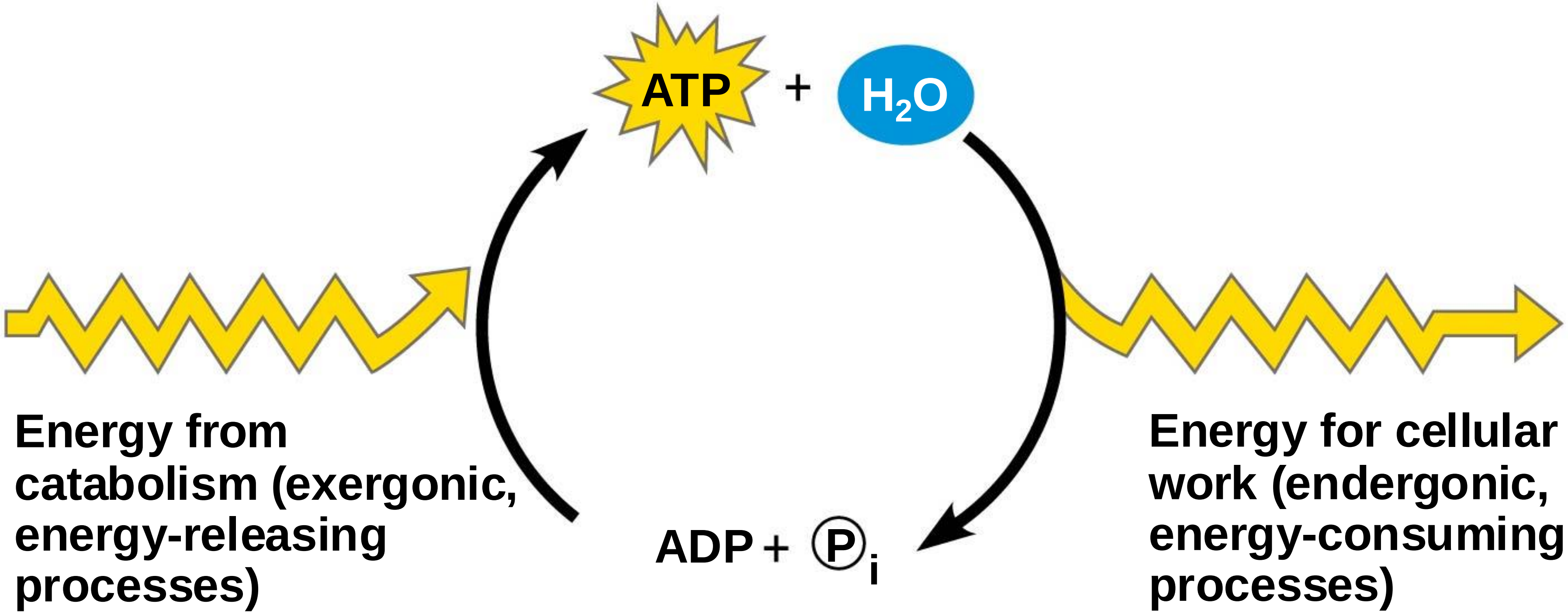
Examples:

- ATP powers transport and mechanical work in the cell
- ATP hydrolysis leads to a change in protein shape and binding ability



The Regeneration of ATP

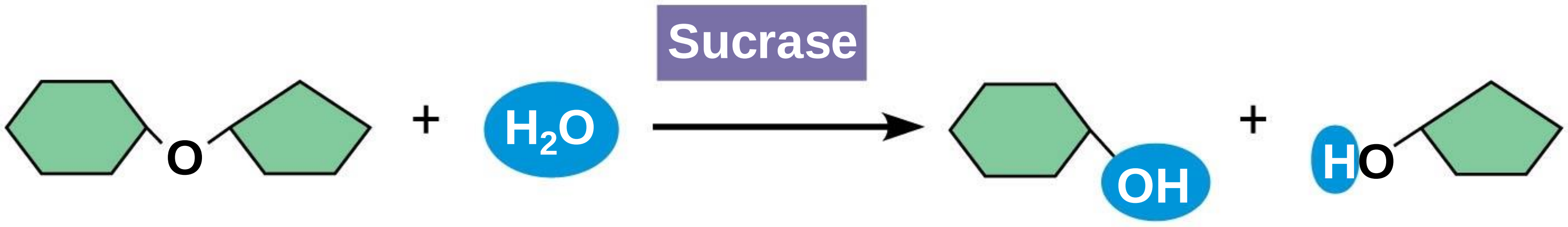
- ATP is a renewable resource that is regenerated by **addition of a phosphate group** to adenosine diphosphate (ADP)
- The energy to phosphorylate ADP comes from catabolic reactions in the cell
- The ATP cycle is a revolving door through which energy passes during its transfer from catabolic to anabolic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



Enzymes speed up metabolic reactions by lowering energy barriers

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



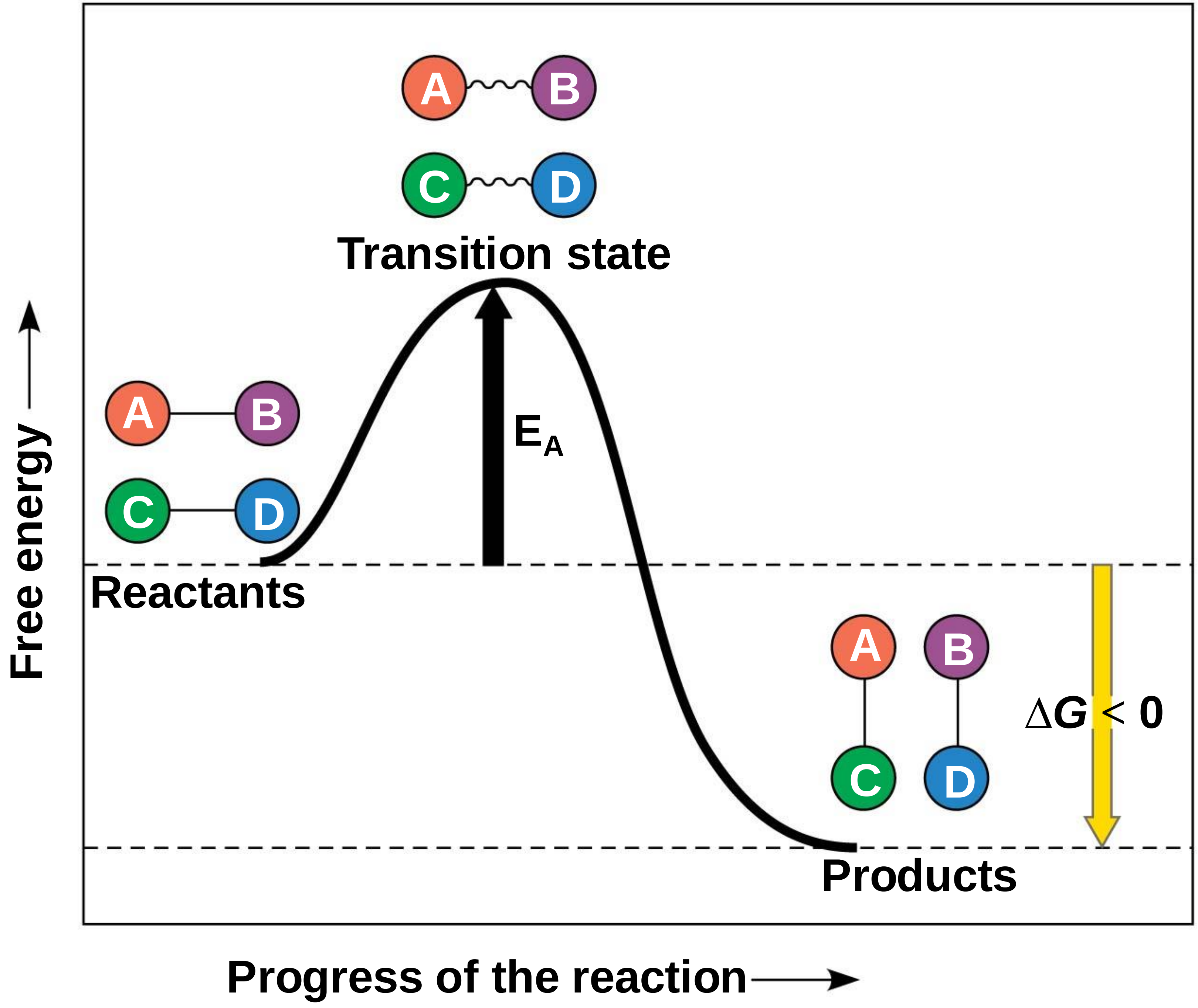
Sucrose ($C_{12}H_{22}O_{11}$)

Glucose ($C_6H_{12}O_6$)

Fructose ($C_6H_{12}O_6$)

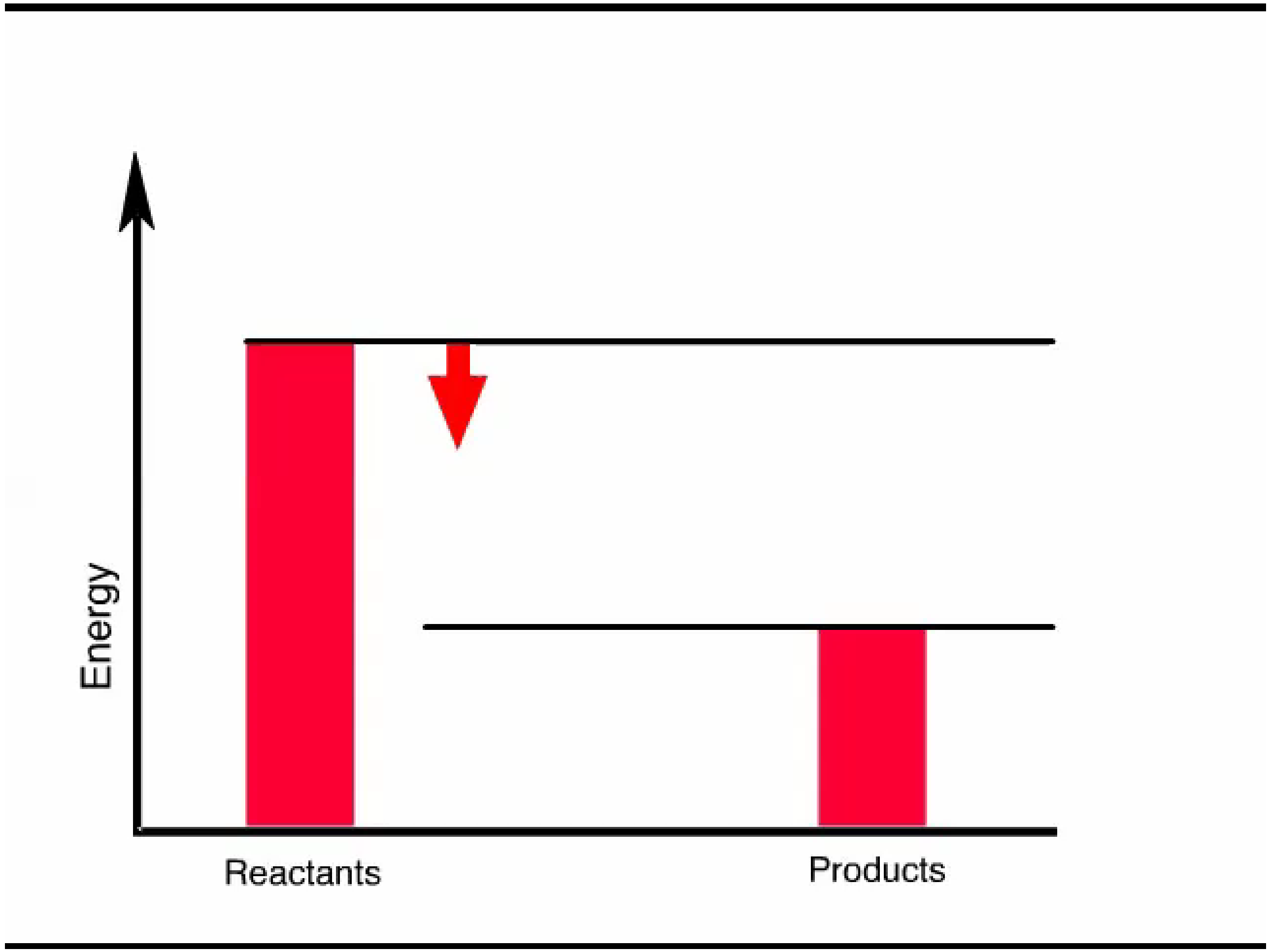
The Activation Energy Barrier

- 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



A
B
C
D
Transition state
E_A
Reactants
Products
$\Delta G < 0$
Free energy
Progress of the reaction

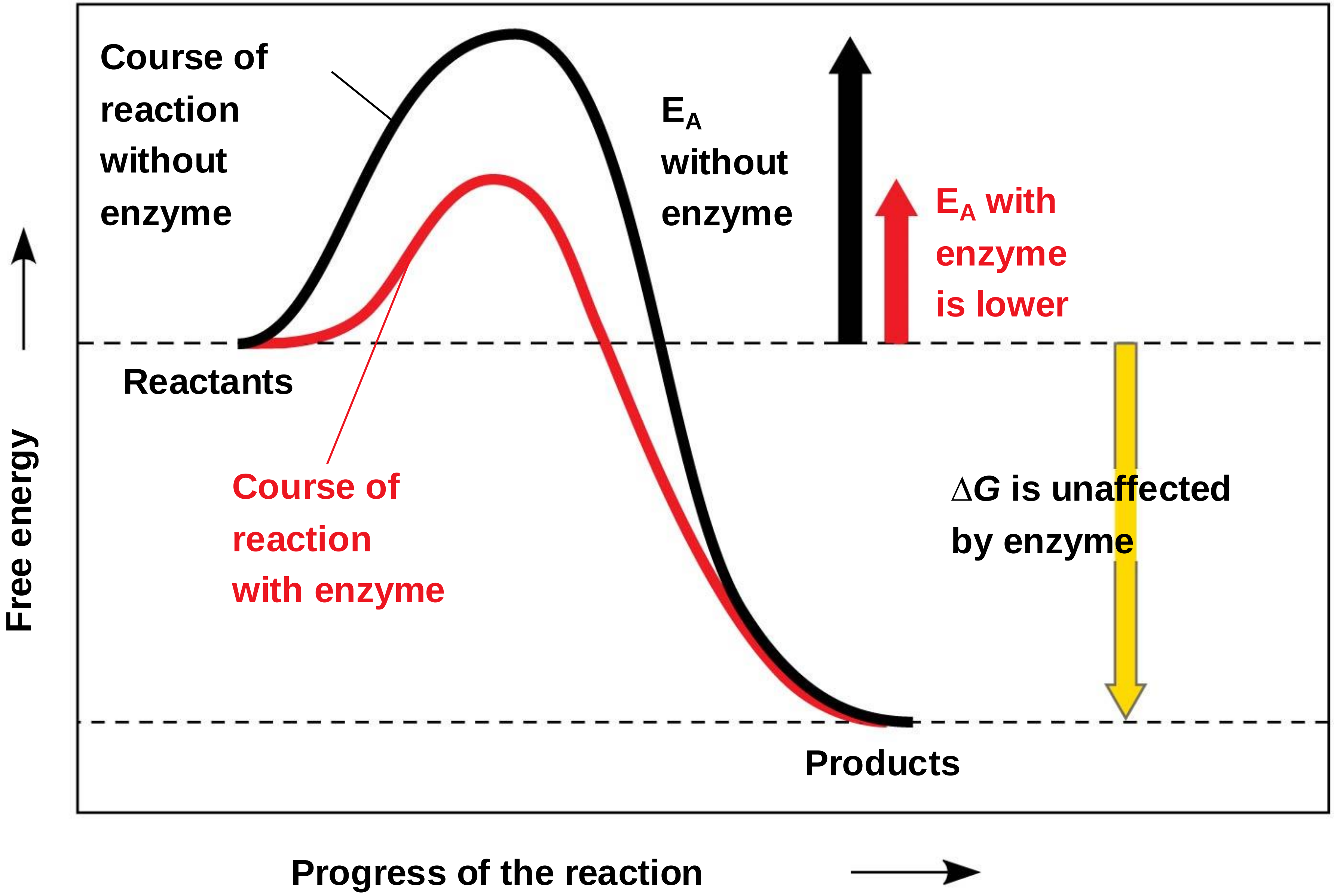
Animation: How Enzymes Work



How Enzymes Speed Up Reactions

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

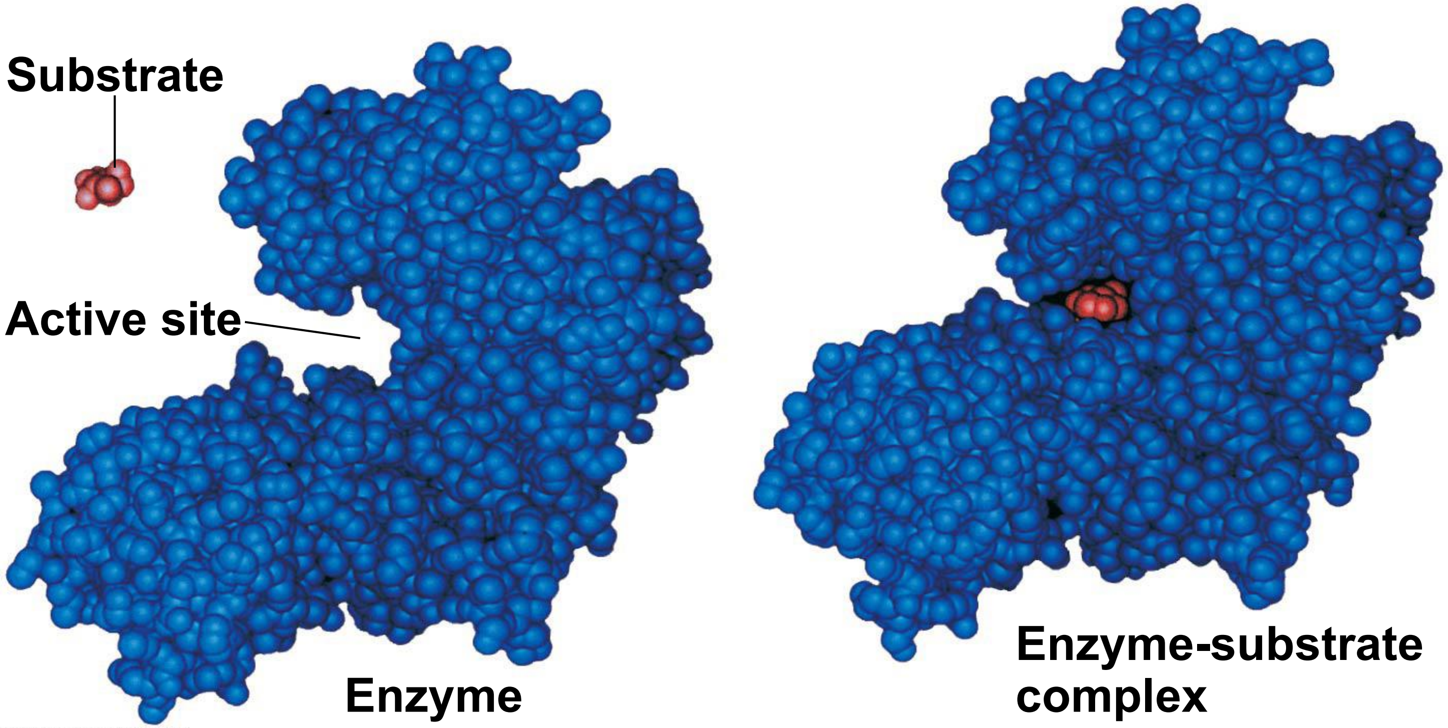
The effect of an enzyme on activation energy

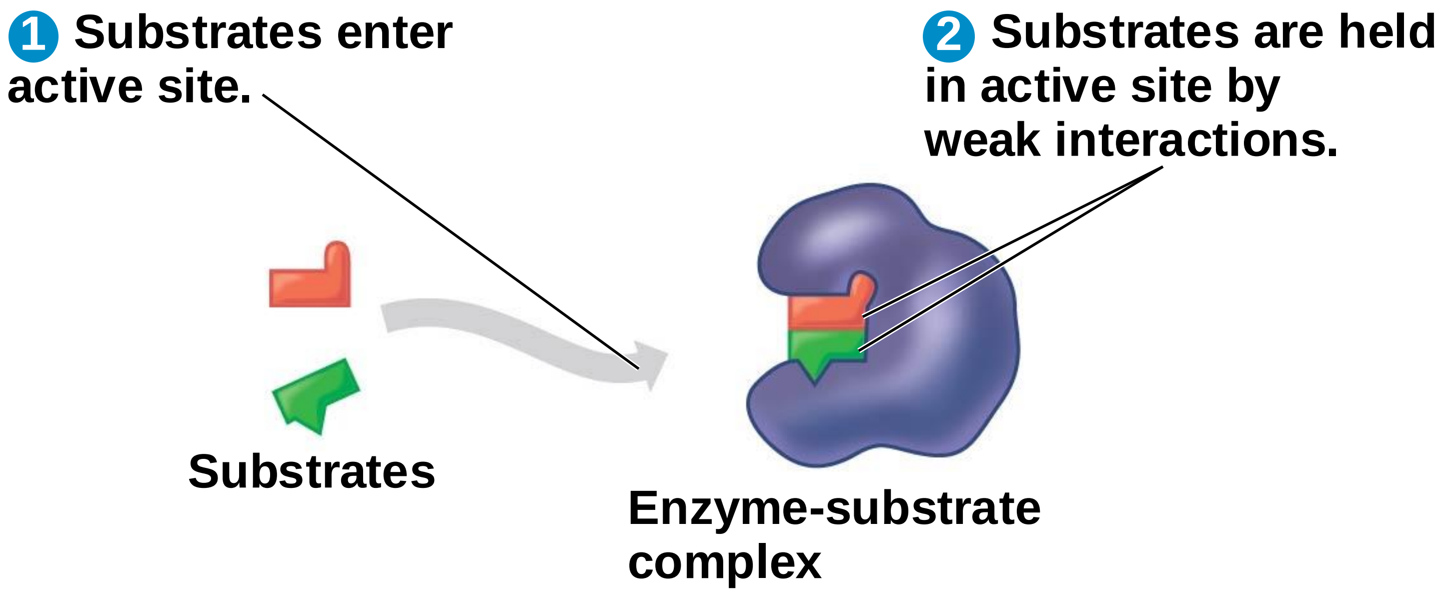


Substrate Specificity of Enzymes

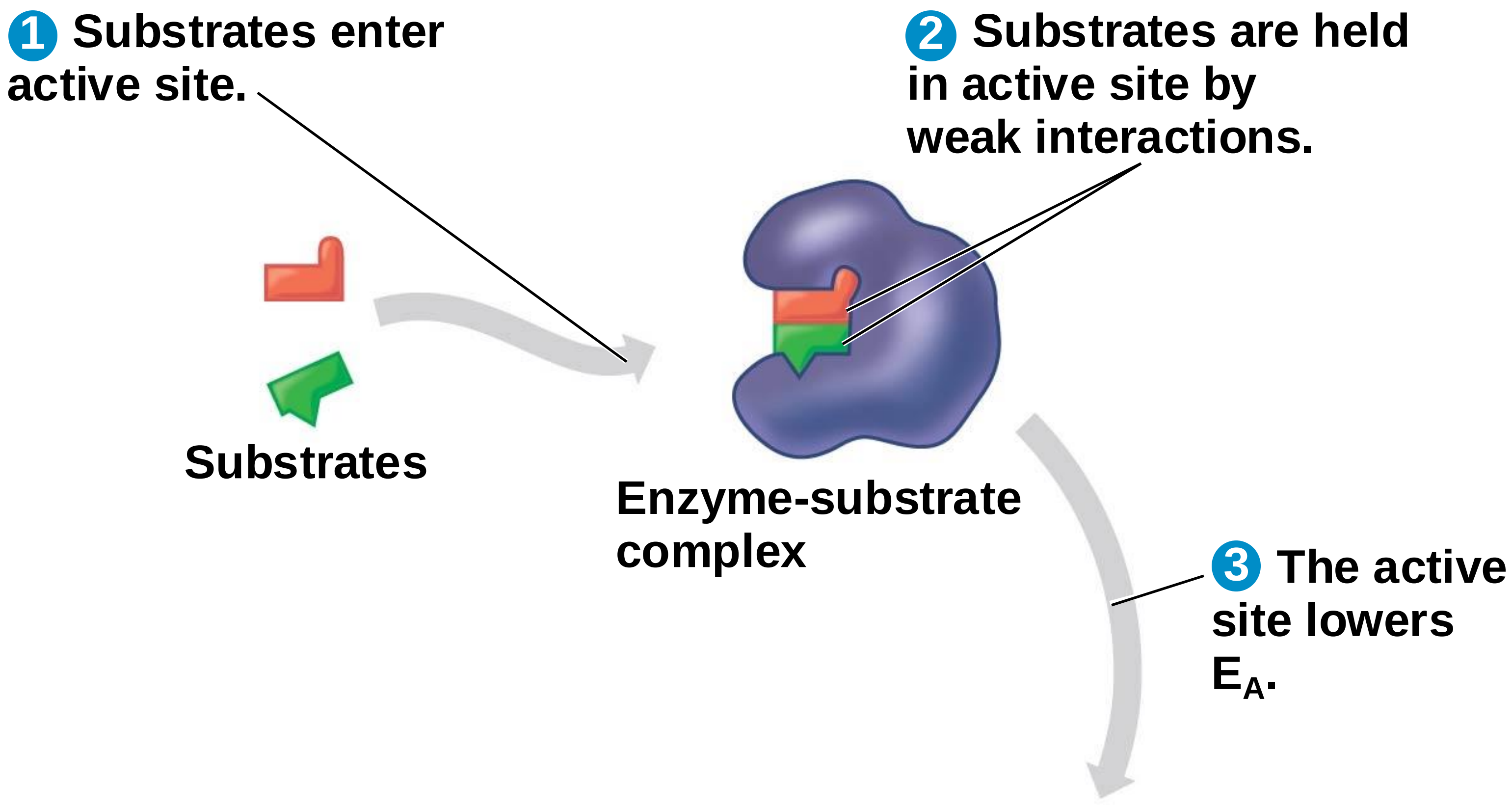
- The reactant that an enzyme acts on is called the enzyme’s **substrate**
- The enzyme binds to its substrate, forming an **enzyme-substrate complex**
- While bound, the activity of the enzyme converts substrate to product

- 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



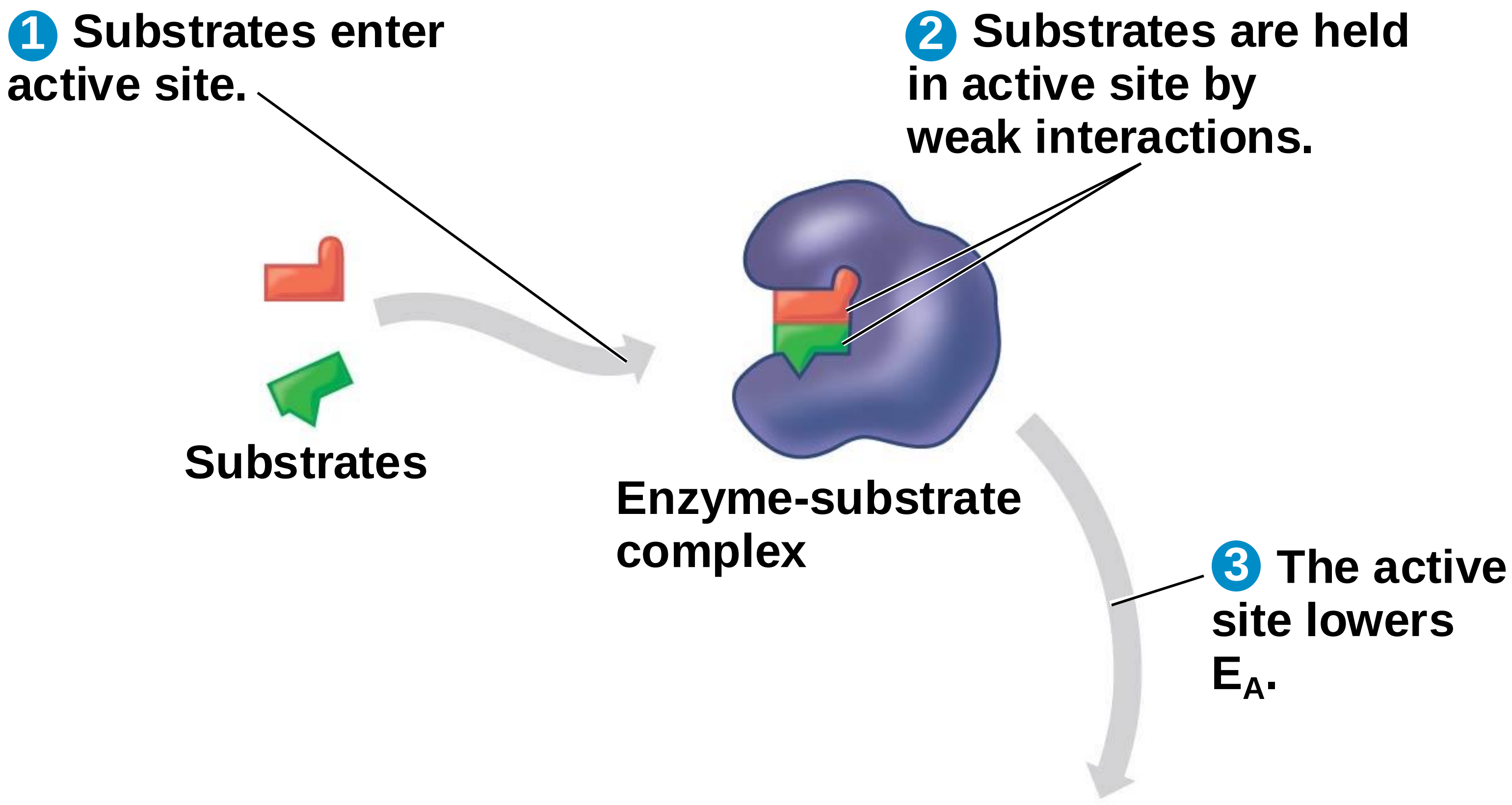


1 Substrates enter active site.
2 Substrates are held in active site by weak interactions.
Substrates
Enzyme-substrate complex


1 Substrates enter active site.
2 Substrates are held in active site by weak interactions.
Substrates
Enzyme-substrate complex
3 The active site lowers E_A.

The active site of an enzyme can lower an E_A barrier by:

- orienting substrates correctly
- straining substrate bonds
- providing a favorable microenvironment
- covalently bonding to the substrate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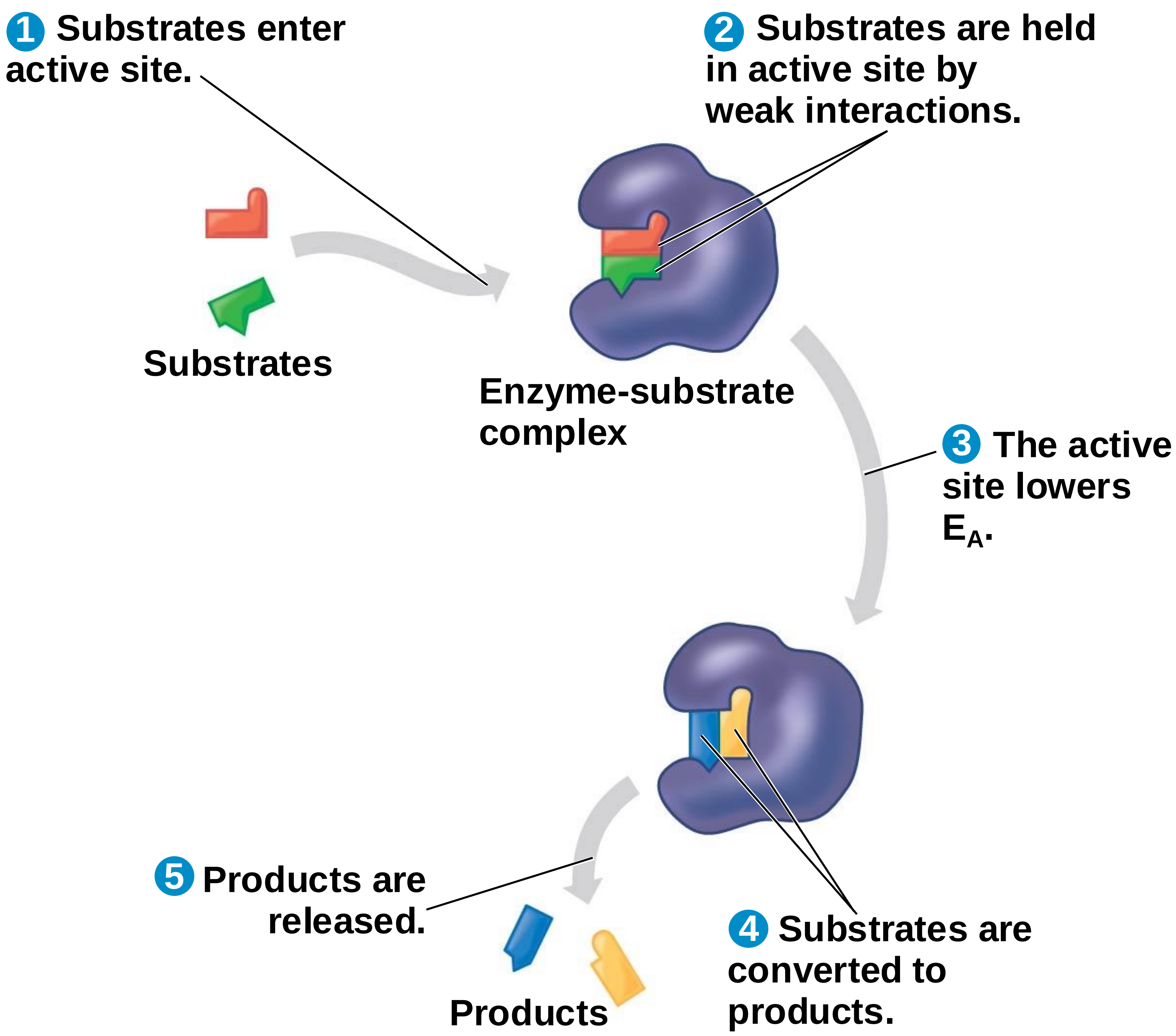
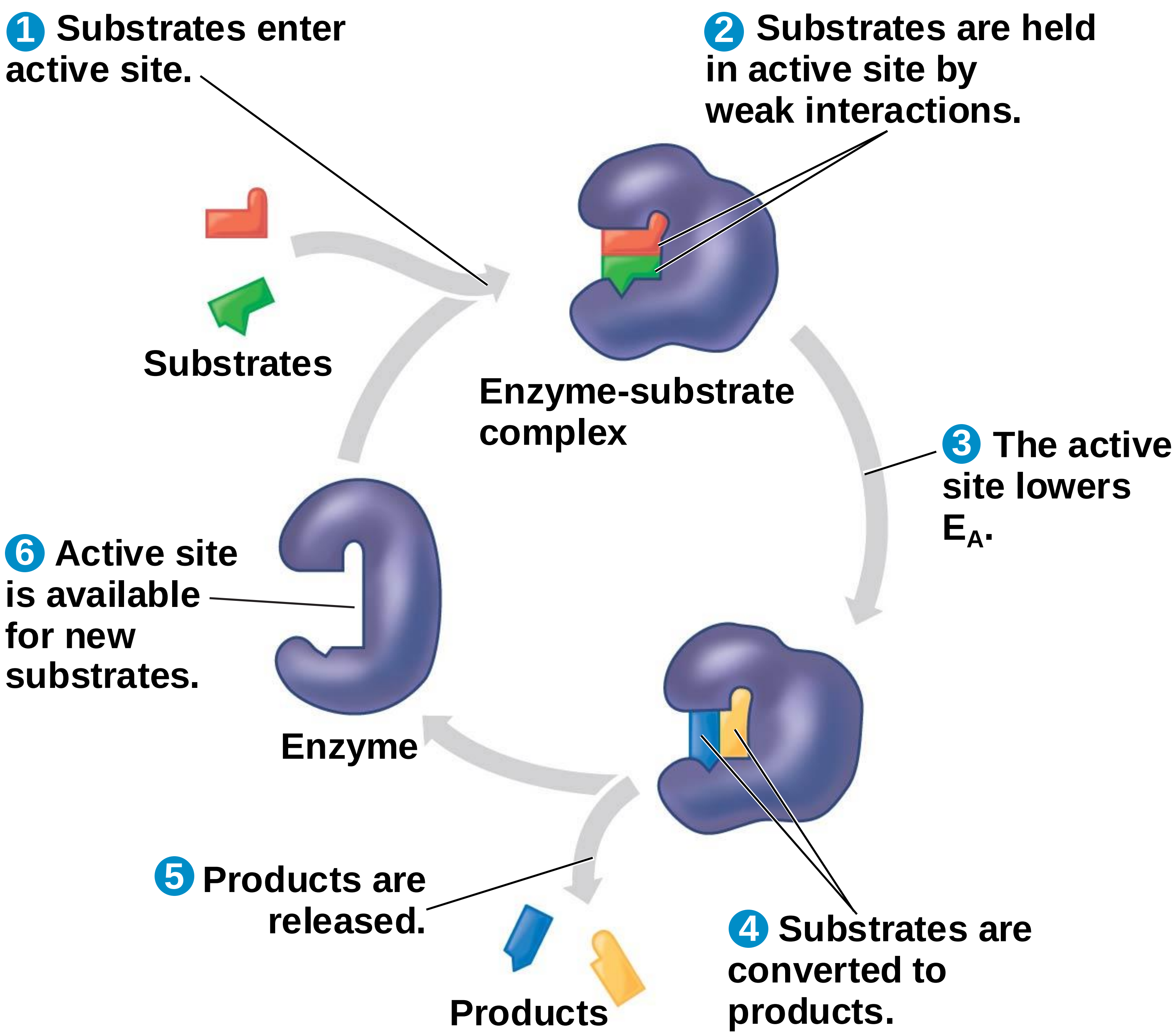
Enzyme-substrate complex
3 The active site lowers E_A.


1 Substrates enter active site.
2 Substrates are held in active site by weak interactions.
Substrates
Enzyme-substrate complex
3 The active site lowers E_A.
4 Substrates are converted to products.
5 Products are released.
Products

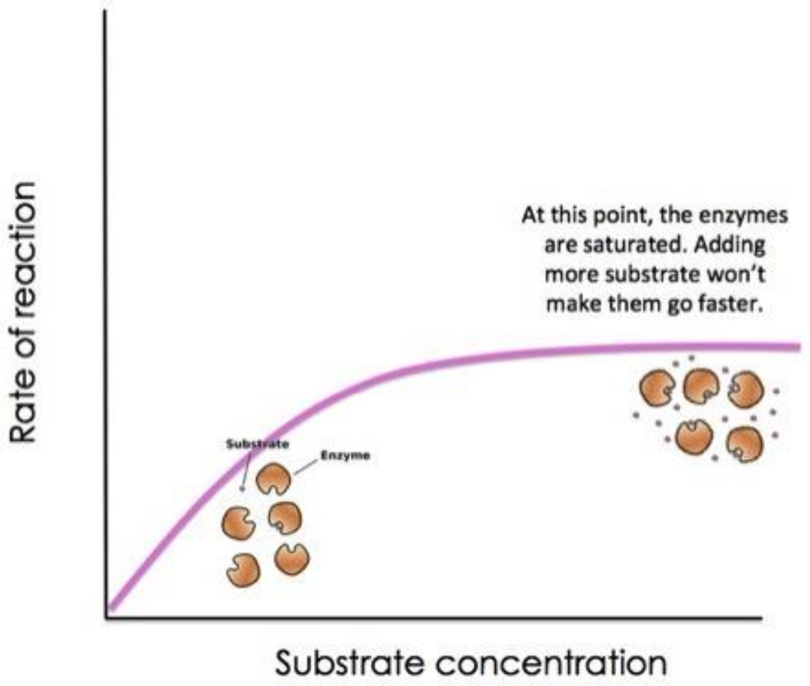


1 Substrates enter active site.
2 Substrates are held in active site by weak interactions.
Substrates
Enzyme-substrate complex
3 The active site lowers E_A.
6 Active site is available for new substrates.
Enzyme
5 Products are released.
4 Substrates are converted to products.
Products

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 **reused repeatedly** in catalytic cycles

- 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

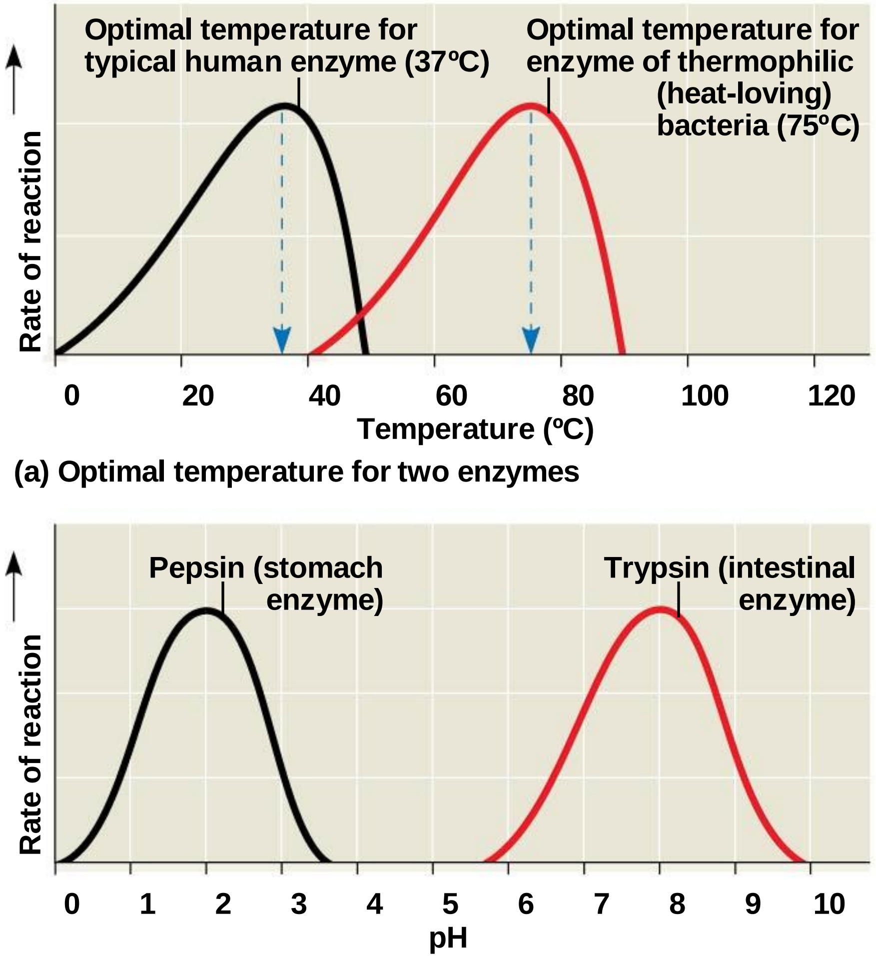


Effects of Local Conditions on Enzyme Activity

- An enzyme's activity can be affected by
  - general environmental factors, such as temperature and pH
  - Presence of chemicals/molecules that specifically influence the enzyme (cofactors, inhibitors…)

Effects of Temperature and pH on enzymes

- 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

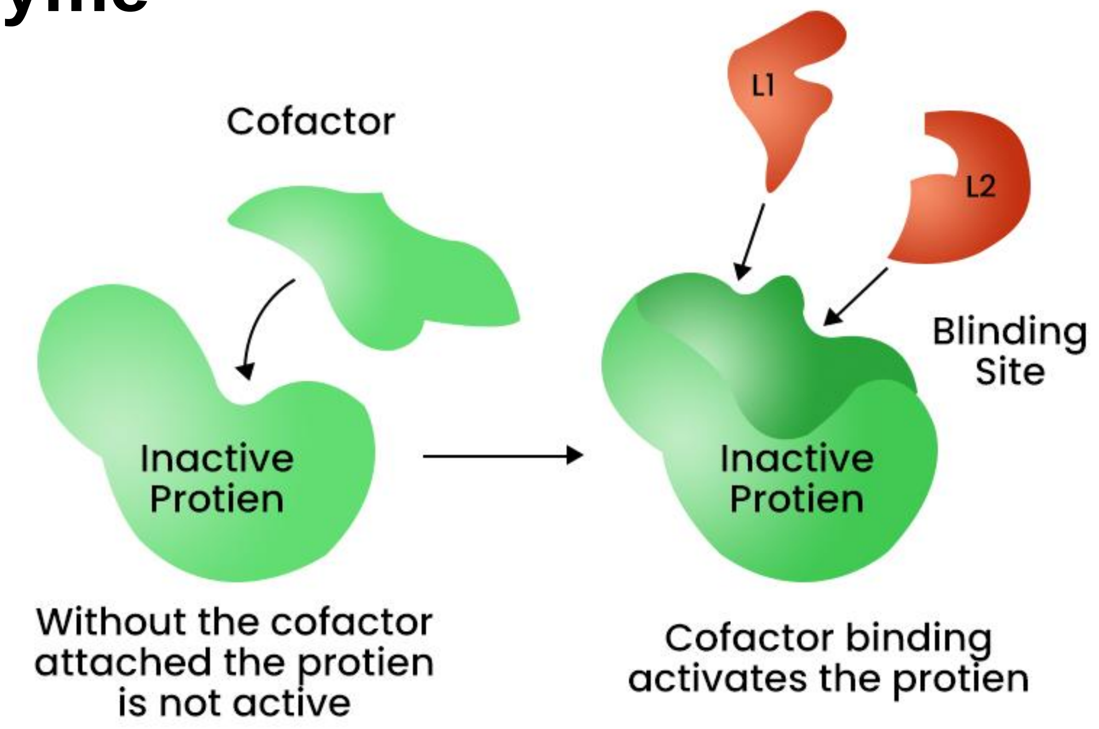


(a) Optimal temperature for two enzymes

(b) Optimal pH for two enzymes

Enzyme cofactors

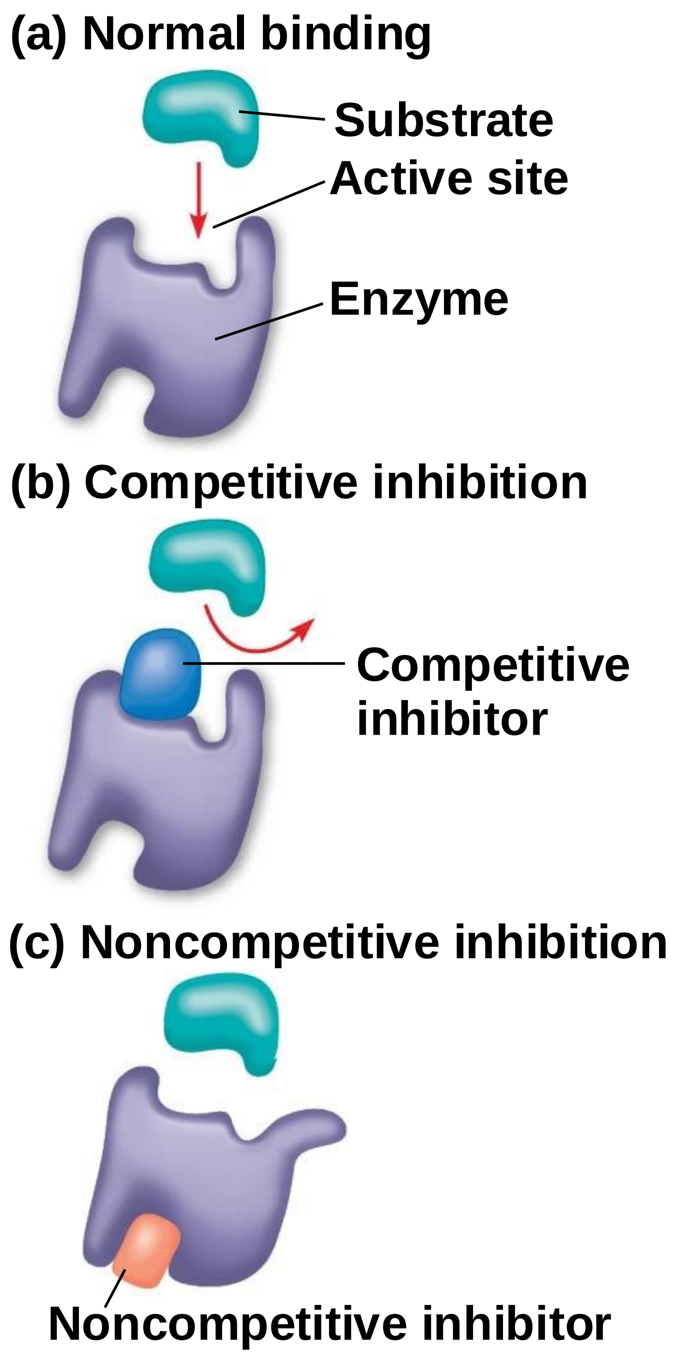
- **Cofactors** are nonprotein enzyme helpers
- Cofactors may be inorganic (such as a metal in ionic form) or organic
- An organic cofactor is called a **coenzyme**
- Coenzymes include vitamins



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

Inhibition of enzyme activity



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

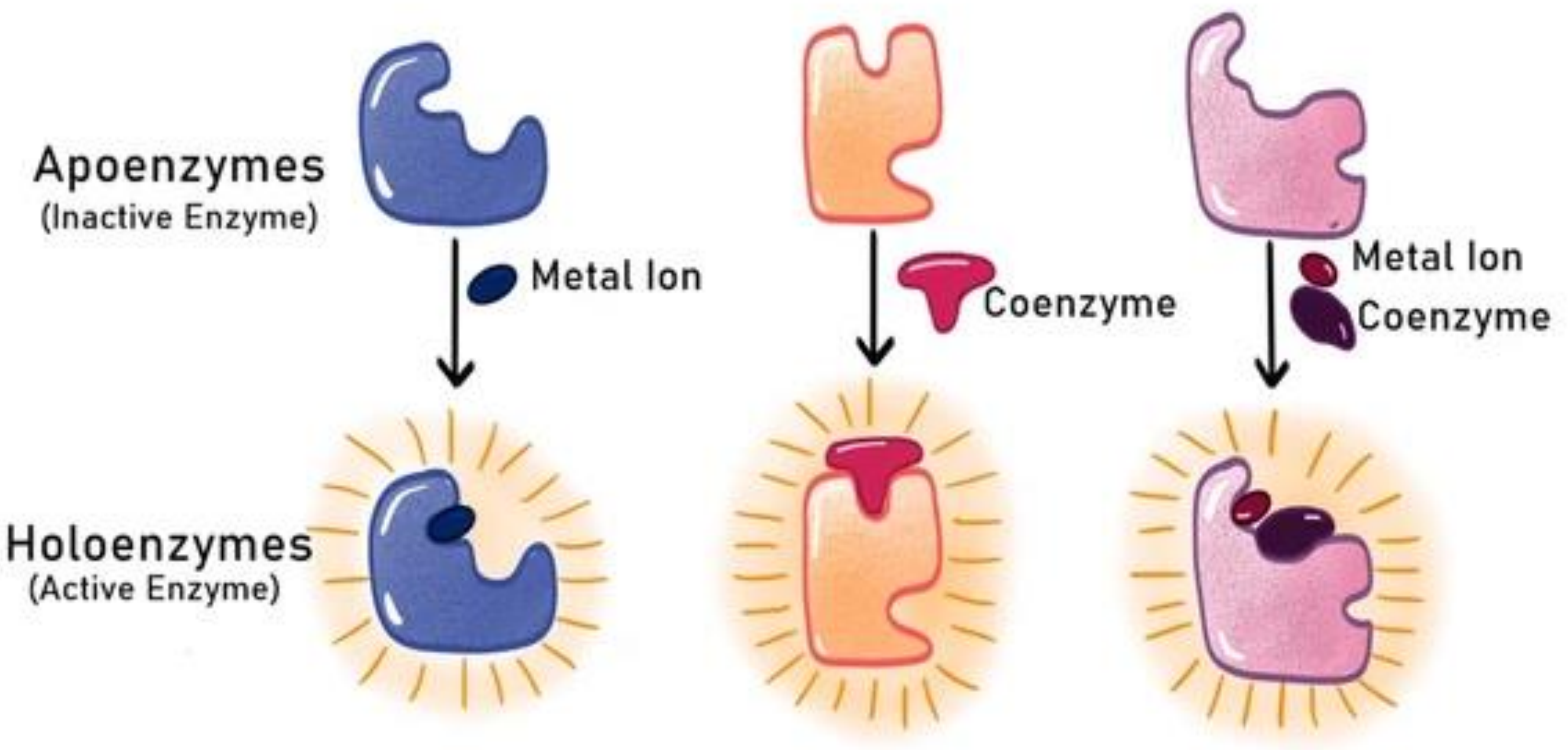
Allosteric Regulation of Enzymes

- **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

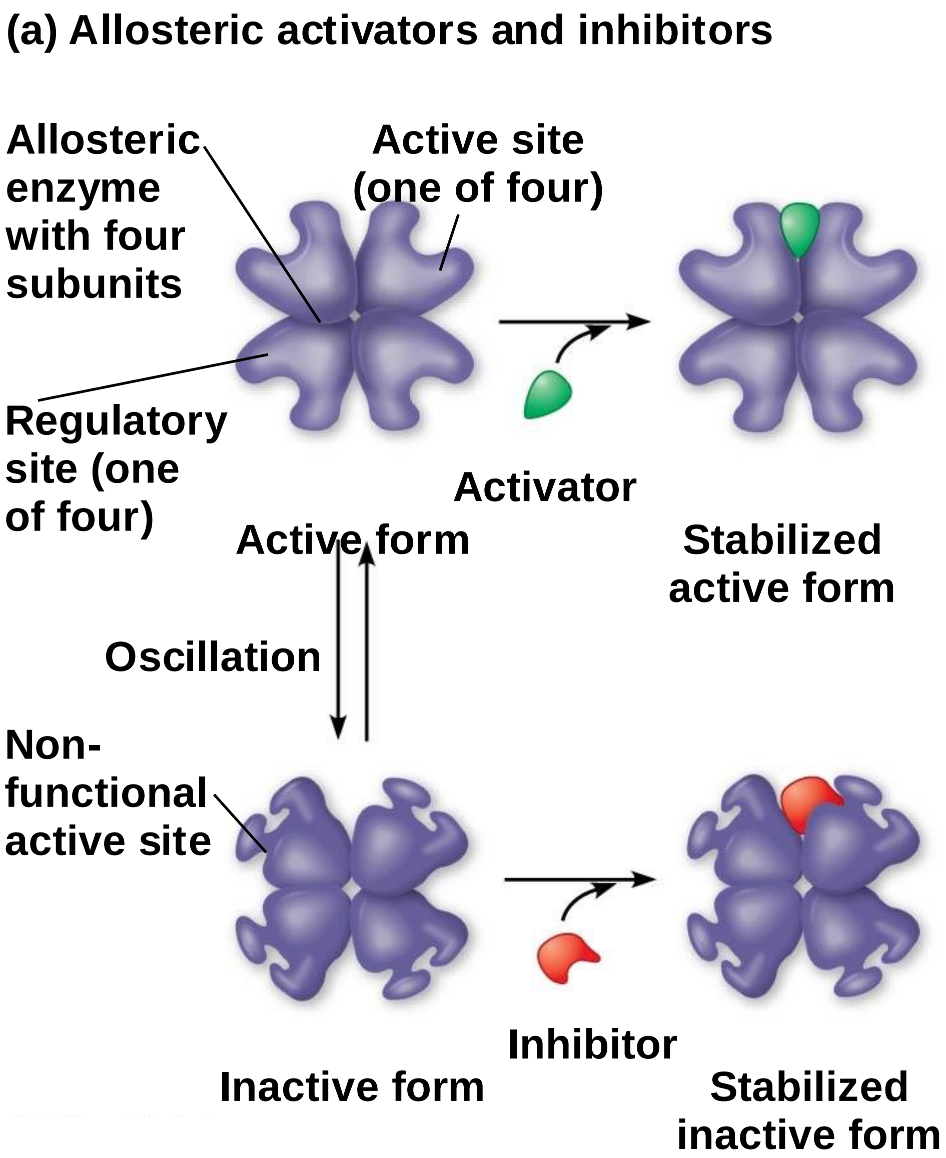
Allosteric Activation and Inhibition

- 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 (**Holoenzyme**)
- The binding of an inhibitor stabilizes the inactive form of the enzyme (**Apoenzyme**)

Allosteric Activation and Inhibition: apoenzymes/holoenzymes

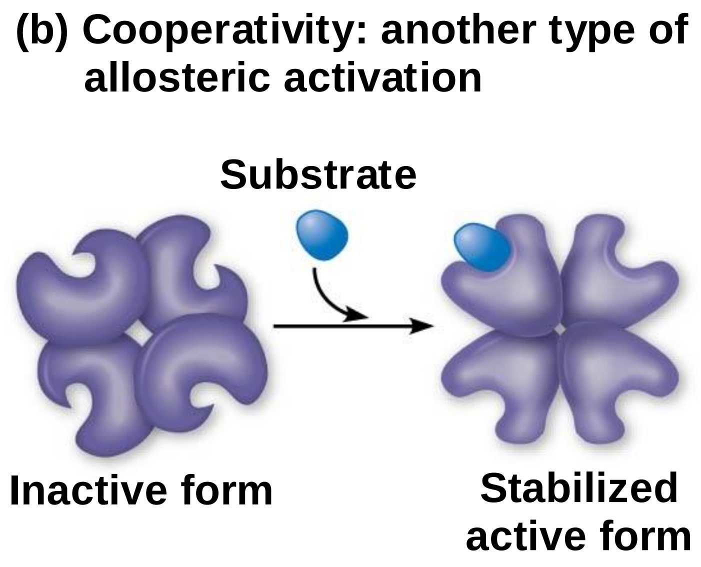


Allosteric regulation of enzyme activity



- **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

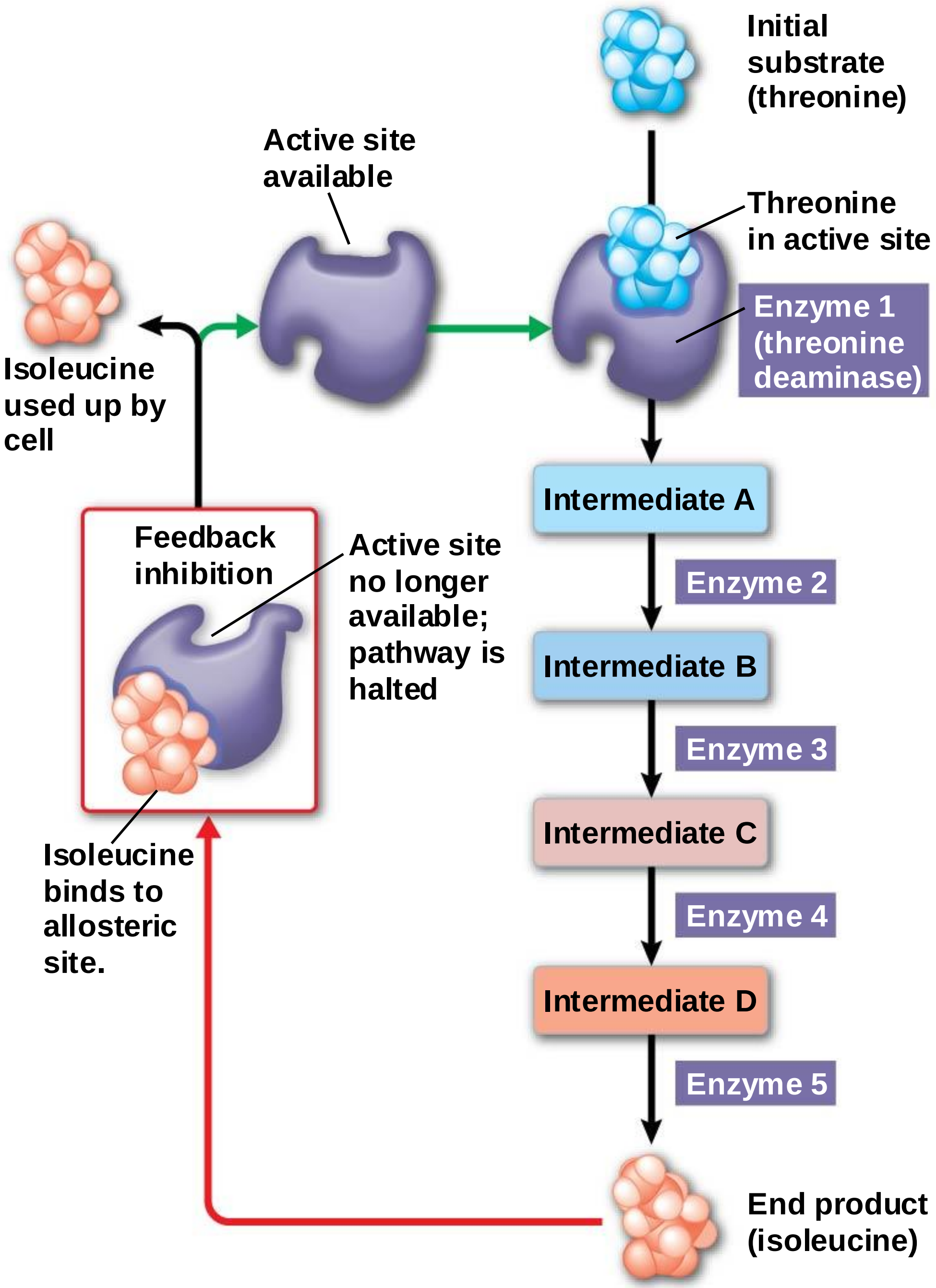
Allosteric regulation of enzyme activity



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

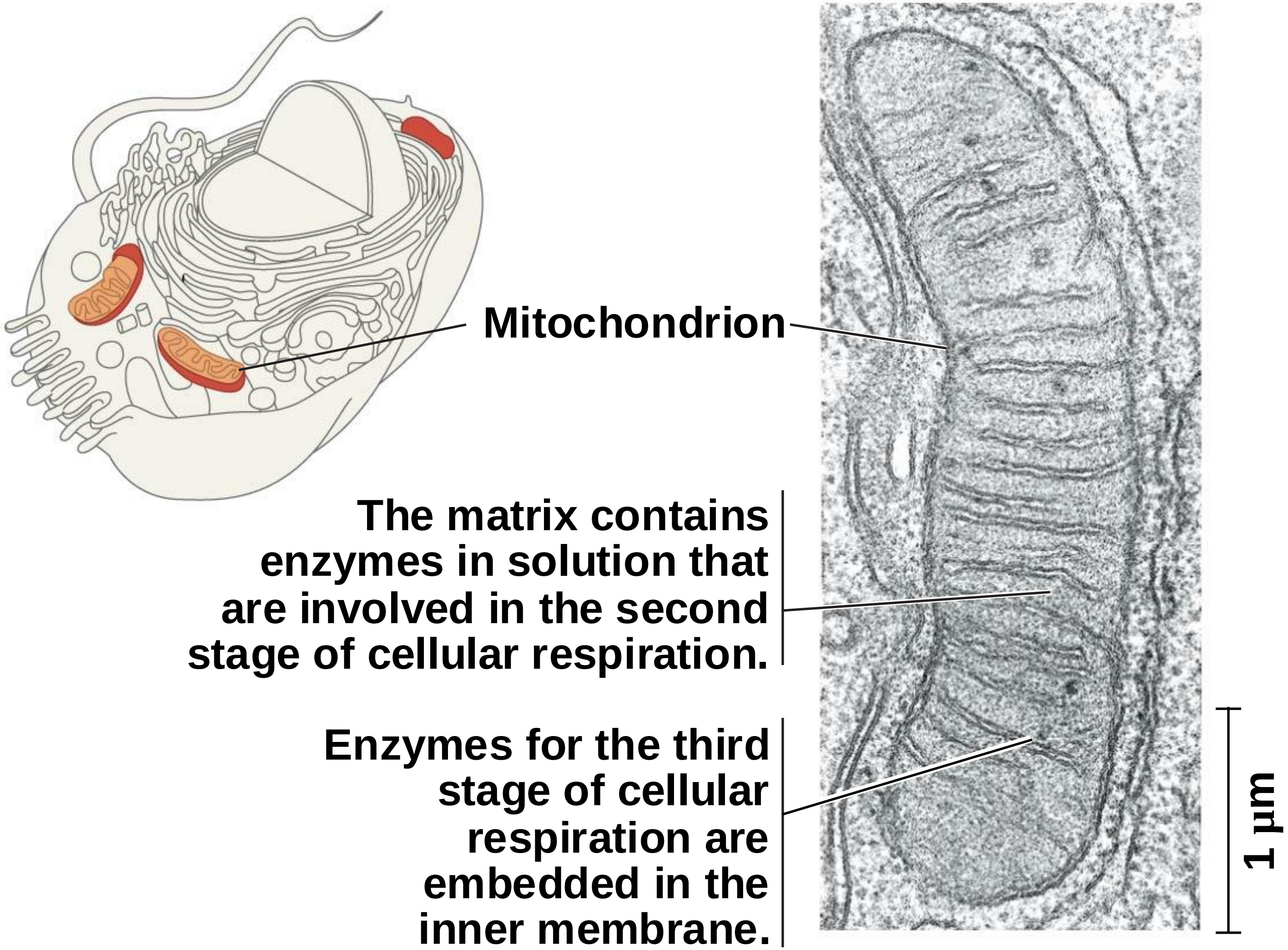
Feedback inhibition



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

Organelles and structural order in metabolism



Summary of key concepts: enzymes and activation energy