Introduction to Biophysics

Transformation of Energy

- **Energy-** capacity to do work or cause change
- **Kinetic energy-** motion.
- **Potential energy-** stored energy
  - – **Chemical energy-** potential energy in molecules.

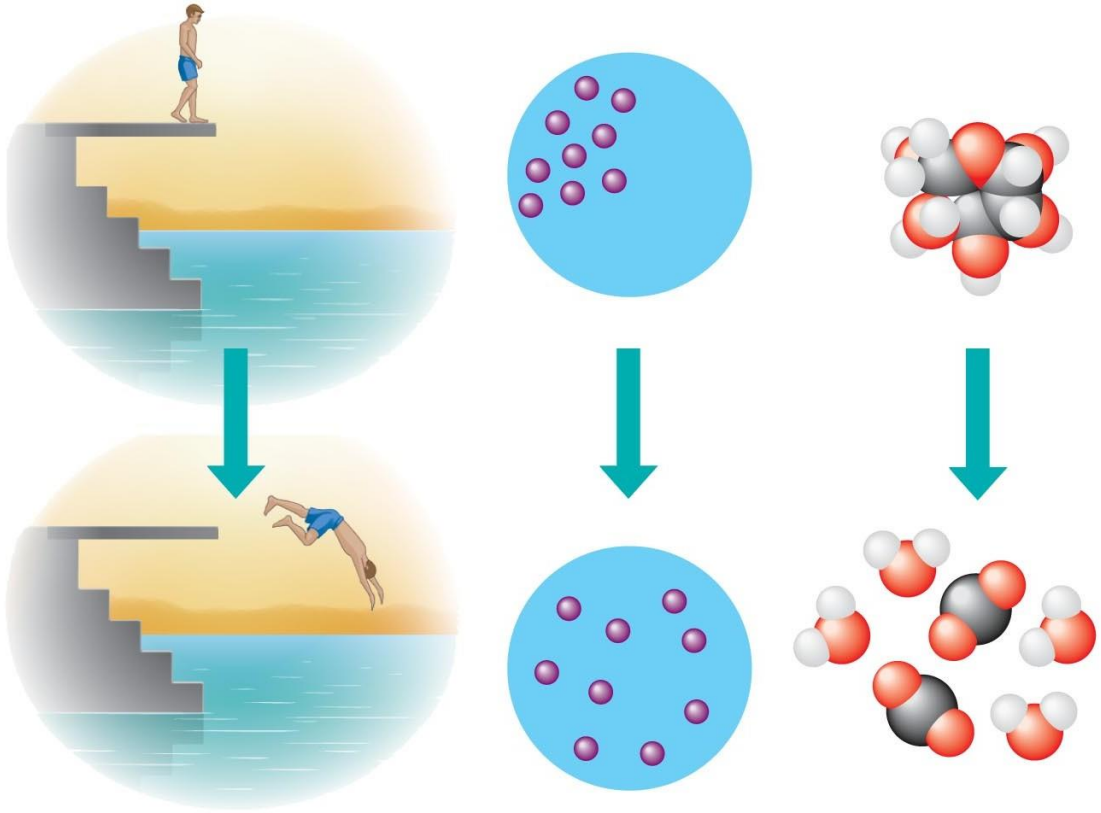
Free Energy

- The portions of a system's energy that is able to perform work.
- A measure of spontaneity of a system and stability.

- More free energy
- 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

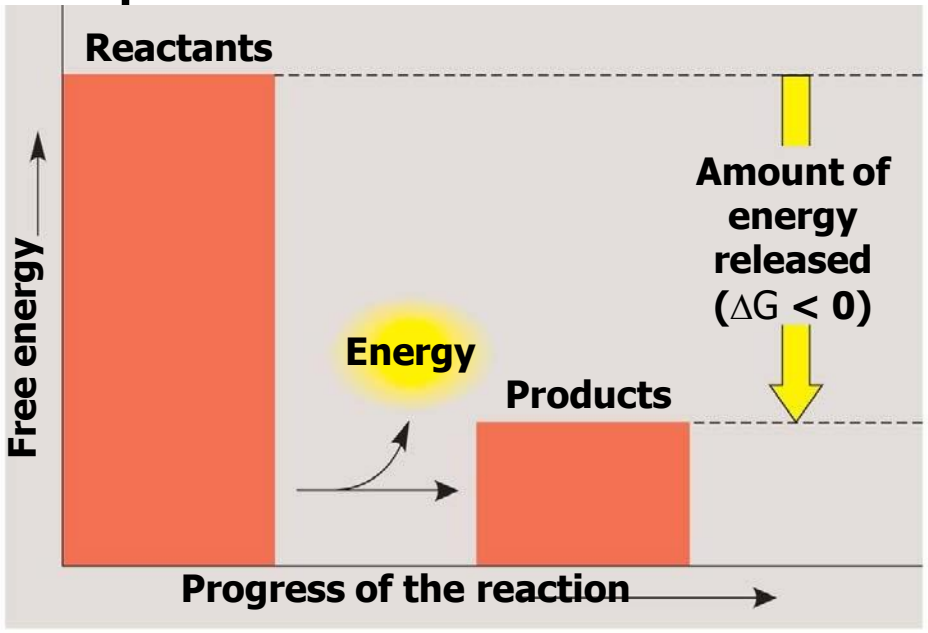
- Less free energy
- More stable
- Less work capacity



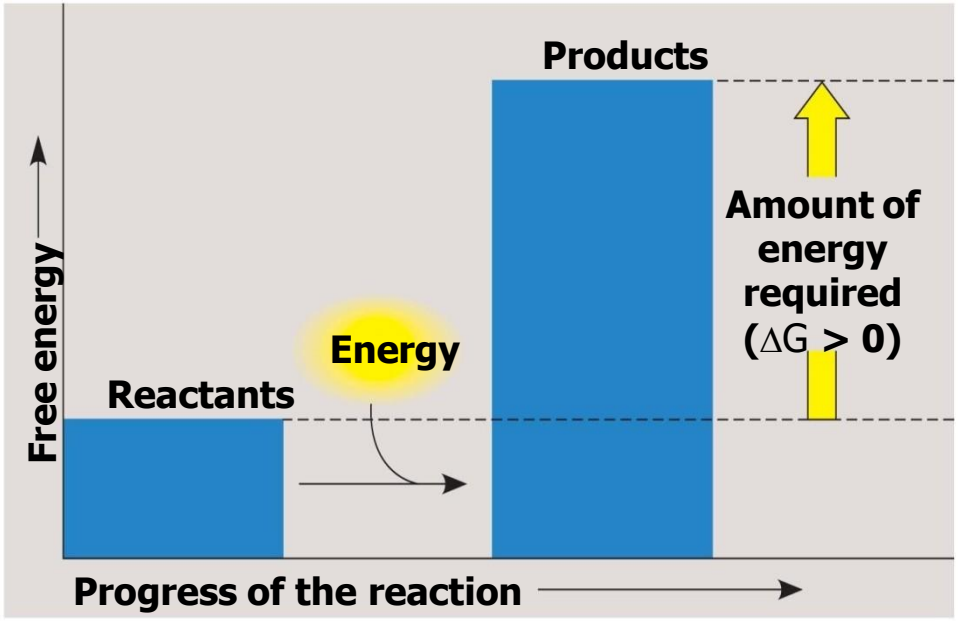
Chemical Reactions and Free Energy

- Exergonic reactions release free energy, ΔG is negative.

- Endergonic reactions absorb energy, ΔG is positive



(a) Exergonic reaction: energy released



(b) Endergonic reaction: energy required

What is the difference between EX and -endergonic

Exergonic	Endergonic
Spontaneous	Non-spontaneous
Releases free energy	store energy from surroundings
$\Delta G<0$, negative	$\Delta G>0$, positive

Metabolism and Energy Transformation

- **Chemical reactions**:
  – forming or breaking of bonds between atoms (change in chemical energy).

- **Metabolism:**
  - sum of the chemical reactions in an organism involves energy transformations.

Metabolism and Cellular Energy

Metabolism- a set of life-sustaining chemical transformations within the cells of living organisms.
Biochemical Conversion The changing of organic matter into other chemical forms such as fuels.
Energy Transformation A process in which energy changes from one form to another form while some of the energy is lost to the environment.
Adenosine Triphosphate (ATP) A molecule that provides energy for cellular reactions and processes. ATP releases energy when one of its high-energy bonds is broken to release a phosphate group.
Bioenergetics The study of energy flow (energy transformations) into and within living systems.
chemical energy in the bonds of "food" molecules is released and partially captured in the bonds of adenosine triphosphate (ATP) molecules.

Plants:

- Autotrophs – they make their own sugars during photosynthesis = Producers - Produce food for all other organisms

Animals:

- Heterotrophs – must get their sugars (carbohydrates) for energy from other sources = Consumers – Consume the food provided by plants

Sun

Ultimate source of energy because it provides the energy for the plants which is then passed down to other organisms

Chemosynthesis

The synthesis of organic compounds within an organism with chemical reactions providing the energy source.

Photosynthesis

$$6CO_2 \text{ Carbon dioxide} + 6H_2O \text{ Water} \xrightarrow{\text{Light}} C_6H_{12}O_6 \text{ Sugar} + 6O_2 \text{ Oxygen}$$

Chloroplast *An organelle found in plant cells and the cells of other eukaryotic photosynthetic organisms where photosynthesis occurs.*

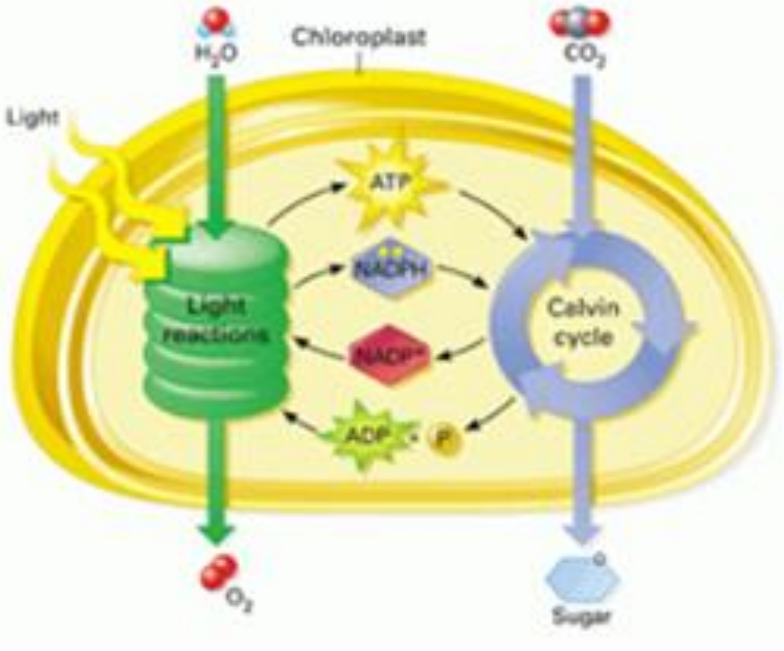
Photosynthesis

- Takes place in the chloroplasts
- Chlorophyll is the molecule that receives the sun's energy
- Solar radiation is chemically captured by chlorophyll molecules and through a set of controlled chemical reactions resulting in the potential chemical energy in the bonds of carbohydrate molecules.

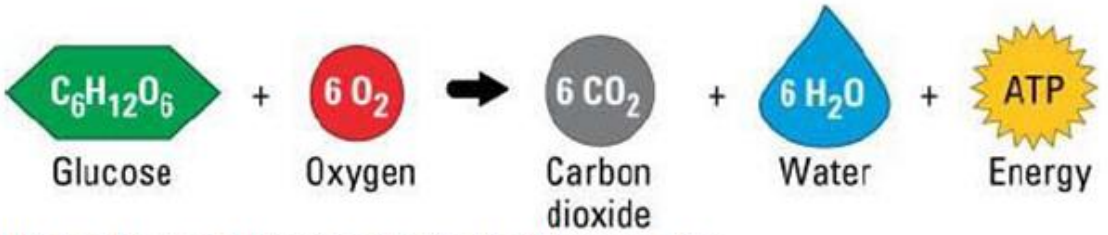
There are two major reactions in photosynthesis

1. Light Dependent reactions (photolysis) (Light Reactions)
    a. Light energy is absorbed by chlorophyll, which uses the energy to split water. Oxygen is released to the outside of the cell, the "H" part of H_2O is carried to the dark reactions with NADPH
    b. Some ATP (energy) is made here—will be used up in Light Independent reaction

2. Light Independent reactions (Dark Reactions)(Calvin Cycle)
    a. CO_2 from the outside is combined with the "H" part of NADPH to make sugars for the cell
        i. NADP+ goes back to light dependent reactions
    b. ATP is used to combine the CO_2 and H to form sugar
        i. ADP goes back to light dependent reactions



Respiration



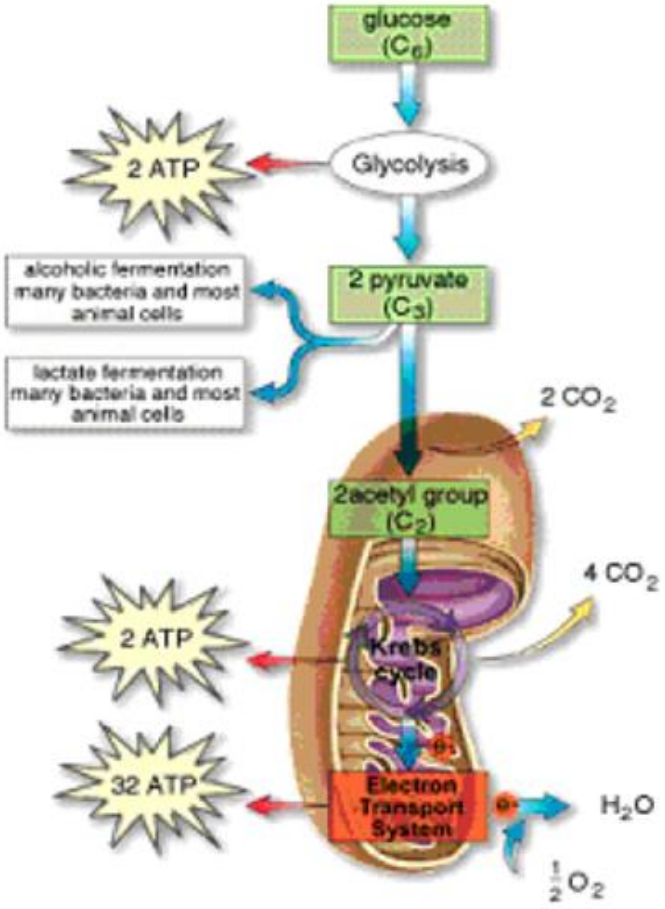
Mitochondrion A membrane-bound organelle found in most eukaryotic cells; site of cellular respiration.

Steps of Cellular Respiration

1. Glycolysis -- glucose is split into 2 3-carbon compounds and a small amount of energy is released.
    a. Cytoplasm of all cells

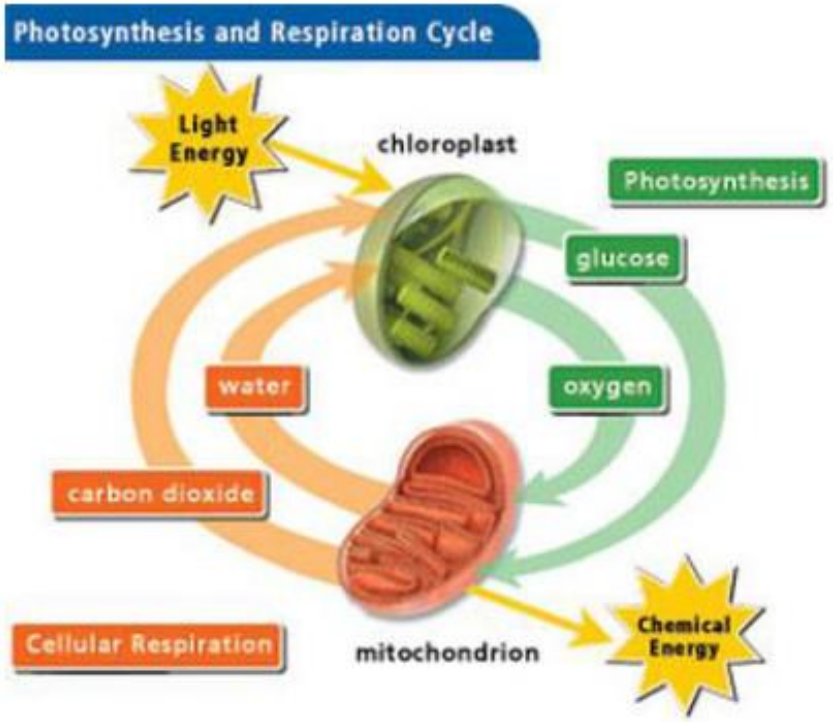
2. Kreb's cycle – takes 3-carbon compounds and breaks them down into carbon dioxide
    a. Inner part of mitochondria (matrix)

3. Electron transport chain – takes electron carriers and materials to create a concentration gradient that ultimately creates ATP
    a. Inner folds of mitochondria (cristae)
    b.



In the absence of oxygen, some organisms will use the products of glycolysis and go through fermentation.

A. Alcoholic fermentation—makes alcohol and CO_2 as the byproducts. Creates no ATP, but "refreshes" carriers so glycolysis can continue
B. Lactic acid fermentation—makes lactic acid as the byproduct. Creates no ATP, but "refreshes" carriers so glycolysis can continue

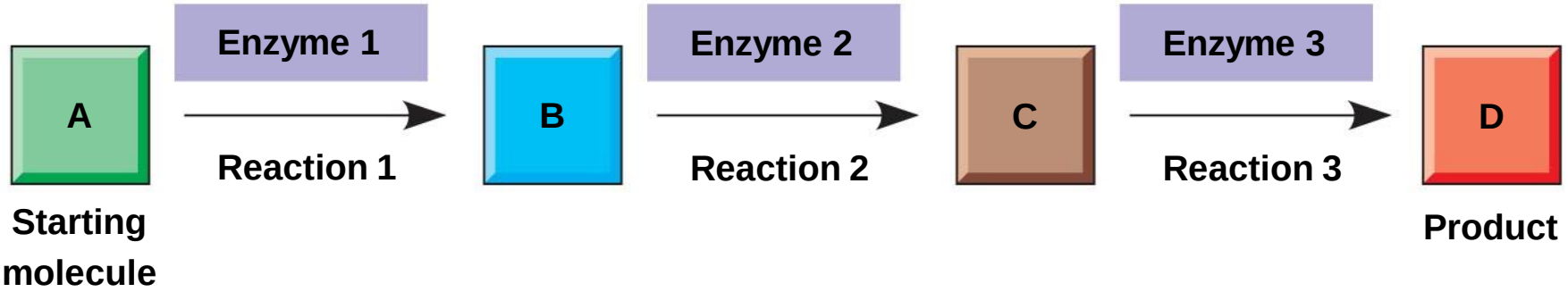


Types of Metabolism

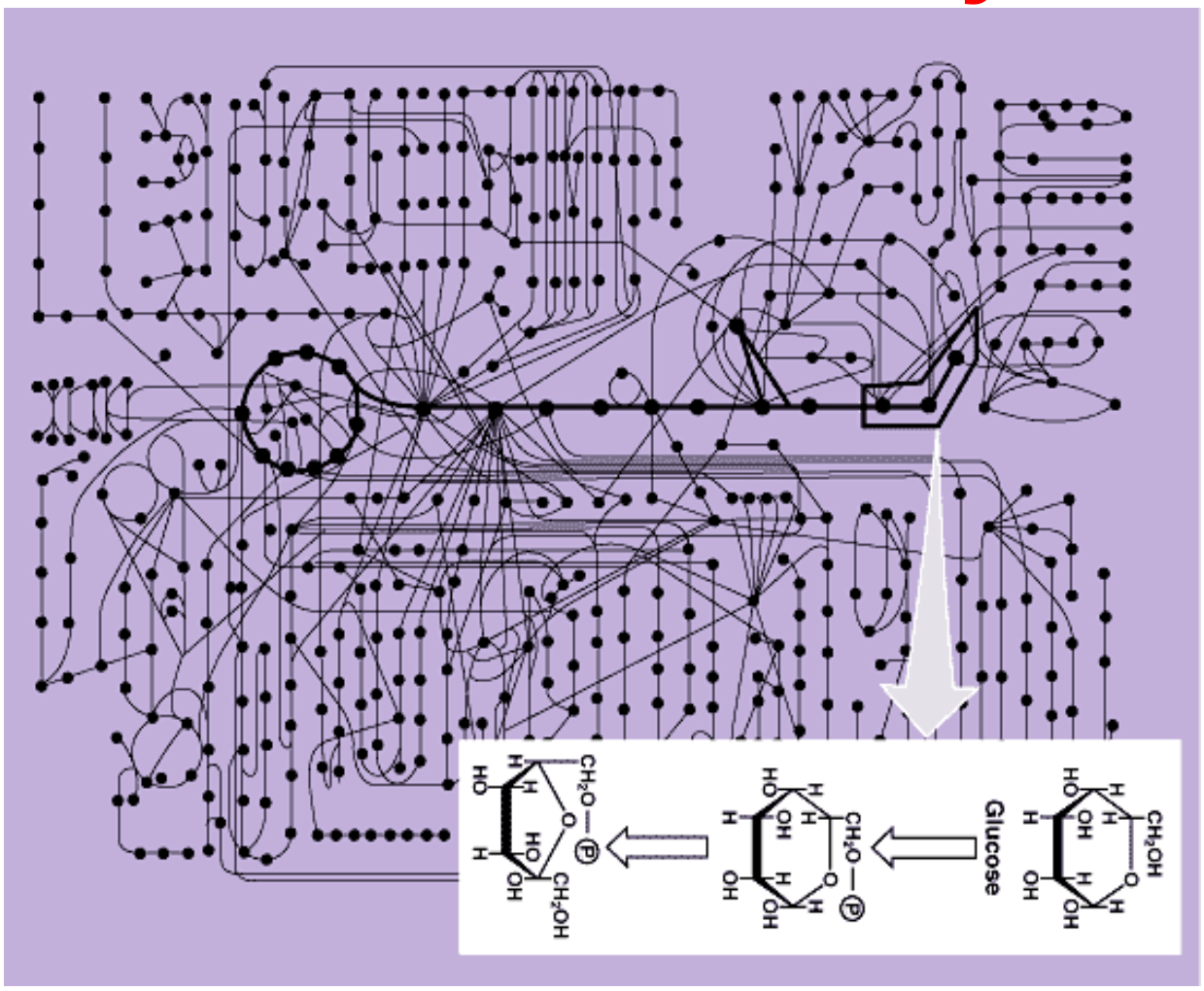
- **Anabolism**:
  - energy-consuming
  - building complicated molecules from simpler compounds

- **Catabolism**:
  - energy-releasing
  - breaking down complex molecules to simpler compounds

Metabolic pathways are a series of steps that alter molecules



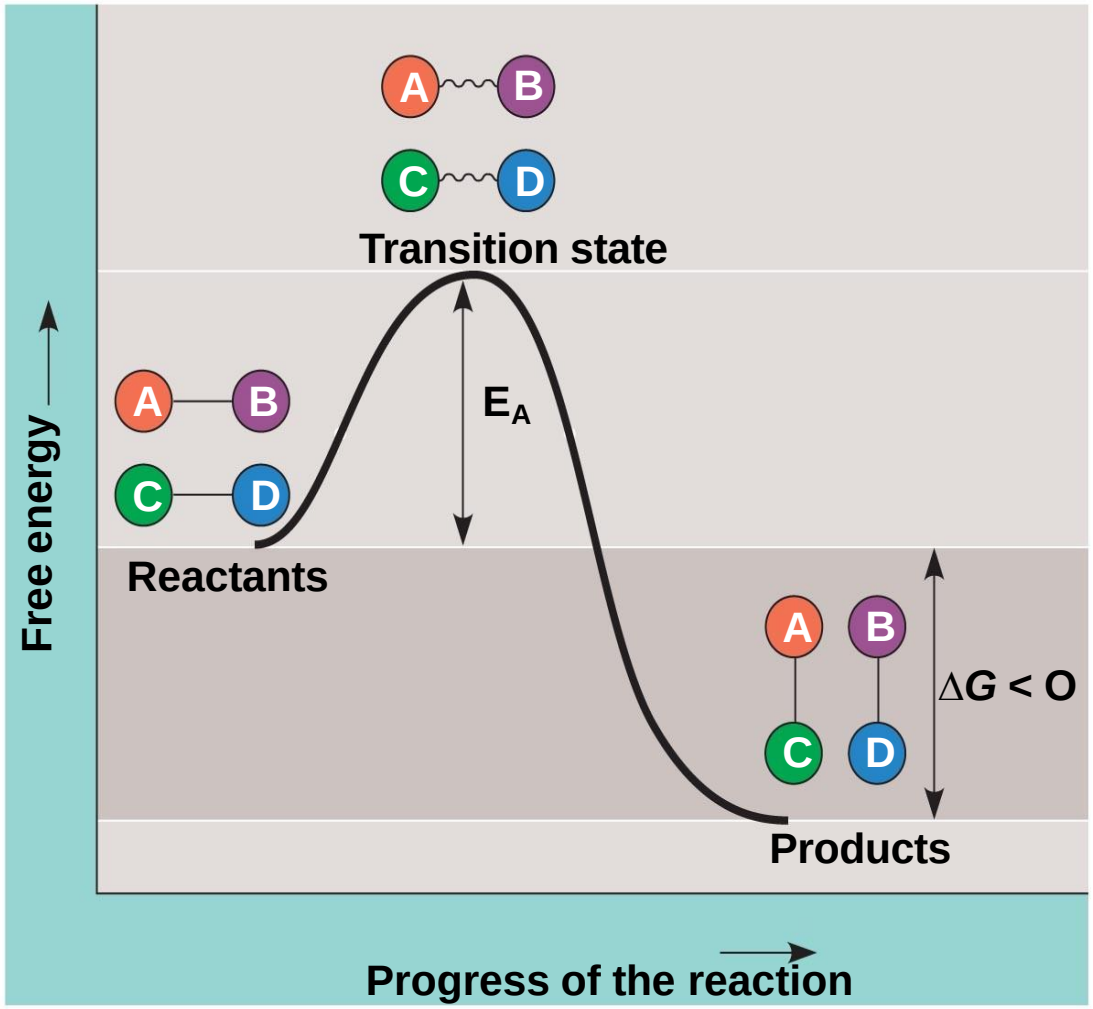
Metabolic Pathways



How do chemical reactions occur?

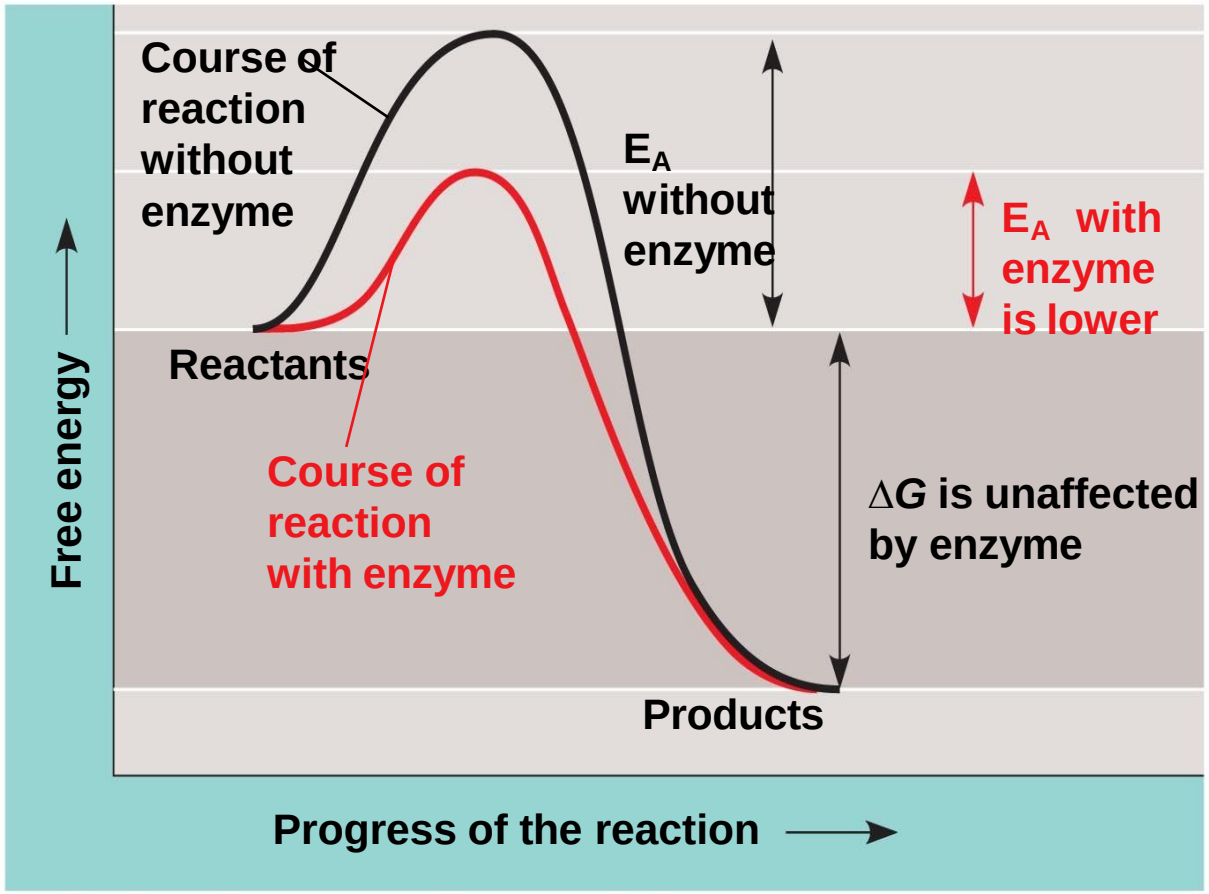
- The **collision theory-** chemical reactions occur when atoms, ions, and molecules collide.
- **Activation energy-** to disrupt electronic configurations.
- Reaction rate related to **frequency of collisions**
- Reaction rate- increased by raising temperature or pressure or by catalysts such as **enzymes**.

- Activation energy
- Transition State
- Δ G

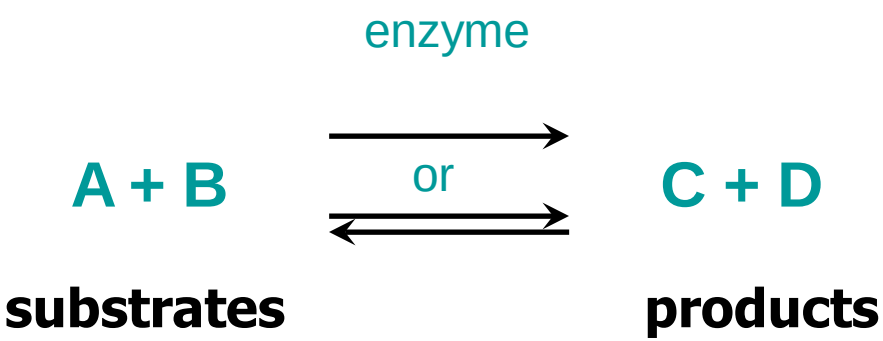


- Enzymes act by **lowering** the activation energy (E_A).
  - The transition state can then be reached even at moderate temperatures.

- Enzymes do not change ΔG.

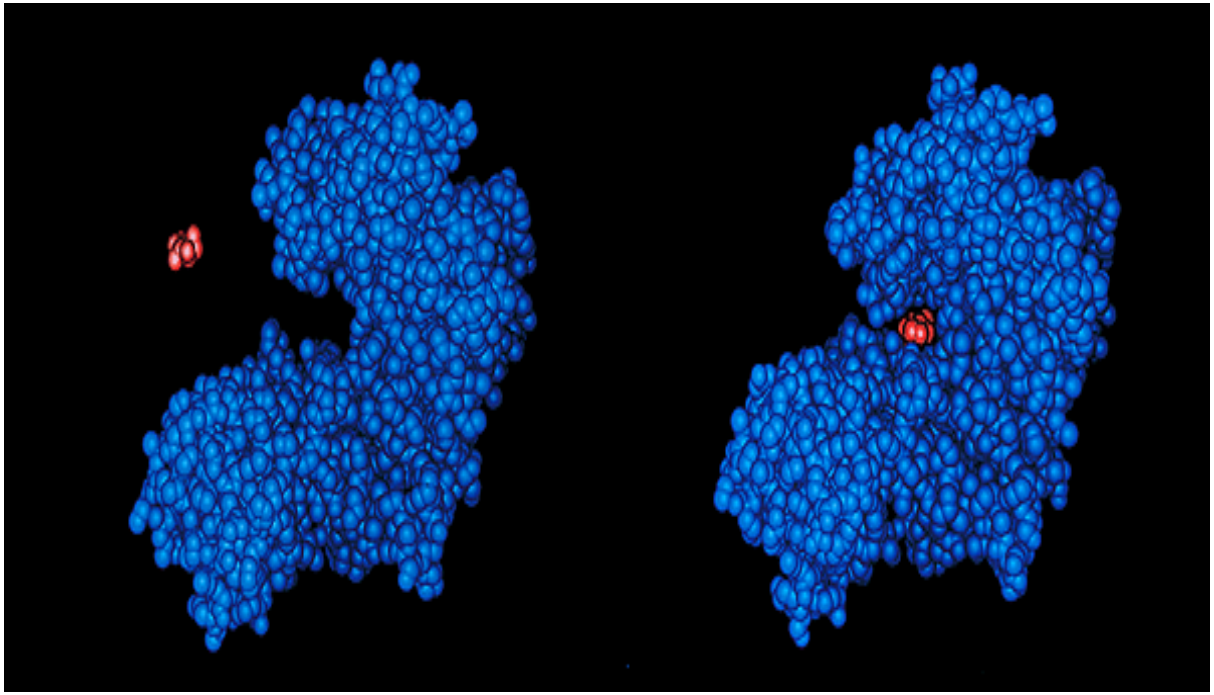


Biochemical reactions catalyzed by enzymes



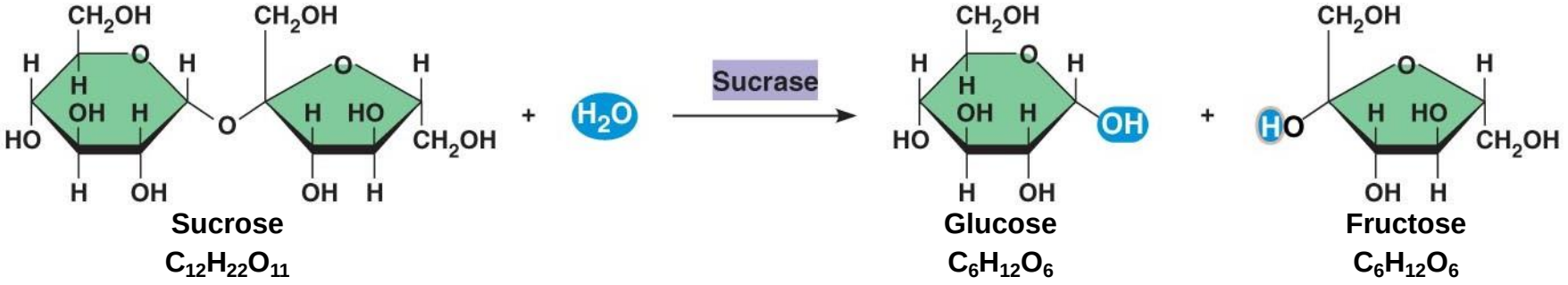
The tertiary or quaternary structure create an **active site**

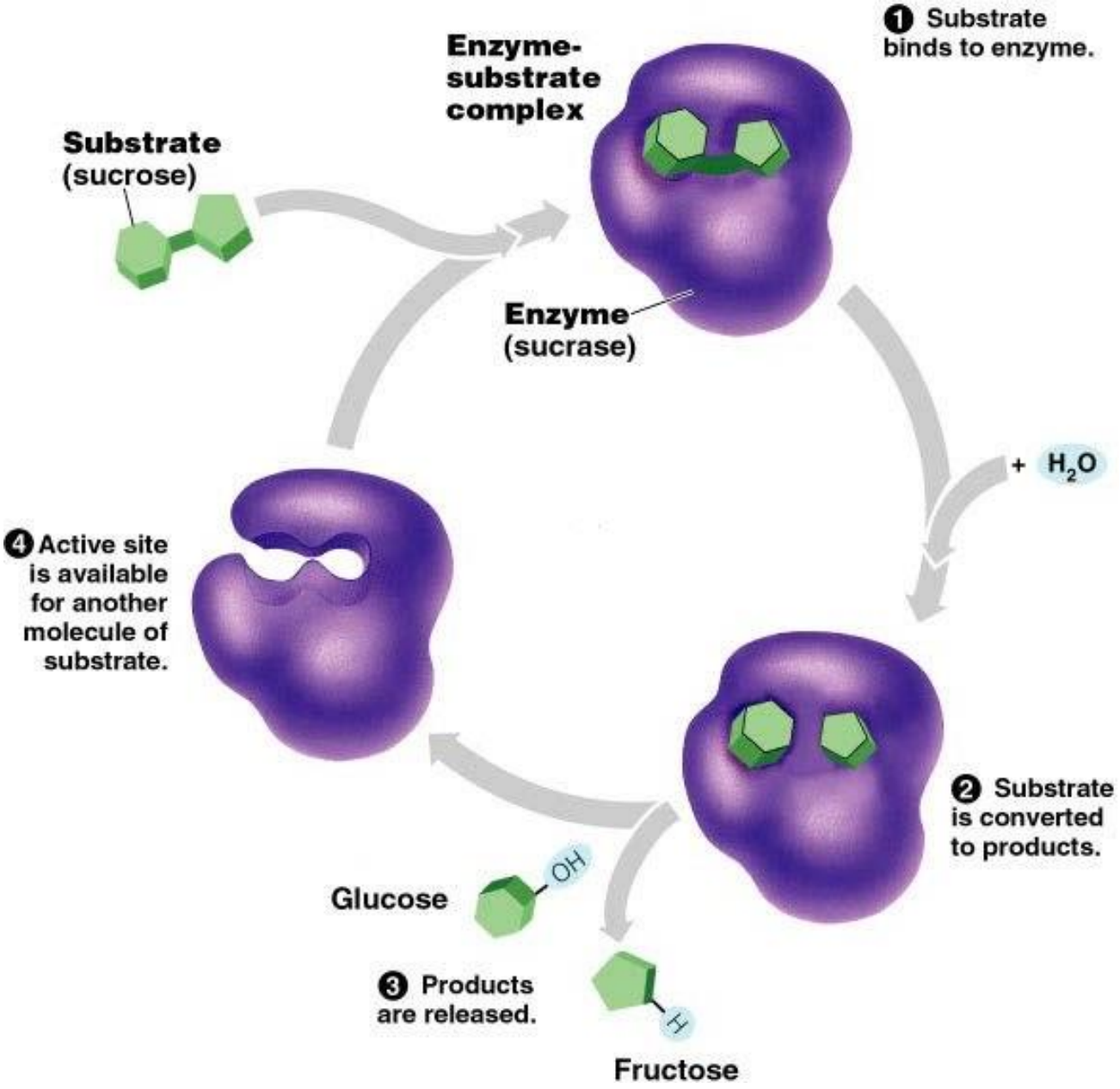
- **Substrates** fit into the active site and are held by hydrogen bonds and ionic bonds.
- **induced fit**



- Specificity of enzymes determined by “lock and key model”
- The turnover number is generally 1-10,000 molecules per second.
- The enzyme is recovered unchanged after the release of products.

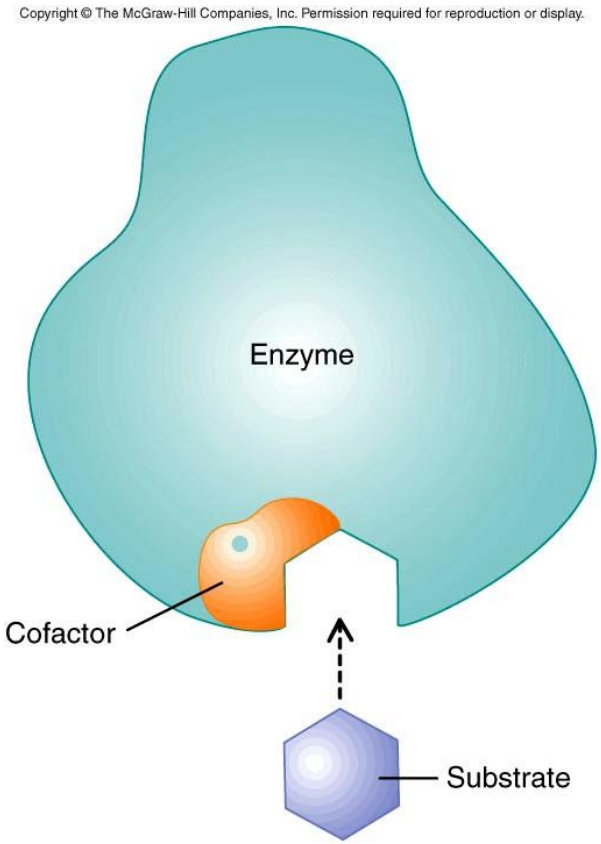
- **Enzymes**
  - proteins
  - substrate specific
  - names based on substrate ending with ***ase***.




1 Substrate binds to enzyme.
Enzyme-substrate complex
Substrate (sucrose)
Enzyme (sucrase)
+ H_2O
2 Substrate is converted to products.
Glucose
OH
3 Products are released.
H
Fructose
4 Active site is available for another molecule of substrate.

Non-protein helpers necessary for the activity of some enzymes

- **Co-factors**: inorganic elements or metals such as zinc, iron, and copper.



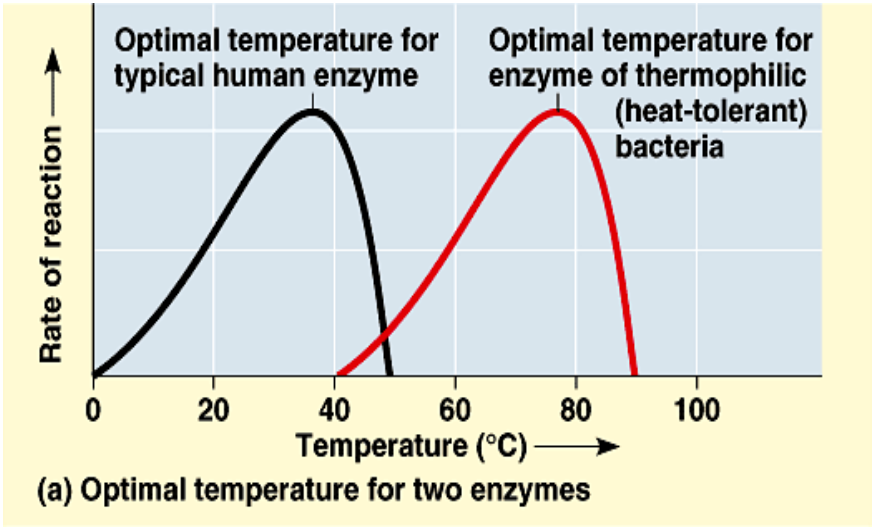
Holoenzyme: Apoenzyme + cofactor

Cellular organic molecules necessary for specific enzyme catalyzed biochemical reactions

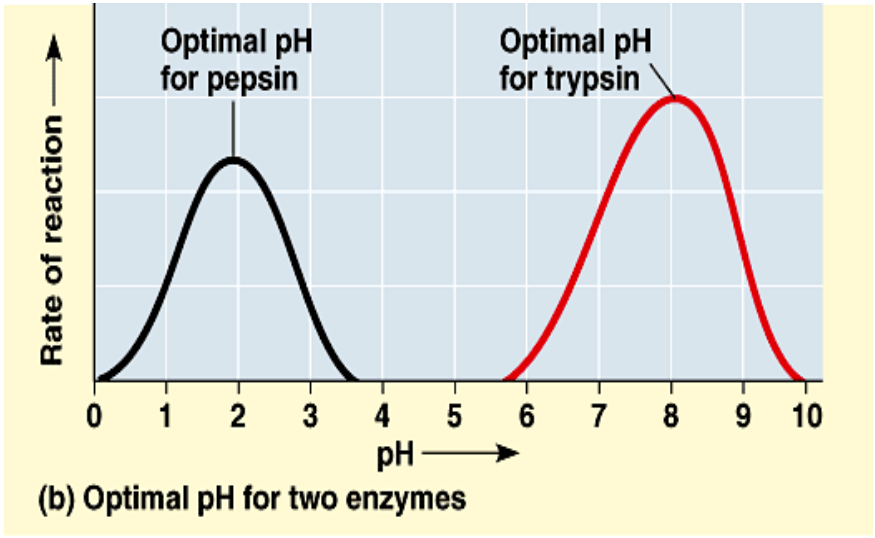
- Organic substrates needed for specific reactions

- **Co-enzymes**: organic molecules that resemble nucleotides, vitamins or molecules derived from vitamins

Factors affecting enzyme activity

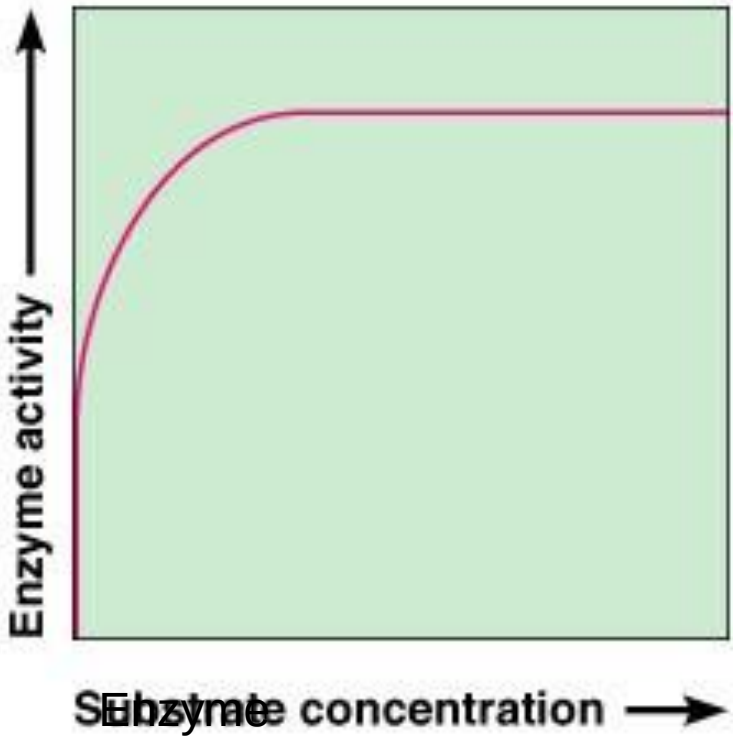


(a) Optimal temperature for two enzymes



(b) Optimal pH for two enzymes

Substrate concentration



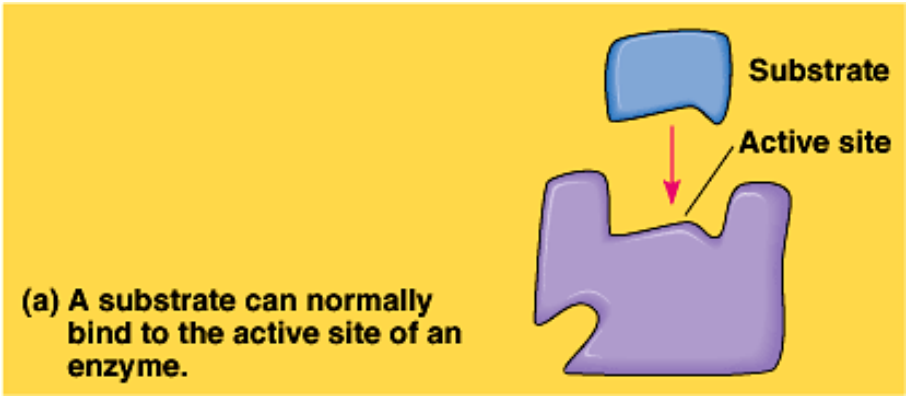
(c) Substrate concentration

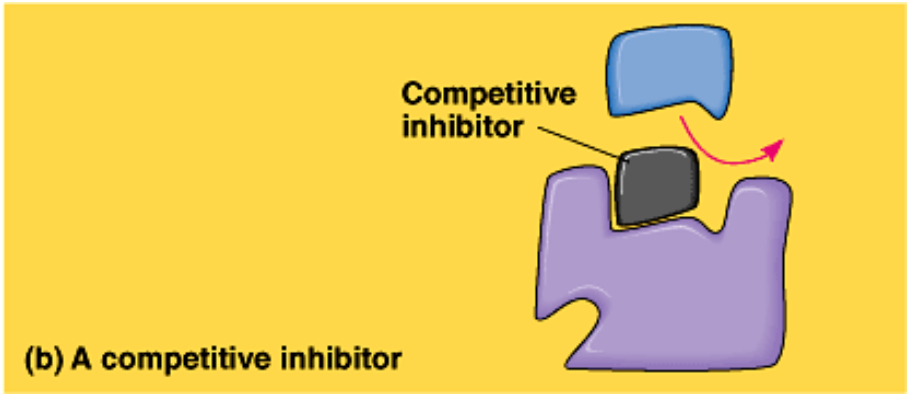
Maximal enzyme activity at substrate saturation of all active sites

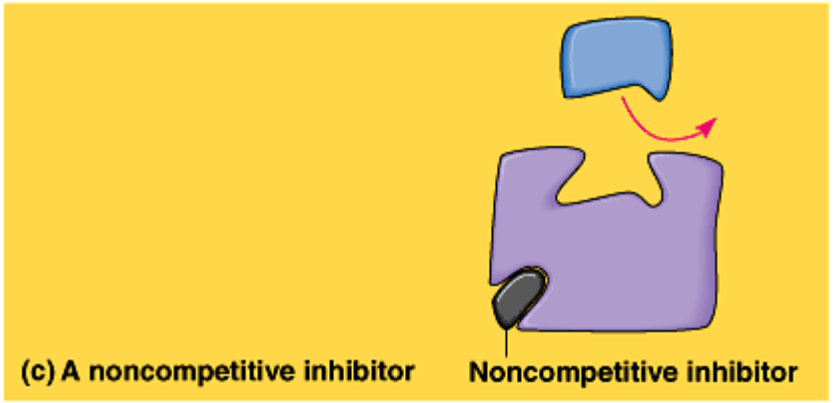
Inhibitors of enzyme activity

Competitive- bind to active site and prevent substrate binding.

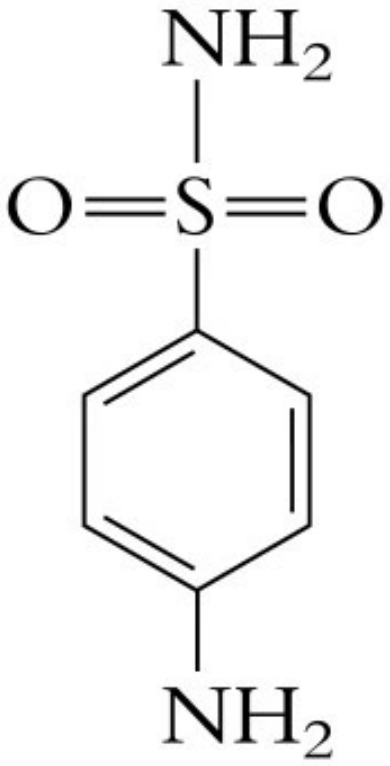
Non-competitive: bind to sites other than active site, change shape of active site preventing substrate from binding





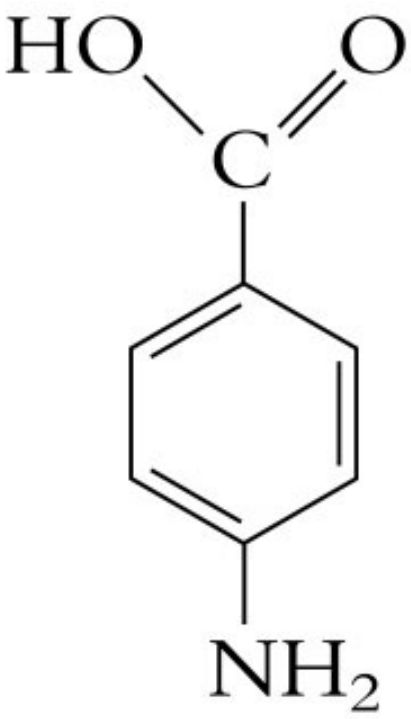


Example of a competitive inhibitor



Sulfanilamide

Sulfa drug



PABA

para-amino benzoic acid

Precursor of folic acid in bacteria

Aspirin

- Slows of blood clotting by inhibition of the enzyme cycloxygenase in blood platelets.
- Acts as an irreversible inhibitor of the cyclo-oxygenase

Feedback inhibition

http://www.mhhe.com/biosci/genbio/espv2/data/cells/004/index.html

Pathways and feedback inhibition

http://highered.mcgraw-hill.com/sites/0072437316/student_view0/chapter8/animations.html#

Thermodynamics

Study of energy transformations

System- the matter under study

Surroundings- everything outside the system

- *Closed systems*
- *Open systems*

Energy transformations and the laws of thermodynamics

First law: Energy is neither created nor destroyed, but it may change forms.

Second Law: Every energy transformation must make the universe more disordered.

Energy transfer from one form to another is not 100% efficient.

- Some energy is lost as heat, the energy or random motion.

- Entropy is the measure of disorder or randomness

Spontaneous process

- Occurs without outside help.
- Leads to decrease in free energy of system

  delta **G = G $_{\text{final state}}$ - G $_{\text{starting state}}$**

  Δ G must be **negative**.

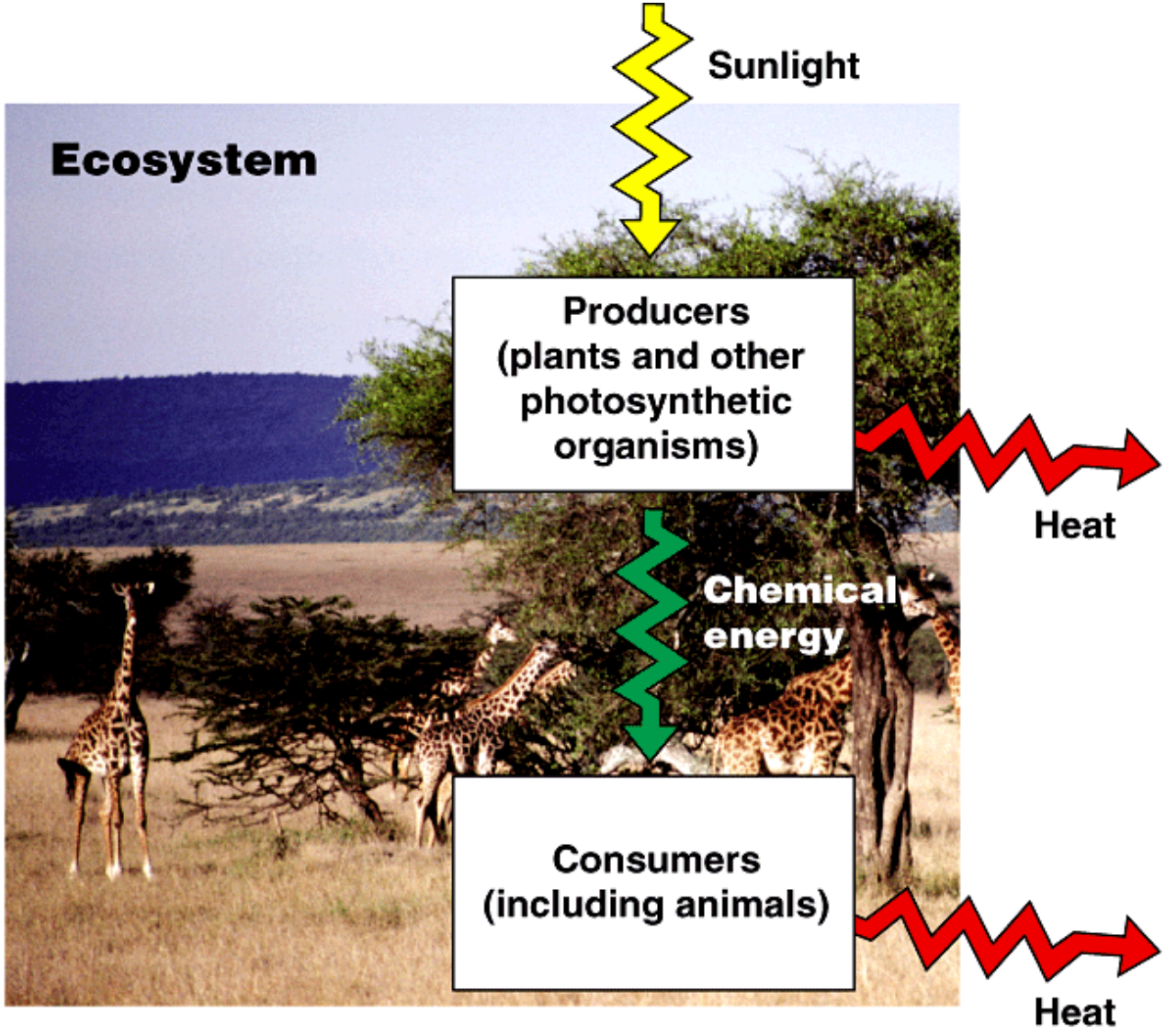
Equilibrium

- A system at equilibrium is at maximum stability

  $\Delta G = 0$ and the system can do no work.

Non-spontaneous Process

- Movement away from equilibrium requires the addition of energy from an outside energy source (the surroundings).



Heat is the energy of random motion

A central property of living organisms is the ability to metabolize i.e. to transform energy

Metabolism and Energy transformation

- **Photosynthesis** transforms energy of light into chemical energy in organic molecules.
- **Cellular respiration** and breakdown pathways release energy stored in sugar and other complex molecules.
- Energy available for cellular work

Three kinds of cellular work that require energy

- ***Mechanical work:***
  - cilia, contraction of muscle.
- ***Transport work***
  - pumping substances across membranes against the direction of spontaneous movement
- ***Chemical work***
  - driving endergonic reactions (example, synthesis of polymers from monomers)

The currency of energy for immediate cellular work is **ATP**

Exergonic	Endergonic
spontaneous	non-spontaneous
Releases free energy	store energy from surroundings

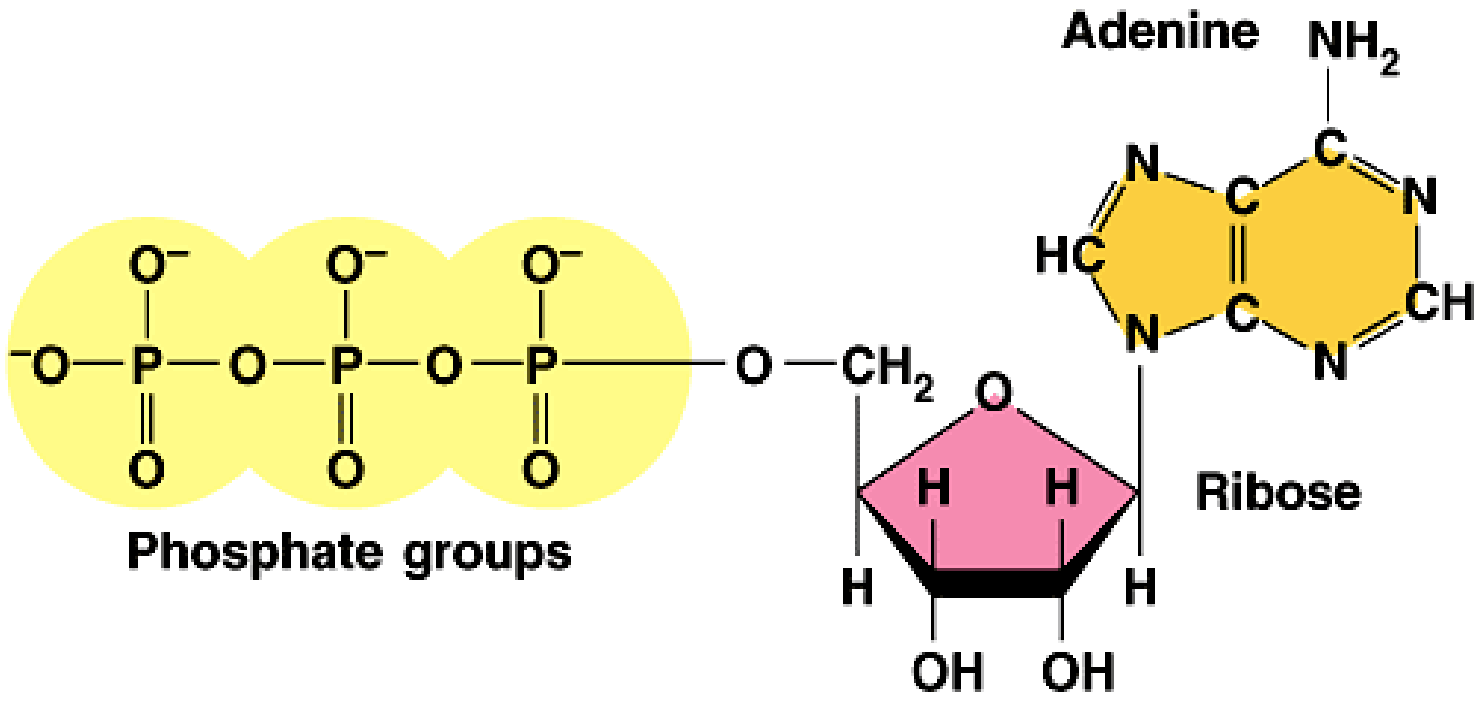
Energy coupling:

Cells use exergonic reactions to fuel endergonic reactions

ATP is a nucleotide

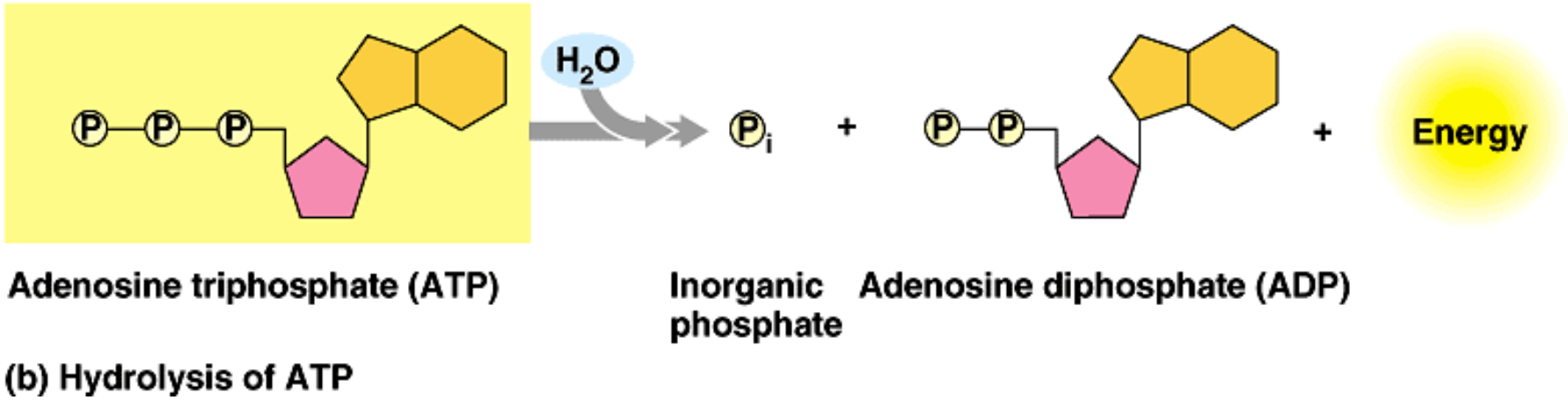
Nucleoside/Adenosine

Nucleotide



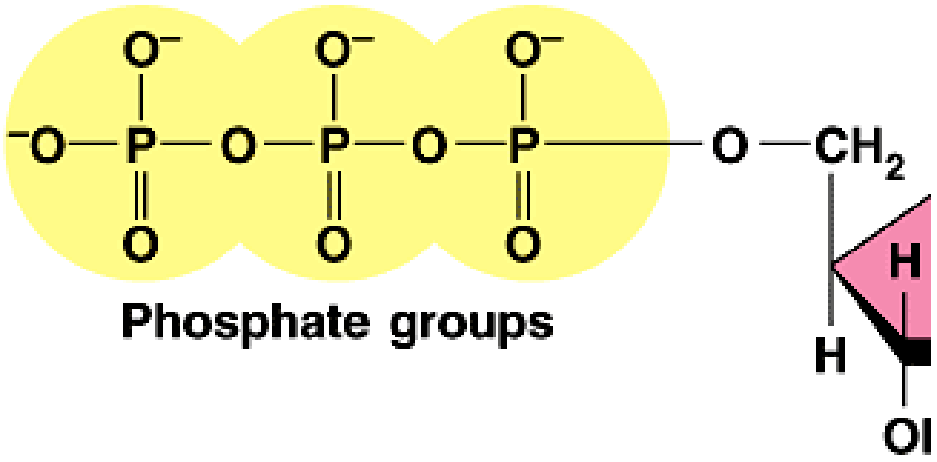
(a) Structure of adenosine triphosphate ATP

Hydrolysis of ATP



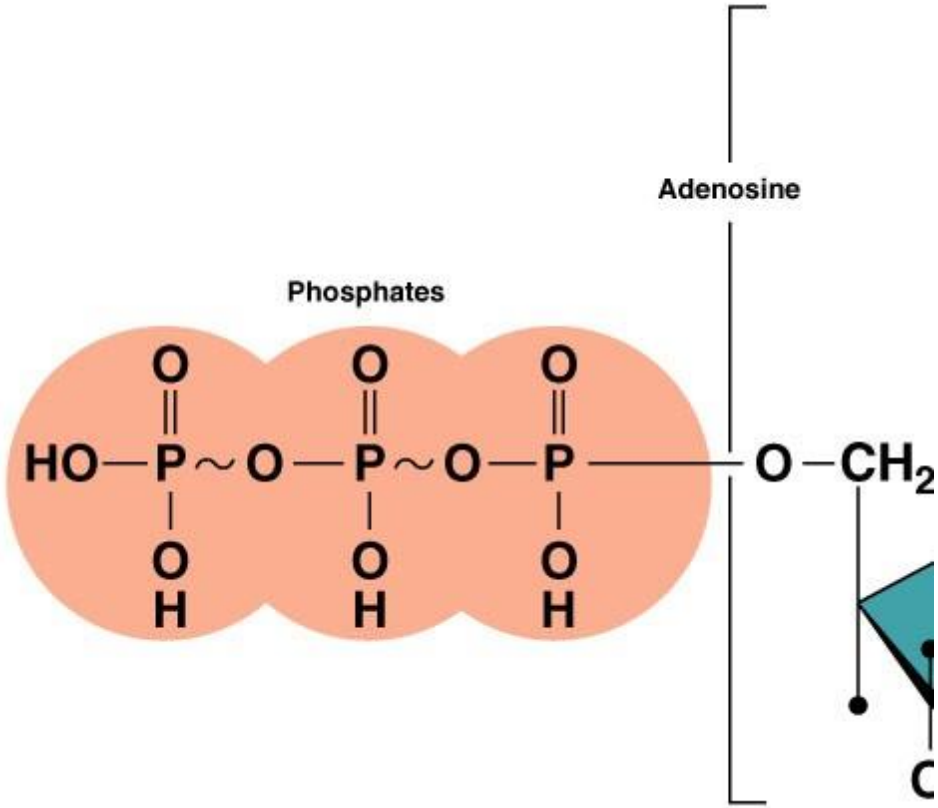
(b) Hydrolysis of ATP

The energy of ATP lies in the bonds between its phosphate groups

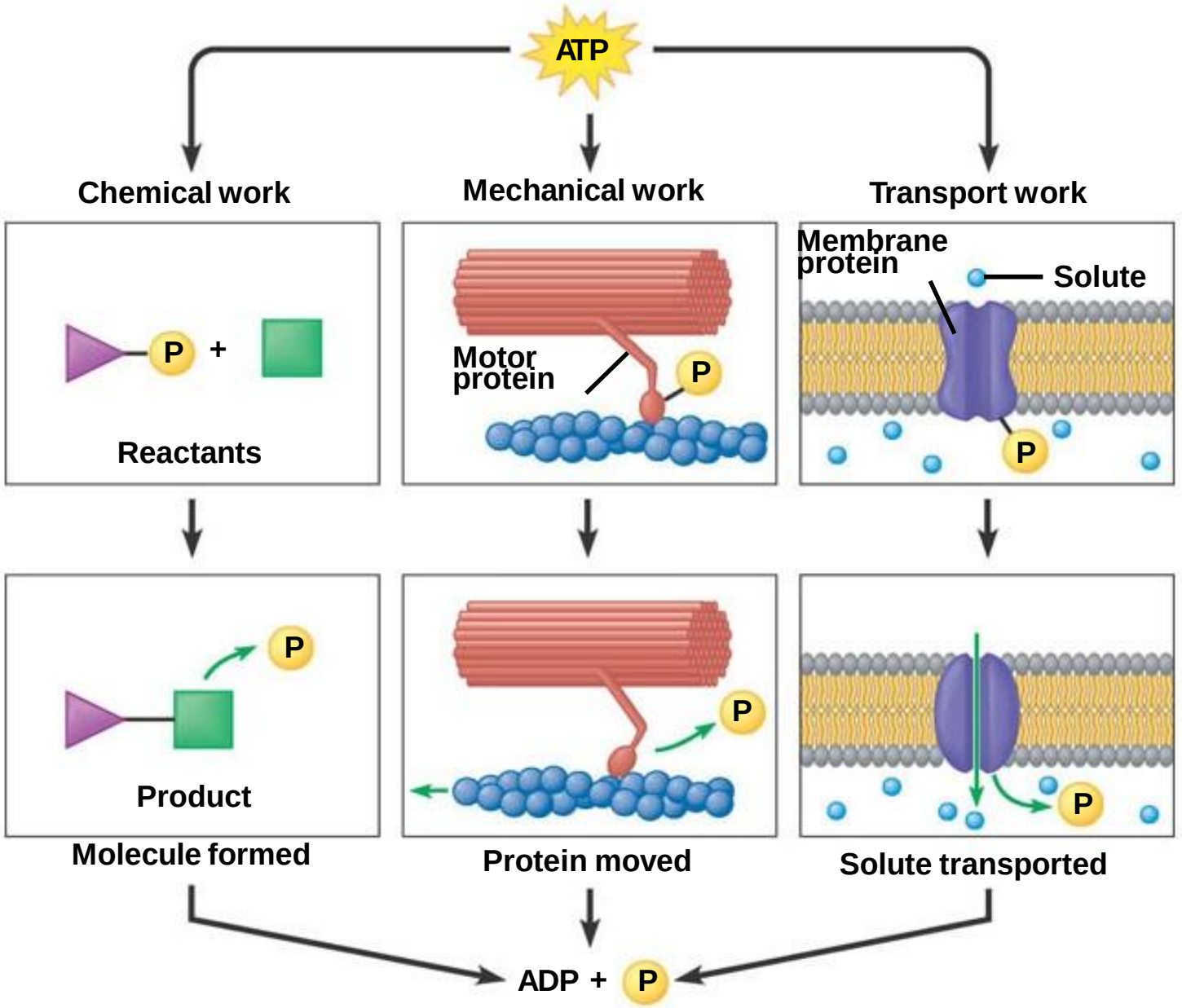


(a) Structure of adenosine triphospl

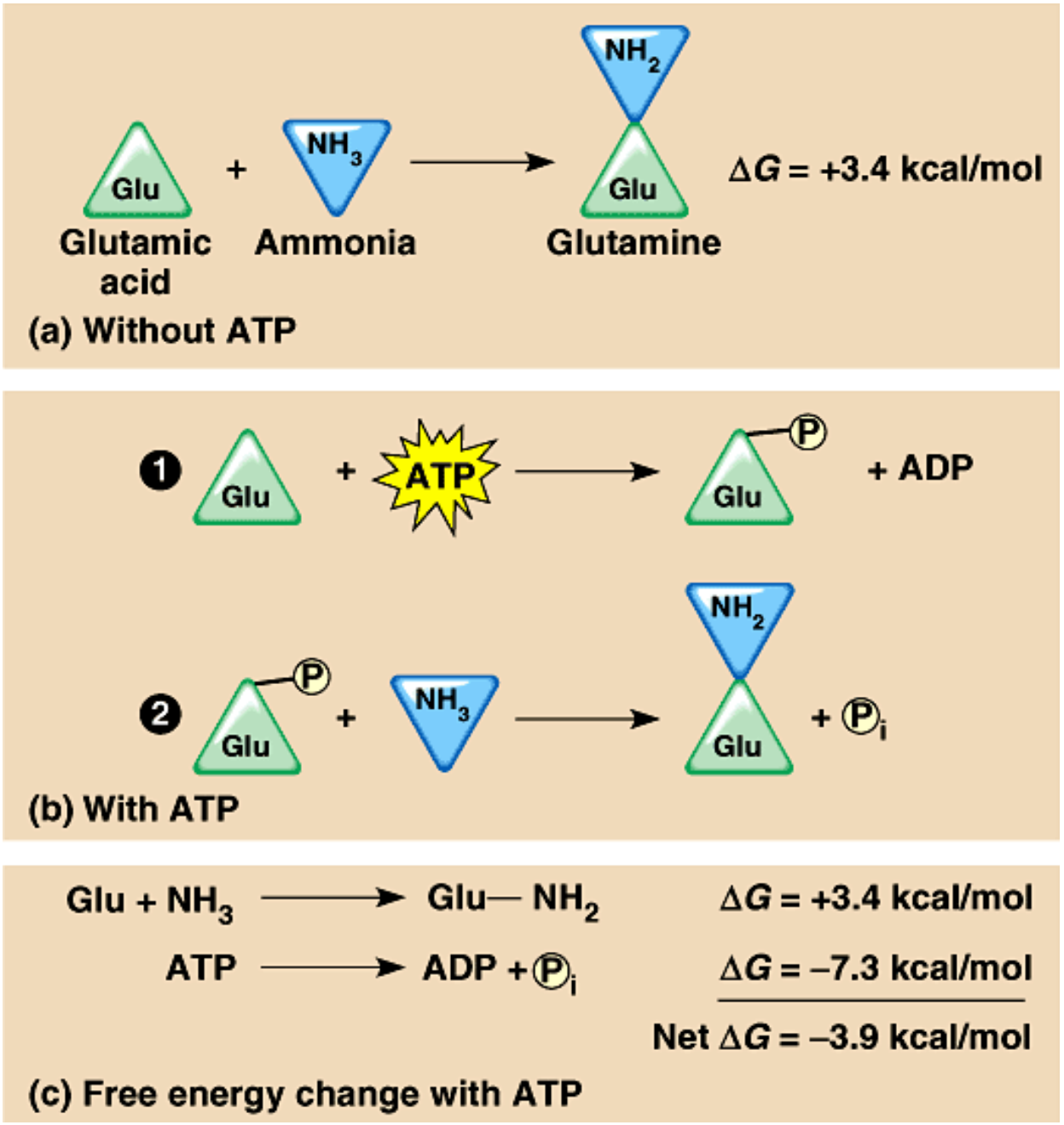
High-energy phosphate bonds that are actually fairly weak covalent bonds.



ATP drives endergonic reactions by phosphorylation



Coupling to ATP hydrolysis drives endergonic reaction that synthesizes glutamine from glutamic acid through the transfer of a phosphate group from ATP

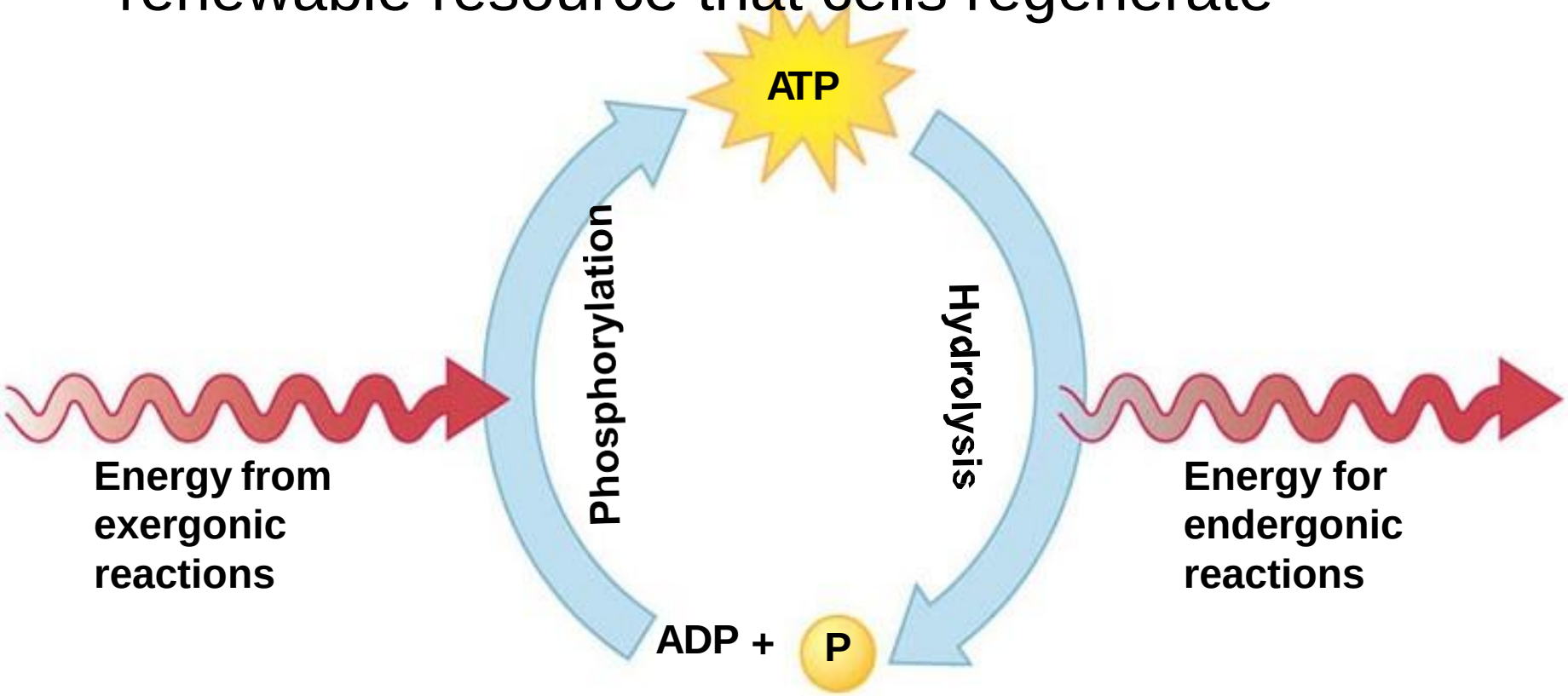


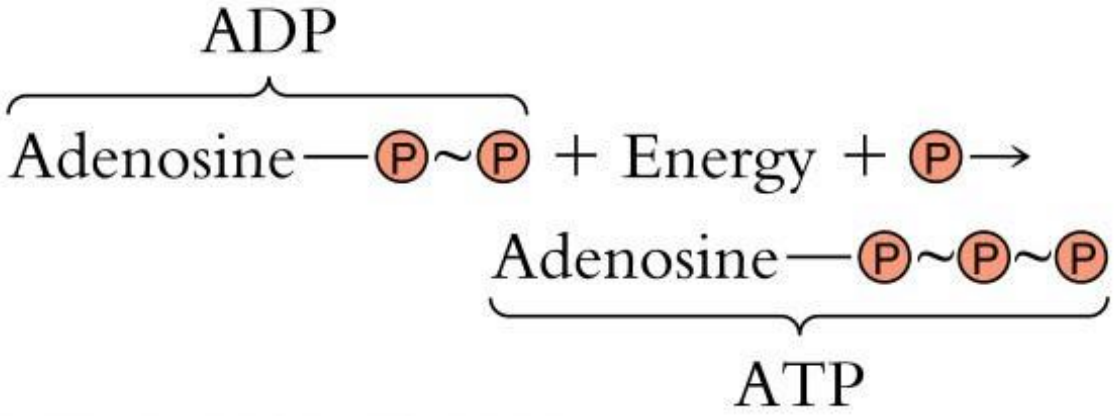
In the cell, the energy from the hydrolysis of ATP is coupled directly to endergonic processes by transferring the phosphate group to another molecule.

- This molecule becomes **phosphorylated**
- A phosphorylated molecules has a higher free energy and is now more reactive.

Activity: Chemical Reactions and ATP

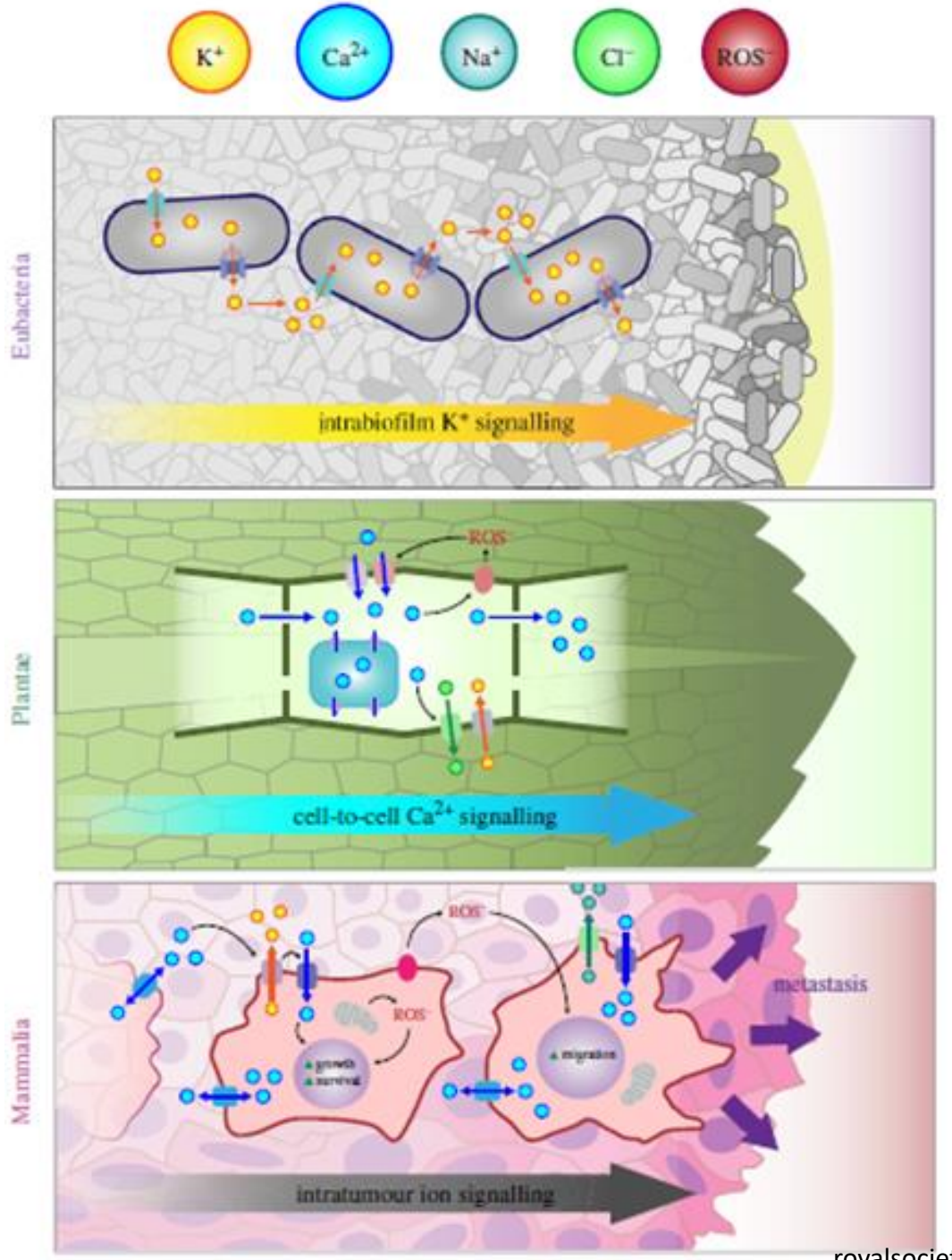
Cellular work can be sustained because ATP is a renewable resource that cells regenerate





delta G = 7.3 kcal/mol

Bioelectrical and Engineering of Cell Biology

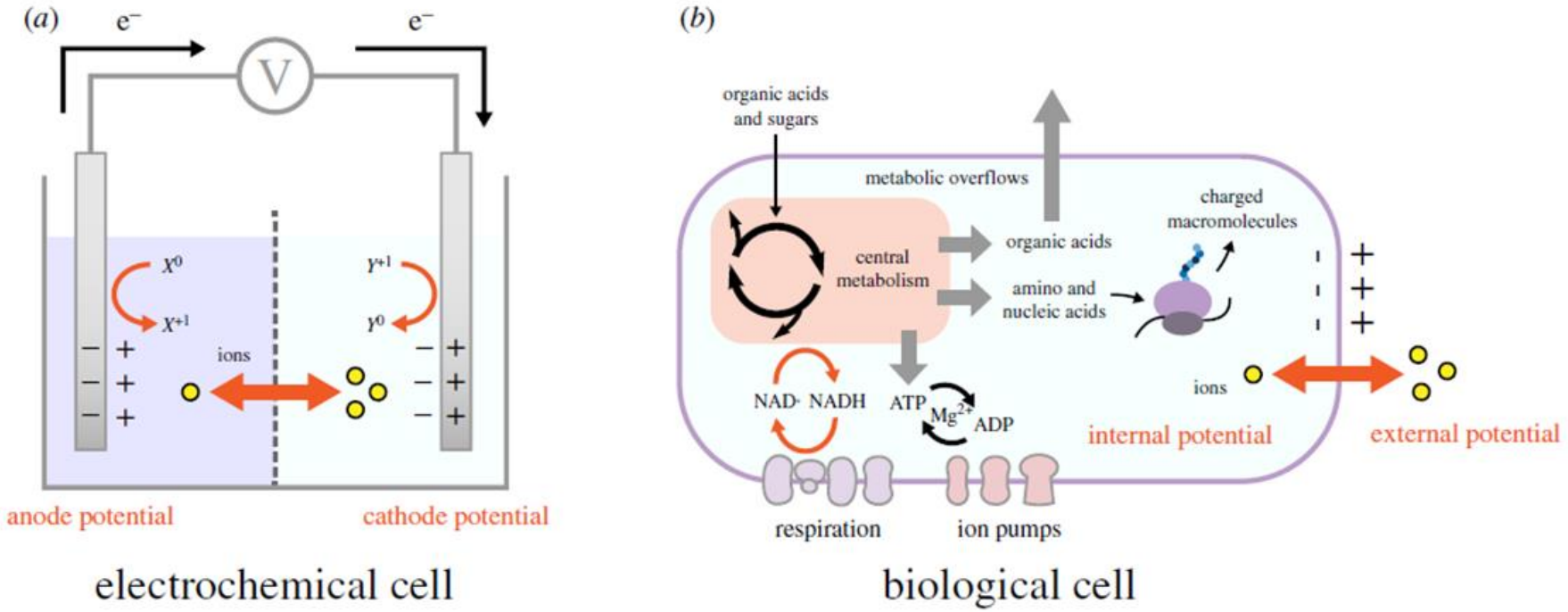


Recent research shows that both prokaryotes and eukaryotes use:

ion- and redox- `based electrochemical signals for communication.

It has been shown that such communication enables the organization of growth and developmental processes across multiple length scales.

The Cell Bioelectrical Nature



Both systems rely on ion flows and redox reactions across interfaces.

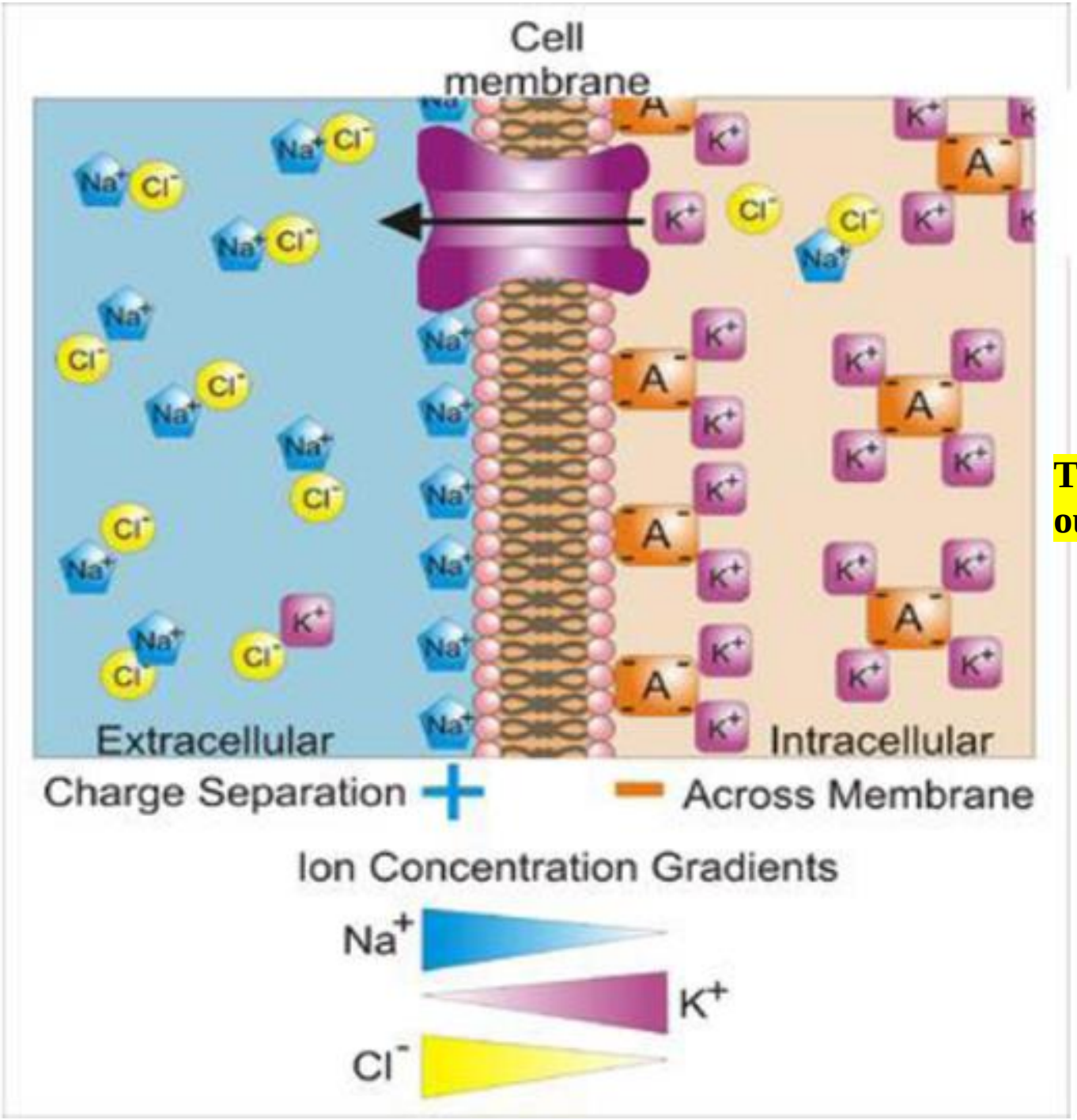
royalsocietypublishing.org/journal/rsif J. R. Soc. Interface 17: 20200013

The Nature of Bioelectricity

Bioelectricity is fundamental to all of life's processes.

We need to understand how bioelectricity is generated, **propagated**, and **optimally measured**.

Bioelectricity is a cellular phenomenon. Every living cell has a membrane potential (of about **-70mV**), with the inside of the cell being **negative** relative to its external surface.



The concentrations of ions outside and inside the cell.

Energy Equilibrium:

Equilibrium between the concentration gradient and the Coulomb force

Nernst equation:

Energy balance equation that describes the voltage that will be created by the difference in concentration, **BUT** this equation only for a membrane that is permeable to a single type of ion perfect and perfect is not permeable to all other ions.

$$V = V_{in} - V_{out} = -2,30\frac{KT}{Ze}\left(\log C_{in} - \log C_{out}\right)$$

V is the potential difference (**Vin** minus **Vout**)
Cin and **Cout** are the concentrations of ions to which the membrane is permeable,
k is Boltzmann's constant,
T is the absolute temperature,
Ze is the charge on the ion multiplied by the electron charge (Z is valence ions).

The minus sign indicates that the excess positive ions can diffuse in the fluid inside the cell produces a negative voltage in the cell. The most important aspect is that the Nernst equation potential difference is proportional to the concentration difference.

Example 10.1:

Calculate the potential of the membrane to K+ ions at a temperature of 310 K, if the concentration of K+ ions inside the cell is 140 mol/m3 and outside the cell is 10 mol/m3. Boltzmaan constant k = 1.38 × 10-23 J / K. K+ ion charge is e = 1.60 × 10-19 C.

Completion:

We use equation (10.1) with z = 1, in order to obtain

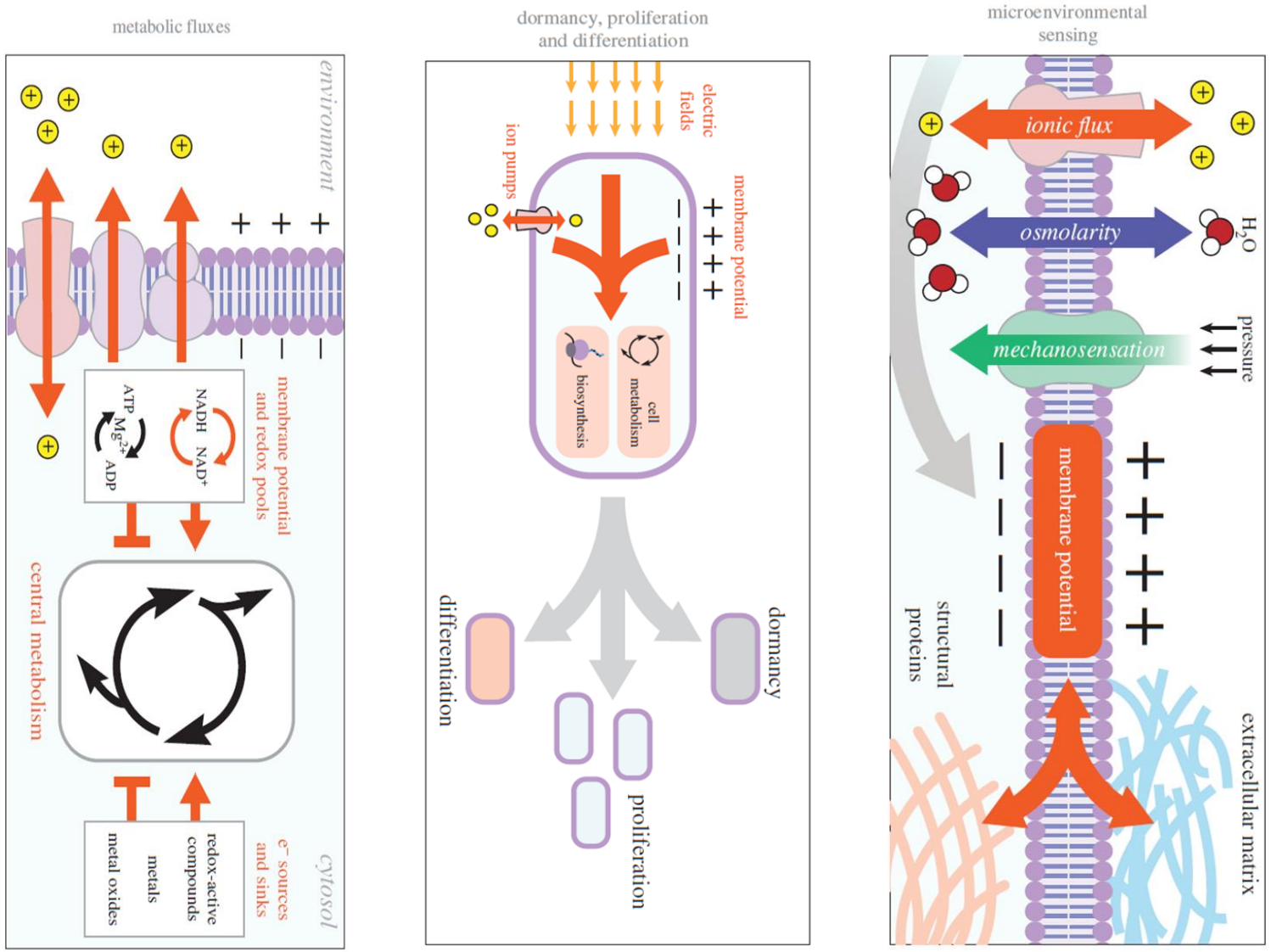
$$V = V_{in} - V_{out} = -2,30\frac{kT}{Ze}(\log C_{in} - \log C_{out})$$

$$V = -2,30\frac{(1,38\times10^{-23}\,J/K)(310K)}{(1)(1,60\times10^{-19}\,C)}(\log 140\ mol/m^3 - \log 5\ mol/m^3)$$

$$V = (-614,9625\times10^{-4})(1,447158032)\ volt$$

$$V = -88,9947921\times10^{-3}\ volt$$

$$V = -89\ mV.$$



Cartoon illustration of the coupling between the bioelectrical nature of the cell, in particular membrane potential (MP) and ion motive forces, IMFs (IMFs), and higher level cellular behaviors.

Activation energy: the amount of initial energy necessary for reactions to occur

Active site: a specific region on the enzyme where the substrate binds

Allosteric inhibition: the mechanism for inhibiting enzyme action in which a regulatory molecule binds to a second site (not the active site) and initiates a conformation change in the active site, preventing binding with the substrate

Anabolic: describes the pathway that requires a net energy input to synthesize complex molecules from simpler ones

Bioenergetics: the concept of energy flow through living systems

Catabolic: describes the pathway in which complex molecules are broken down into simpler ones, yielding energy as an additional product of the reaction

Competitive inhibition: a general mechanism of enzyme activity regulation in which a molecule other than the enzyme's substrate is able to bind the active site and prevent the substrate itself from binding, thus inhibiting the overall rate of reaction for the enzyme

Endergonic: describes a chemical reaction that results in products that store more chemical potential energy than the reactants

Enzyme: a molecule that catalyzes a biochemical reaction

Exergonic: describes a chemical reaction that results in products with less chemical potential energy than the reactants, plus the release of free energy

Feedback inhibition: a mechanism of enzyme activity regulation in which the product of a reaction or the final product of a series of sequential reactions inhibits an enzyme for an earlier step in the reaction series

Heat energy: the energy transferred from one system to another that is not work

Kinetic energy: the type of energy associated with objects in motion

Metabolism: all the chemical reactions that take place inside cells, including those that use energy and those that release energy

Noncompetitive inhibition: a general mechanism of enzyme activity regulation in which a regulatory molecule binds to a site other than the active site and prevents the active site from binding the substrate; thus, the inhibitor molecule does not compete with the substrate for the active site; allosteric inhibition is a form of noncompetitive inhibition

Potential energy: the type of energy that refers to the potential to do work

Substrate: a molecule on which the enzyme acts

Thermodynamics: the science of the relationships between heat, energy, and work

Energy and Metabolism

https://opentextbc.ca/biology/chapter/4-1-energy-and-metabolism/

Thank you