

# Bioenergetics

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**Bioenergetics**

1. Potential and kinetic energy
2. Laws of thermodynamics
3. Gibbs free energy
4. Exergonic and endergonic reactions
5. High energy compounds
6. Energy coupling

# Bioenergetics

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- **Bioenergetics** describes the **transfer** and **utilization** of **energy** in biologic systems.
- It concerns the initial and final energy states of the reaction components, not the reaction mechanism or how much time it takes for the chemical change to occur.
- Bioenergetics predicts if a process is possible, whereas kinetics measures the reaction rate.

# Definitions

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- **Thermodynamics:** discipline of physical chemistry that deals with the energy transformation between a system and its surroundings
- **Bioenergetics:** is the application of thermodynamics to biological systems
  - mainly deals with the study of energy changes during biochemical reactions taking place inside the body

# Laws of thermodynamics

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Law of thermodynamics applied to living organisms

- The **first law** is the principle of the conservation of energy: for any physical or chemical change, the total amount of energy in the universe remains constant; energy may change form, or it may be transported from one region to another, but it cannot be created or destroyed.
- The **second law** of thermodynamics, which can be stated in several forms, says that the universe always tends toward increasing disorder: in all natural processes, the entropy of the universe increases.

# Energy Changes

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Three thermodynamic quantities that describe the energy changes occurring in a chemical reaction:

1. **Free energy, G** ( $\Delta G = \text{joules/mole}$ )
2. **Enthalpy, H** ( $\Delta H = \text{joules/mole}$ )
3. **Entropy, S** ( $\Delta S = \text{joules/mole} \cdot \text{K}$ )

**Neither** of these thermodynamic quantities by itself **is sufficient** to determine whether a chemical reaction will proceed spontaneously in the direction it is written.

However, when **combined mathematically**, **enthalpy and entropy can be used to define** a third quantity, free energy (G), which predicts the direction in which a reaction will spontaneously proceed.

# Free energy, G

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- Free energy, **G** (for J. Willard Gibbs), expresses the **amount** of **energy capable of doing work during a reaction** at constant temperature and pressure.
- When a reaction proceeds with the **release** of free energy (that is, when the system changes, so as to possess less free energy), the free energy change,  $\Delta G$ , has a **negative value** and the reaction is said to be **exergonic**.
- In **endergonic** reactions, the system **gains** free energy and  **$\Delta G$  is positive**.

# Enthalpy, H

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- Enthalpy, H, is the heat content of the reacting system.
- It reflects the **number** and kinds of **chemical bonds** (covalent and noncovalent) in the reactants and products.
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- When a chemical reaction **releases heat**, it is said to be **exothermic**; the **heat content of the products is less than that of the reactants**, and the change in enthalpy,  $\Delta H$ , has **a negative value**.
- Reacting systems that take up heat from their surroundings are endothermic and have **positive values of  $\Delta H$** .



# Entropy, S

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- Entropy, S, is a **quantitative expression for the randomness or disorder in a system.**
- When the **products** of a reacting system are **less complex** and **more disordered** than the **reactants**, the reaction is said to proceed with a **gain in entropy.**
- $\Delta S$  has a **positive sign** when entropy increases.

# Free Energy Change ( $\Delta G$ )

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$\Delta G$  is the change in free energy

$\Delta H$  is the enthalpy; a measure of the change in heat content of the reactant compared to the product

$\Delta S$  is entropy; a measure of the change in randomness or disorder of reactants and products

$T$  is the absolute temperature in Kelvin

\*In systems of constant pressure and volume, the value  $T\Delta S$  is the amount of energy dispersed and unavailable for work

## $\Delta G$ : CHANGE IN FREE ENERGY

- Energy available to do work
- Approaches zero as reaction proceeds to equilibrium
- Predicts whether a reaction is favorable

## $\Delta H$ : CHANGE IN ENTHALPY

- Heat released or absorbed during a reaction
- Does not predict whether a reaction is favorable

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

## $\Delta S$ : CHANGE IN ENTROPY

- Measure of randomness
- Does not predict whether a reaction is favorable

# $\Delta G$ and reaction direction

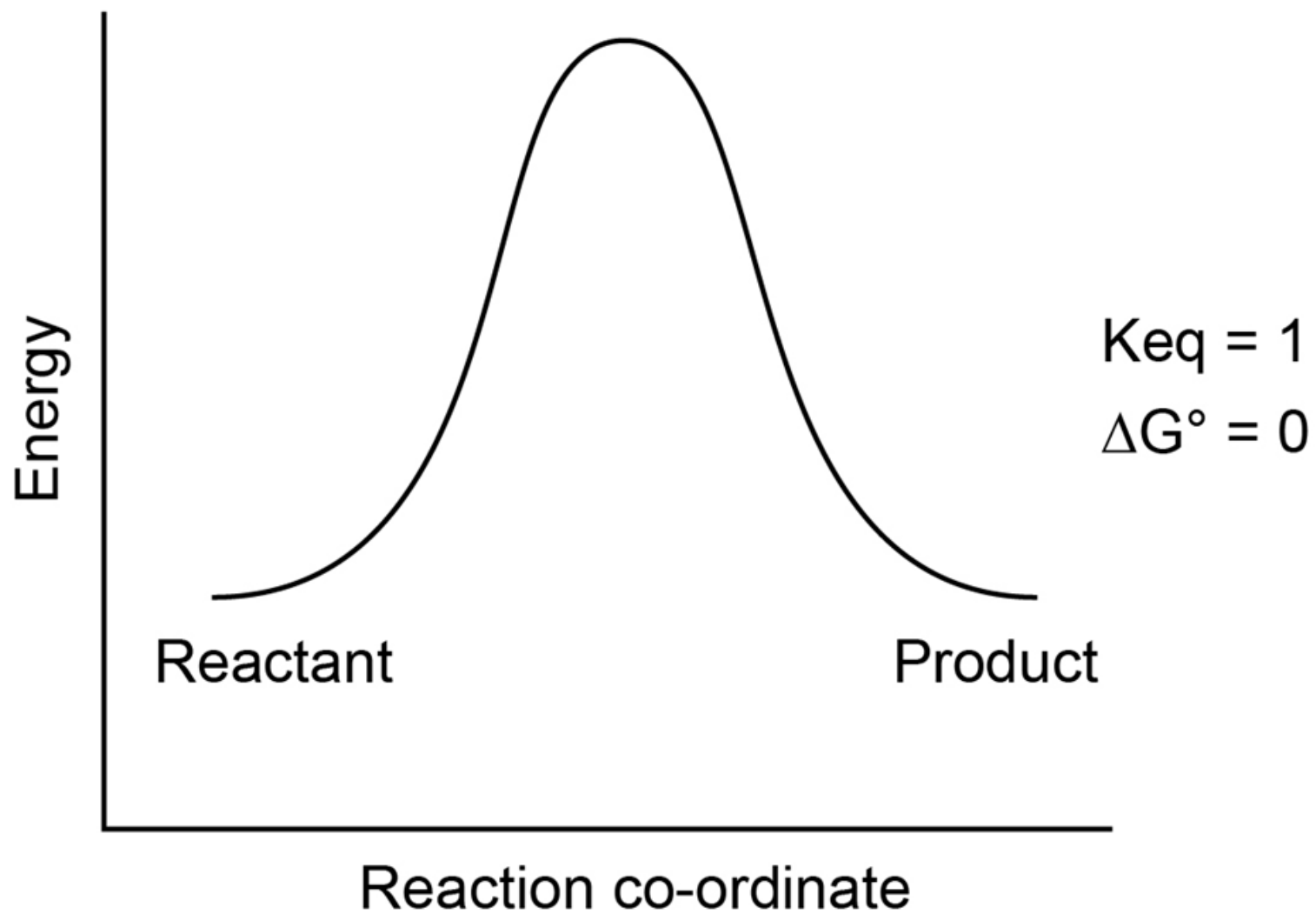


- When a reacting system is not at equilibrium, the tendency to move toward equilibrium represents a driving force, the magnitude of which can be expressed as the free-energy change for the reaction,  $\Delta G$ .
- The sign of  $\Delta G$  can be used to predict the direction of a reaction at constant temperature and pressure.
- The  $\Delta G$  of the reaction  $A \rightarrow B$ , depends on the concentration of the reactant and product.

# Keq and $\Delta G$

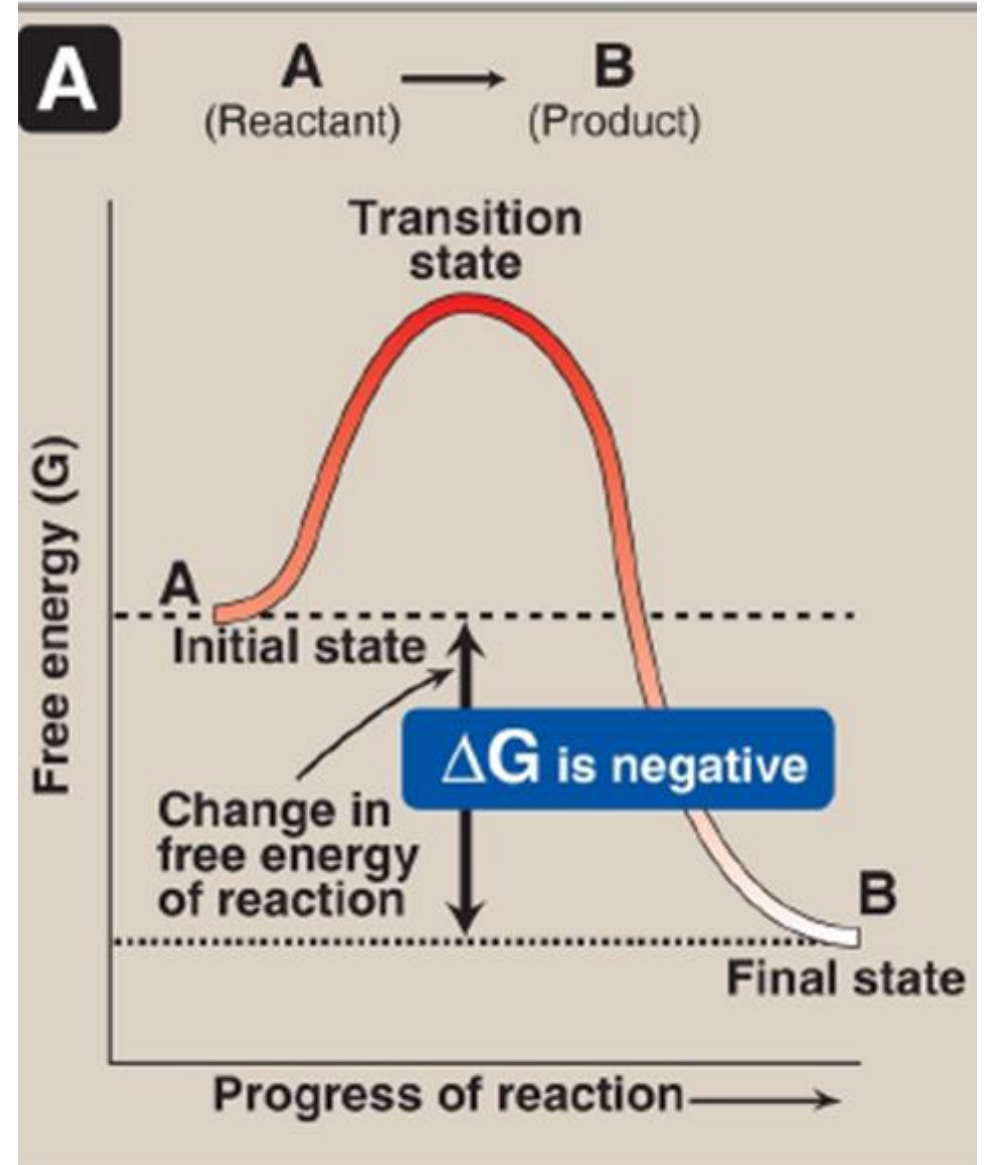
- The composition of a reacting system (a mixture of chemical reactants and products) tends to continue changing until equilibrium is reached.
- **In the case of an organism, equilibrium is reached only after death and complete decay.**
- At the equilibrium concentration of reactants and products, the rates of the forward and reverse reactions are exactly equal, and no further net change occurs in the system.
- The concentrations of reactants and products at equilibrium define the equilibrium constant, Keq (Keq=1).

If  $\Delta G$  is zero (Energy of Products = Energy of Reactants), the reaction is reversible and the reaction is at equilibrium; isothermic reaction



# Exergonic Reaction

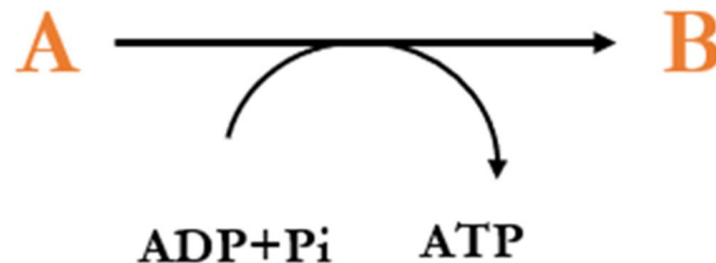
- $\Delta G$  is negative
- Net loss of energy
- Reaction goes spontaneously as written (that is, A is converted into B)



# Exergonic reactions

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- If  $\Delta G$  is negative, the products contain less free energy than the reactants  
(Energy of Products < Energy of Reactants)  
→ the reaction will proceed spontaneously under standard conditions → exergonic reaction
- The difference in the energy may be given up by the system as heat, work, etc.
- Termed catabolism: the breakdown or oxidation of fuel molecules



# Endergonic reactions

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- If  $\Delta G$  is positive (Energy of products  $>$  Energy of Reactants)  $\rightarrow$  **endergonic reaction**
- For this type of reaction to proceed, it is **coupled to another exergonic reaction** representing the source of required energy
- Synthetic reactions that build up substances (**anabolism**)

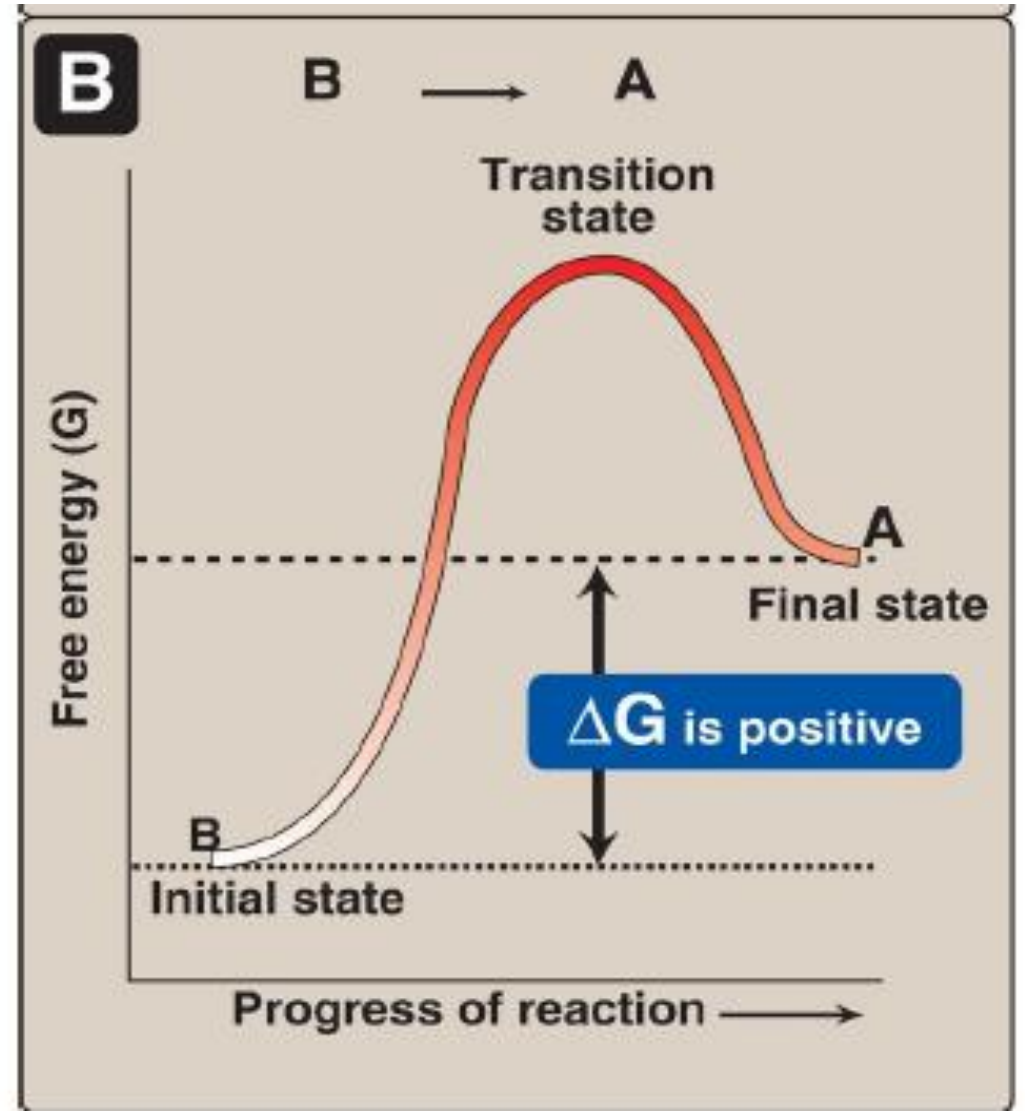




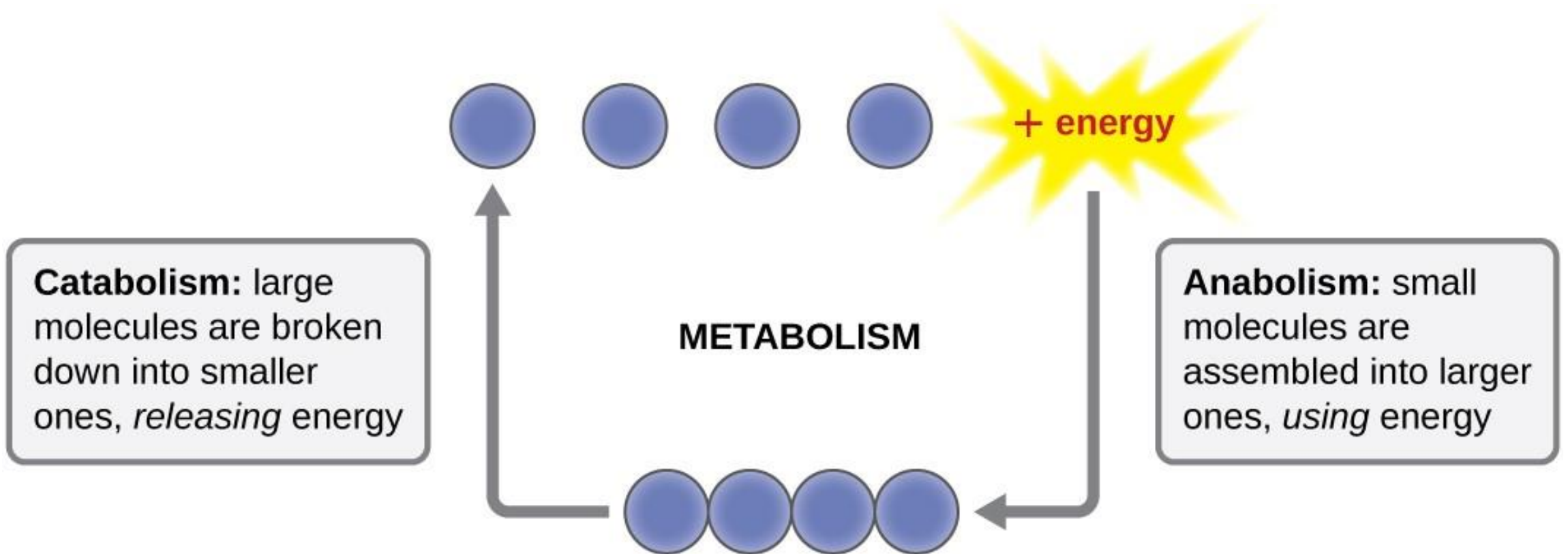
# Endergonic reactions

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- Net **gain** of energy
- The reaction **does not go spontaneously from B to A**
- Energy must be added to the system to make the reaction go from B to A.



- The combined catabolic and anabolic processes constitute metabolism

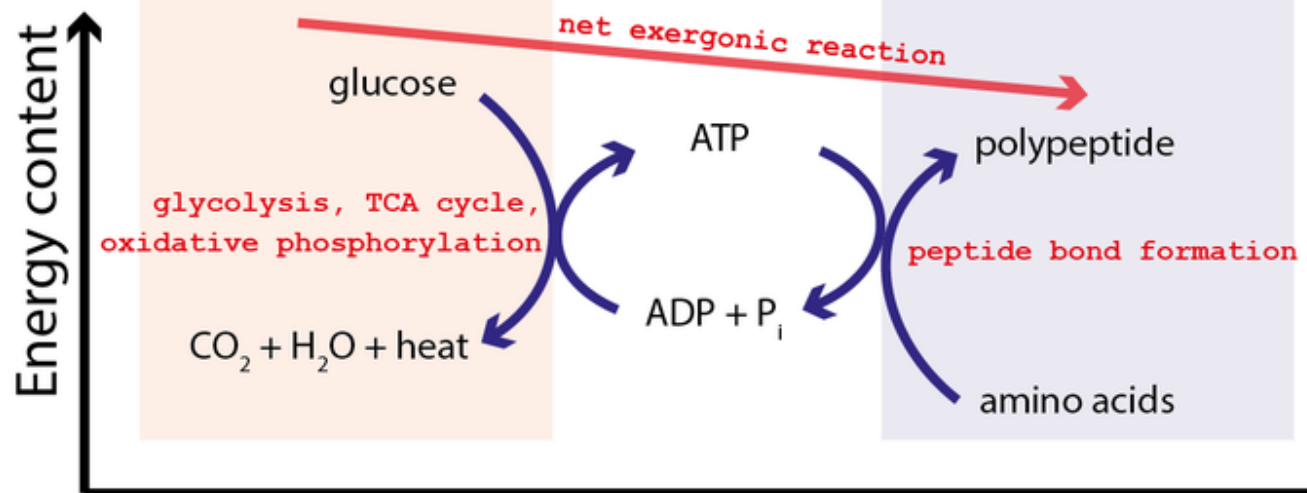
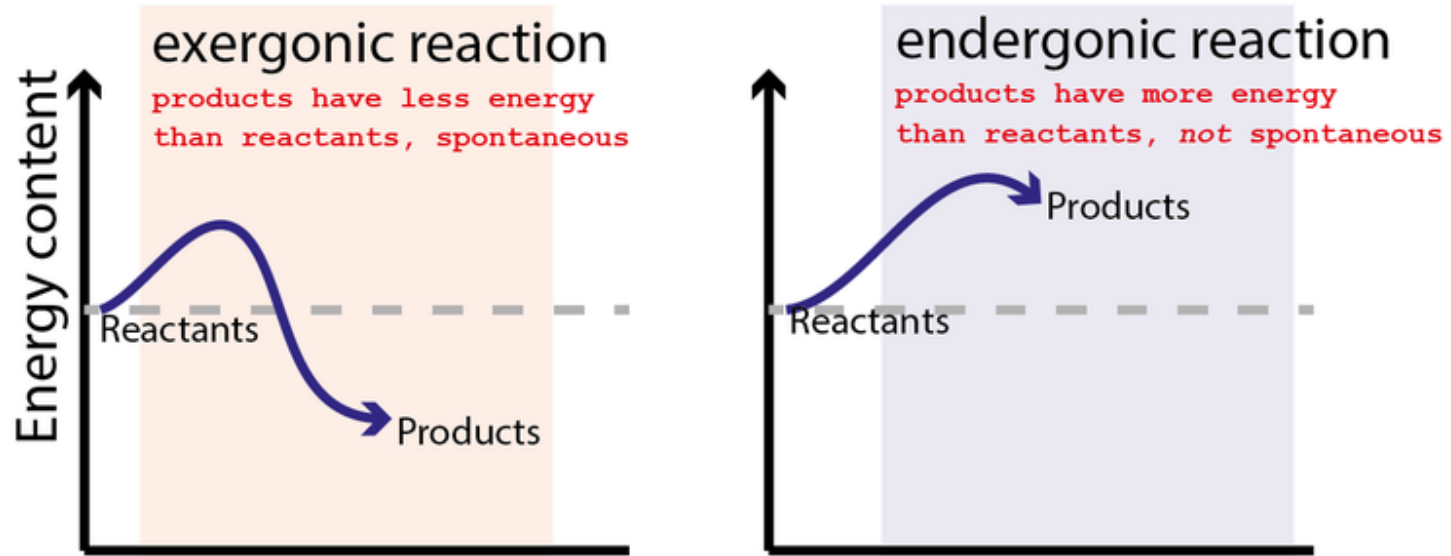


# Exergonic and endergonic reactions

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## Coupling between exergonic and endergonic reactions

- Generally, the reason for this coupling is to **energize** endergonic reactions on the expense of exergonic reactions
- In practice, an endergonic process cannot exist independently, but must be a component of a coupled exergonic– endergonic system where the overall net change is exergonic.
- The simplest example of energy coupling in biologic reactions occurs when the **energy-requiring and the energy-yielding reactions share a common intermediate.**



# Coupling mechanisms

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Endergonic process proceeded by coupling to exergonic processes

- The **overall process must be accompanied by the loss of free energy** (must be exergonic).
- In its **simplest form**, this type of coupling may be represented by:
  - The conversion of metabolite A to metabolite B occurring with release of free energy and is coupled to another reaction in which:
  - Free energy is required to convert metabolite C to metabolite D.

# ATP Coupling

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- Phosphorylation of glucose to glucose-6-phosphate, the first reaction of glycolysis.
  - Highly endergonic and cannot proceed under physiologic conditions.



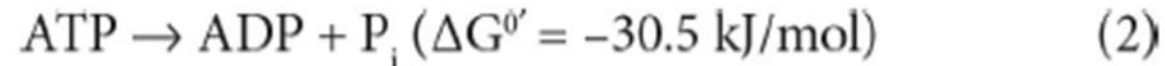
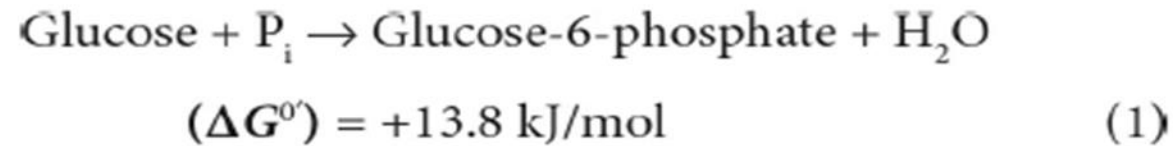
$$(\Delta G^{\circ}) = +13.8 \text{ kJ/mol} \quad (1)$$

- Thus, in order to take place, the **reaction must be coupled with another more exergonic reaction** such as the hydrolysis of ATP.

# ATP Coupling

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When (1) and (2) are coupled in a reaction catalyzed by **hexokinase**, phosphorylation of glucose readily proceeds in a **highly exergonic reaction** that under physiologic conditions is irreversible.



<i>(a)</i>				<u><math>G^{\circ\prime}</math> (kJ·mol<sup>-1</sup>)</u>
<b>Endergonic half-reaction 1</b>	$P_i + \text{glucose}$	$\rightleftharpoons$	$\text{glucose-6-P} + \text{H}_2\text{O}$	+13.8
<b>Exergonic half-reaction 2</b>	$\text{ATP} + \text{H}_2\text{O}$	$\rightleftharpoons$	$\text{ADP} + P_i$	-30.5
<hr/>				
<b>Overall coupled reaction</b>	$\text{ATP} + \text{glucose}$	$\rightleftharpoons$	$\text{ADP} + \text{glucose-6-P}$	-16.7



# High energy compounds

- Substances that release energy  $\geq$ ATP, including ATP (-7.3 kcal/mol).
- Substances that release energy lower than ATP are called **low** energy compounds (e.g. glycosidic bonds, peptide bonds, ester bonds).
- **ATP is the most important high energy molecule**; it is the energy currency of the cell.

# Synthesis of high energy compound

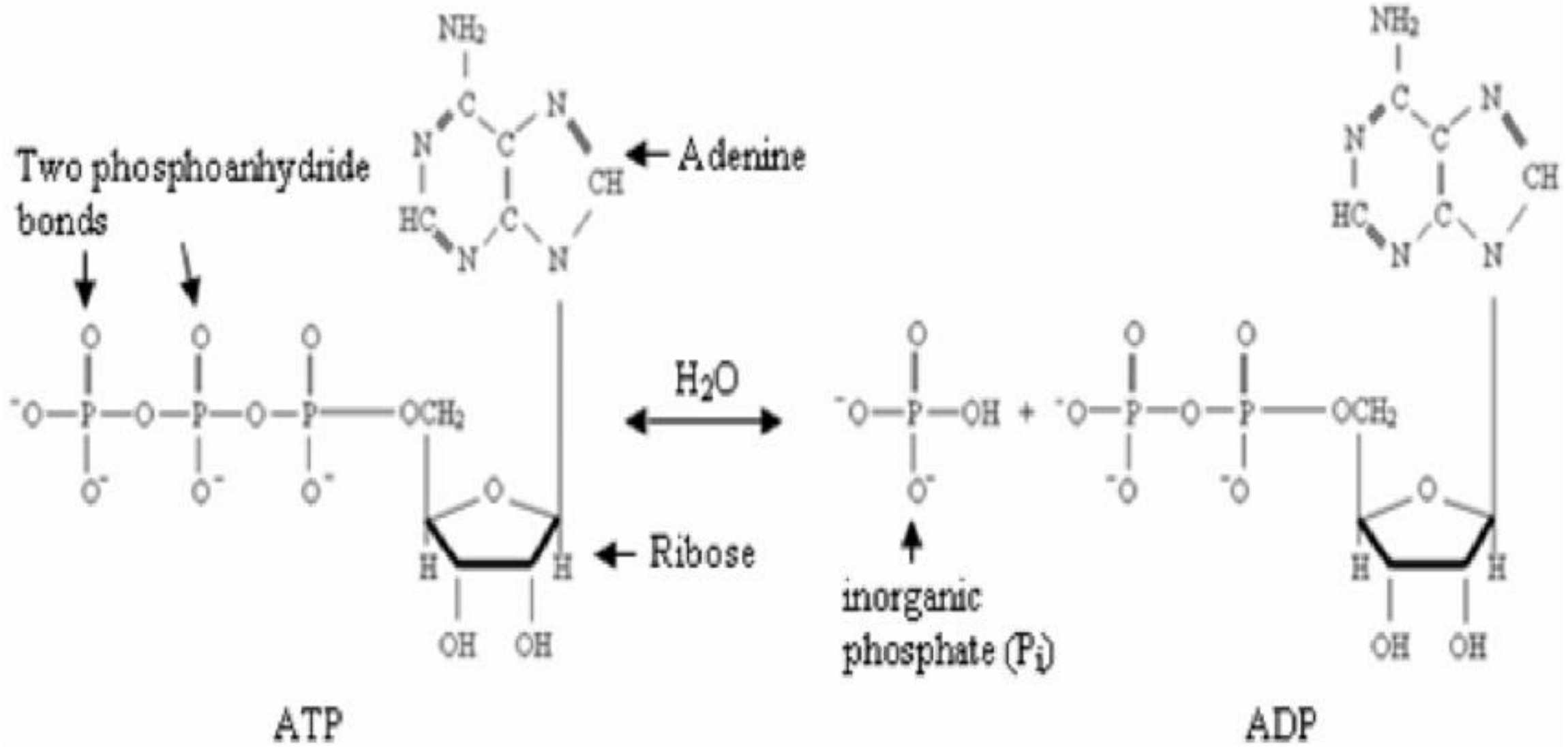
- Uses high energy compounds (e.g. ATP)
  - Advantages
    - Ensures tight control of the reaction
    - Collects energy from exergonic reactions and **donates** it to endergonic reactions
  - Cells obtain free energy in a chemical form by catabolism of nutrients, and they use this energy to make ATP from ADP and Pi
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# Synthesis of high energy compound

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**ATP is used in endergonic reactions as an energy source**

- synthesis of macromolecules from small precursors,
- transport of substances across membranes against concentration gradients and mechanical motion
  
- ATP **allows coupling** of energetically unfavorable (endergonic) reactions to favorable (exergonic) reactions.
  
- The free energy hydrolysis of ATP is **large and negative**
  
- The hydrolytic cleavage of the terminal phosphoric acid anhydride bonds in ATP separates off one of the three negatively charged phosphates
  - **Hydrolysis of ATP is highly exergonic and occurs only when catalyzed by an enzyme**

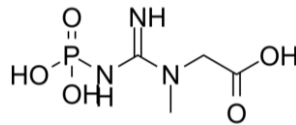


# Group transfer potential compounds

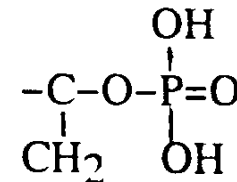
High phosphoryl group transfer potential (high-energy phosphate compounds):

1. ATP and its relatives: GTP, CTP (Cytidine triphosphate) and UTP (Uridine triphosphate)

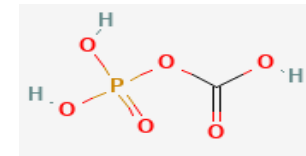
2. **Creatine phosphate**: in muscles



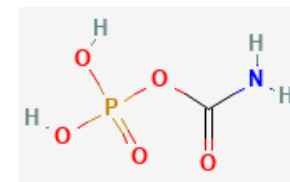
3. Enol phosphate: **phosphoenolpyruvate** (glycolysis)



4. Carboxy phosphate: as phosphate # 1 of 1,3 BPG (glycolysis)



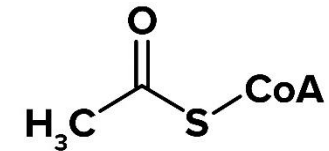
5. Carbamoyl phosphate: in urea cycle and pyrimidine synthesis



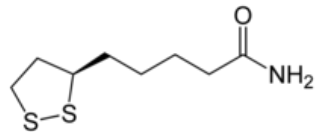
# Group transfer potential compounds

Thioesters having high group transfer potential:

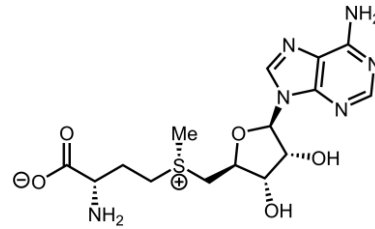
1. CoASH derivatives as acetyl CoA, succinyl CoA, acyl CoA, etc



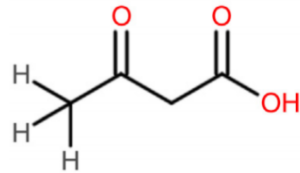
2. Lipoamide derivatives as **acetyl lipoamide** “intermediate in oxidative decarboxylation of pyruvate”



3. **S-adenosyl methionine (SAM)**

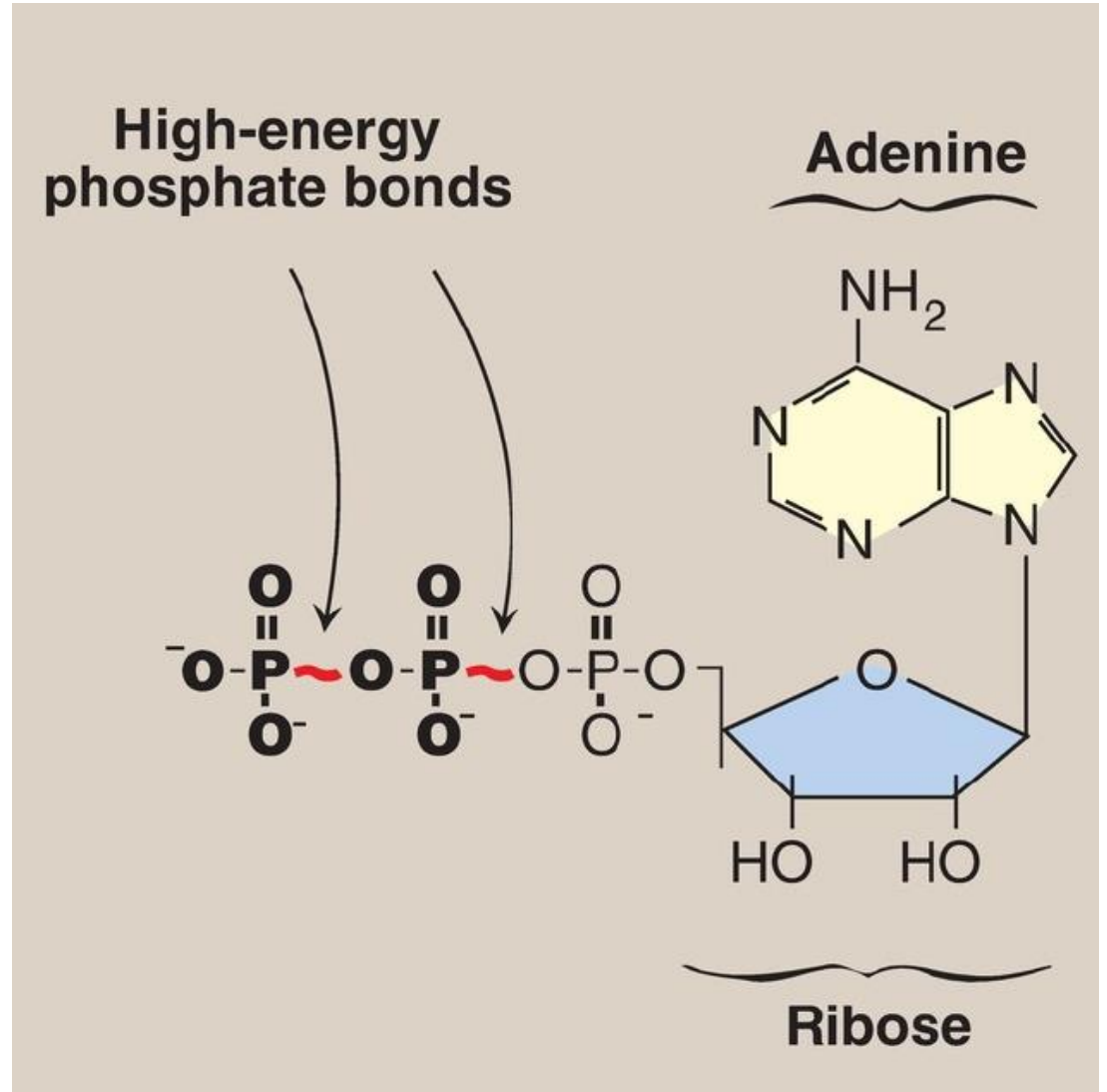


4. **Beta keto acid**



# Structure of ATP

- Consists of adenine, ribose and triphosphate moiety linked by phosphoanhydride bond.
- In ATP molecule, the second and third phosphate bonds are “high energy” bonds.



# ATP as the energy currency of the cell

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- ATP is the major link between energy yield (catabolic) and energy requiring (anabolic) processes.
- Removal of one phosphate produces ADP, and removal of two phosphates produces adenosine monophosphate (AMP)  
$$\text{ATP} + \text{H}_2\text{O} \rightarrow \text{ADP} + \text{P}_i \quad (\Delta G = -30.5 \text{ kJ/mol})$$
$$\text{ATP} + \text{H}_2\text{O} \rightarrow \text{AMP} + \text{PP}_i \quad (\Delta G = -61 \text{ kJ/mol})$$
- ATP can carry energy in the form of high energy bonds:
  - This energy is used to drive endergonic reactions with release of Pi or to transfer the phosphate group to another substance such as glucose forming glucose 6-phosphate which is more reactive than glucose.



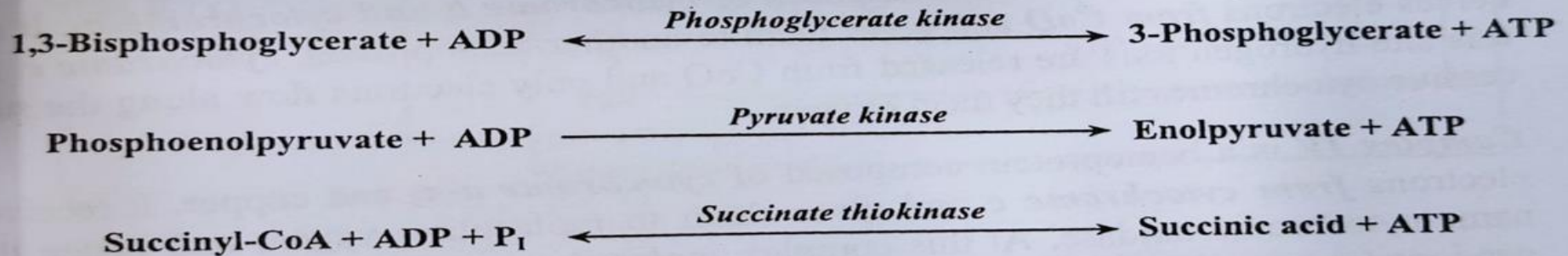
Compound	$\Delta G^{0'}$	
	kJ/mol	kcal/mol
Phosphoenolpyruvate	-61.9	-14.8
Carbamoyl phosphate	-51.4	-12.3
1,3-Bisphosphoglycerate (to 3-phosphoglycerate)	-49.3	-11.8
Creatine phosphate	-43.1	-10.3
ATP $\rightarrow$ AMP + PP <sub>i</sub>	-32.2	-7.7
ATP $\rightarrow$ ADP + P <sub>i</sub>	-30.5	-7.3
Glucose-1-phosphate	-20.9	-5.0
PP <sub>i</sub>	-19.2	-4.6
Fructose-6-phosphate	-15.9	-3.8
Glucose-6-phosphate	-13.8	-3.3
Glycerol-3-phosphate	-9.2	-2.2

# Mechanisms of energy collection

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## 1. Substrate level phosphorylation

A high-energy bond is formed in the substrate while being oxidized. ATP is then generated at the expense of this high-energy bond, as in the following reactions:



## 2. Oxidative phosphorylation

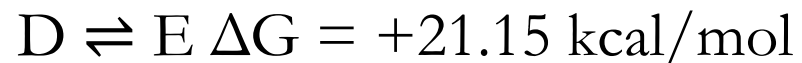
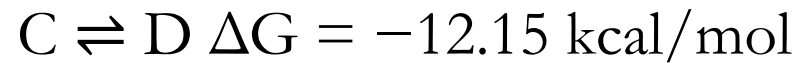
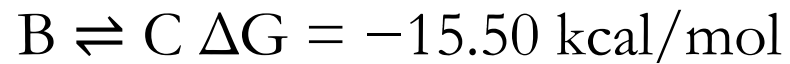
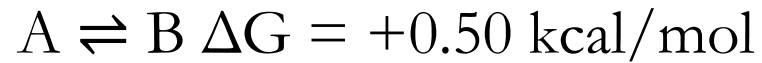
- Occurs in mitochondria
- Major energy generating process of nearly all cells (RBCs lack mitochondria)
- Transfer of electrons/ protons  $\rightarrow$  ATP synthesis via electron transport chain

## DEGRADATION OF FOODSTUFFS

- (1) *No free energy* is obtained from the breakdown of the big organic molecules of foodstuffs into smaller molecules (glycogen to glucose-1-phosphate; triacylglycerols to glycerol and fatty acids; and proteins to amino acids).
- (2) *Some free energy* is obtained from the breakdown of glucose, glycerol, fatty acids, and amino acids to acetyl-CoA.
- (3) *Most of the free energy* is obtained from the breakdown of acetyl-CoA via the citric acid cycle to carbon dioxide and water.

# Questions

Consider the following reaction sequence:



• Under standard conditions, which intermediate would accumulate?

(A) A

(B) B

(C) C

(D) D

(E) E

# Entropy - randomness or disorder in a system

- Living organisms consist of collections of molecules much more highly organized than the surrounding materials from which they are constructed, and organisms maintain and produce order, seemingly immune to the second law of thermodynamics.
- But living organisms do not violate the second law; they operate strictly within it. To discuss the application of the second law to biological systems, we must first define those systems and their surroundings.

# Entropy - randomness or disorder in a system

- The reacting system is the collection of matter that is undergoing a particular chemical or physical process; it may be an organism, a cell, or two reacting compounds.
- The reacting system and its surroundings together constitute the universe. In the laboratory, some chemical or physical processes can be carried out in isolated or closed systems, in which no material or energy is exchanged with the surroundings.

# Entropy - randomness or disorder in a system

- Living cells and organisms, however, are open systems, exchanging both material and energy with their surroundings; living systems are never at equilibrium with their surroundings, and the constant transactions between system and surroundings explain how organisms can create order within themselves while operating within the second law of thermodynamics.
- In short, living organisms preserve their internal order by taking from their surroundings free energy in the form of nutrients or sunlight, and returning to their surroundings an equal amount of energy as heat and entropy.