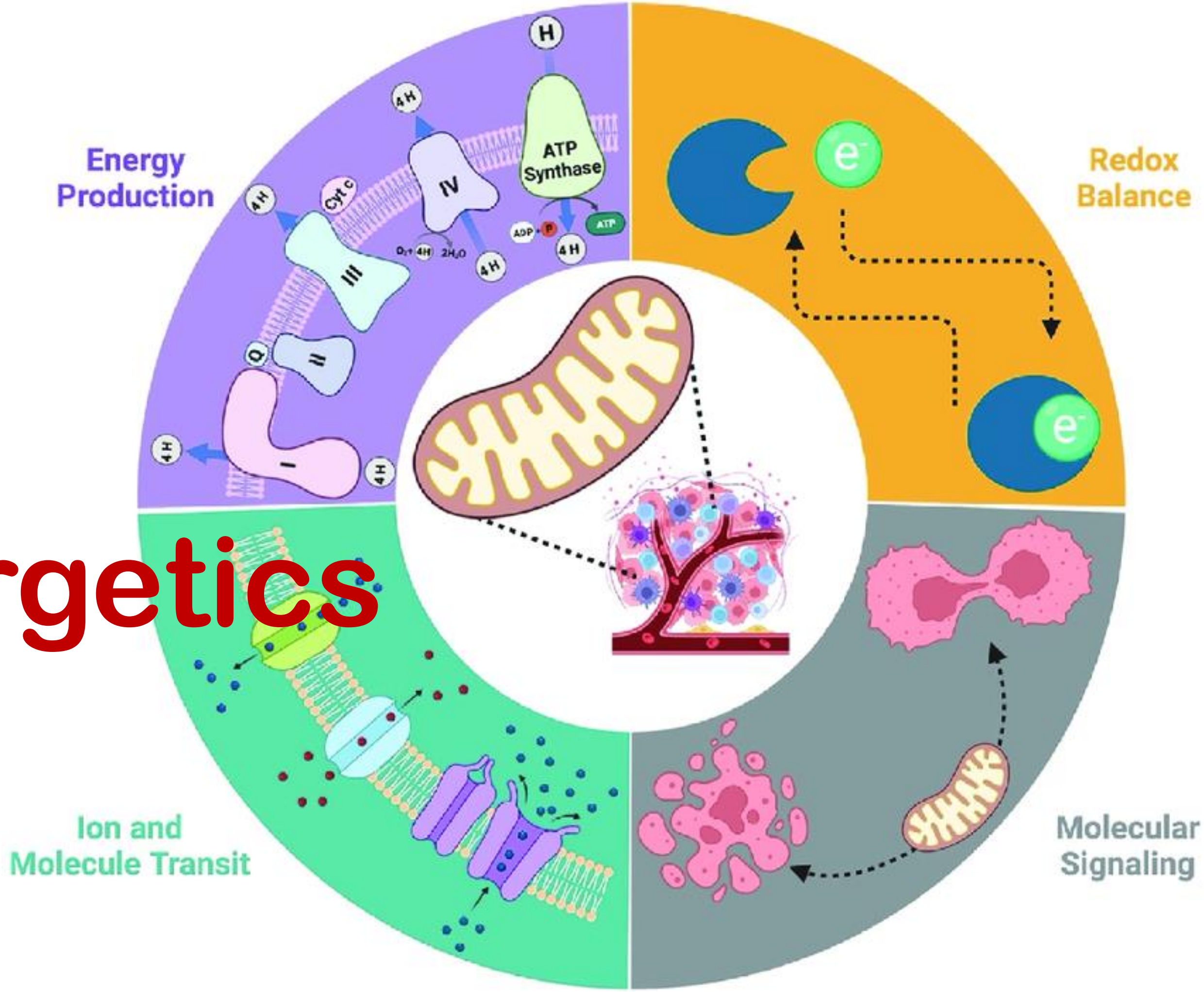
Bioenergetics



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Patcharee Boonsiri

https://www.researchgate.net/publication/381387570/figure/fig3/AS:11431281261456328@1721622248135/Mitochondrial-bioenergetic-regulation-of-cancer-cell-survival-and-death-evasion.png

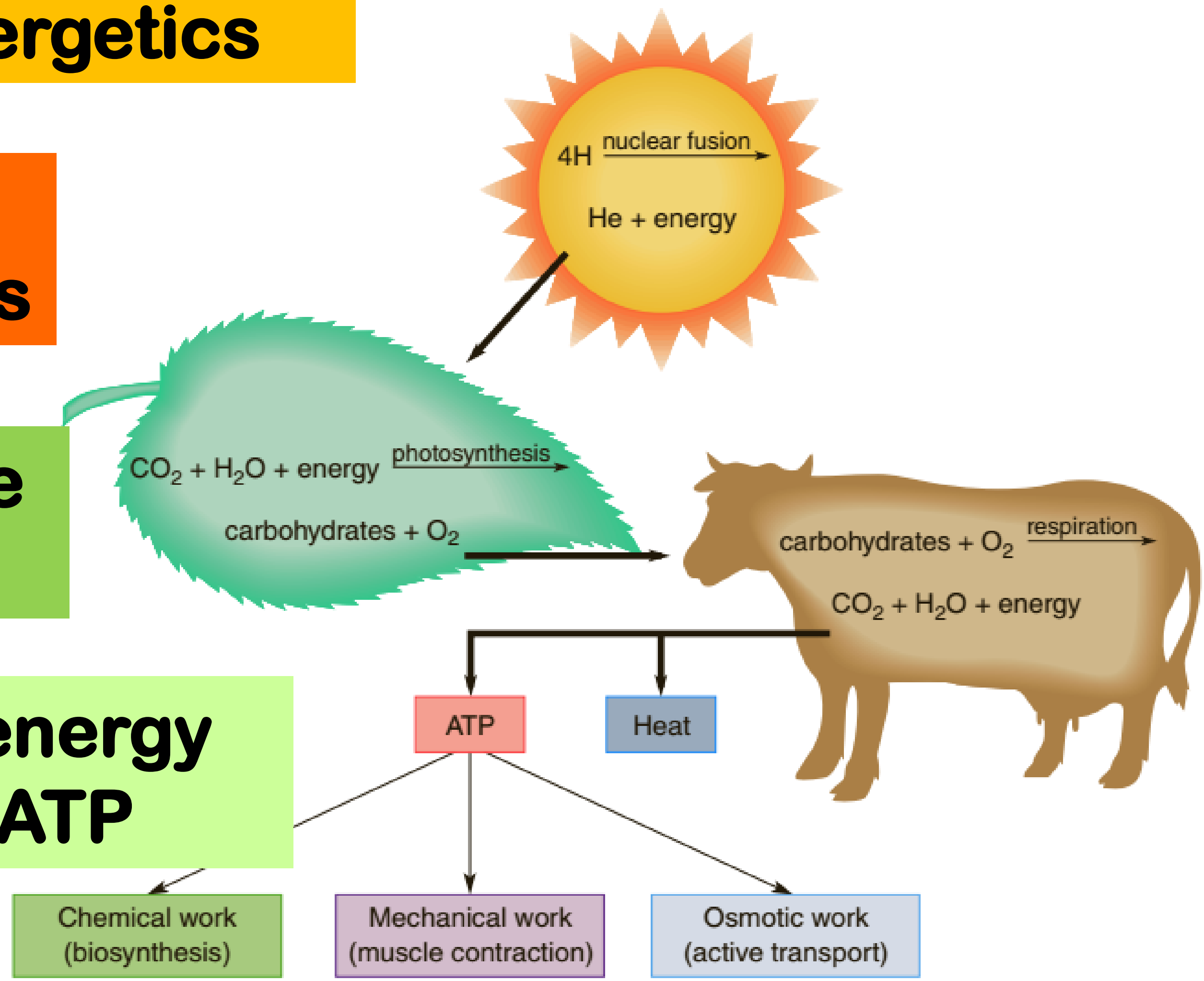
Outline

Part 1 Bioenergetics

Part 2 Thermodynamics

Part 3 Gibb's free energy (G)

Part 4 High energy compound - ATP



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Part 1 - Bioenergetics

Key idea ENERGY

1. Cells need energy to accomplish the tasks of life

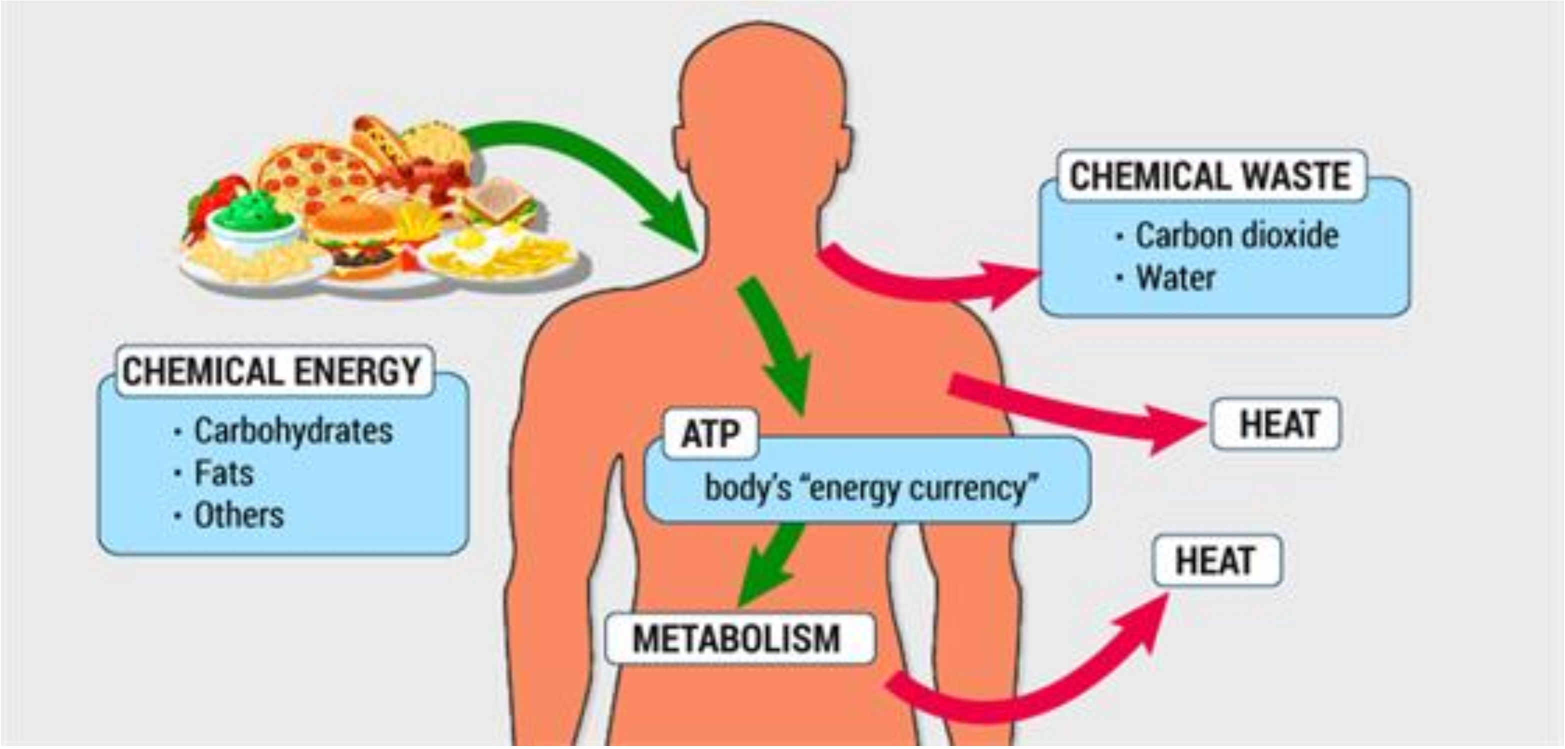
2. Energy sources are obtained in the form of sunlight and food molecules

3. Eukaryotic cells make energy-rich molecules (ATP and NADH) via energy pathways including photosynthesis, glycolysis, Krebs' cycle, and oxidative phosphorylation

4. Excess energy is stored in polysaccharides (starch and glycogen) and lipids

Cell bioenergetics is the study of
how cells
- Acquire energy
- Transform energy
- Utilize energy

to perform biological work



https://cdn1.byjus.com/wp-content/uploads/2018/02/ENERGY-AND-HUMAN-LIFE-2.png

Living organisms need 4 essential things to maintain their life

What are the 4 essential things the cells need?

1.molecular building blocks
2.chemical catalysts (enzymes)
3.genetic information
4.en____ to drive reactions and processes essential for life

The activities of living things require energy

What is energy?

Energy is ability to do w____

Work = force x distance

Unit of Energy: Calorie, Joule (SI unit)

1 cal = 4.184 J

What is work?

Work is the use of energy to drive all processes

Examples of biological works

1. Synthetic work
2. Mechanical work
3. Electric work
4. Concentration work
5. Heat production
6. Bioluminescence

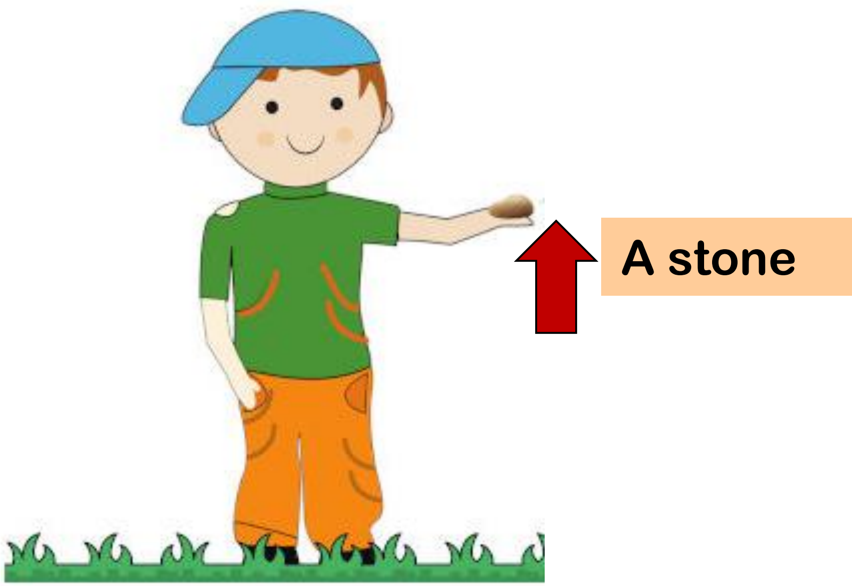
All works take en____.

https://mgronline.com/onlinesection/detail/9610000069094

How many form of energy?

There are __ forms of energy

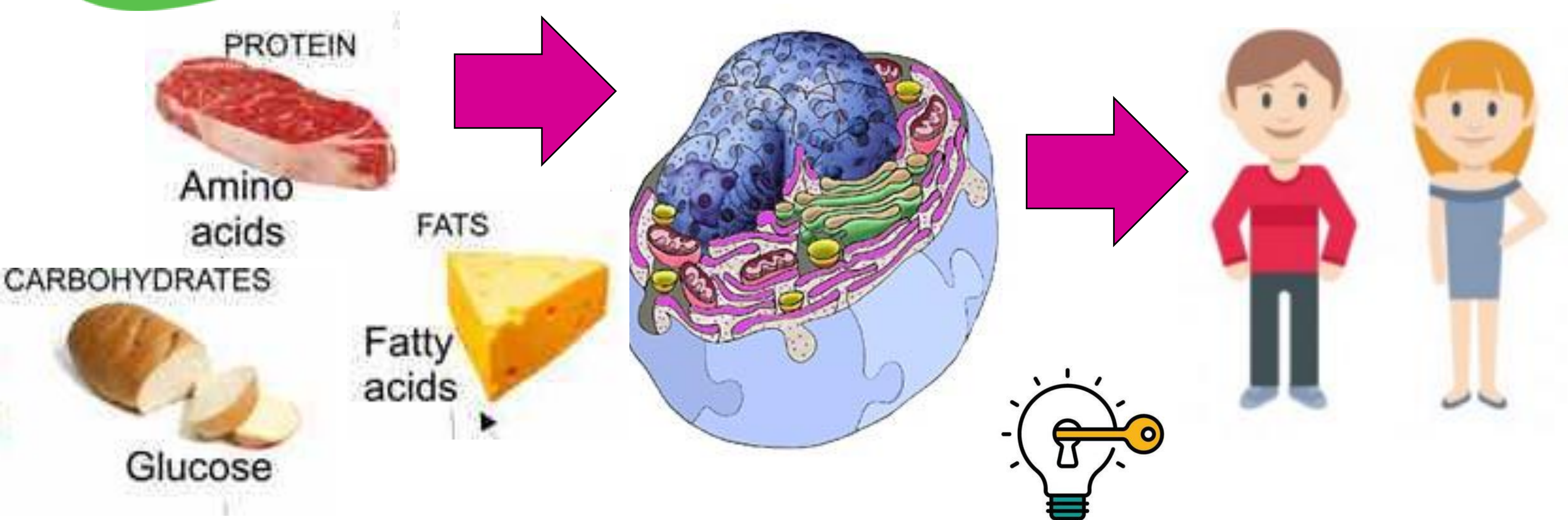
1.Potential energy - is stored energy (chemical, conc.gradient, electrical potential)



2.Kinetic energy - energy that is actively engaged in doing work (radient, thermal, mechanical)

Cells require a constant supply of energy to generate and maintain the biological order → this keeps them alive

What is (are) the energy source for living cells?

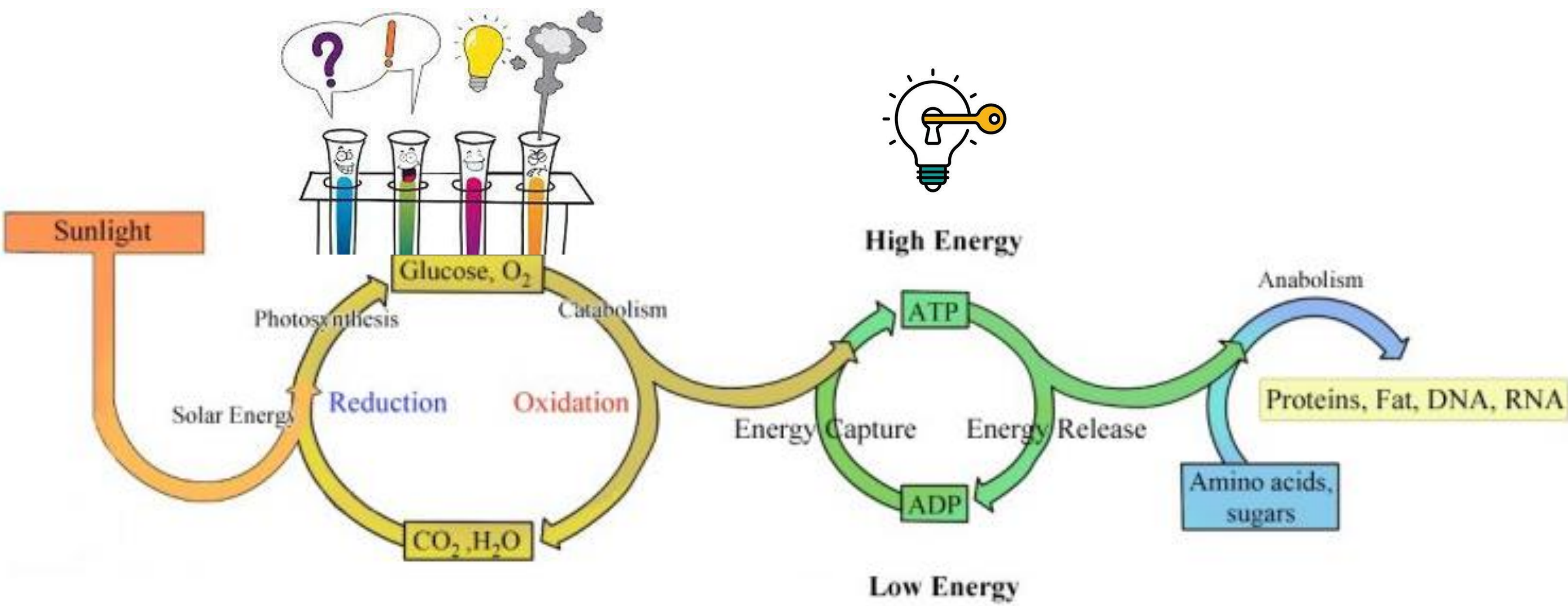


Example of energy source: f___ molecules (produce energy by metabolism of carbohydrate, fat and protein)

How do the food metabolized?

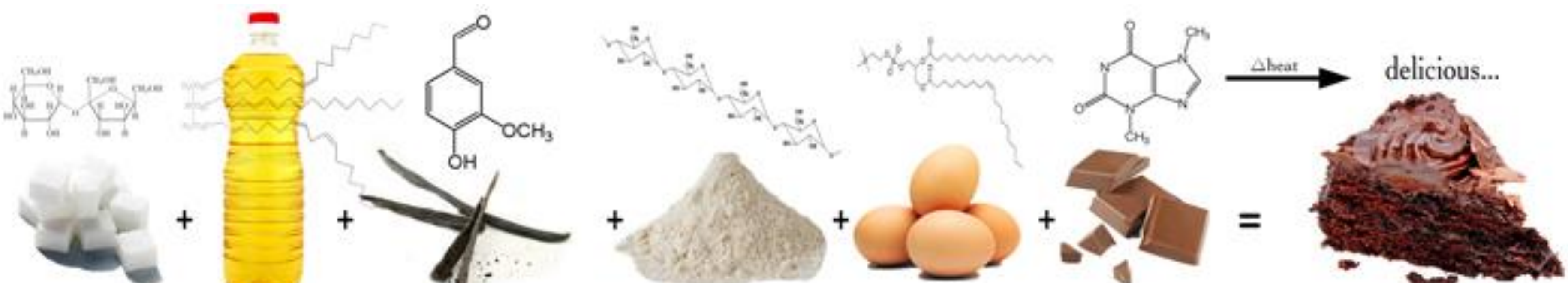
By metabolic network system

Metabolism consists of a network of ch______ reactions called pathways.



Metabolic Energy Flow

Energy is derived from the **chemical b___** in **food molecules** (fuel for cells)

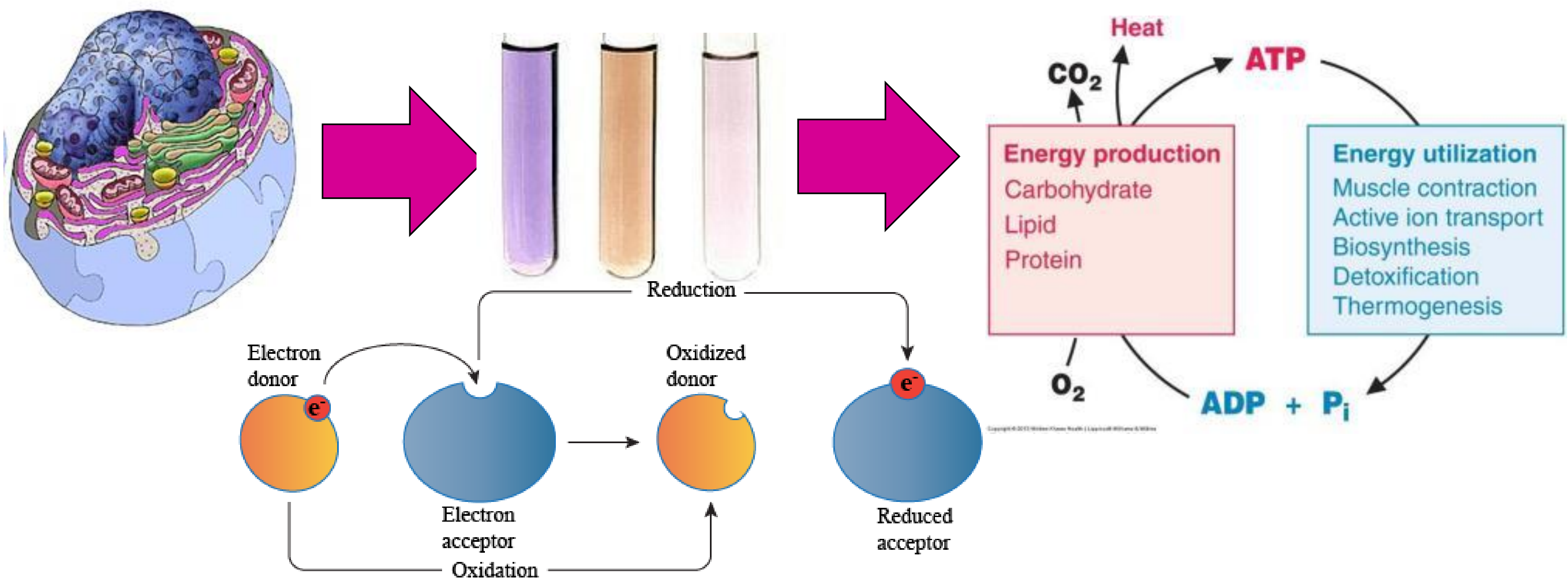


https://bondingwithfood.files.wordpress.com/2010/02/work.jpg

How do living cells get energy from food?

Cells release the energy stored in their food molecules through a series of ox_____ reactions

The living cell generates thousands of different reactions.



Oxidation rx. : electrons are transferred from one molecule to another

→ changing the composition and energy content of both the donor and acceptor molecules

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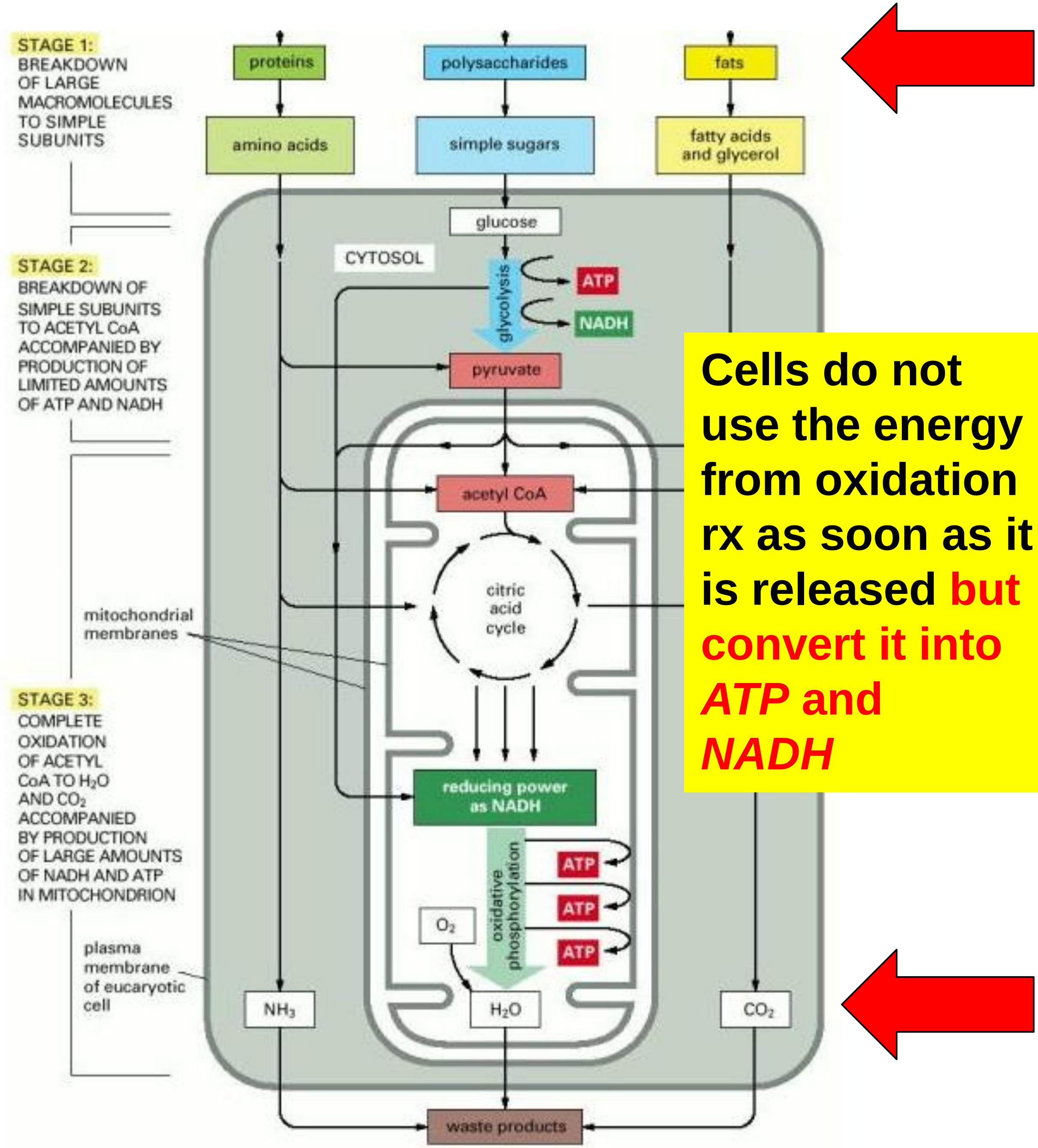


Cells do not use the energy from oxidation rx as soon as it is released but convert it into *ATP* and *NADH*

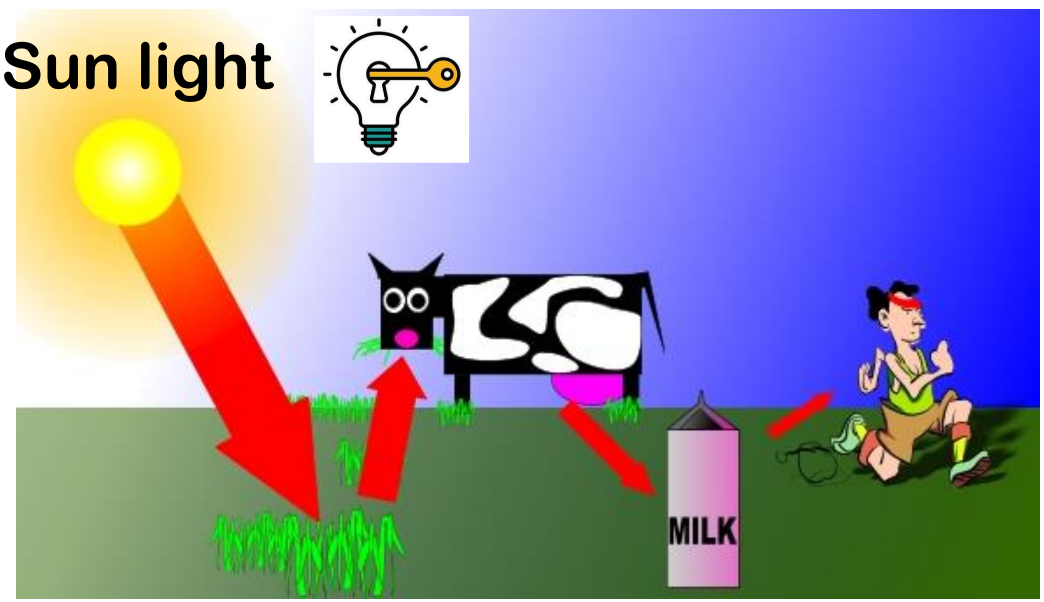
Food molecules act as electron donors

- During food breakdown (catabolism),product of oxidation rx has a lower energy than the donor molecule
- At the same time, e- acceptor molecules capture some energy lost from the food molecule and store it for later use
- When C atoms from food molecule are fully oxidized at the end of the rx → they are released as CO_2

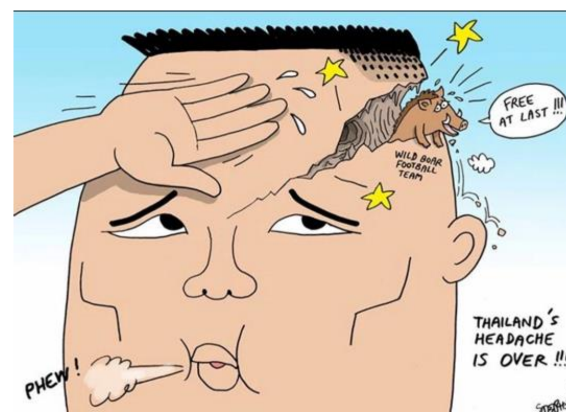
Living organisms manage their energy resources through metabolic pathways

Energy flows into an ecosystem in the form of l___ and exits in the form of h____

Sun light



Heat

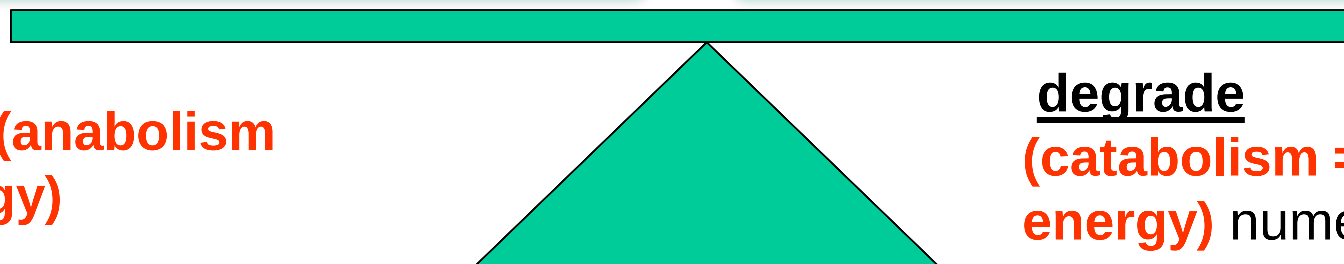


https://www.firsttheseedfoundation.org/wp-content/uploads/2016/08/energy-path2.jpg

Metabolism is the totality of an organism's reactions that arise from interactions between molecules.

anabolic pathway - form complex molecules from simpler molecules; biosynthesis requires energy input

Catabolic pathway- breakdown complex molecules into simpler molecules



Cells **build** **(anabolism = use energy)**

degrade **(catabolism = get energy)** numerous molecules and structures

Note that - body has balance between anabolism and catabolism

A catabolic pathway in a cell releases free energy in a series of reactions

Summary Part 1

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4. Excess energy is stored in polysaccharides (starch and glycogen) and lipids

Part 2 –Thermodynamics

Key idea FLOW OF ENERGY

1. The 1st law of Thermodynamics
   - Energy cannot be created or destroyed
   - Energy can be transferred and transformed
2. The 2nd law
   - The disorder (entropy) in the universe is continuously increasing
3. During every energy transfer or transformation, some energy is unusable, often lost as heat
4. Living systems
   - Use energy to maintain order
   - Increase the entropy of the universe

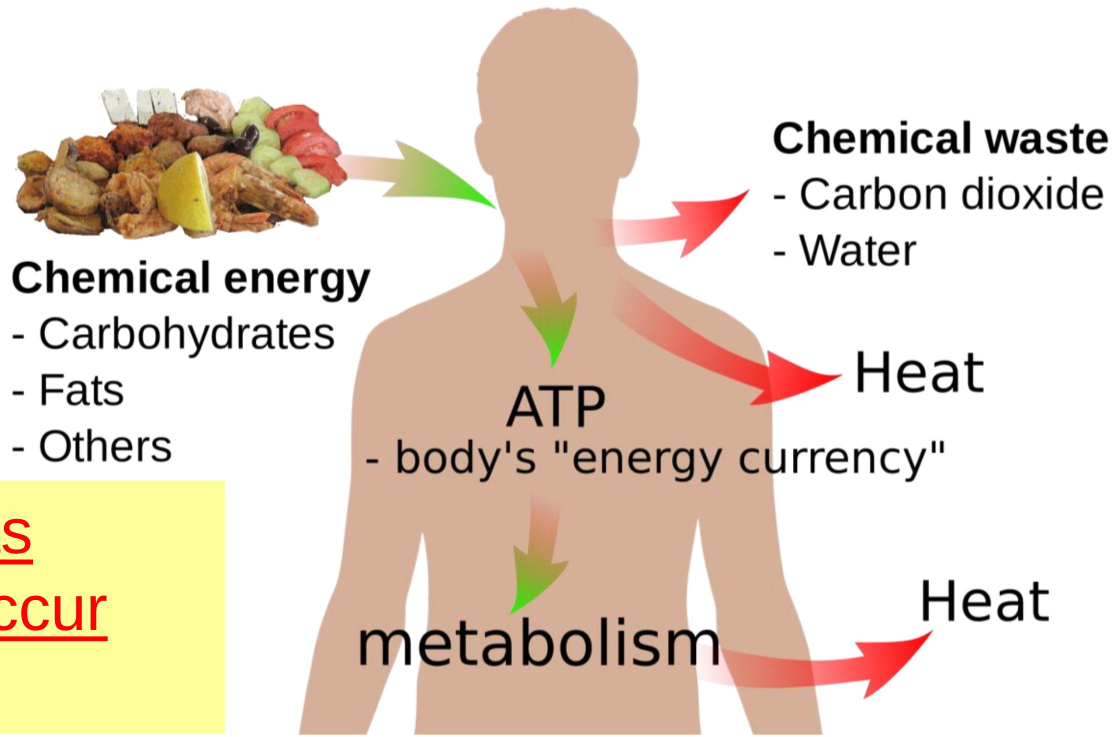
What is Thermodynamics?

Thermodynamics is the study of energy transformations

Energy flow is governed by the principle of Thermodynamics

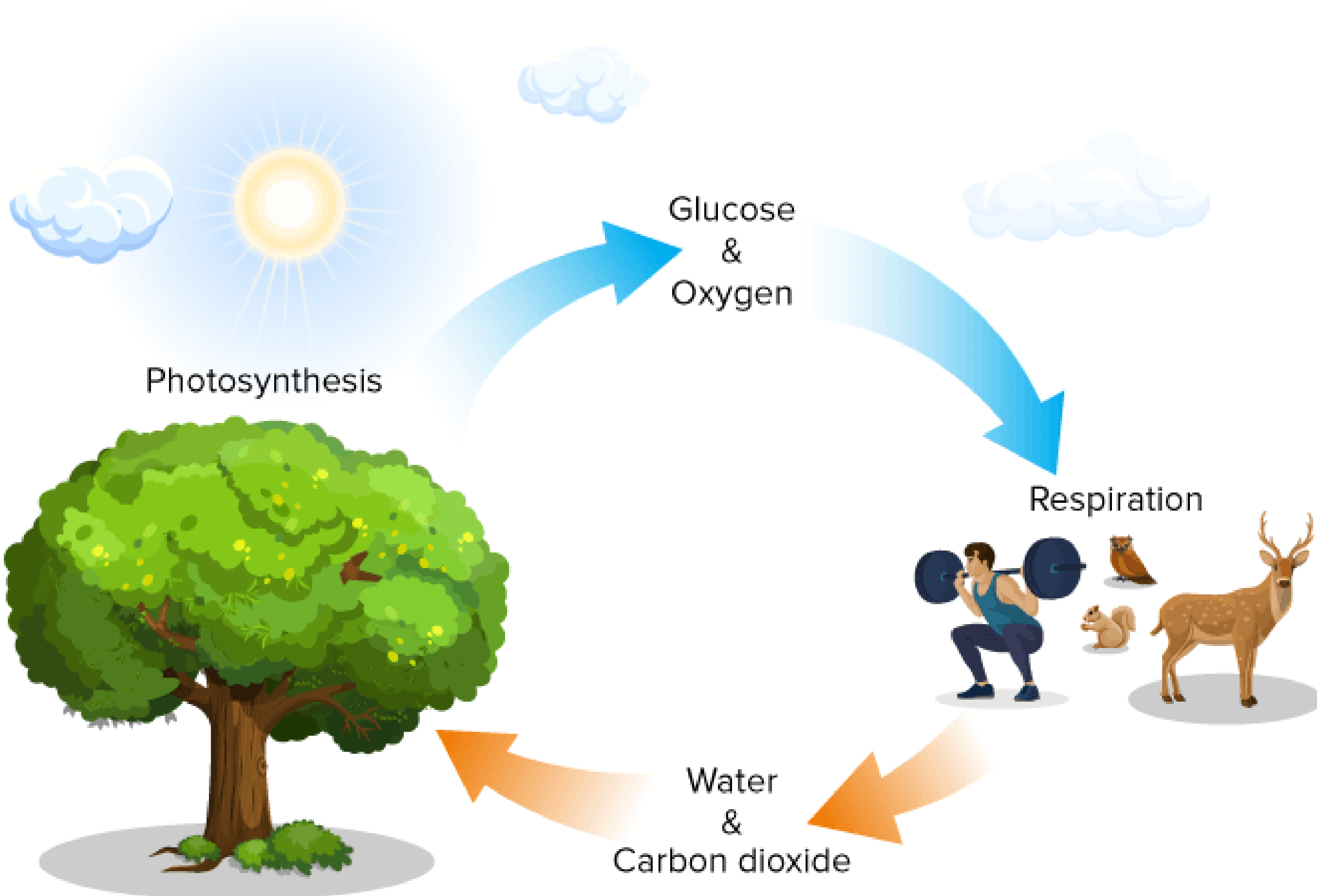
An organism's metabolism transforms matter and energy according to the laws of thermodynamics.

Bioenergetics applies principle of Thermodynamics to the biological world



Thermodynamics <u>predicts whether a reaction will occur spontaneously</u>

Living organisms are o___ systems with a constant flow of materials in and out. (exchange both energy and matter)



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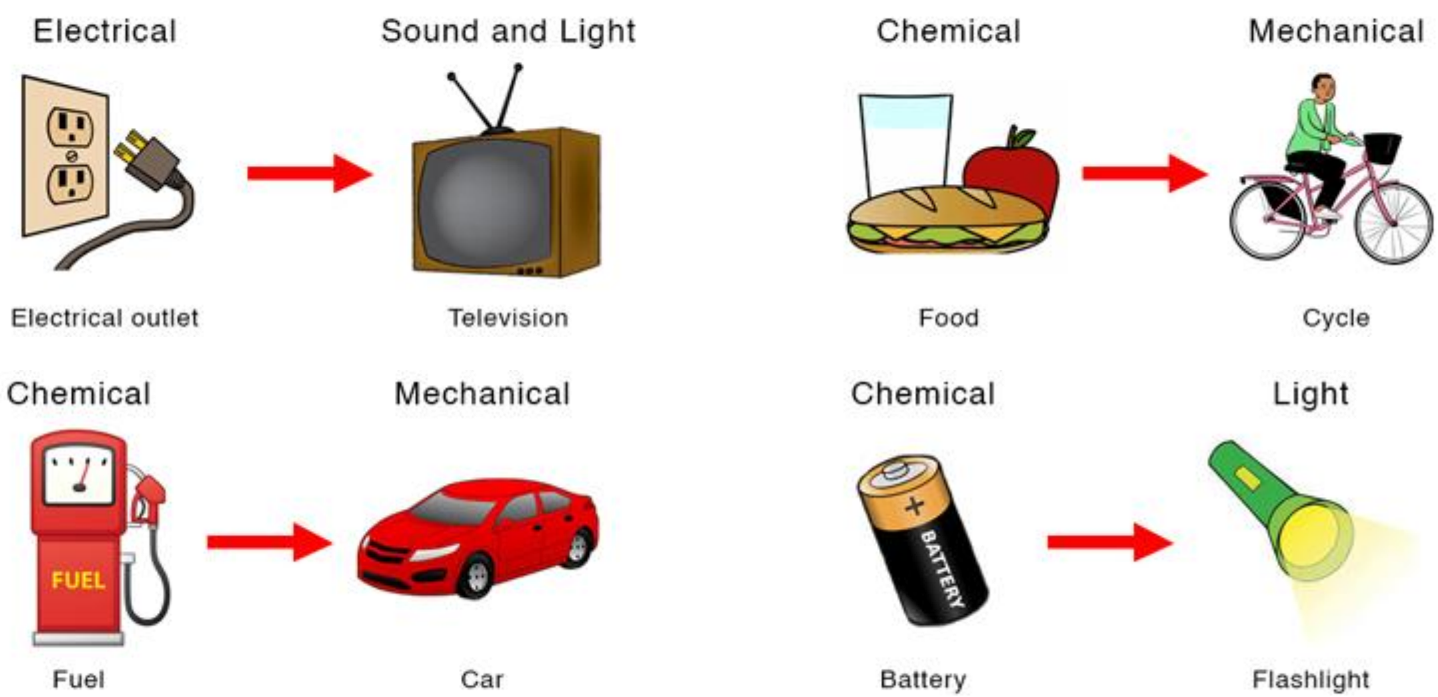
How is the energy conserved in living organism?

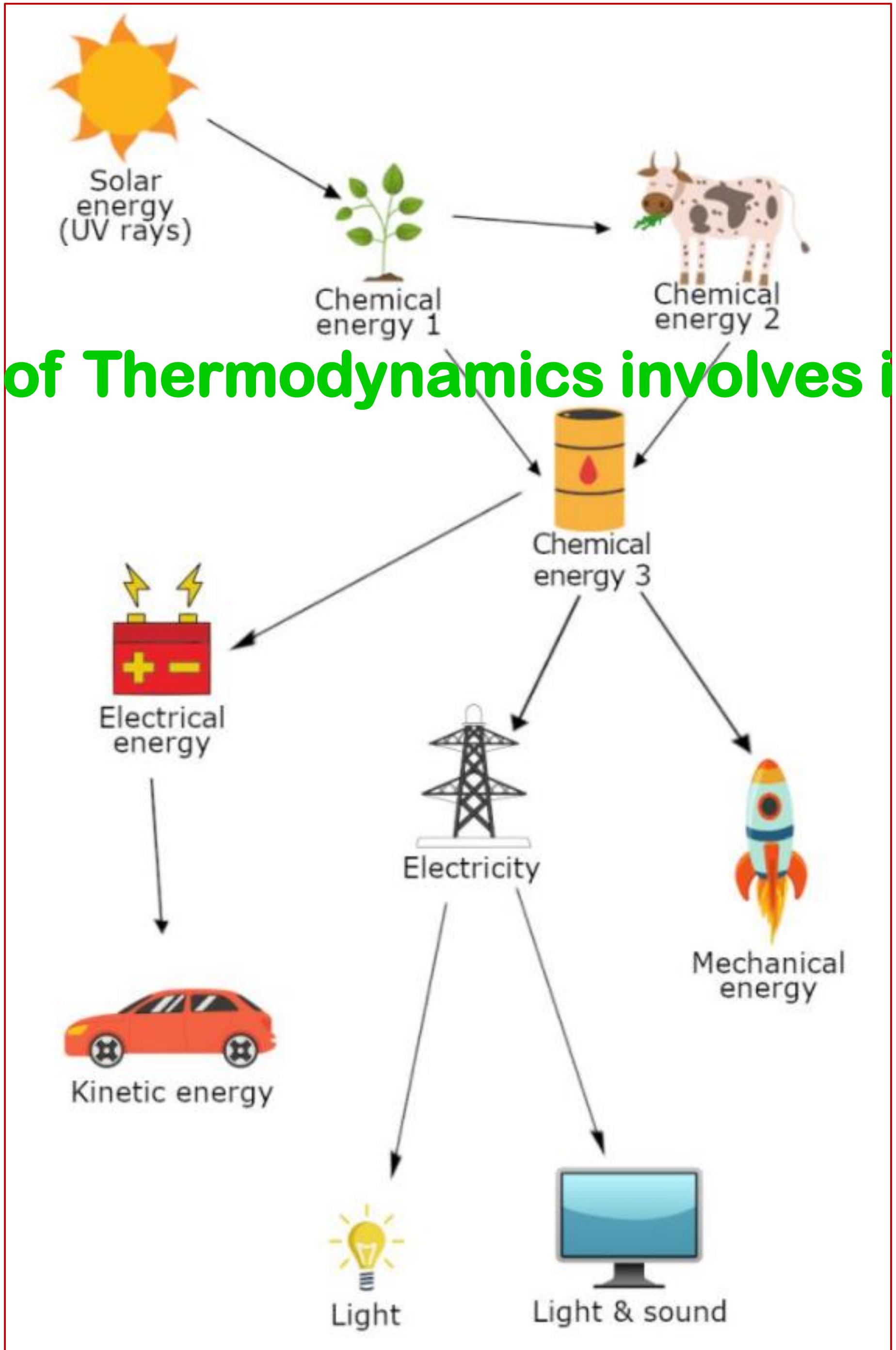
The 1st law of Thermodynamics (Conservation of energy)

Energy can be transferred and transformed, but it cannot be created or destroyed



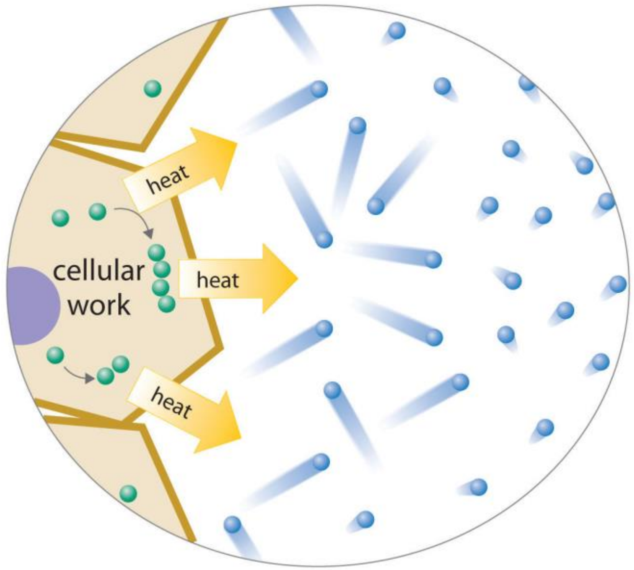
https://www.sciencefacts.net/wp-content/uploads/2022/03/Energy-Transformation.jpg

The 1st law of Thermodynamics involves in daily life



Can cells use 100% of energy from food?

No process in biological system is 100% efficient



$\Delta S_{sys} + \Delta S_{surr} > 0$

Some energy is lost as heat

And dissipated into the environment

Some of this heat is used

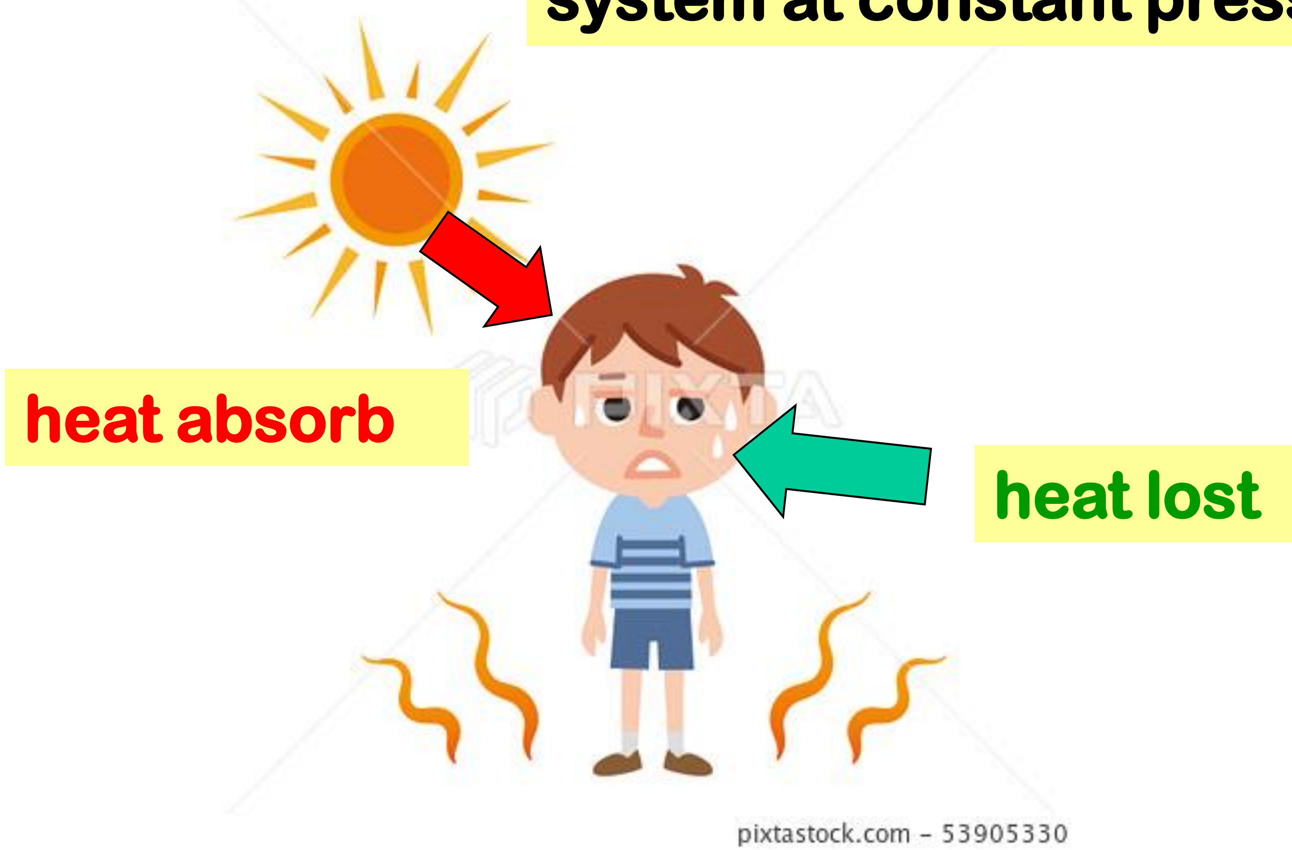
In some plants: to melt snow around them

In warm-blooded animals: to maintain body temperature

http://2012books.lardbucket.org/books/principles-of-general-chemistry-v1.0/section_22/35393b221c5e9e0bebd1bb2cf0504ab3.jpg

What is enthalpy?

Enthalpy (H) is the heat absorb or lost of a chemical system at constant pressure



Enthalpy (H)

เอนทัลปี (enthalpy, H) คือ ปริมาณความร้อนที่ผ่านเข้าหรือออกจากระบบในกระบวนการที่ความดัน (P) คงที่

$$H = E + PV$$

E = internal energy
P = pressure
V = volume
of the system

At constant pressure
Enthalpy change (ΔH) is equal to energy flow as heat

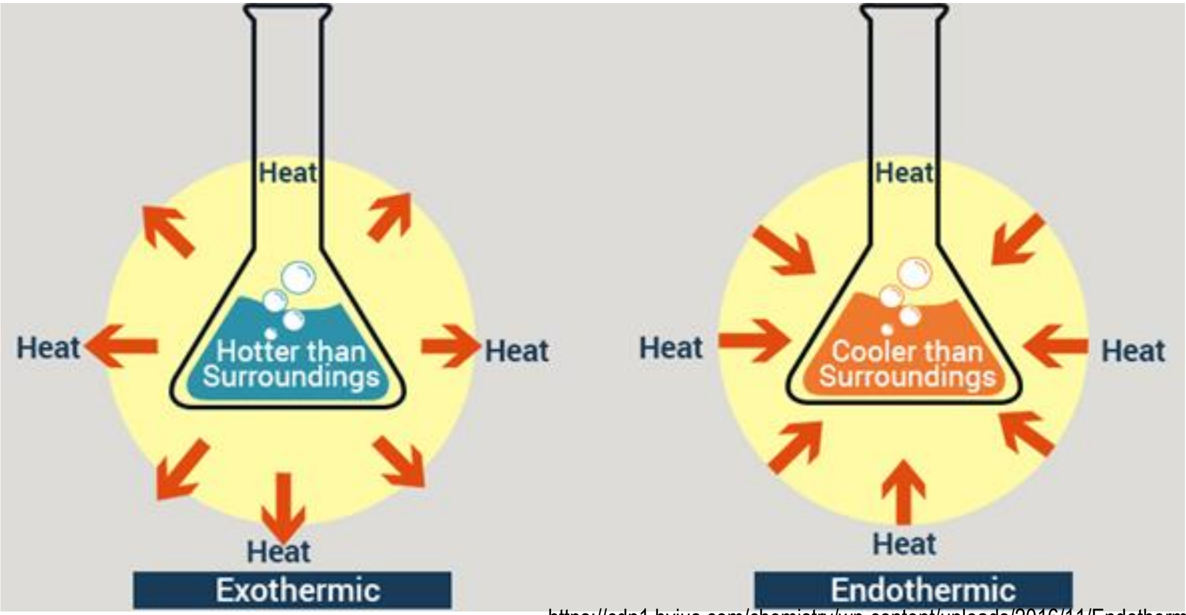
Enthalpy change (ΔH) is **heat transfer in chemical process**

การวัด H ทำได้ยาก ดังนั้นสิ่งที่วัดได้จริง ๆ จากการทดลอง คือ **การเปลี่ยนแปลงเอนทัลปีของปฏิกิริยา (enthalpy of reaction; ΔH)**

$$\Delta H = H_{product} - H_{reactant}$$

ΔH = +ve endothermic rx (ปฏิกิริยาดูดความร้อน)

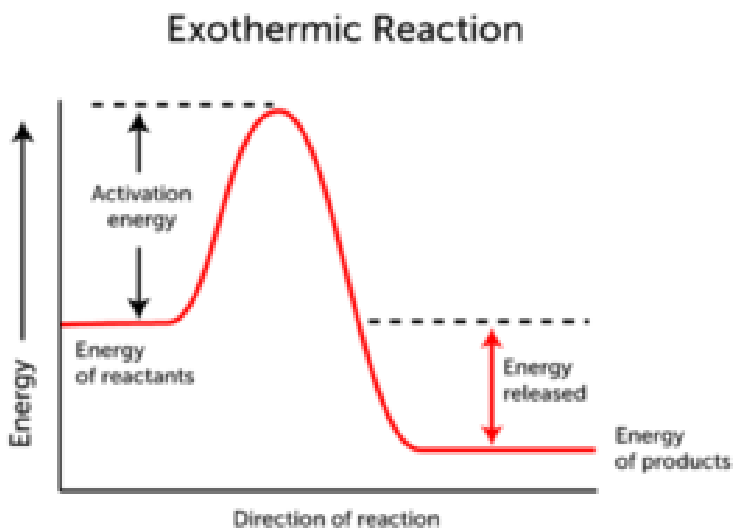
ΔH = -ve exothermic rx (ปฏิกิริยาคายความร้อน)

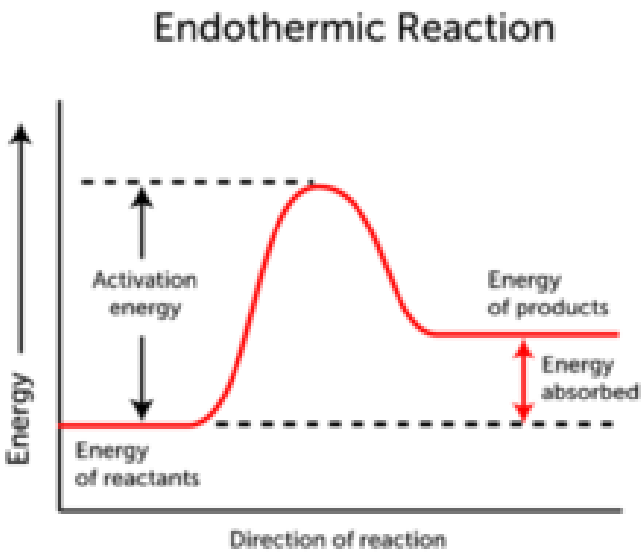


https://cdn1.byjus.com/chemistry/wp-content/uploads/2016/11/Endothermic-and-Exothermic-Reactions.png

ΔH = - Exothermic คายความร้อน

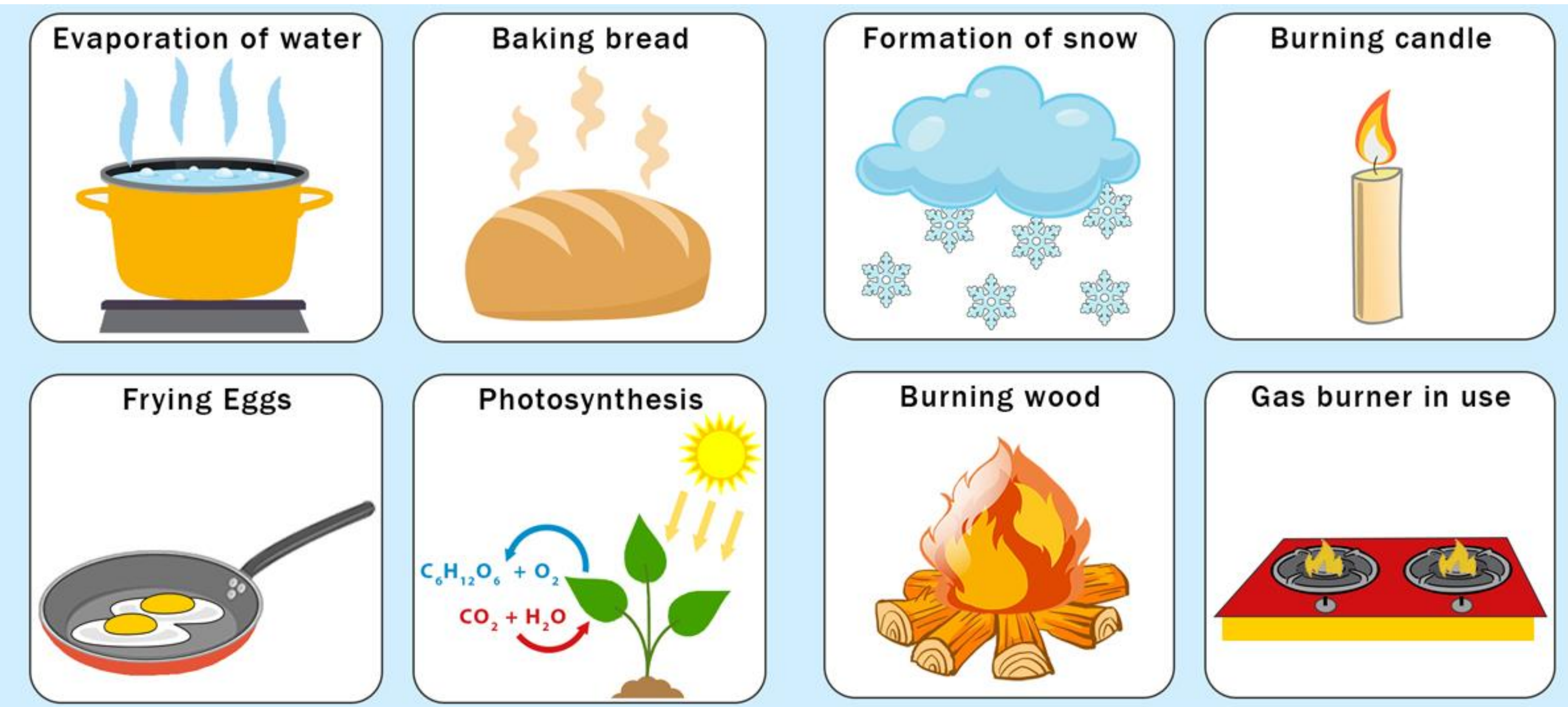
ΔH = + Endothermic ดูดความร้อน





Which is (are) endothermic?

Which is (are) exothermic?



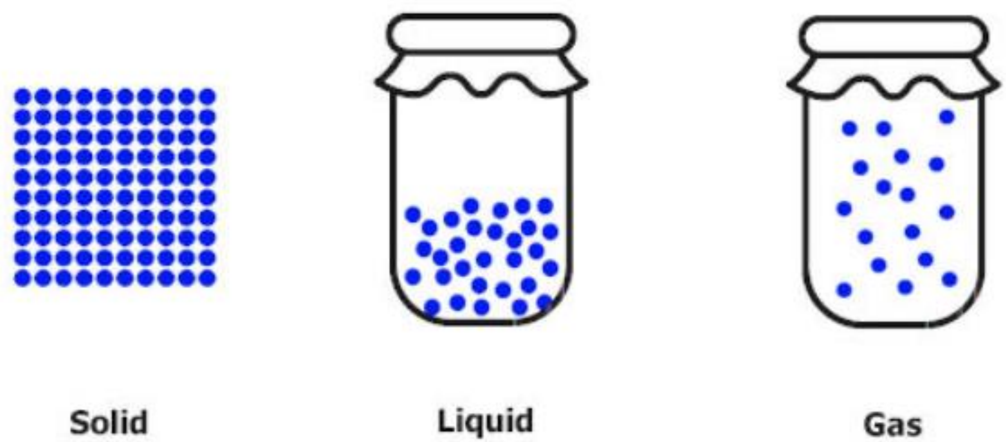
What is entropy?

Entropy (S) = order/disorder of the system

เอนโทรปี (entropy) คือ ปริมาณที่บอกถึงความไม่เป็นระเบียบของระบบ
ยิ่งระบบมีความไม่เป็นระเบียบสูง เอนโทรปีก็จะยิ่งมีค่าสูง

The 2nd law of Thermodynamics
The universe tends toward greater disorder

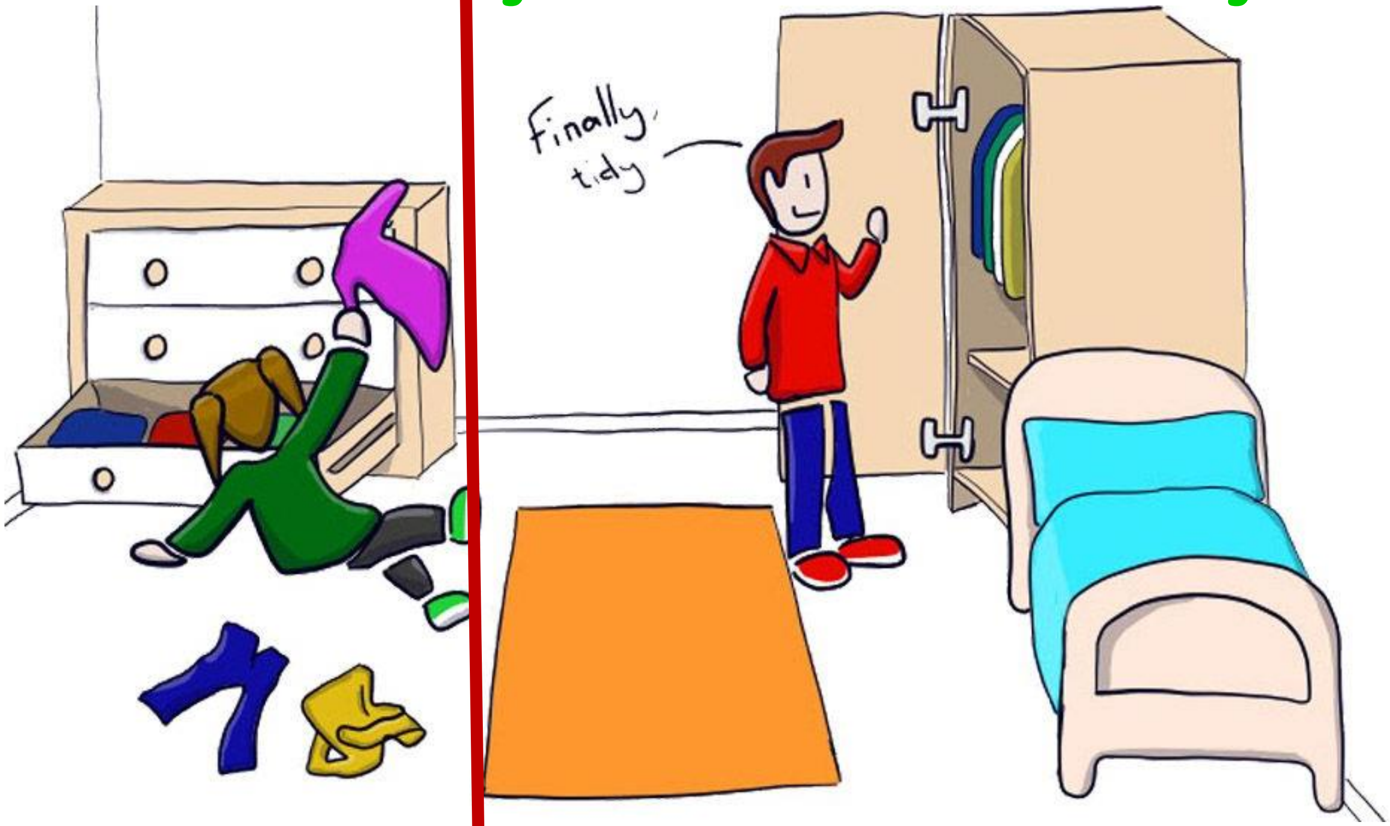
All energy transformations
Increase entropy of the system



Systems tend to proceed from

ordered to disordered states (increase entropy)

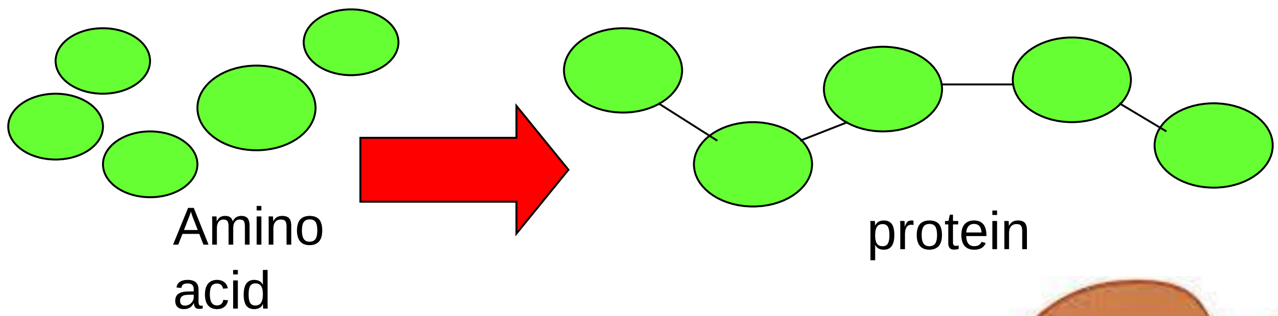
The 2nd law of Thermodynamics involves in daily life

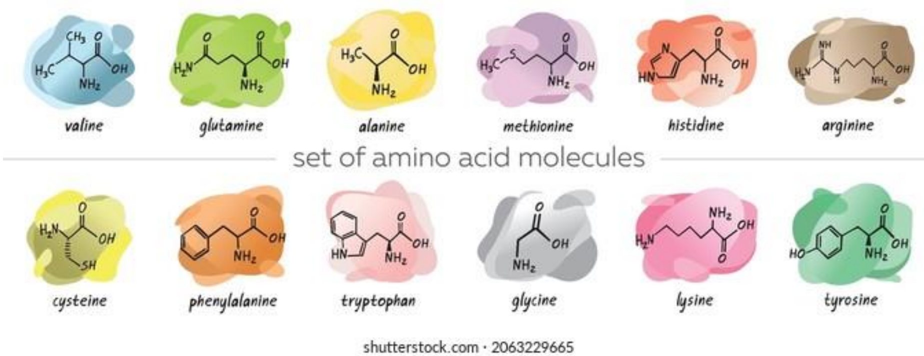


Disorder happens spontaneously

Organization requires energy

ΔS is + or – or 0?



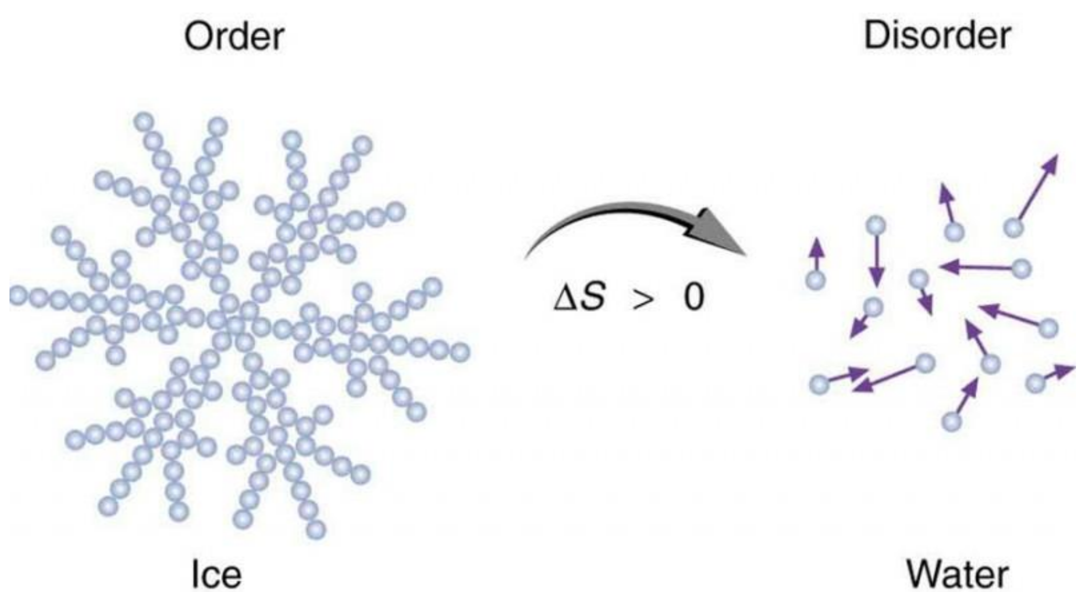


ΔS = + the rx.occur spontaneous
ΔS = - the rx. occur in opposite direction
ΔS = 0 the rx.occur is in equilibrium

What is the advantage of the 2nd law of Thermodynamics?

Use to check the d______ of the process (spontaneously occur or not)

In all the spontaneous process, the entropy increase



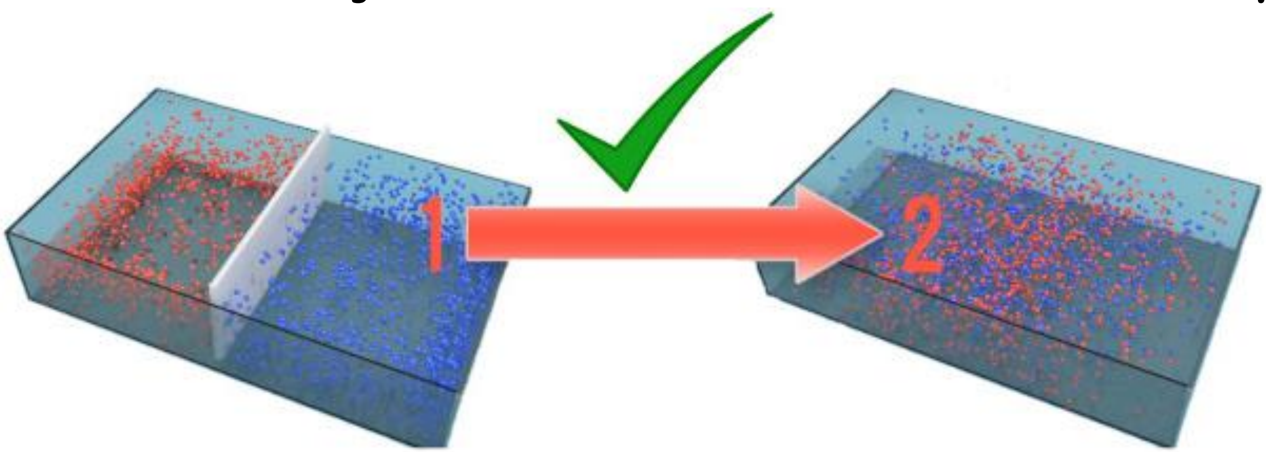
https://s3-us-west-2.amazonaws.com/courses-images-archive-read-only/wp-content/uploads/sites/222/2014/12/20104949/Figure_16_06_06.jpg

What is the different between the 1st and the 2nd law of Thermodynamics?

The 1st law of Thermodynamics

cannot tell us the direction of the process

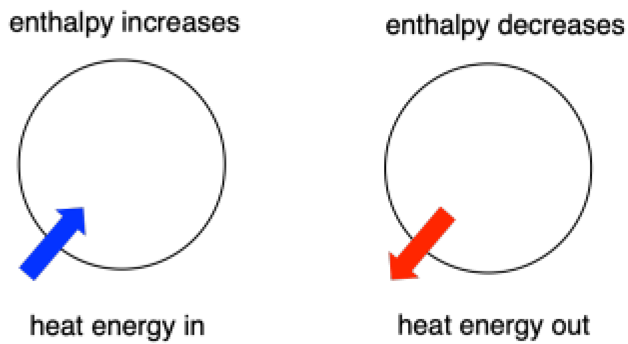
The 2nd law of Thermodynamics tell us the direction of the process



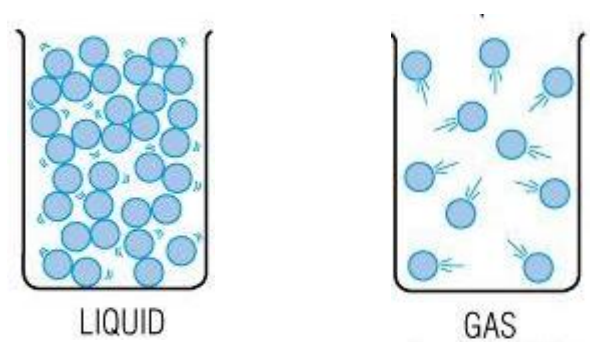
If we remove the separator, the red and blue gases will mixed up by their own

What is the different between enthalpy and entropy?

Enthalpy is to measure the overall am_ _nt of energy in the system



Entropy is to measure the r_nd_mn_ss of activity in the system



Summary Part 2

1. The 1st law of Thermodynamics
   - Energy cannot be created or destroyed
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2. The 2nd law
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3. During every energy transfer or transformation, some energy is unusable, often lost as heat

4. Living systems
   - Use energy to maintain order
   - Increase the entropy of the universe

Part 3 – Gibb's free energy and Energy coupling

Key idea FREE ENERGY

1.A living system's free energy is energy that can do work under cellular conditions (break and form chemical bonds)

2.Gibbs' free energy (G) – in a cell is the amount of energy contained in a molecule's chemical bonds (at constant temperature and pressure)

3.Change in free energy (ΔG)

- Endergonic - any reaction that requires an input of energy
- Exergonic - any reaction that releases free energy

4.Living organisms have the ability to couple exergonic and endergonic reactions

What is free energy?

Free enegy (G) is the energy available to do work when temperature and pressure is uniform throughout the system, as in a living cell

ΔG link the 1st and the 2nd law

1st 2nd

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

ΔG = Gibbs free energy

H = enthalpy (bond energy)

S = entropy

T = temp. (Kelvin)

Unit of ΔG and ΔH --> J/mol or cal/mol

Unit of ΔS --> J/mol.K or cal/mol.K

ΔG during the rx is influenced by

- Temperature
- Pressure
- Initial concentration of substrate and product
- pH of solution

In biological system

Const. Temperature

Const. Pressure

conc. of reactant < 1 M

at standard condition

ΔG^o	Temp. 25^{o}C (298 Kelvin) Pressure 1 atm Initial conc. of 1 M for all reactants and products
$\Delta G^{o'}$	Temp. 25^{o}C (298 Kelvin) Pressure 1 atm Initial conc. of 1 M for all reactants and products pH 7

Examples of ΔG change in chemical reaction

TABLE 13–4 Standard Free-Energy Changes of Some Chemical Reactions at pH 7.0 and 25 °C (298 K)

Reaction type	$\Delta G'^{\circ}$ (kJ/mol)	$\Delta G'^{\circ}$ (kcal/mol)
Hydrolysis reactions		
Acid anhydrides		
Acetic anhydride + $H_2O \longrightarrow$ 2 acetate	−91.1	−21.8
ATP + $H_2O \longrightarrow$ ADP + P_i	−30.5	−7.3
Oxidations with molecular oxygen		
Glucose + $6O_2 \longrightarrow 6CO_2 + 6H_2O$	−2,840	−686
Palmitate + $23O_2 \longrightarrow 16CO_2 + 16H_2O$	−9,770	−2,338

ΔG predicts direction of rx

ΔG is directly related to K_{eq}

$$K_{eq} = \frac{[C][D]}{[A][B]}$$

Keq = equilibrium const

$$A + B \rightleftharpoons C + D$$

$$\Delta G = -RT\ln K_{eq} = -2.303\ RT \log K_{eq}$$

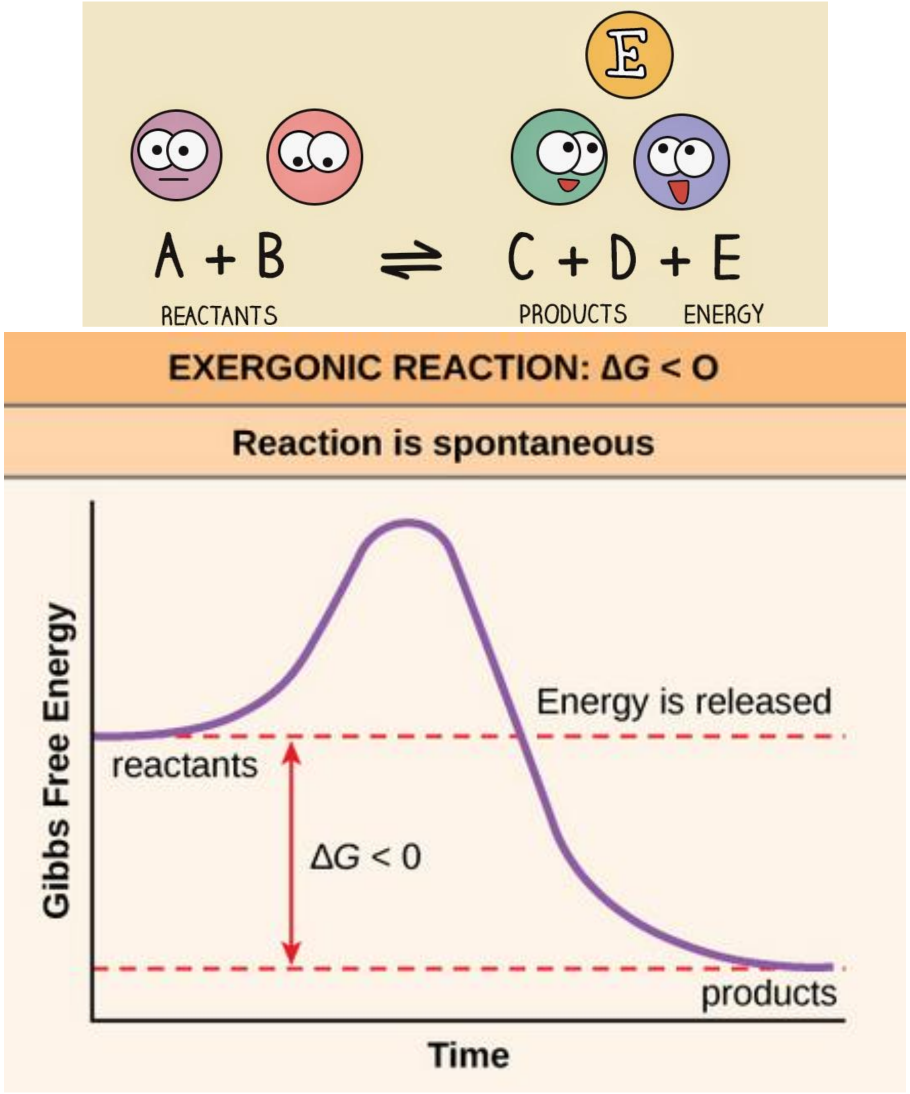
R = gas constant = 8.315 J/mol.K = 1.987 cal/mol.K T = 298 K

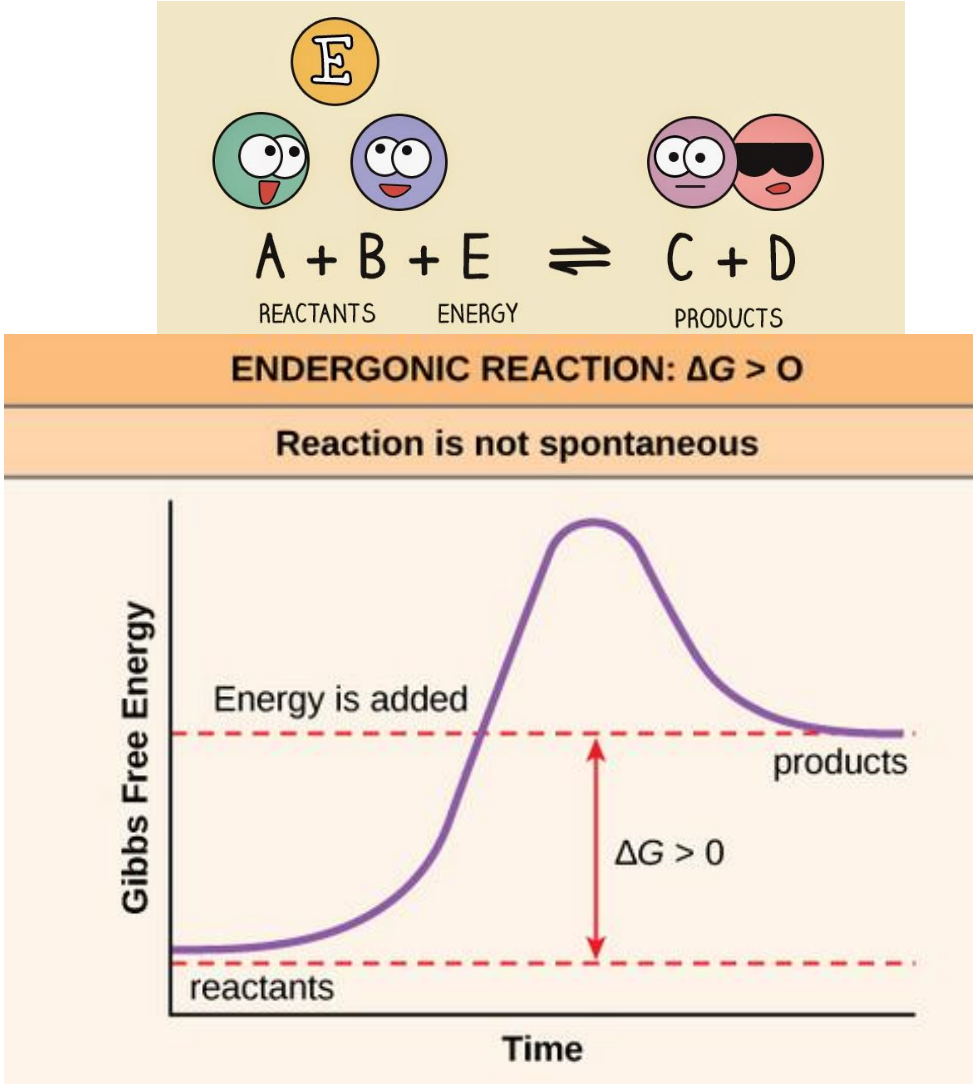
คายพลังงาน

$K_{eq} > 1$	ΔG = -ve	forward rx.	Exergonic
$K_{eq} = 1$	ΔG = 0	equilibrium	
$K_{eq} < 1$	ΔG = +ve	backward rx.	Endergonic

ดูดพลังงาน

for constant T, P processes





Reactants have more free energy than the products
→release of energy
(increase in entropy)
Occur spontaneously

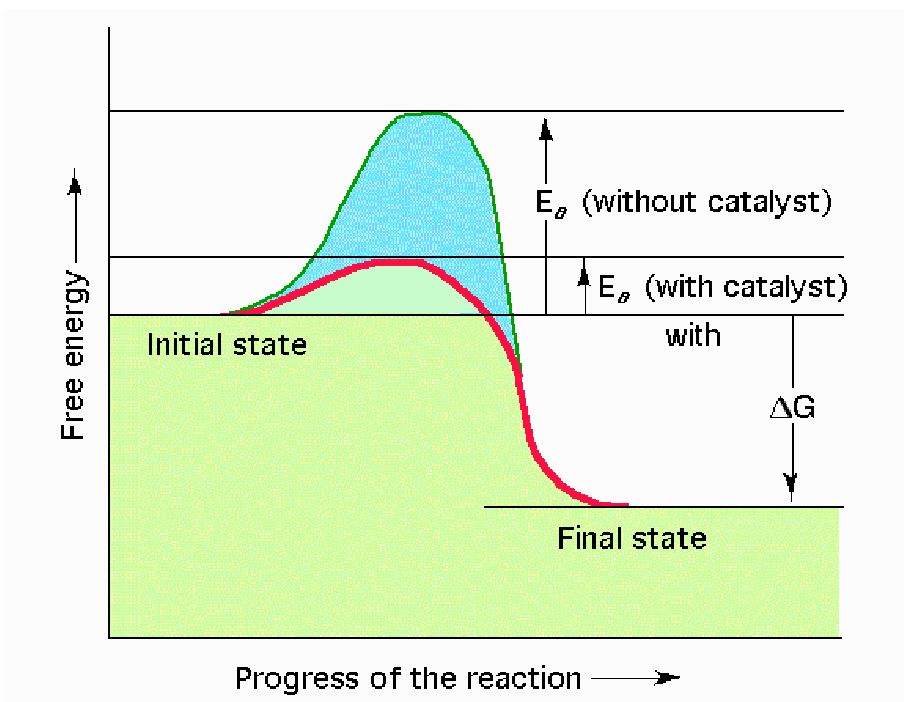
Reactants have less free energy than the products
→ Need input of energy
(decrease in entropy)
Do not occur spontaneously

Why enzymes are needed for biochemical reaction?

To c_t_lyz_ rx.

Rate of rx. is determined by

enzyme activity



ΔG can tell that the rx. can occur but cannot tell the rate (how fast) of rx.

How can we make the unfavorable reaction occur?

By **coupling reaction (with ATP)**, the overall chemical process is made exergonic so it can occur spontaneously due to –ve ΔG.

take the energy from the "rich" and bring it to the "poor"

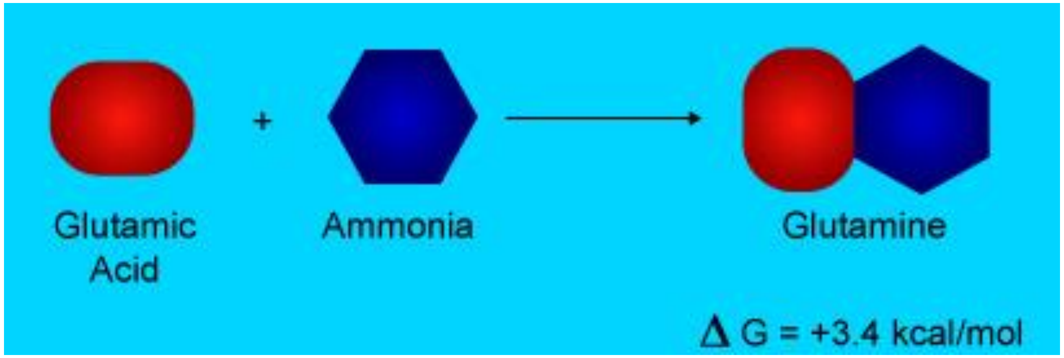
$$\text{Glucose} + \text{Pi} \longrightarrow \text{Glucose-6 P} + H_2O \qquad \Delta G^{o\prime} = +14\ \text{kJ/mol}$$

$$\text{ATP} + H_2O \longrightarrow \text{ADP} + \text{Pi} \qquad \Delta G^{o\prime} = -30.5\ \text{kJ/mol}$$

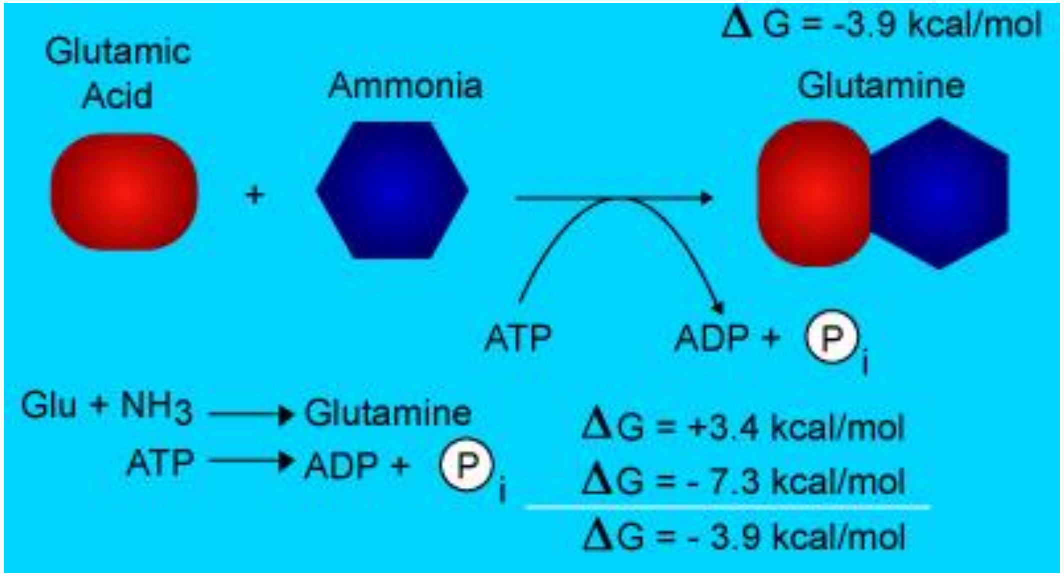
$$\text{Glucose} + \text{ATP} \longrightarrow \text{Glucose-6 P} + \text{ADP} \qquad \Delta G^{o\prime} = -17\ \text{kJ/mol}$$

Living organisms have the ability to couple exergonic and endergonic reactions

How can we make this reaction occur?



Ans. Coupling reaction



https://wikispaces.psu.edu/download/attachments/40044557/glutamine_formation.jpg

Summary Part 3

1. A living system's free energy is energy that can do work under cellular conditions (break and form chemical bonds)

2. Gibbs' free energy (G) – in a cell is the amount of energy contained in a molecule's chemical bonds (at constant temperature and pressure)

3. Change in free energy (ΔG)

- Endergonic - any reaction that requires an input of energy
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4. Living organisms have the ability to couple exergonic and endergonic reactions

Part 4 – ATP and high energy compound

Key idea HIGH ENERGY COMPOUND

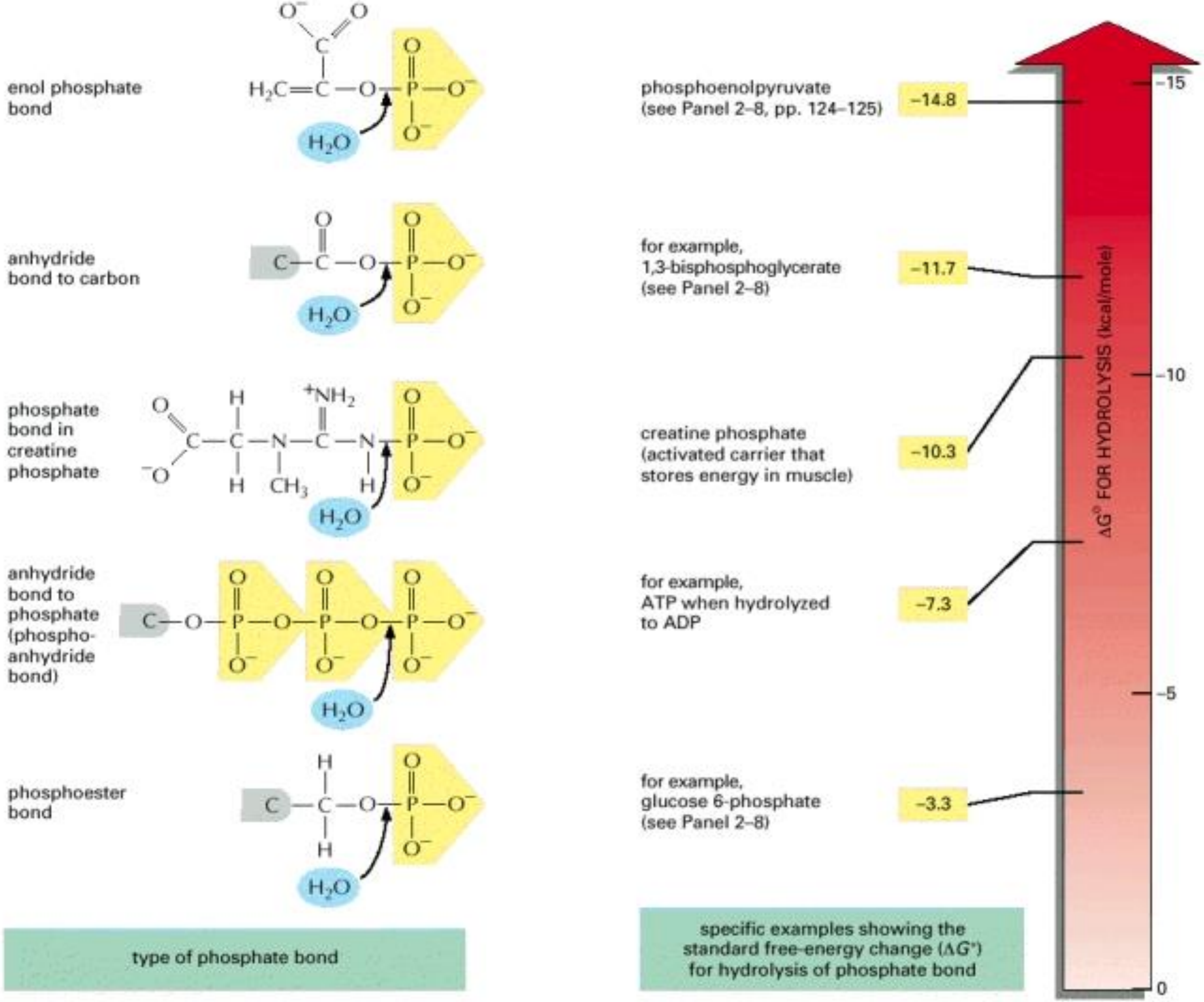
1. ATP is the energy currency of living cell.
   ATP $\longrightarrow$ ADP + Pi (exergonic rx.)
   can couple with many endergonic rx.

2. We get NADH and $FADH_2$ (reducing equivalents which can give e- to complex in Electron Transport System) from metabolism e.g. glycolysis, Kreb's cycle

3. In ETS, e- pass from complex I, II, III, IV and O_2 is the final e- acceptor

4. ATP synthase use energy from proton gradient to generate ATP (oxidative phosphorylation)

There are many high energy compounds

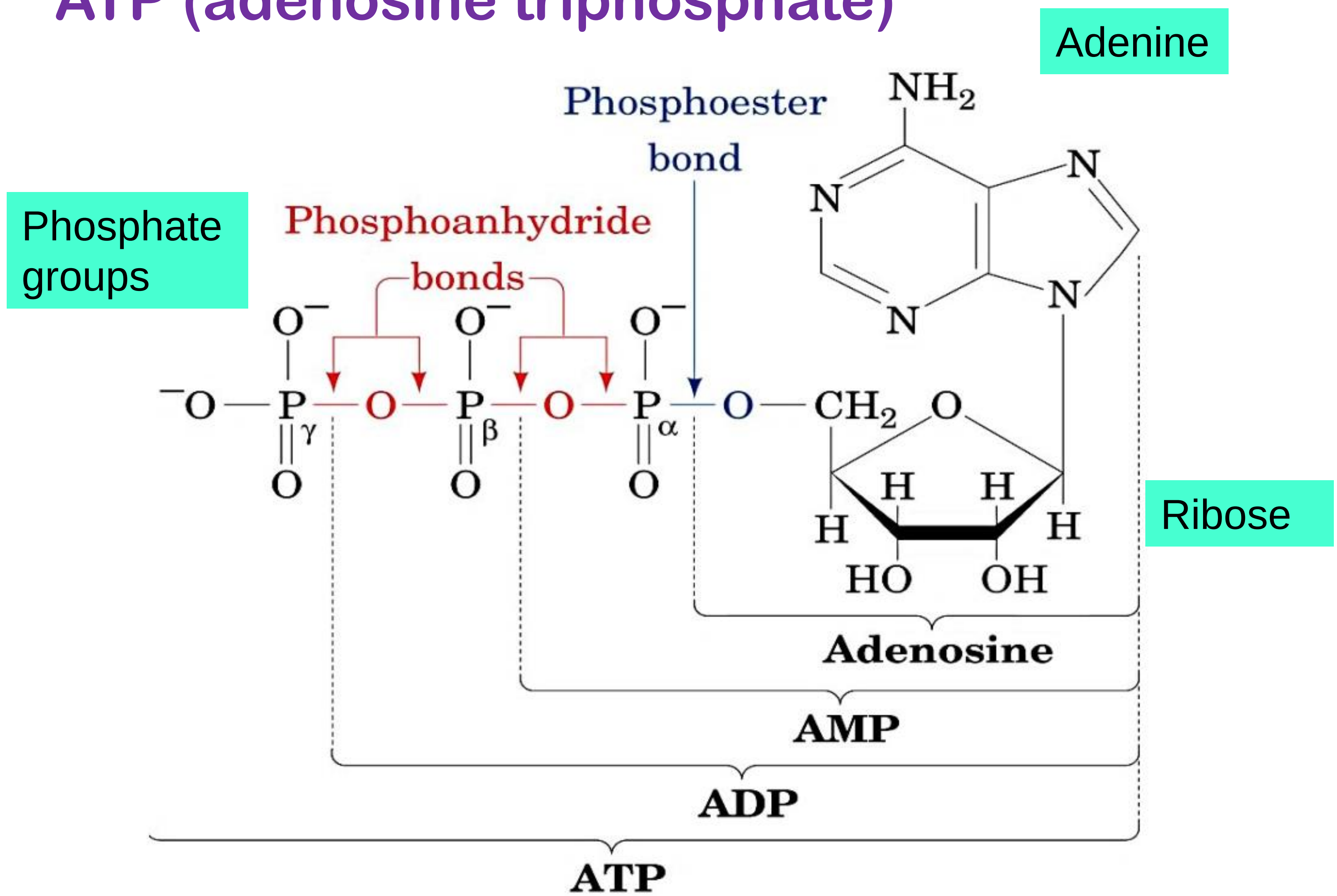


Compound	ΔG ($kJ \cdot mol^{-1}$)
Phosphoenolpyruvate	−61.9
1,3-Bisphosphoglycerate	−49.4
Acetyl phosphate	−43.1
Phosphocreatine	−43.1
PP_i	−33.5
ATP (→ AMP + PP_i)	**−32.2**
ATP (→ ADP + P_i)	**−30.5**
Glucose-1-phosphate	−20.9
Fructose-6-phosphate	−13.8
Glucose-6-phosphate	−13.8
Glycerol-3-phosphate	−9.2

ATP is an important high energy compound for cells

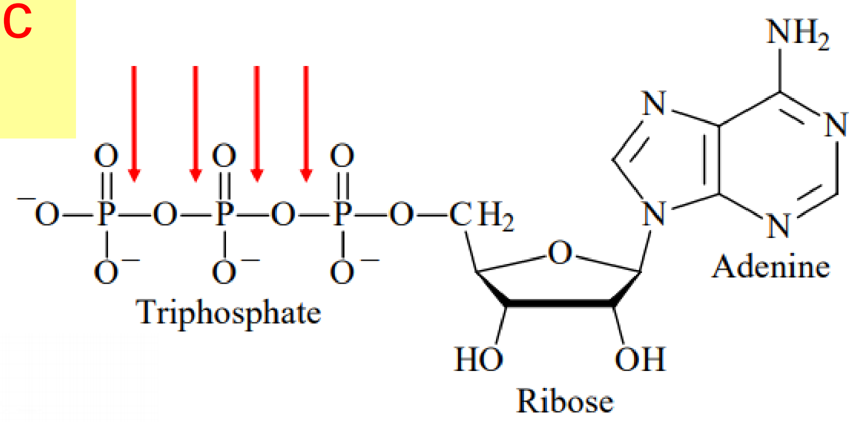
Source: Jencks, W.P., *in* Fasman, G.D. (Ed.), *Handbook of Biochemistry and Molecular Biology* (3rd ed.), *Physical and Chemical Data,* Vol. I, *pp.* 296–304, CRC Press (1976).

ATP (adenosine triphosphate)

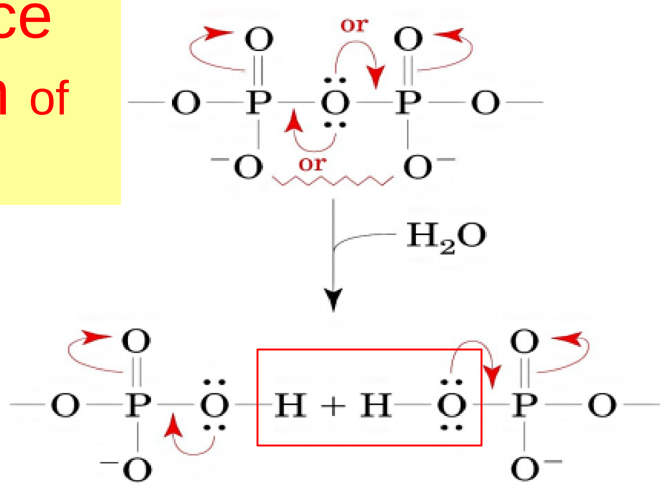


Base on the chemical structure of ATP, why it is high energy compound ?

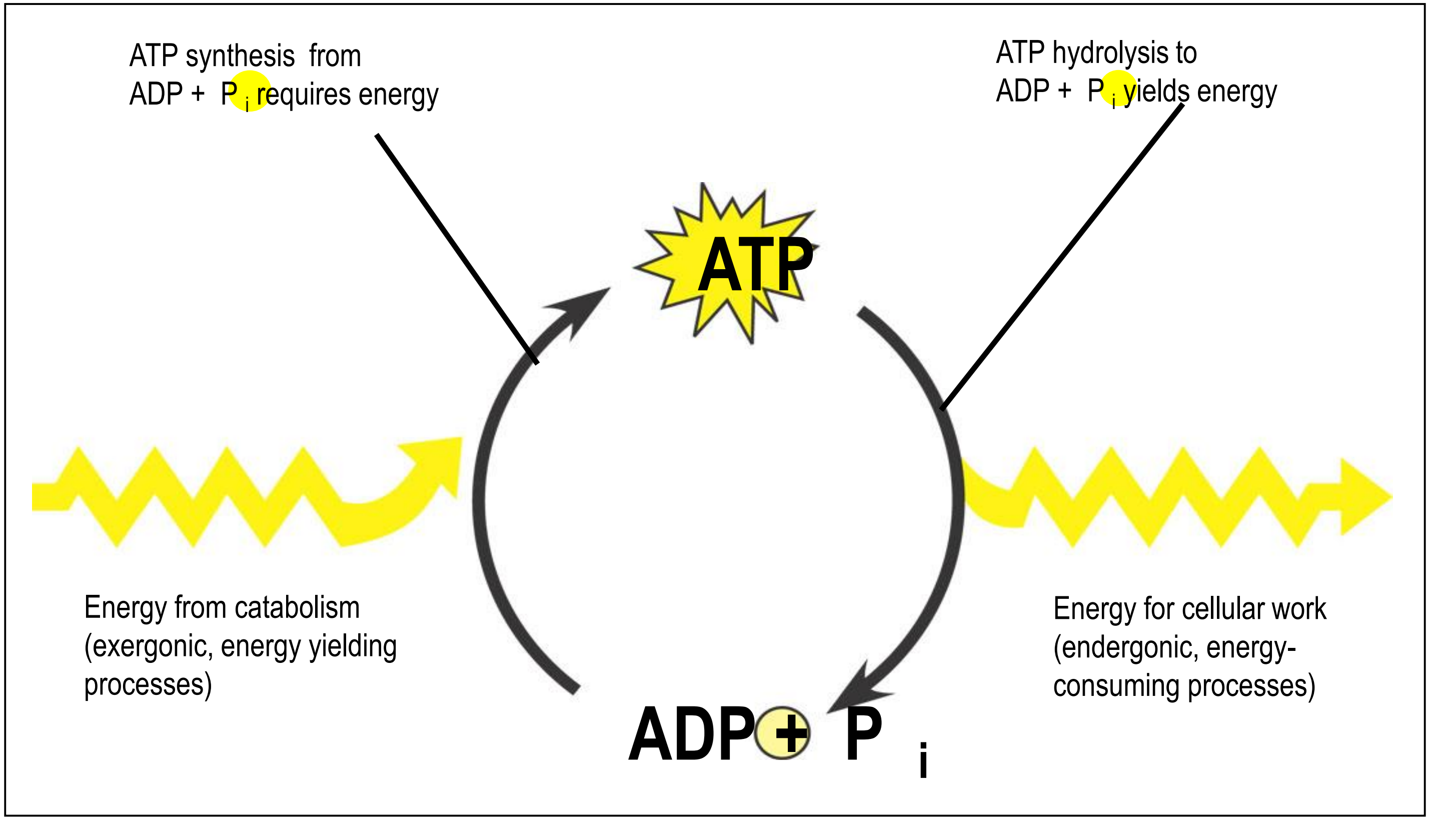
1.Electrostatic repulsion



2.Resonance stabilization of the product



Conversion from ATP to ADP is an important reaction for the supplying of energy for life processes

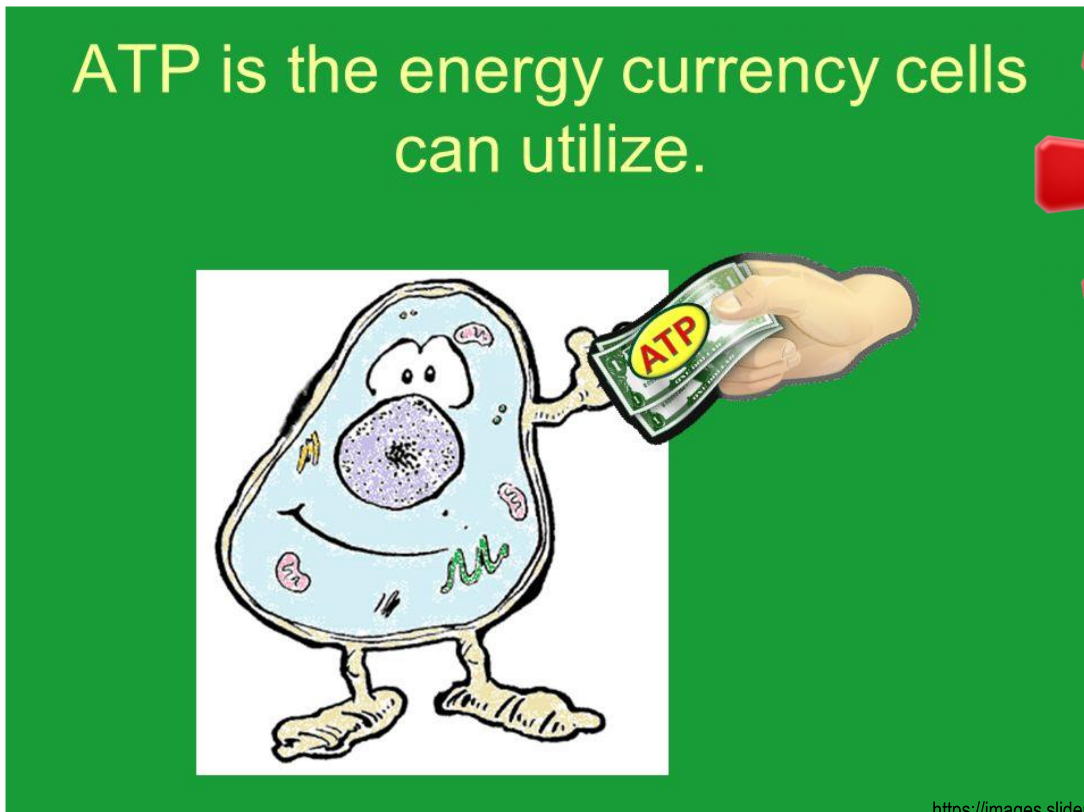


- **Cut phosphate from ATP can generate ADP (exergonic)**
- **Link phosphates to ADP can make ATP (endergonic)**
- **Catabolic pathways drive the regeneration of ATP from ADP and phosphate**

Why ATP is called energy currency ?

1.A l_t of ATP in cells

2.It carries a large amount of energy in phosphate bond (that are easily broken when needed)



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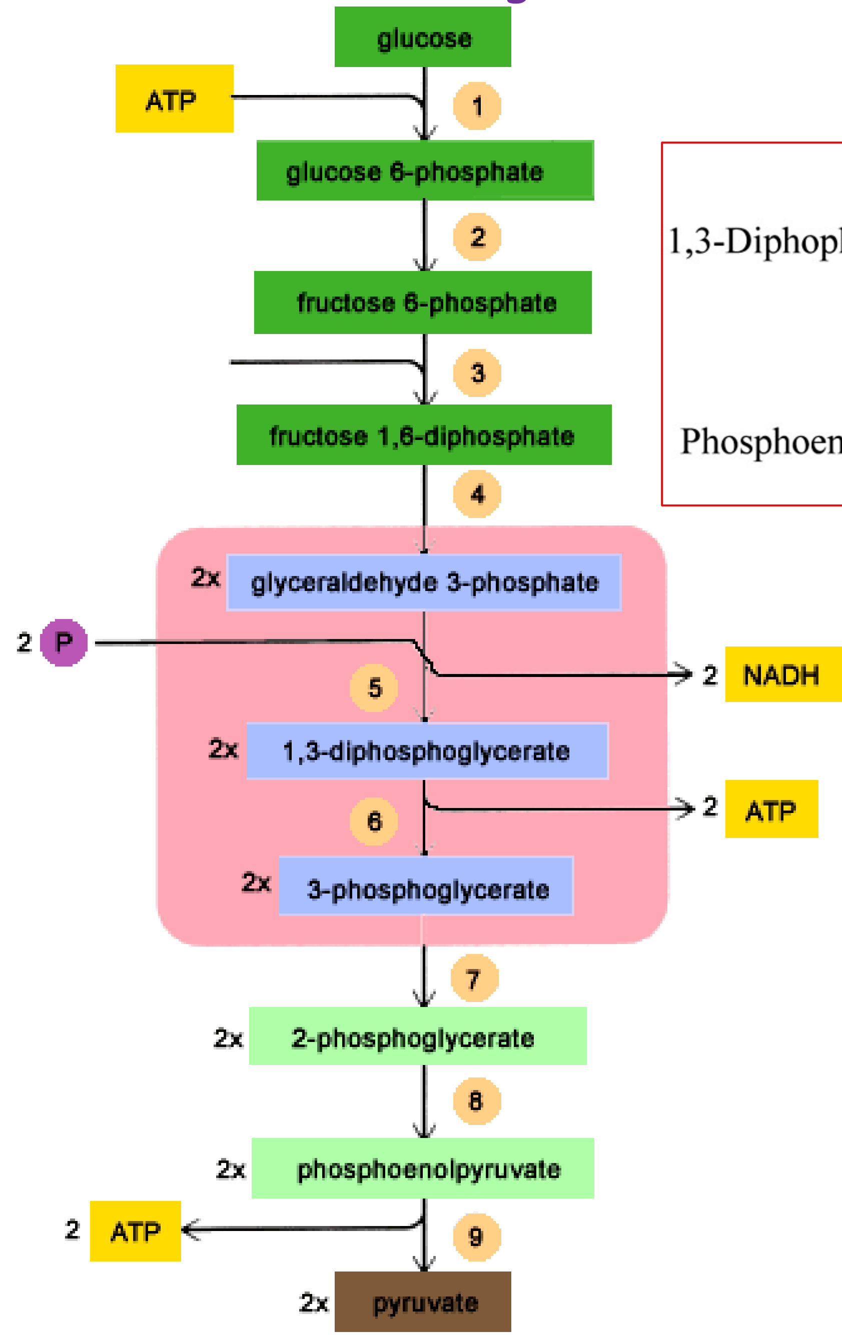
ATP can be synthesized by



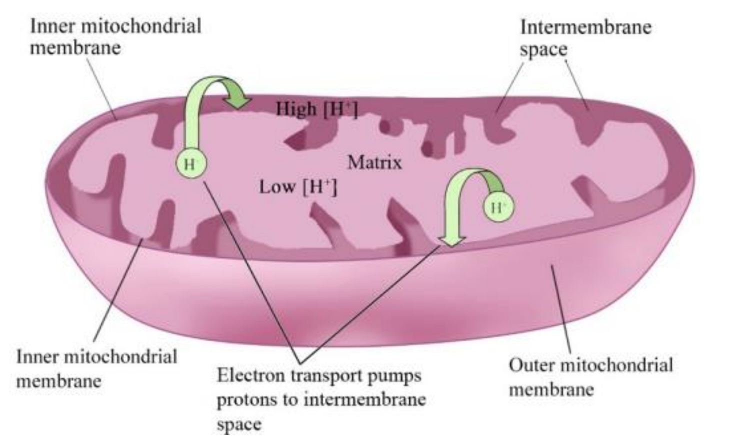
1.Substrate level phosphorylation

1,3-Diphophoglycerate + ADP ⇌ (Phosphoglycerate kinase) 3-Phophoglycerate + ATP

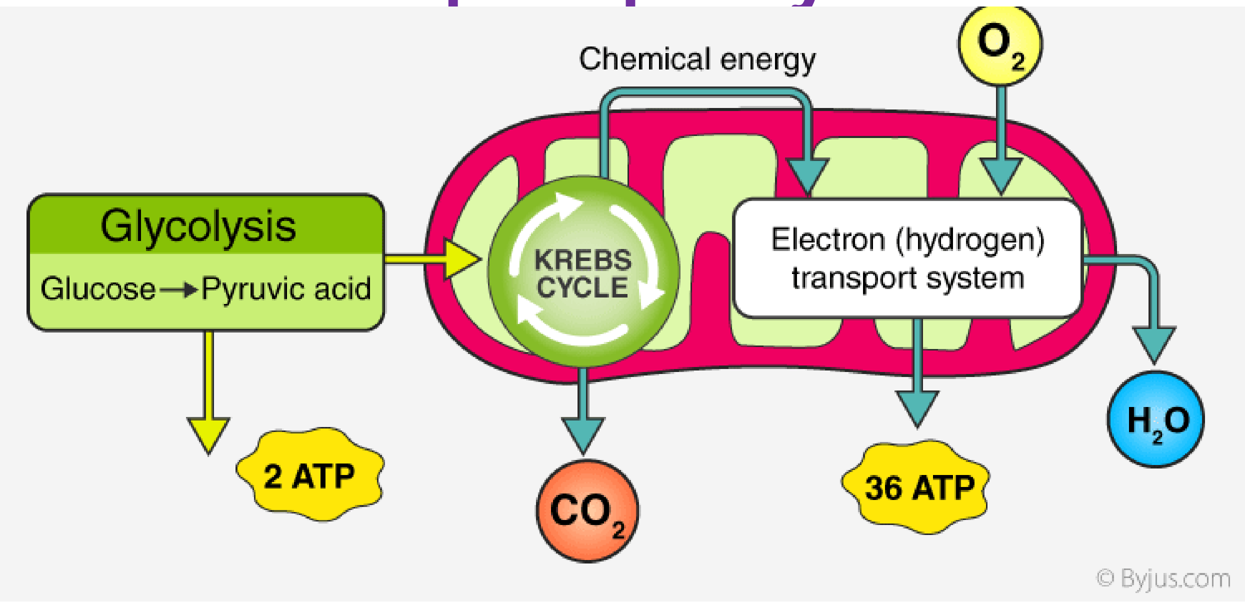
Phosphoenolpyruvate + ADP ⇌ (Pyruvatekinase) Pyruvate + ATP

2.Oxidative phosphorylation

At innermembrane of mitochondria



What is the difference between substrate level phosphorylation and oxidative phosphorylation?



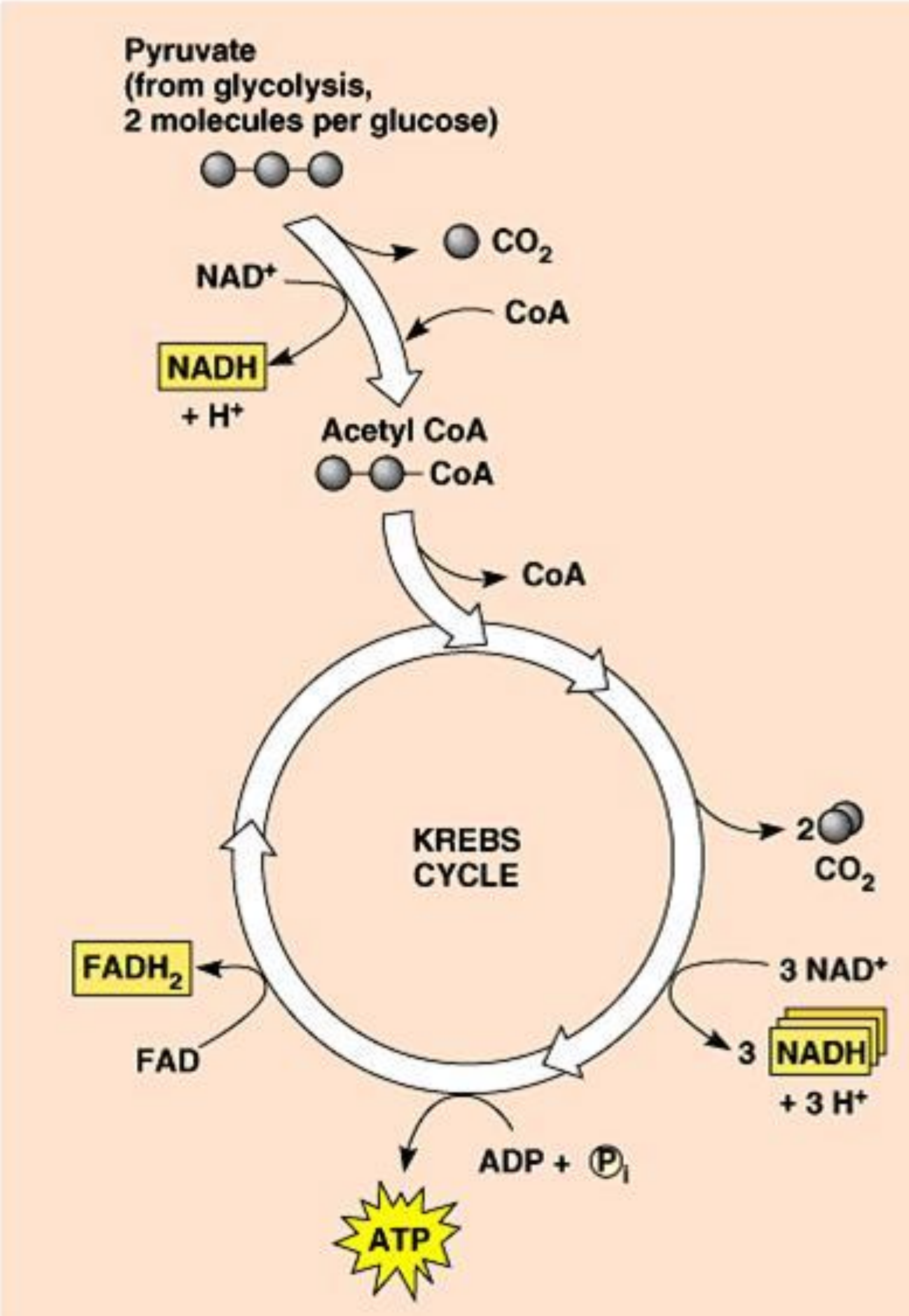
Substrate level phosphorylation

Direct formation of ATP (by transfer phosphate group from substrate to ADP **(occur in glycolysis and Kreb's cycle)**

Oxidative phosphorylation

Indirect formation of ATP (by oxidation of NADH, $FADH_2$) → transfer e- → pump H+ → O2 final e- acceptor **(occur via electron transport chain)**

https://cdn1.byjus.com/wp-content/uploads/2018/11/Aerobic-Respiration.png



Electron transport chain and oxidative phosphorylation

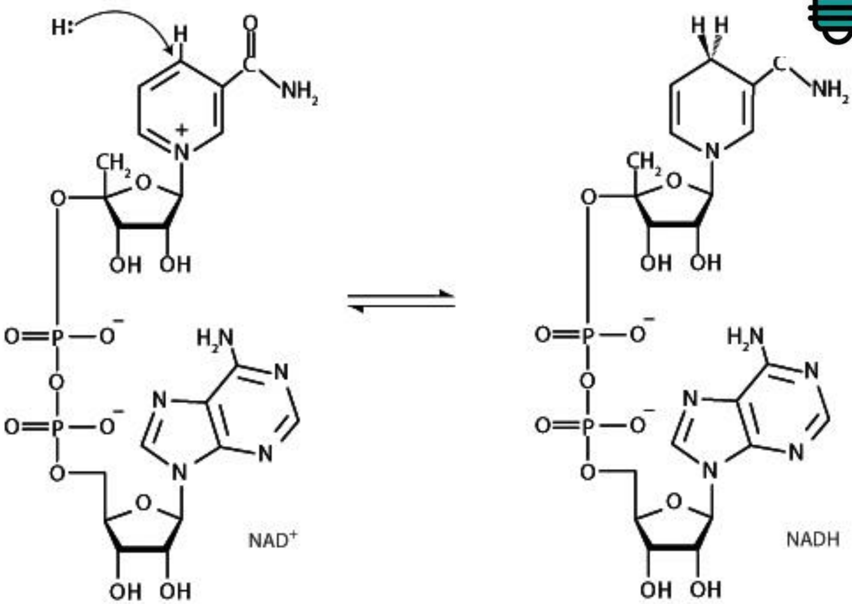
capture the energy in the redox potential of NADH and $FADH_2$

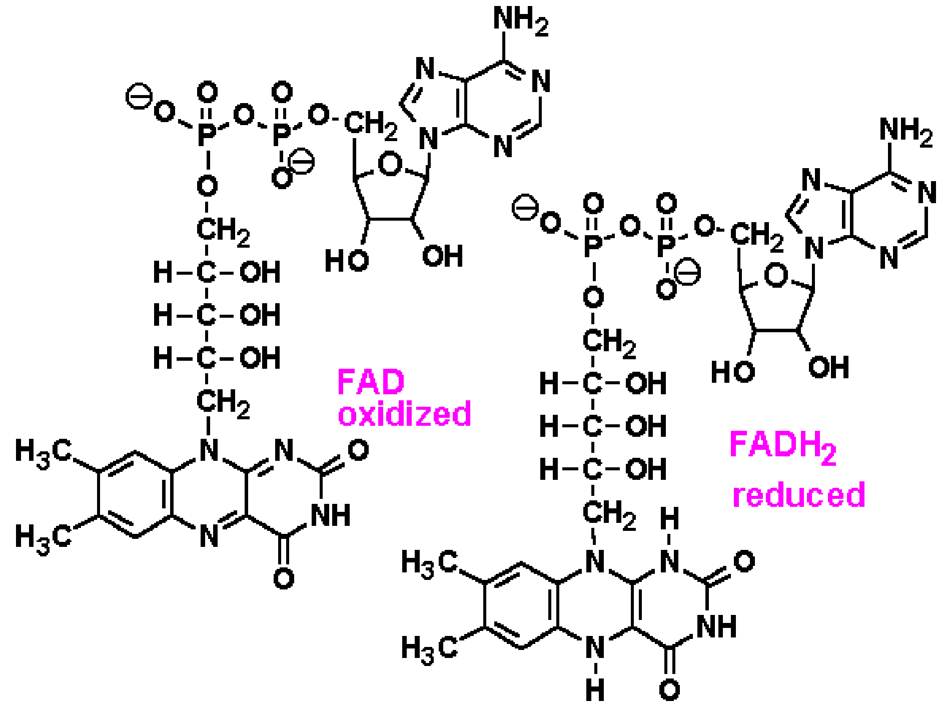
result in ATP production

NADH and $FADH_2$ are reduced forms of high energy molecules or called reducing equivalent.

NADH = nicotinamide adenine dinucleotide

$FADH_2$ = Flavin adenine dinucleotide

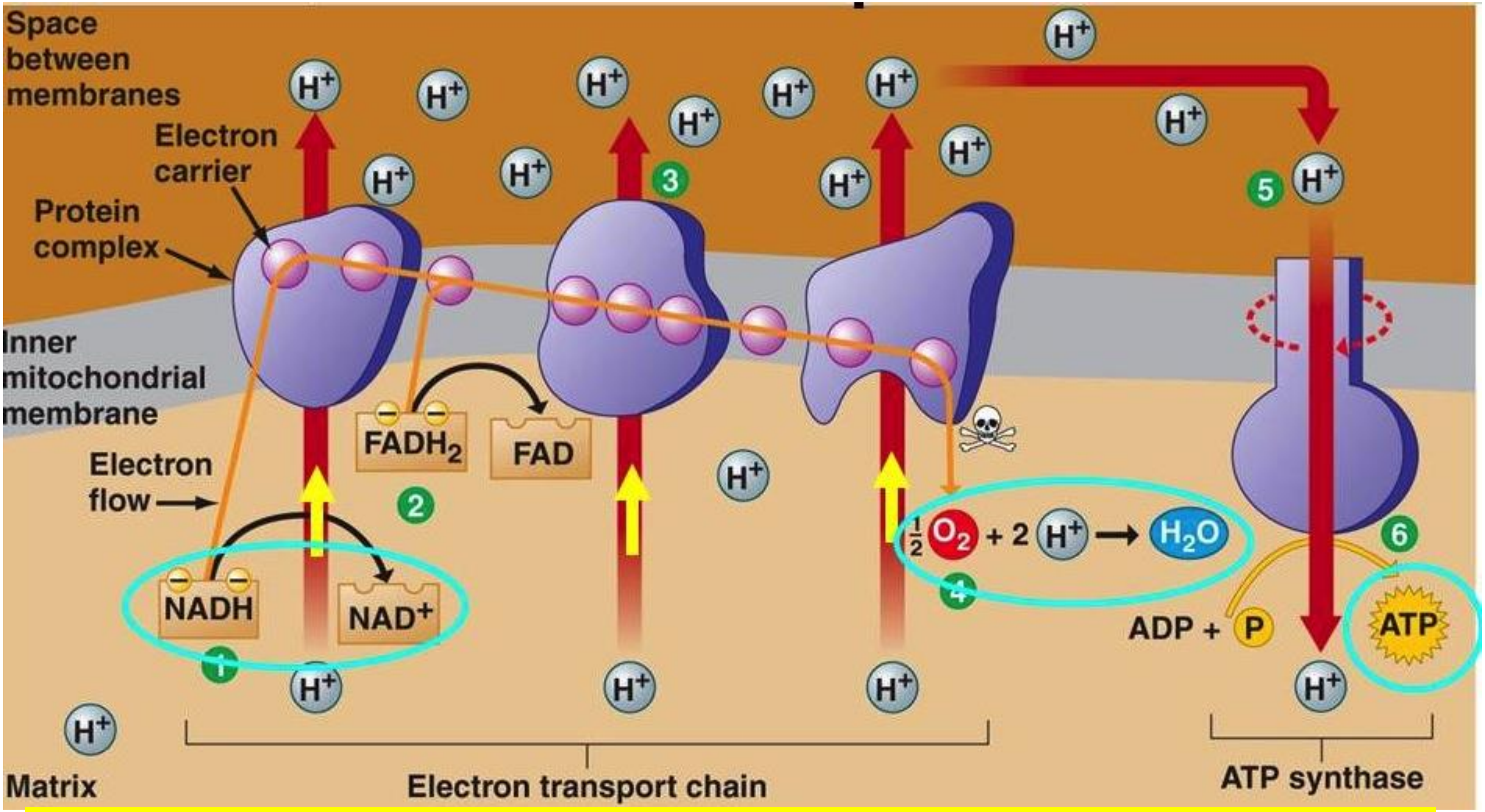




NADH and $FADH_2$ donate their e- to the electron carriers of the electron transport chain (ETC).
O_2 is the final e- acceptor in this process) ATP is produced by oxidative phosphorylation.

Electron transport chain
(at innermembrane of Mitochondria)

Oxidative phosphorylation

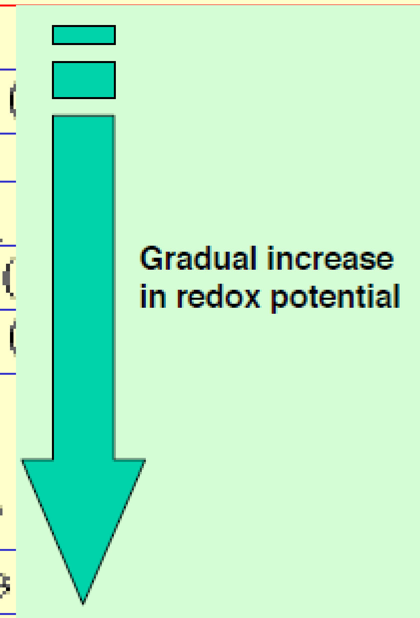


Electron is transported from Complex I (or II) → III → IV → V, create concentration and pH gradients

Std reduction potential for biological rx.

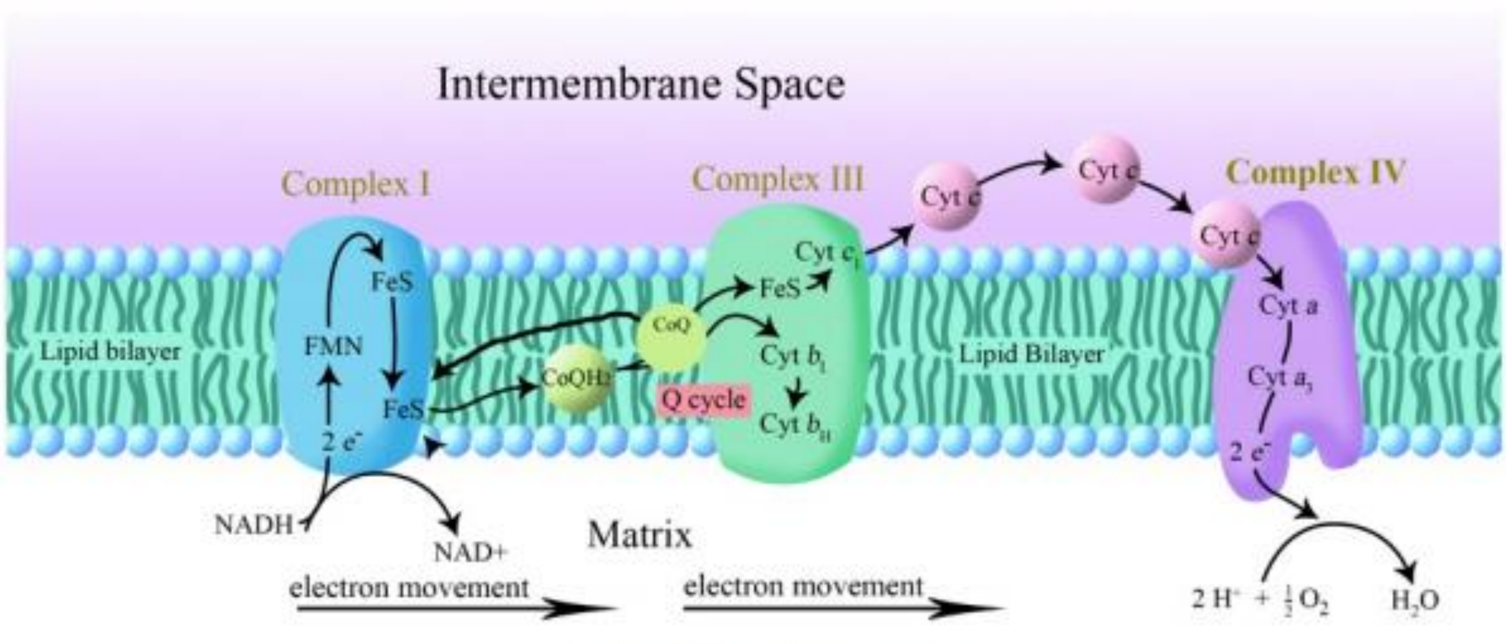
Oxidant	Reductant	*n*	E'_0, V
Acetate + CO_2 + $2H^+$	Pyruvate + H_2O	2	−0.70
Succinate + CO_2 + $2H^+$	α-Ketoglutarate + H_2O	2	−0.67
Acetate + $3H^+$	Acetaldehyde + H_2O	2	−0.60
O_2	O_2^-	1	−0.45
Ferredoxin (oxidized)	Ferredoxin (reduced)	1	−0.43
$2H^+$	H_2	2	−0.42
Acetoacetate + $2H^+$	β-Hydroxybutyrate	2	−0.35
Pyruvate + CO_2 + H^+	Malate	2	−0.33
NAD^+ + H^+	NADH	2	−0.32
$NADP^+$ + H^+	NADPH	2	−0.32
FMN (enzyme-bound) + $2H^+$	$FMNH_2$ (enzyme-bound)	2	−0.30
Lipoate (oxidized) + $2H^+$	Lipoate (reduced)	2	−0.29
1,3-Bisphosphoglycerate + $2H^+$	Glyceraldehyde-3-phosphate + P_i	2	−0.29
Glutathione (oxidized) + $2H^+$	2 Glutathione (reduced)	2	−0.23
FAD + $2H^+$	$FADH_2$	2	−0.22

Acetaldehyde + $2H^+$	Ethanol	2	−0.20
Pyruvate + $2H^+$	Lactate	2	−0.19
Oxaloacetate + $2H^+$	Malate	2	−0.17
α-Ketoglutarate + $\overset{+}{N}H_4$ + $2H^+$	Glutamate + H_2O	2	−0.14
Methylene blue (oxidized) + $2H^+$	Methylene blue (reduced)	2	0.01
Fumarate + $2H^+$	Succinate	2	0.03
CoQ + $2H^+$	$CoQH_2$	2	0.04
Cytochrome *b* (+3)	Cytochrome *b* (	1	0.07
Dehydroascorbate + $2H^+$	Ascorbate	2	0.08
Cytochrome c_1 (+3)	Cytochrome c_1	1	0.23
Cytochrome *c* (+3)	Cytochrome *c* (	1	0.25
Cytochrome *a* (+3)	Cytochrome *a* (	1	0.29
½O_2 + H_2O	H_2O_2	2	0.30
Ferricyanide	Ferrocyanide	2	0.36
Nitrate + $2H^+$	Nitrite + H_2O	1	0.42
Cytochrome a_3 (+3)	Cytochrome a_3	1	0.55
Fe (+3)	Fe (+2)	1	0.77
½O_2 + $2H^+$	H_2O	2	0.82



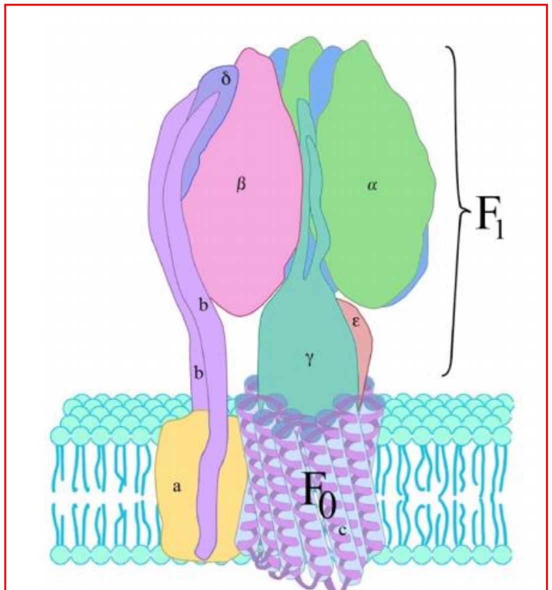
Note: E_0' is the standard reduction potential at pH 7 and 25°C, *n* is the number of electrons transferred, and each potential is for the partial reaction written as follows: Oxidant + ne^- ⟶ reductant.

Why there are many steps in electron transport chain ?



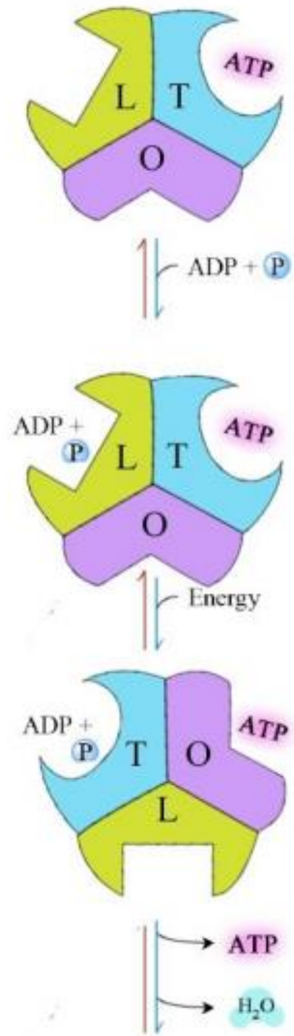
Electron Transport

How can ATP synthase generate ATP ?

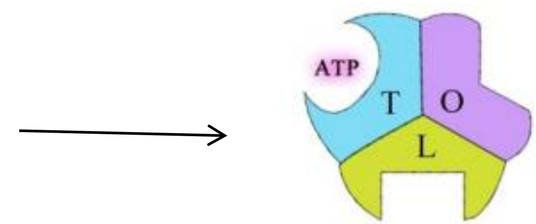


ATP Synthase

ATP is generated because the protons (H^+) move through a transmembrane protein called ATP synthase. This enzyme makes ATP from ADP and Pi.



Proton flow through the Fo channel → C unit rotates → conformation change → ATP synthesized



Three States of ATP Synthase

Why do we give name “oxidative phosphorylation”?

Energy stored in NADH, $FADH_2$ is used to produce ATP

Oxidation step

$$NADH + H^+ + O_2 \longrightarrow NAD^+ + H_2O$$

$$FADH_2 + O_2 \longrightarrow FAD + H_2O$$

Phosphorylation step

$$ADP + Pi \longrightarrow ATP$$

Summary Part 4

1. ATP is the energy currency of living cell.
   ATP $\longrightarrow$ ADP + Pi (exergonic rx.)
   can couple with many endergonic rx.

2. We get NADH and $FADH_2$ (reducing equivalents which can give e- to complex in ETS) from metabolism e.g. glycolysis, Kreb's cycle

3. In ETS, e- pass from complex I, II, III, IV and O_2 is the final e- acceptor

4. ATP synthase use energy from proton gradient to generate ATP (oxidative phosphorylation)