Biology for Engineers

FY-BTech

Unit 2- Life at Rest

Module-2: Life at rest

LIFE AT REST:
EQUILIBRIUM: RATES AND DURATION; ENERGY, ENTROPY AND FORCES, BIOLOGICAL MEMBRANES.

Thermodynamics and Static Properties of cells

Equilibrium: Mechanical and Chemical Equilibrium in the Living Cell; Cells as Chemical Factories; Chemical equilibrium, rate of reaction. The concept of steady state equilibrium.

Rates and duration: Time scales of small molecules; central dogma, Life cycle of cells.

Energy, Entropy and Forces: Thermal energy, photons and photosynthesis; energy currencies and budget.

Electrostatics

Biological Membranes: membrane permeability: pumps and channels, action potential.

> "An equation is worth a thousand words."
>
> A physical biologist

How cells manage energy and how scientists compute energy transformations ?

Chemical transformations that consume and liberate energy are one of the hallmarks of living systems.

Living cells follow the same principles of conservation of matter and energy as do all other physical systems

How cells manipulate and store chemical energy in ways that can be used to perform material transformations, such as macromolecular synthesis, mechanical work, such as muscle contraction, or even production of light energy, as in a firefly’s abdomen?

Thermodynamics is the study of energy transformations

Thermodynamics studies the energy flow, heat and movement, in structures among the universe.

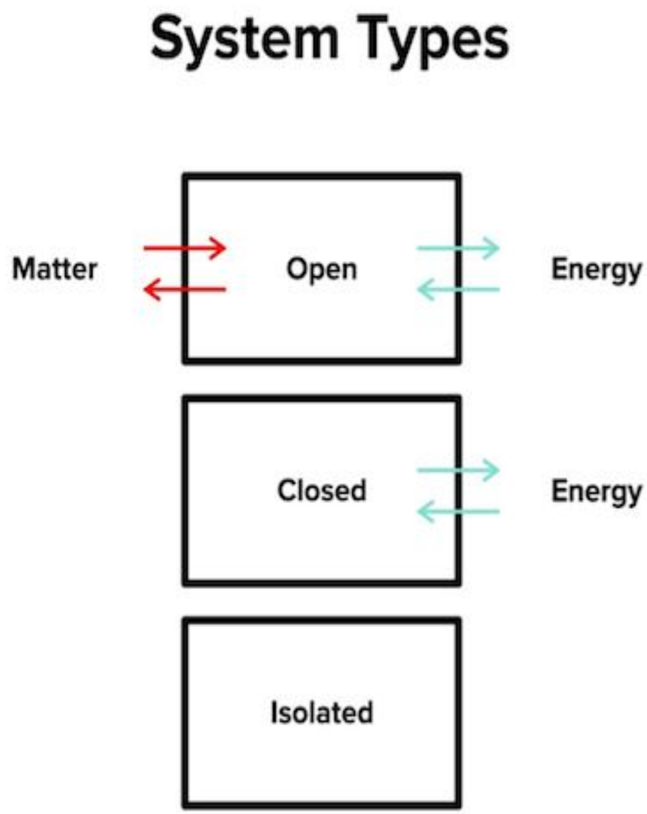
A living system, i.e. a cell, it is usual to refer to **open system thermodynamics** or **nonequilibrium thermodynamics**.

First law of thermodynamics
Energy cannot be created or destroyed

Second law of thermodynamics
Every energy transfer or transformation increases the entropy (disorder) of the universe

To measure "disorder" in the system we use a term "entropy"

Entropy is measure of disorder of a system
Or energy unavailable to do work



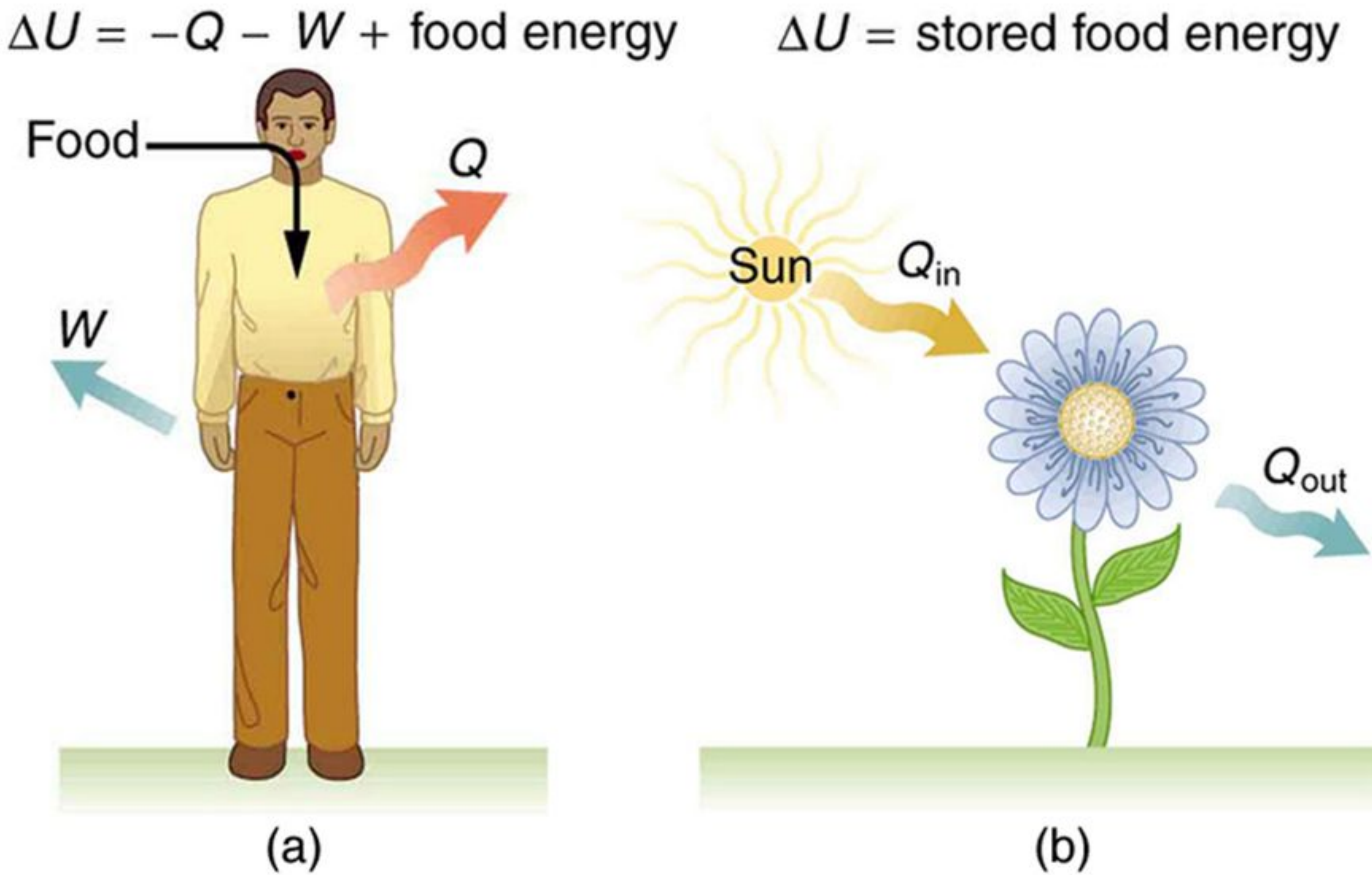
https://www.shemmassianconsulting.com/blog/thermodynamics-mcat

First law of thermodynamics

Energy cannot be created or destroyed

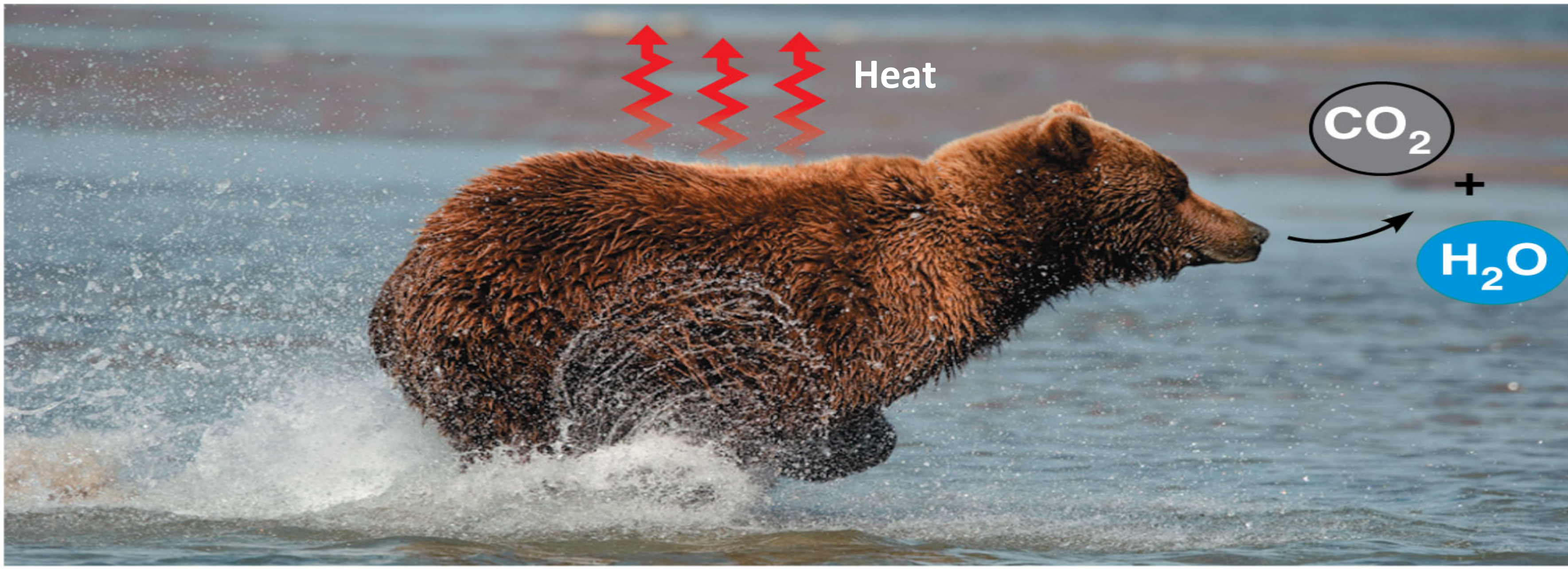
(a) First law of thermodynamics

First Law of Thermodynamics



Second law of thermodynamics

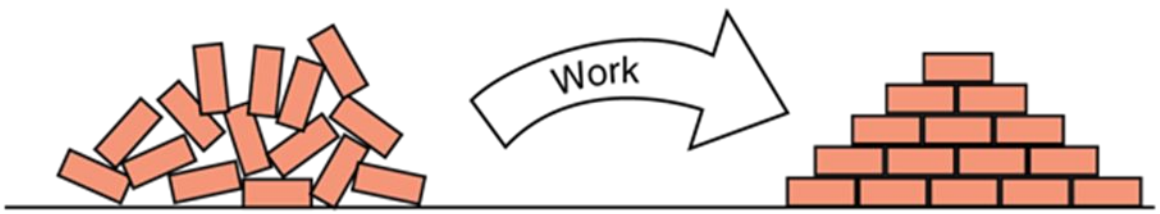
Every energy transfer or transformation increases the entropy (disorder) of the universe



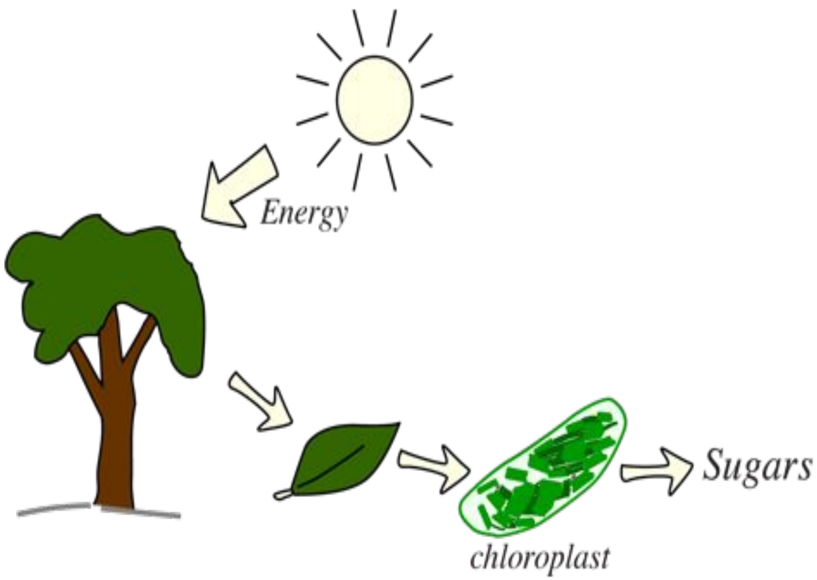
(b) Second law of thermodynamics

- Living cells unavoidably convert organized forms of energy to heat
- **Spontaneous processes** occur without energy input; they can happen quickly or slowly
- For a process to occur without energy input, it must increase the entropy of the universe
- Here, the word *spontaneous* does not imply that such a process would occur quickly; rather, the word signifies that the process is energetically favorable.

Work is generally required to produce order out of disorder, so energy must be used to produce a highly ordered state.



Order can be produced with an expenditure of energy, and the order associated with life on the earth is produced with the aid of energy from the sun.



Plants use energy from the sun in tiny energy factories called chloroplasts.

Using chlorophyll in the process called photosynthesis, they convert the sun's energy into storable form in ordered sugar molecules. In this way, **carbon and water in a more disordered state are combined to form the more ordered sugar molecules.**

In animal systems there are also small structures within the cells called mitochondria which use the energy stored in sugar molecules from food to form more highly ordered structures.

http://hyperphysics.phy-astr.gsu.edu/hbase/thermo/bioentropy.htm

Biological Order and Disorder

- Cells create ordered structures from less ordered materials
- Organisms also replace ordered forms of matter and energy with less ordered forms
- Energy flows into an ecosystem in the form of light and exits in the form of heat
- The evolution of more complex organisms does not violate the second law of thermodynamics
- Entropy (disorder) may decrease in an organism, but the universe’s total entropy increases

Chemical equilibrium
Condition in the course of a reversible chemical reaction in which no net change in the amounts of reactants and products occurs.

A **reversible chemical reaction** is one in which the products, as soon as they are formed, react to produce the original reactants.

At equilibrium, the two opposing reactions go on at equal rates, or velocities, and hence there is no net change in the amounts of substances involved. At this point the reaction may be considered to be completed; i.e., for some specified reaction condition, the maximum conversion of reactants to products has been attained.

A reversible reaction at equilibrium is not static—reactants and products continue to interconvert at equilibrium, but the rates of the forward and reverse reactions are the same.

Mechanical equilibrium
Static equilibrium, also known as mechanical equilibrium, means the reaction has stopped. In other words, the system is at rest. In biology, the equilibrium of a system is called homeostasis.

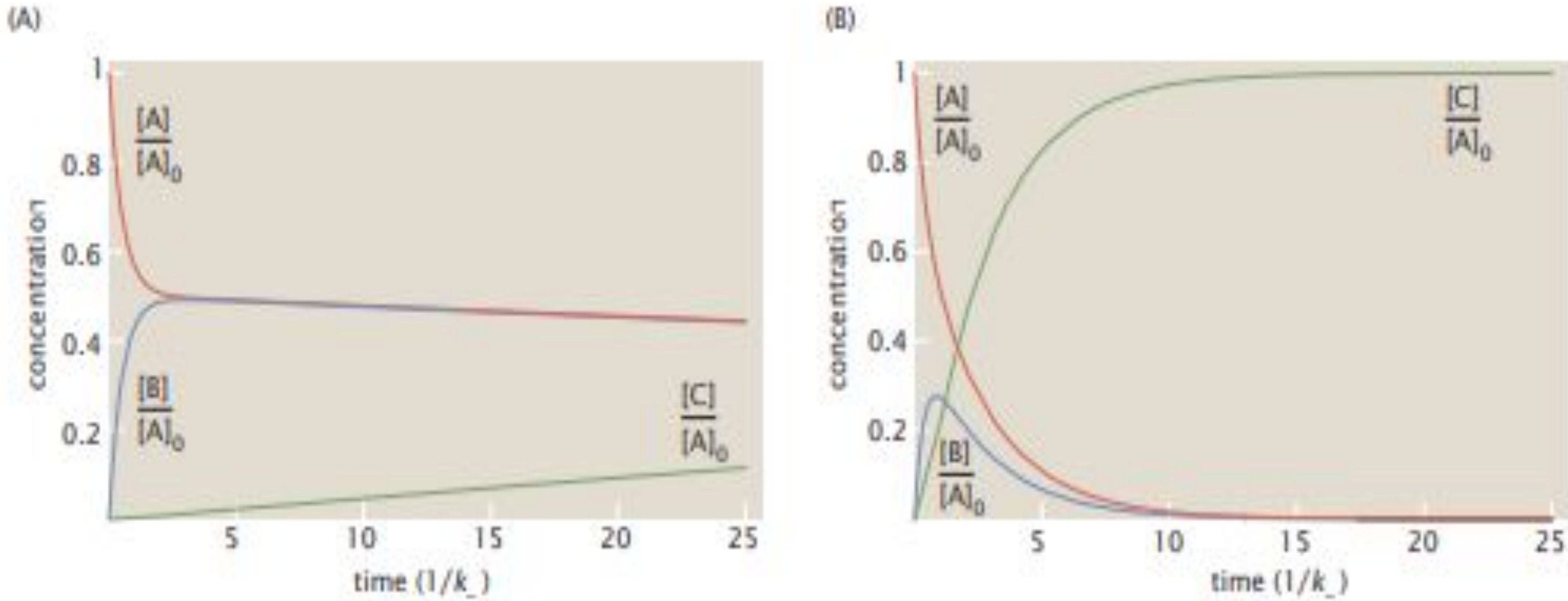
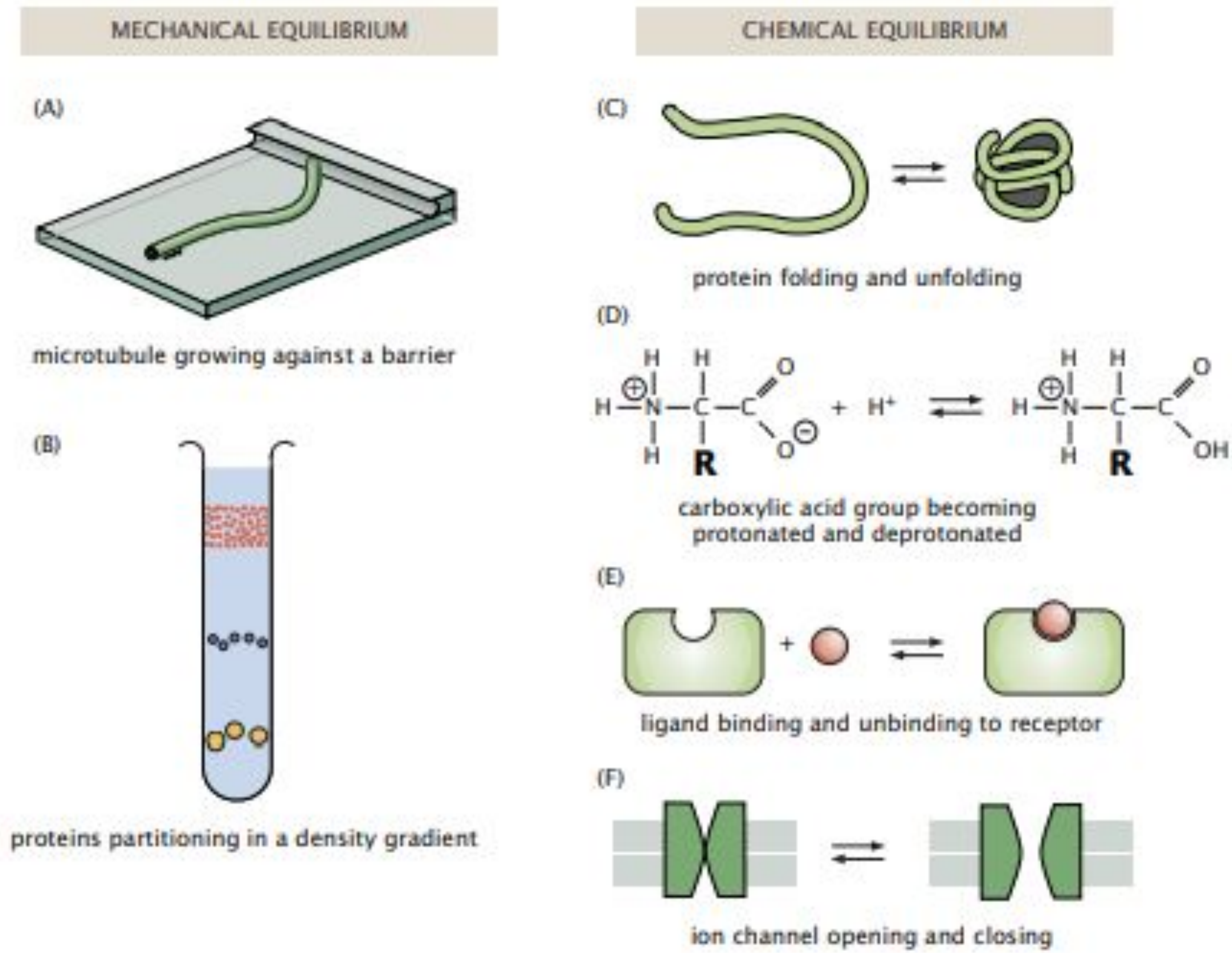


Figure 5.6: Rapid approach to equilibrium of a subprocess. Plot of the time-dependence of the concentrations in the reaction $A \rightleftharpoons B \rightarrow C$ of $A(t)$, $B(t)$ and $C(t)$ described by Equation 5.3. (A) For the case in which the rate for converting B to C is slow in comparison with the rates for the reaction between A and B, after an initial transient period, A and B reach their equilibrium values relative to each other for the remainder of the process. (B) Plot showing the case in which there is no rapid preequilibrium. Time is shown in nondimensional units by expressing it in units of the inverse of the rate k_-.


MECHANICAL EQUILIBRIUM
CHEMICAL EQUILIBRIUM
(A)
microtubule growing against a barrier
(B)
proteins partitioning in a density gradient
(C)
protein folding and unfolding
(D)
carboxylic acid group becoming protonated and deprotonated
(E)
ligand binding and unbinding to receptor
(F)
ion channel opening and closing

Free Energy, Stability, and Equilibrium

- 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

Free-Energy Change, ΔG

- A living system's **free energy** is energy that can do work when temperature and pressure are uniform, as in a living cell

- The change in free energy (ΔG) during a process is related to the change in enthalpy, or change in total energy (ΔH), change in entropy (ΔS), and temperature in Kelvin *(T)*

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

- Only processes with a negative ΔG are spontaneous

- Spontaneous processes can be harnessed to perform work

- The standard transformed free-energy change, $\Delta G0$ is a physical constant that is characteristic for a given reaction and be calculated from the equilibrium constant for the reaction: $\Delta G0 = - RT \ln K'$ eq.

- The actual free-energy change, ΔG, is a variable that depends on $\Delta G0$ and on the concentrations of reactants and products: $\Delta G = \Delta G0 + RT \ln K'$ eq.

- When ΔG is large and negative, the reaction tends to go in the forward direction; when ΔG is large and positive, the reactions tends to go in reverse direction and when $\Delta G=0$ the system is in equilibrium.

- The free-energy change for a reaction is independent of the pathway by which the reactions occurs. Free-energy changes are additive;the net chemical reaction that results from successive reactions sharing a common intermediate has an overall free-energy change that is the sum of the ΔG values for the individual reactions

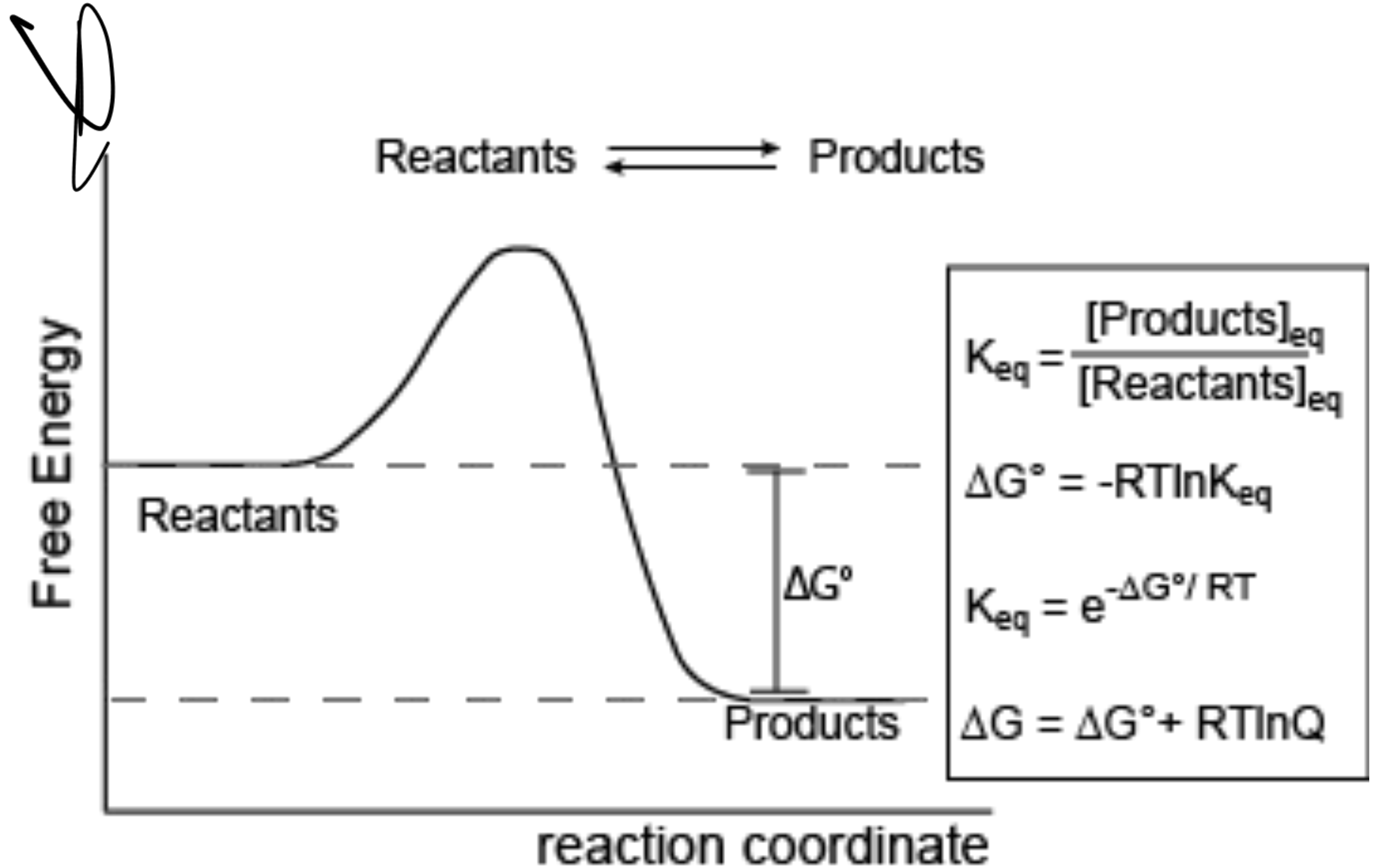


Figure 1. *Reaction coordinate diagram for a generic exergonic reversible reaction. Equations relating Gibbs energy and the equilibrium constant: R = 8.314 J mol^{-1} K^{-1} or 0.008314 kJ mol^{-1} K^{-1}; T is temperature in Kelvin. Attribution: Marc T. Facciotti (original work)*

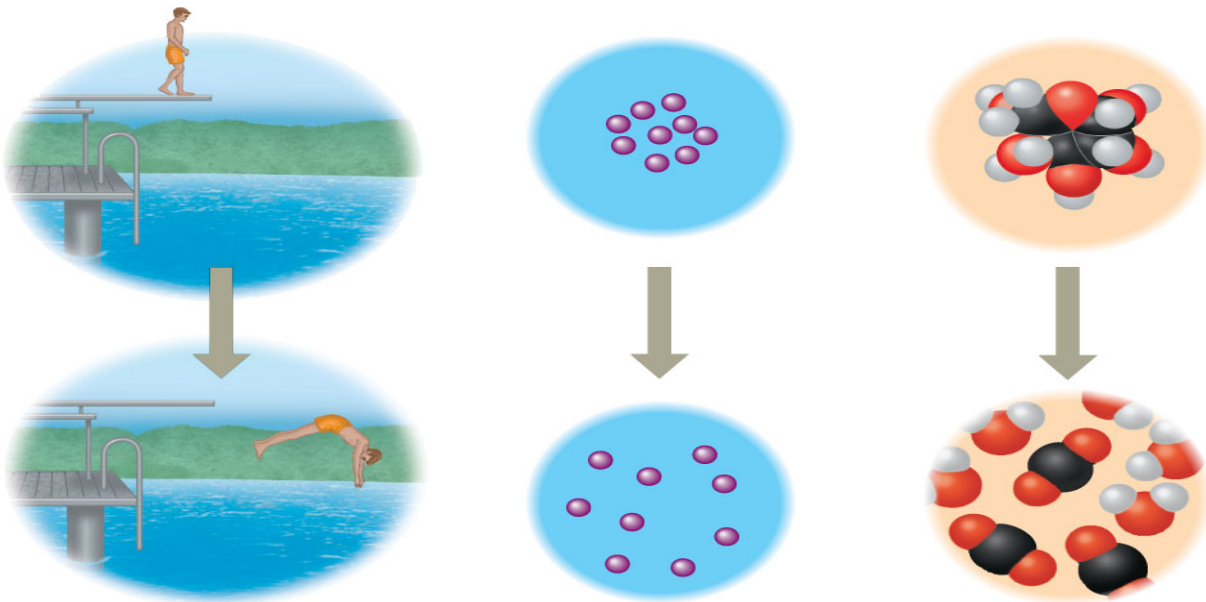
https://bio.libretexts.org/Courses/University_of_California_Davis/BIS_2A%3A_Introductory_Biology_(Easlon)/Readings/07.4%3A_Chemical_EquilibriumPart_2%3A_Free_Energy

Figure 8.5

- 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

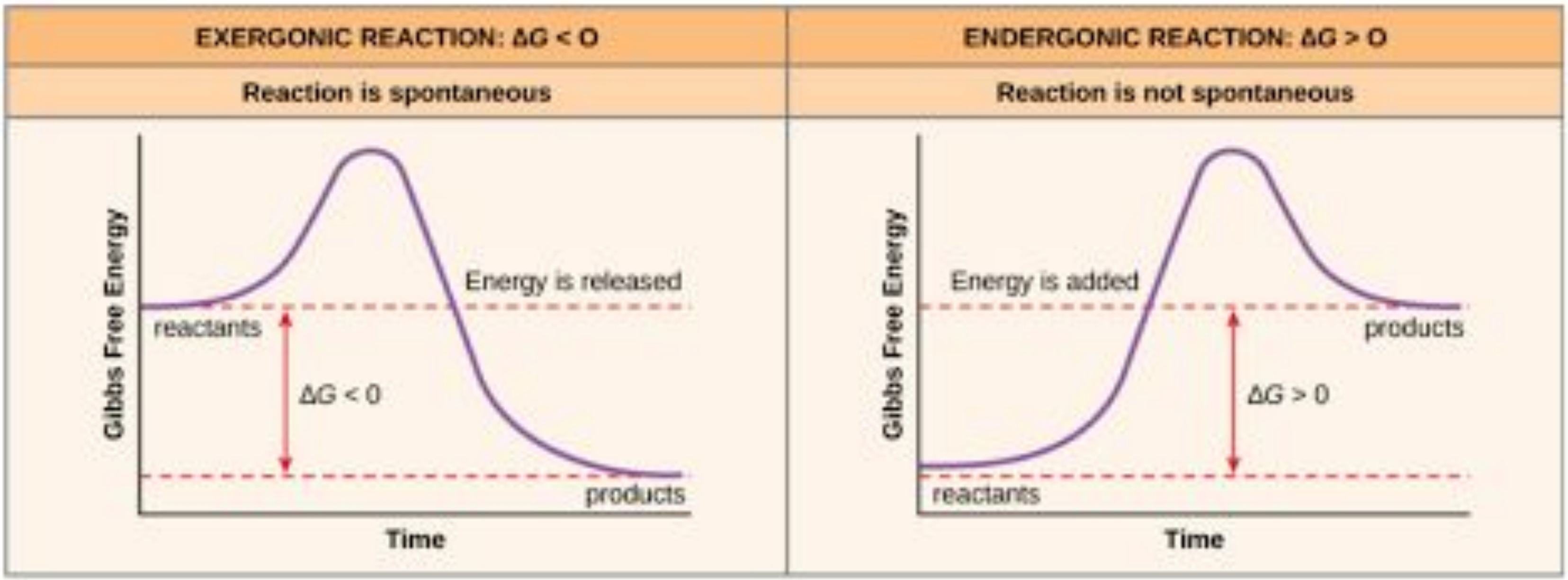
- Less free energy (lower G)
- More stable
- Less work capacity



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

Gibbs free energy – G

The amount of energy capable of doing work during a reaction at constant temperature and pressure. When a reaction proceeds with release of free energy, the free energy change is ΔG has a negative value and the reaction is exergonic reaction. In the endergonic reactions the system gains free energy and ΔG is positive



The free energy is stored in the bonds present in the reactants and products of a reaction. In a thermodynamic reaction, the change in Gibbs free energy (ΔG) is represented as:

ΔG = total free energy of products – total free energy of reactants

When $\Delta G = 0$, the reaction will be in equilibrium, which means the concentration of products and reactants does not change. $\Delta G < 0$, or a decrease in free energy, means energy is released during the reaction, and when $\Delta G > 0$, or an increase in free energy, it means energy is used up in the reaction.

- Living cell constantly perform work. They require energy for maintaining their highly organized structures, synthesizing cellular components, generating currents etc.

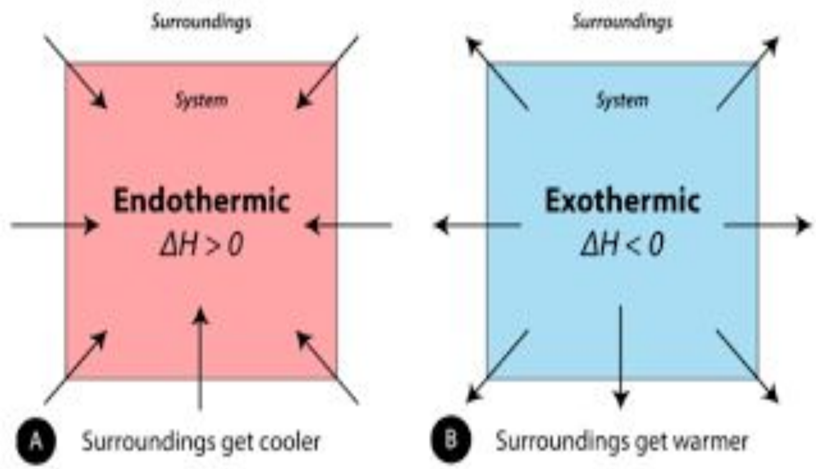
- Bioenergetics is quantitative study of energy conversions in biological systems. Biological energy transformations obey thermodynamics laws.

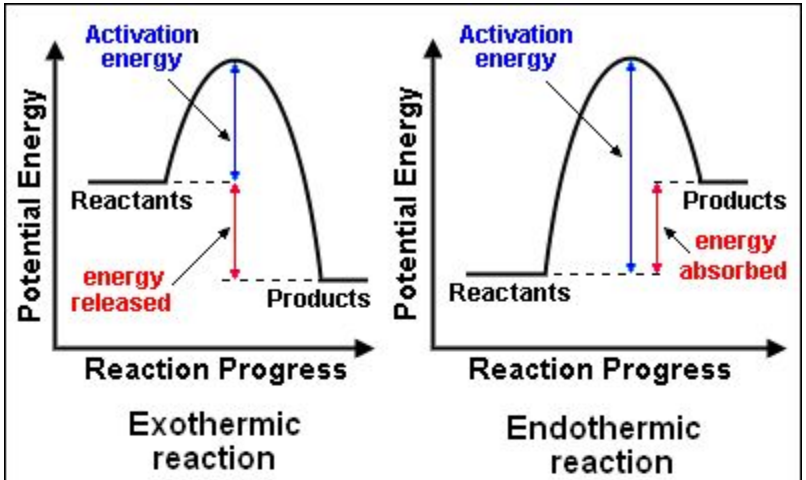
- All chemical reactions are influenced by two forces: tendency to achieve most stable bonding state (enthalpy H) and tendency to achieve the highest randomness (entropy S). The net driving force is ΔG, the free energy change.

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

Enthalpy H

The heat content of the reacting system. It reflects the number and kinds of chemical bonds in the reactants and products. When a chemical reaction releases heat it is said to be exothermic reaction; the heat content of products is less than that of reactants and Δ H has a negative value. Reacting systems that take up heat from surroundings are endothermic and have positive Δ H



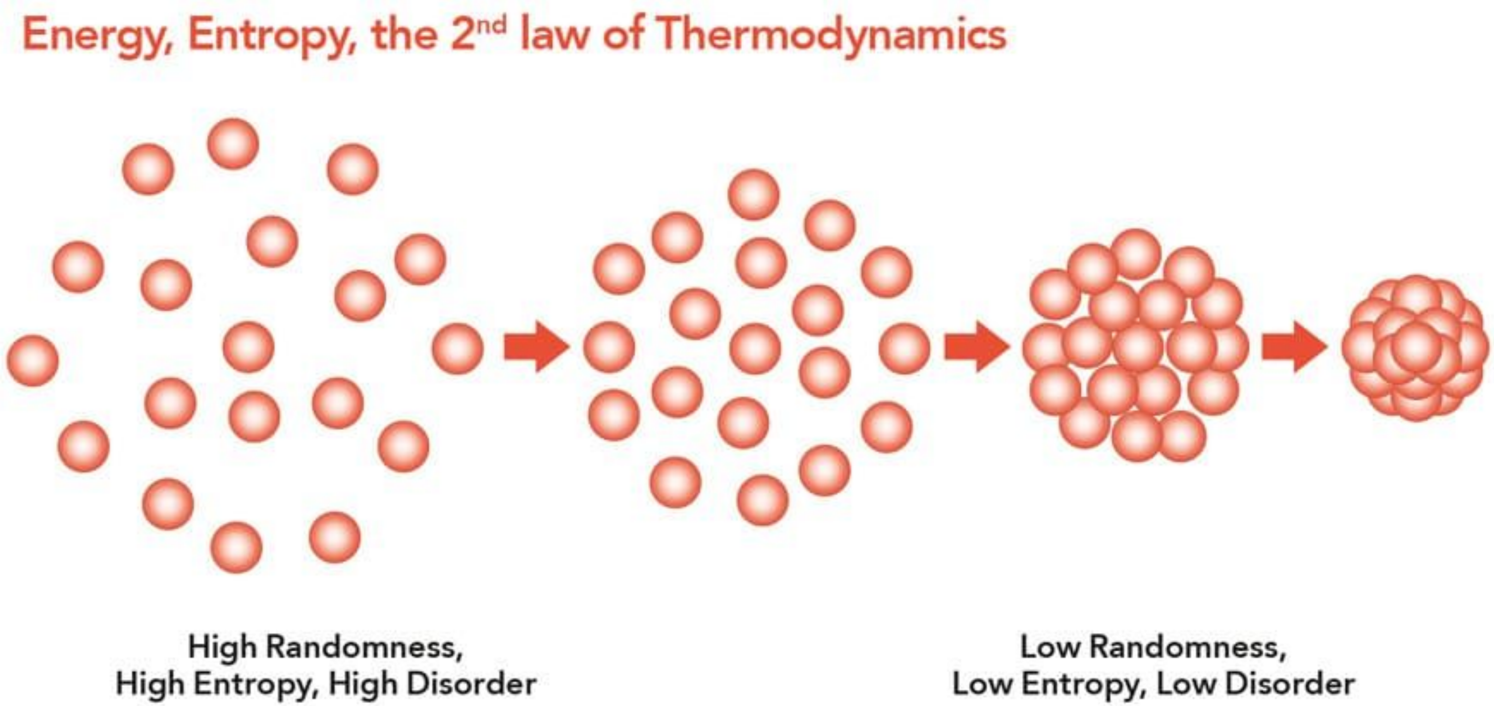


Source: Milton Beychok

Energy level diagrams of exothermic and endothermic reactions.[4][5][6]

Entropy – S

Quantitative expression for the randomness or disorder in a system. When products of a reaction are less complex and more disordered than reactants, the reaction is said to proceed with a gain in entropy

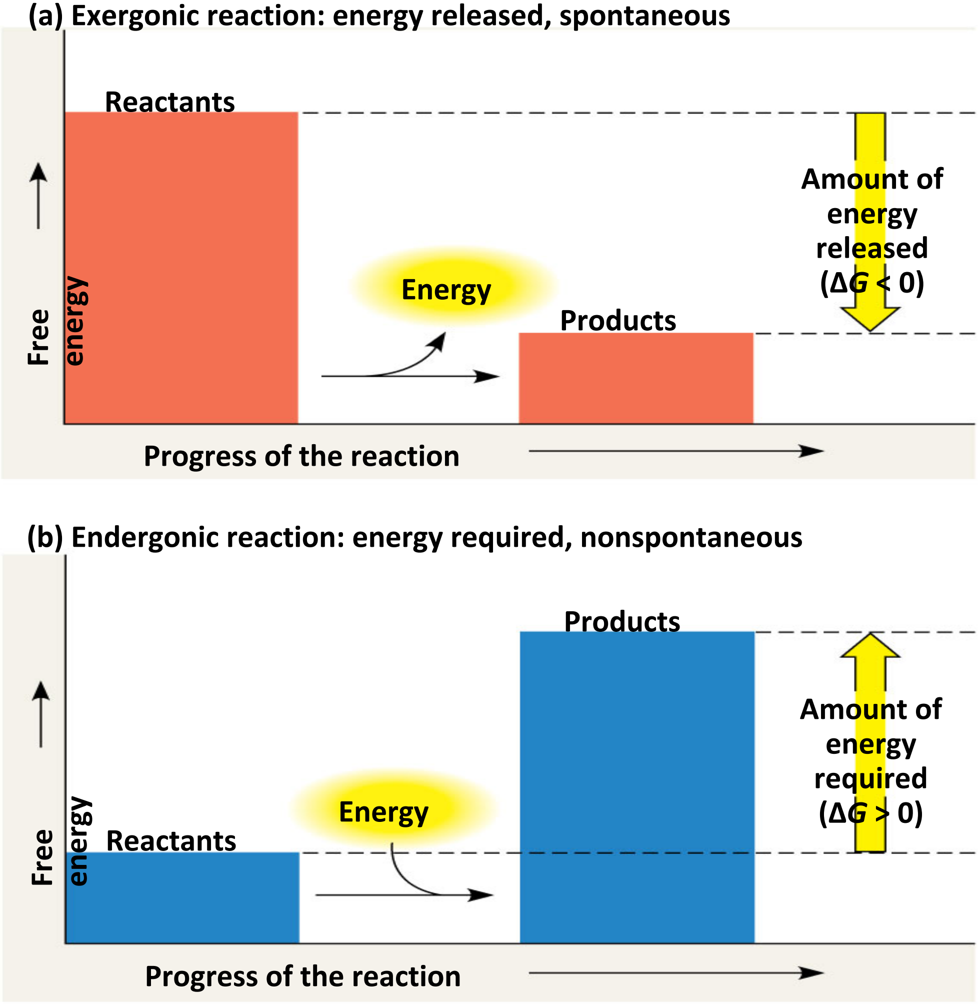


Examples for understanding changes in enthalpy, entropy and free energy with respect to each other

Exergonic and Endergonic Reactions in 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

Figure 8.6

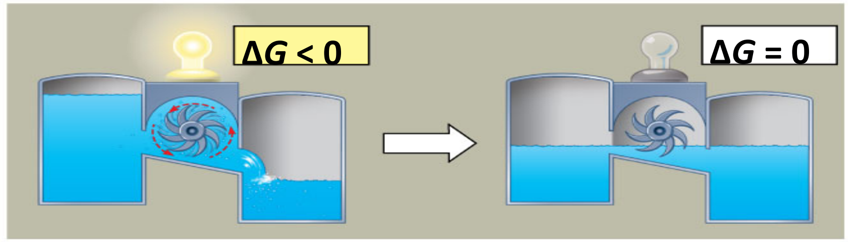


(a) Exergonic reaction: energy released, spontaneous
Reactants
Energy
Products
Amount of energy released ($\Delta G < 0$)
Free energy
Progress of the reaction
(b) Endergonic reaction: energy required, nonspontaneous
Products
Amount of energy required ($\Delta G > 0$)
Energy
Reactants
Free energy
Progress of the reaction

Equilibrium and Metabolism

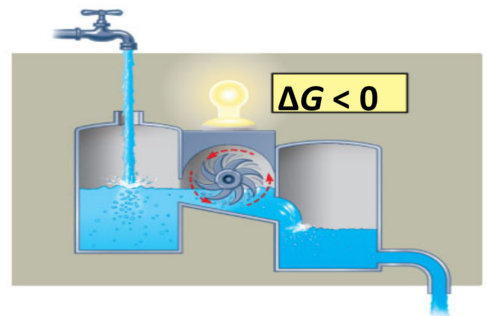
- Reactions in a closed system eventually reach equilibrium and then do no work
- Cells are not in equilibrium; they are open systems experiencing a constant flow of materials
- A defining feature of life is that metabolism is never at equilibrium
- A catabolic pathway in a cell releases free energy in a series of reactions
- Closed and open hydroelectric systems can serve as analogies

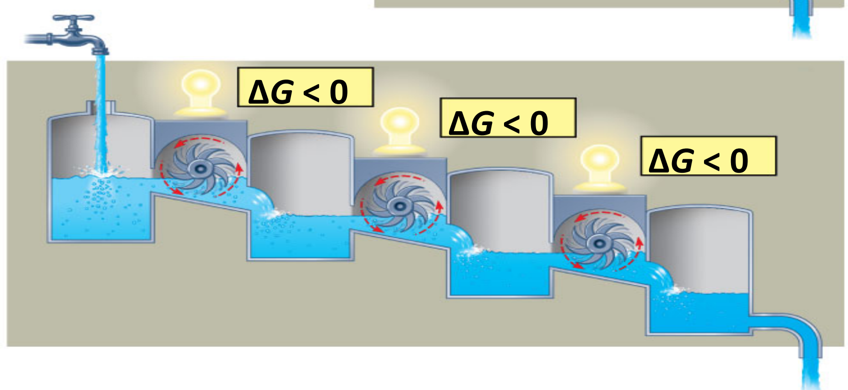
Figure 8.7



(a) An isolated hydroelectric system

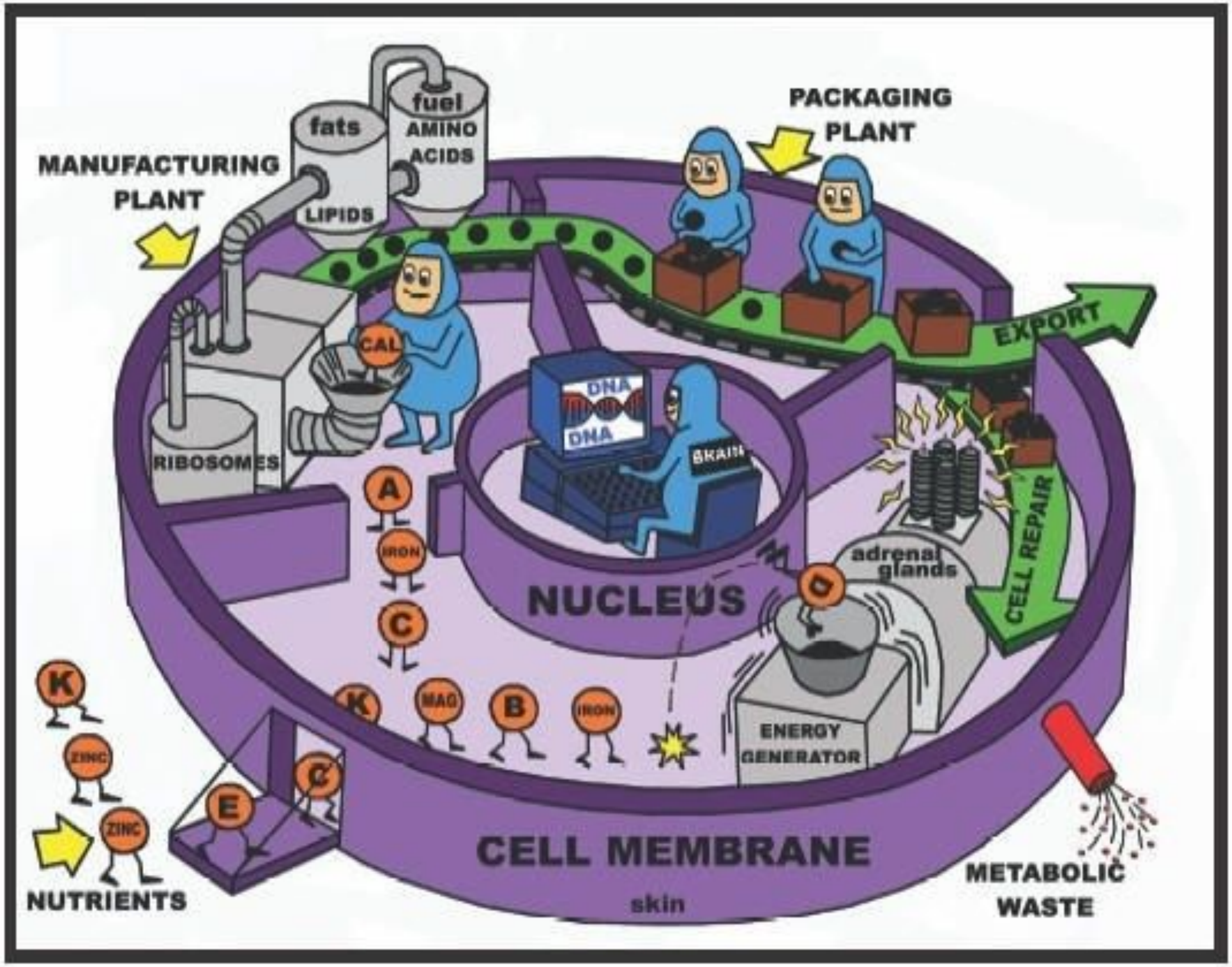
(b) An open hydro-electric system





(c) A multistep open hydroelectric system

Cells as Chemical Factories



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Cells get raw materials — including water, oxygen, minerals and other nutrients — from the foods. Nutrients are transported through the cell membrane: the thin, elastic structure that forms the border of each cell.

● Nucleus - it controls cell function. It contains DNA (deoxyribonucleic acid), the master organizer for how cells work.

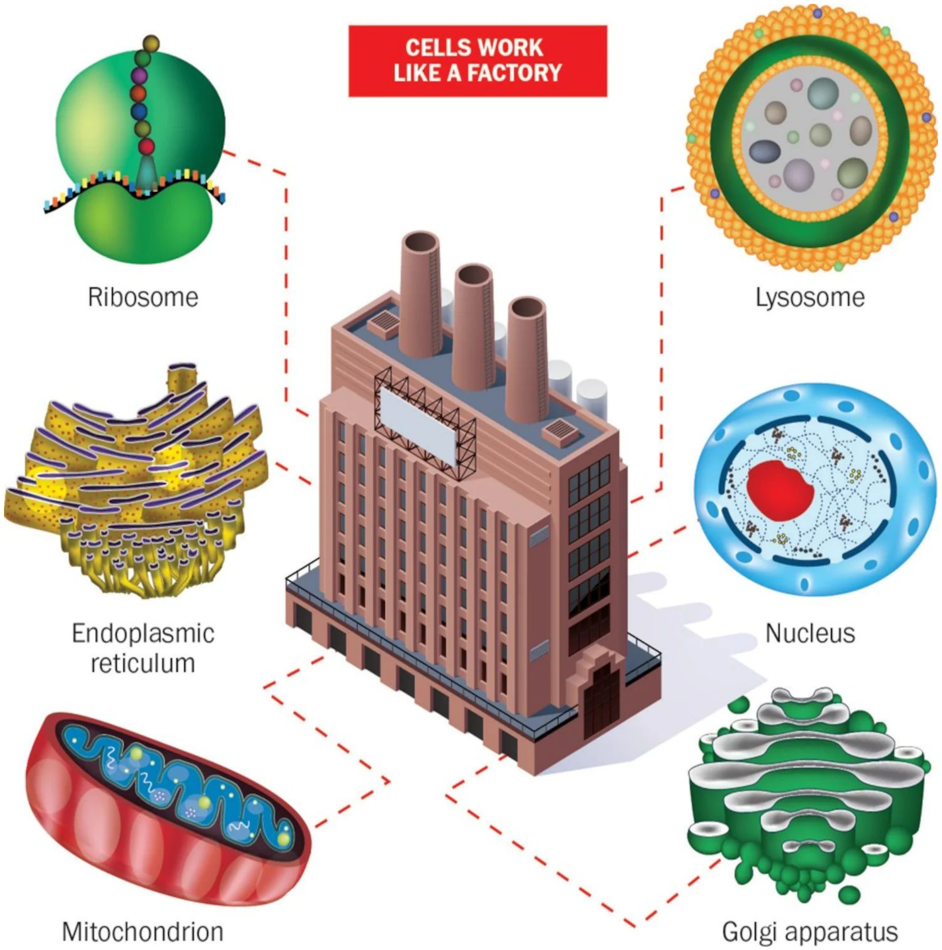
● Mitochondria are the “batteries” in your cells. Chemical reactions within the mitochondria create the energy that powers cell functions.

● Lysosomes are fluid-filled vesicles, or sacs, that act as a waste-disposal system for cells.

● Ribosomes are the cell’s molecule makers. They assemble proteins from amino acids.

● The endoplasmic reticulum is a system of tubelike structures that’s essential for the production of proteins and lipids (fats).

● The Golgi apparatus is like a conveyor belt that “wraps” proteins inside vesicles so they can be “shipped” out of the cell.



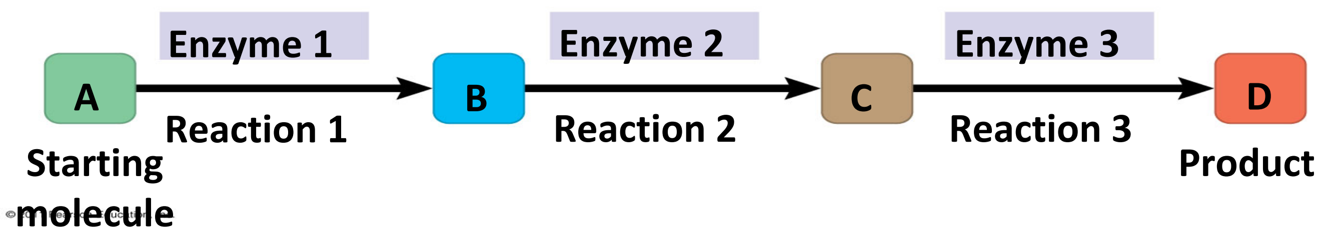
(iStock images/The Washington Post illustration)

Metabolism

- **Metabolism** is the totality of an organism's chemical reactions

- Metabolism is an emergent property of life that arises from interactions between molecules within the cell

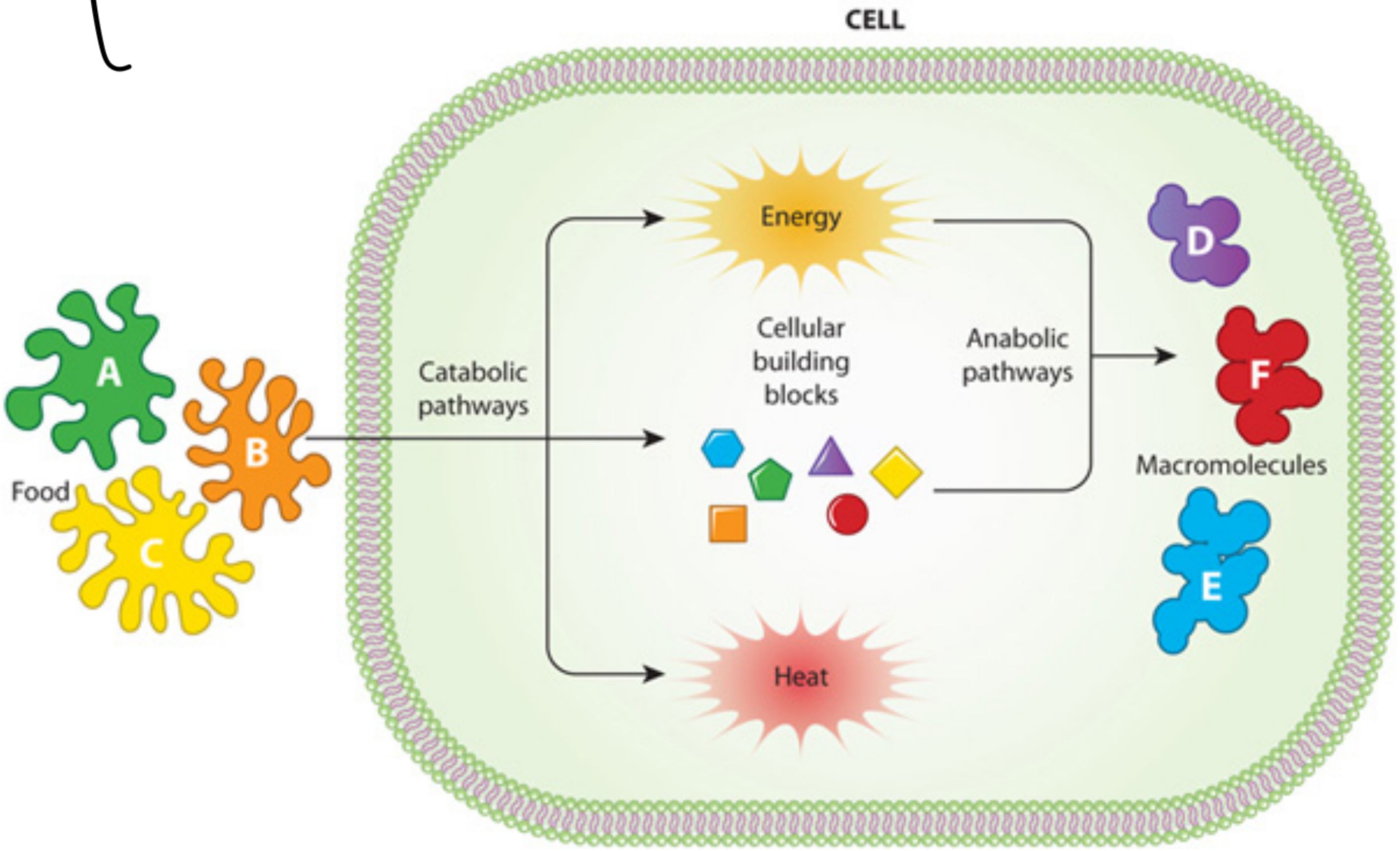
- An organism's metabolism transforms matter and energy, subject to the laws of thermodynamics



- A **metabolic pathway** begins with a specific molecule and ends with a product

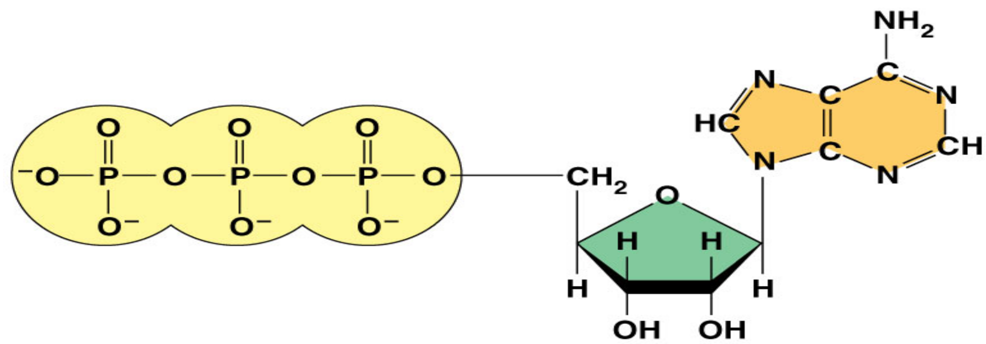
- Each step is catalyzed by a specific enzyme

Catabolism and Anabolism

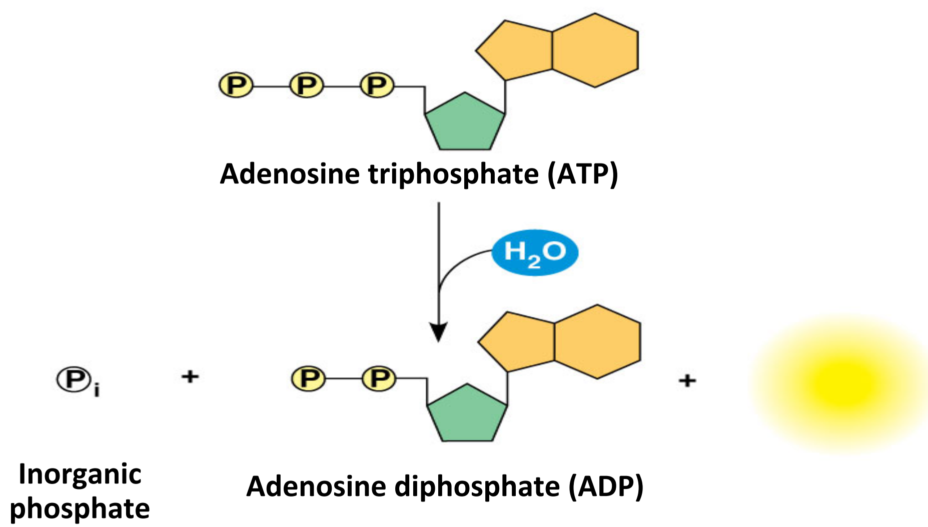


In living cells, energy is stored and transferred in several forms, most commonly in the form of a high-energy chemical bond on the molecule adenosine triphosphate (ATP).

The ultimate source of the energy used to synthesize ATP in fact comes from metabolic breakdown of glucose in a pathway known as glycolysis



(a) The structure of ATP



(b) The hydrolysis of ATP

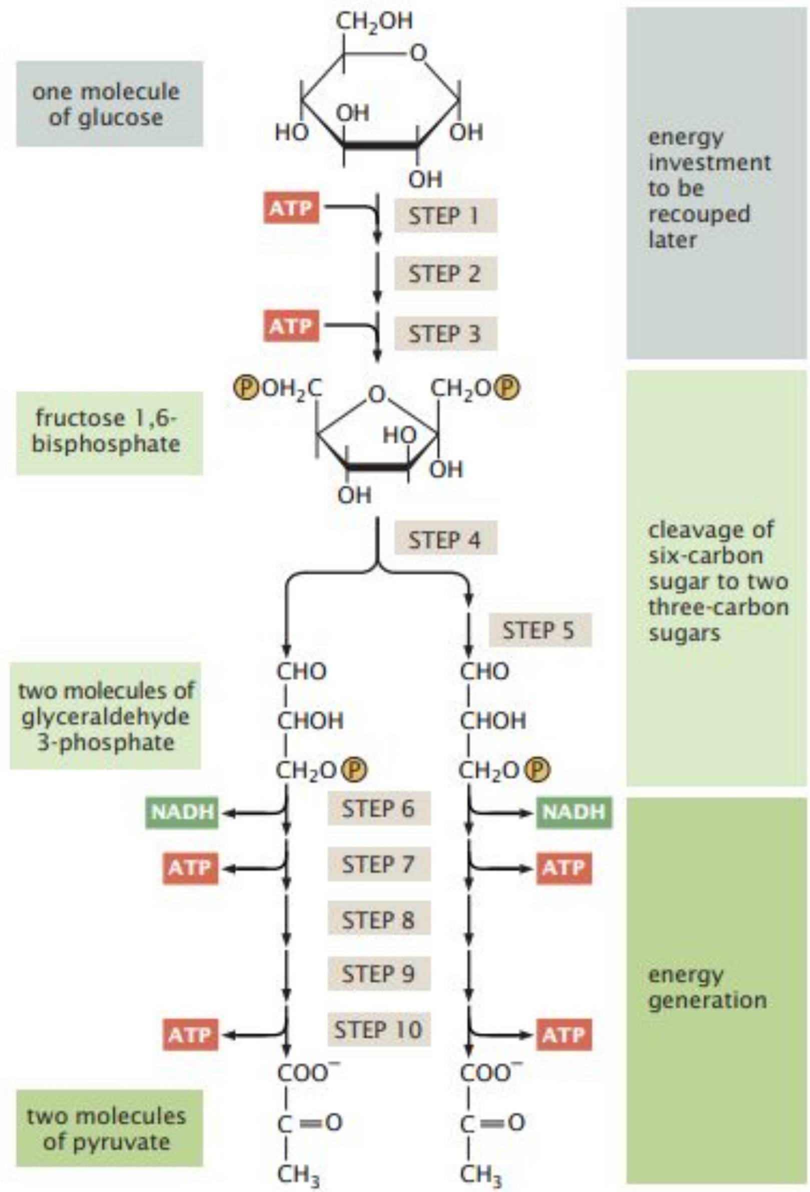


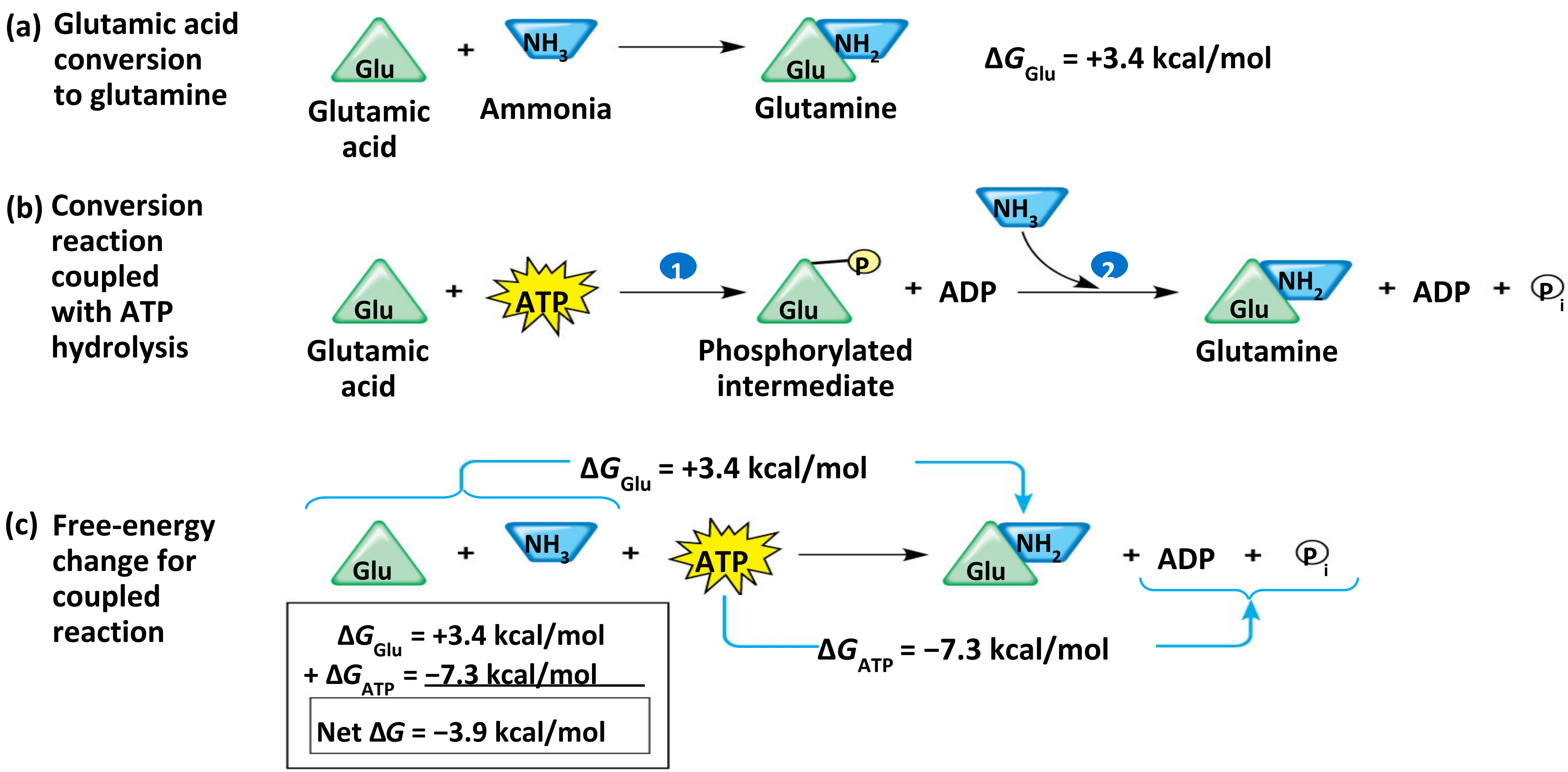
Figure 5.2: A schematic outlining the overall organization of the glycolytic pathway. The outcome of the 10 steps of glycolysis is the conversion of a single molecule of glucose into two molecules of pyruvate and the concomitant net production of two molecules of ATP and two of NADH. (Adapted from B. Alberts et al., Molecular Biology of the Cell, 5th ed. Garland Science, 2008.)

Not here.

How the Hydrolysis of ATP Performs Work

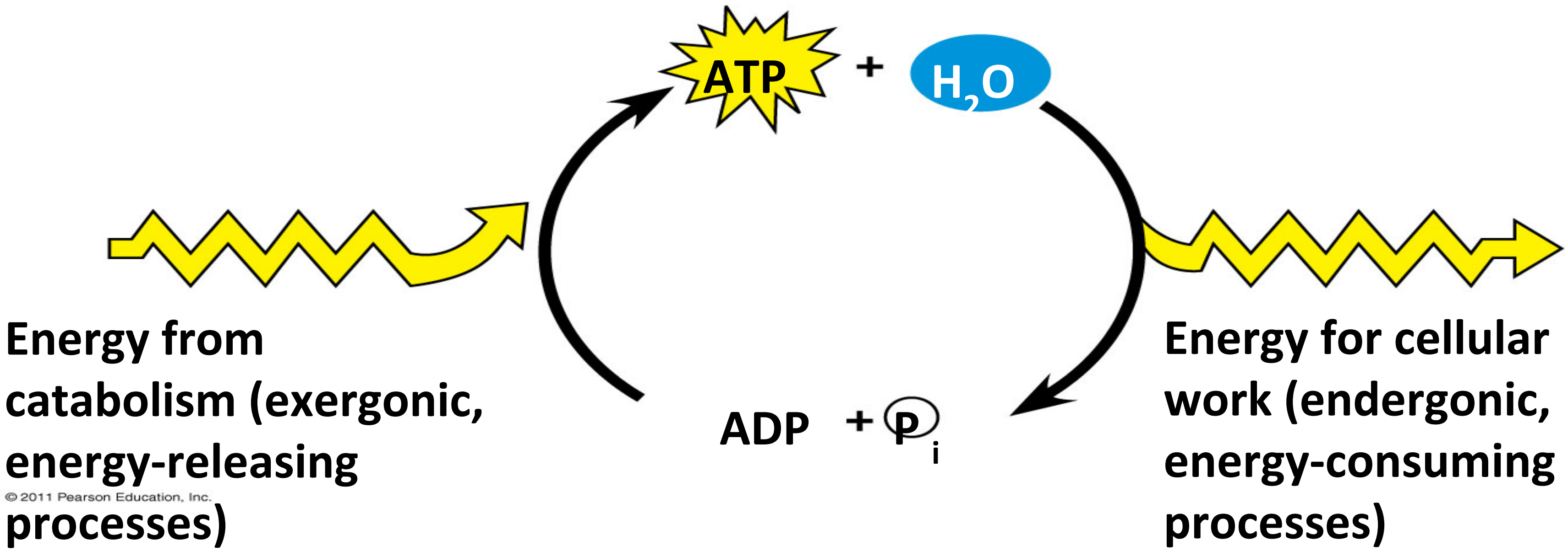
- The three types of cellular work (mechanical, transport, and chemical) are powered by the hydrolysis of ATP
- In the cell, the energy from the exergonic reaction of ATP hydrolysis can be used to drive an endergonic reaction
- Overall, the coupled reactions are exergonic

Figure 8.9


(a) Glutamic acid conversion to glutamine
Glu
+
NH3
Glu NH2
Glutamic acid
Ammonia
Glutamine
ΔG_Glu = +3.4 kcal/mol
(b) Conversion reaction coupled with ATP hydrolysis
Glu
+
ATP
1
P
Glu
+ ADP
NH3
2
Glu NH2
+ ADP + Pi
Glutamic acid
Phosphorylated intermediate
Glutamine
(c) Free-energy change for coupled reaction
ΔG_Glu = +3.4 kcal/mol
Glu + NH3 + ATP
Glu NH2 + ADP + Pi
ΔG_ATP = −7.3 kcal/mol
ΔG_Glu = +3.4 kcal/mol
+ ΔG_ATP = −7.3 kcal/mol
Net ΔG = −3.9 kcal/mol

- 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**

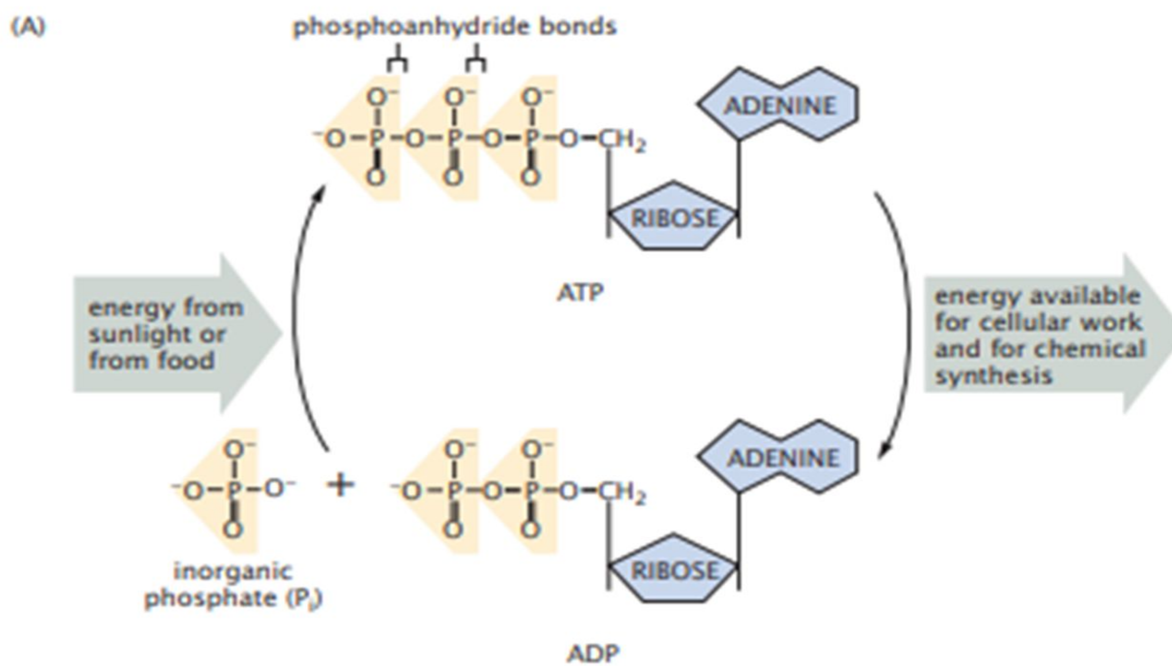
Figure 8.11

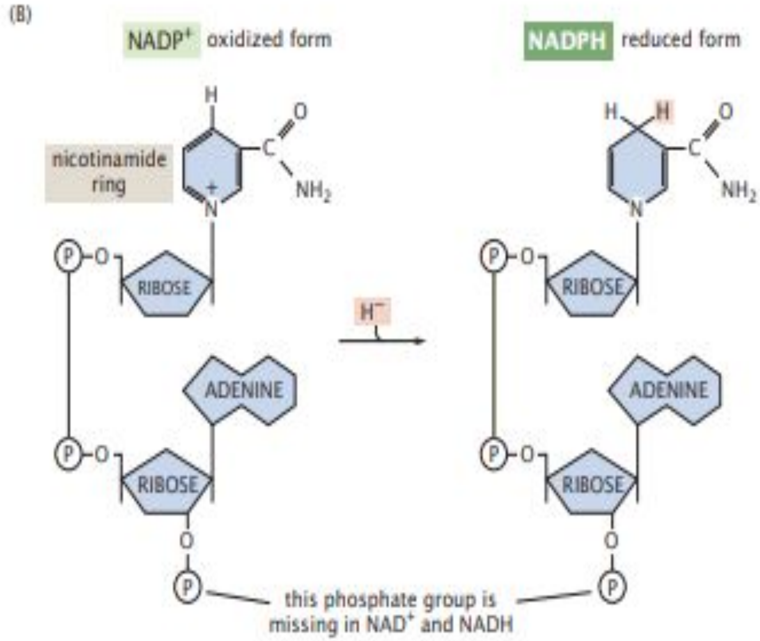

ATP
+
H_2O
Energy from catabolism (exergonic, energy-releasing processes)
ADP
+ P_i
Energy for cellular work (endergonic, energy-consuming processes)

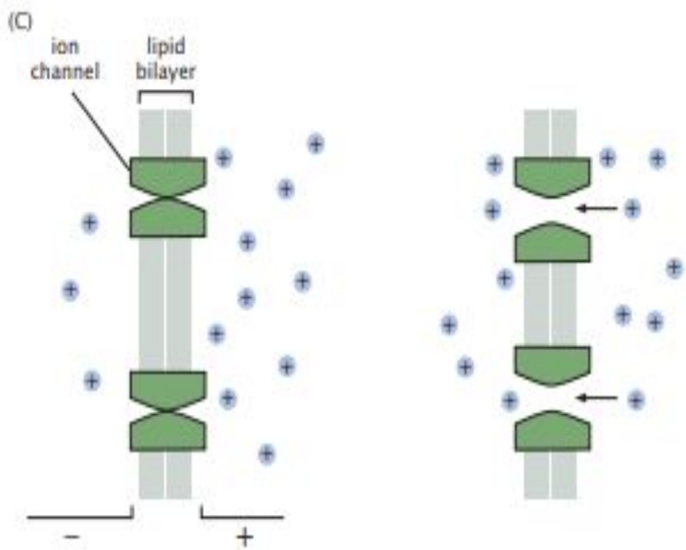
Three important forms of biological energy.

(A) Energy for chemical synthesis and for force generation is stored in the form of ATP, which can be converted to ADP + Pi releasing roughly 20 kBT kT (energy) kT (also written as kBT) is the product of the Boltzmann constant, k (or kB), and the temperature, T.) of useful energy. ADP + Pi can then be converted back to ATP.

While many enzymes use ATP itself, others use guanosine triphosphate (GTP), uridine triphosphate (UTP), or cytosine triphosphate (CTP), but the energies are equivalent.







(B) Reducing potential is carried in the form of transferrable high-energy electrons on NADH (or the very similar molecule NADPH). Two electrons can be transferred from NADPH to reduce an oxidized organic compound, liberating one hydrogen ion (H+) and the oxidized form of the carrier molecule NADP+.

In this case, the energy liberated by oxidation of one mole of NADH can be used to synthesize roughly two or three moles of ATP.

(C) Transmembrane ion gradients, particularly in the form of H+gradients, are also used to store energy. The H+ gradient across the membrane yields a negative potential on the left and a positive potential on the right. When ion channels open, the ions can flow down their electrochemical gradient.

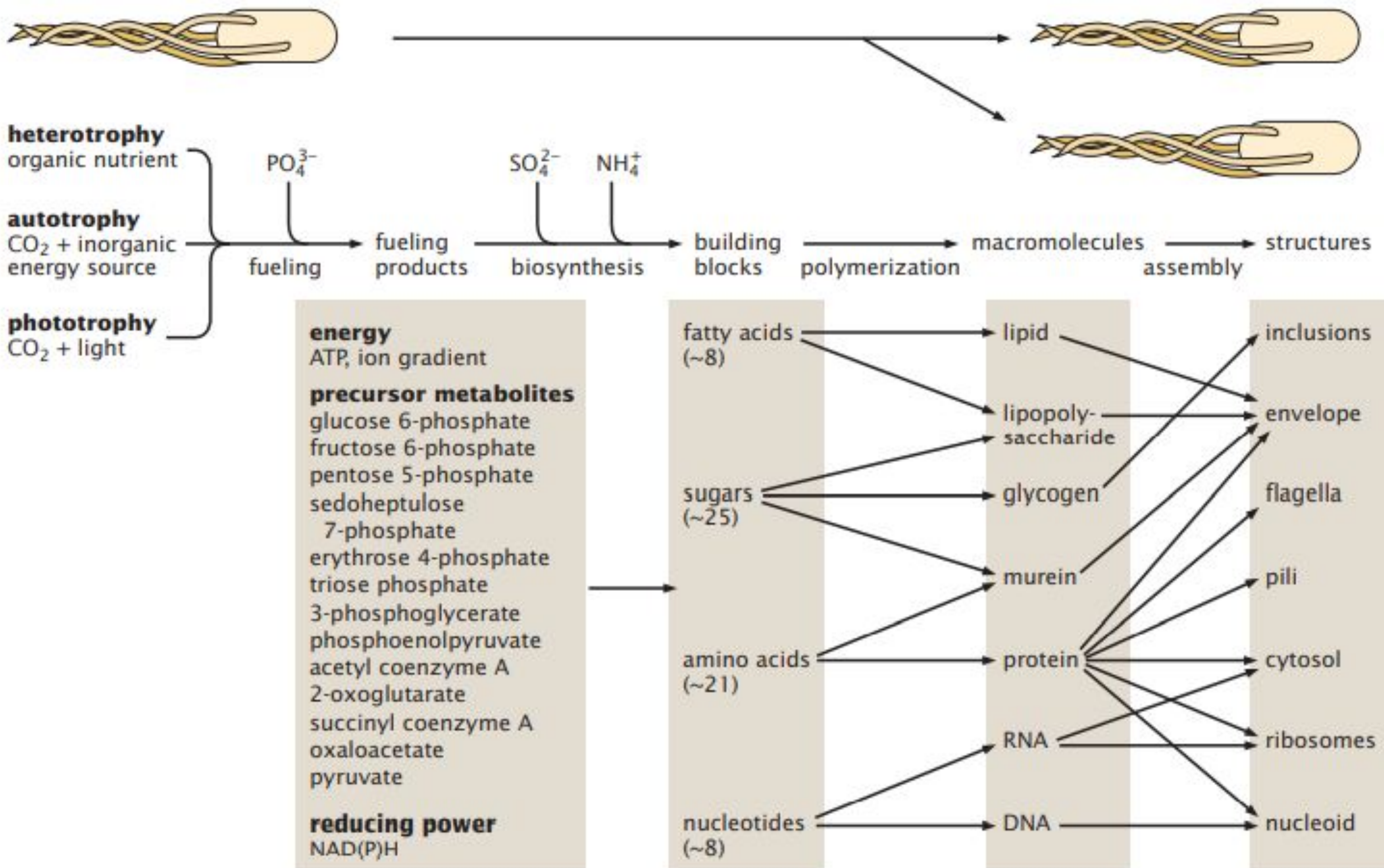


Figure 5.4: Energy and mass costs to make a new bacterial cell. This diagram illustrates the flow of materials and energy required for bacterial duplication. Nutrients are taken from the environment, either organic molecules provided by other organisms or carbon dioxide and light in the case of photosynthetic bacteria. Together with a few inorganic ions such as phosphate, sulfate, and ammonium, the carbon sources consumed by the bacterium are converted into precursor metabolites and then into the fatty acids, sugars, amino acids, and nucleotides that are used to build macromolecules. The macromolecules are further assembled into large-scale structures of the cell. The numbers shown in the "building blocks" column correspond to the rough number of molecular building blocks of each type. (Adapted from M. Schaechter et al., Microbe. ASM Press, 2006.)

Catabolism, metabolism

How it works