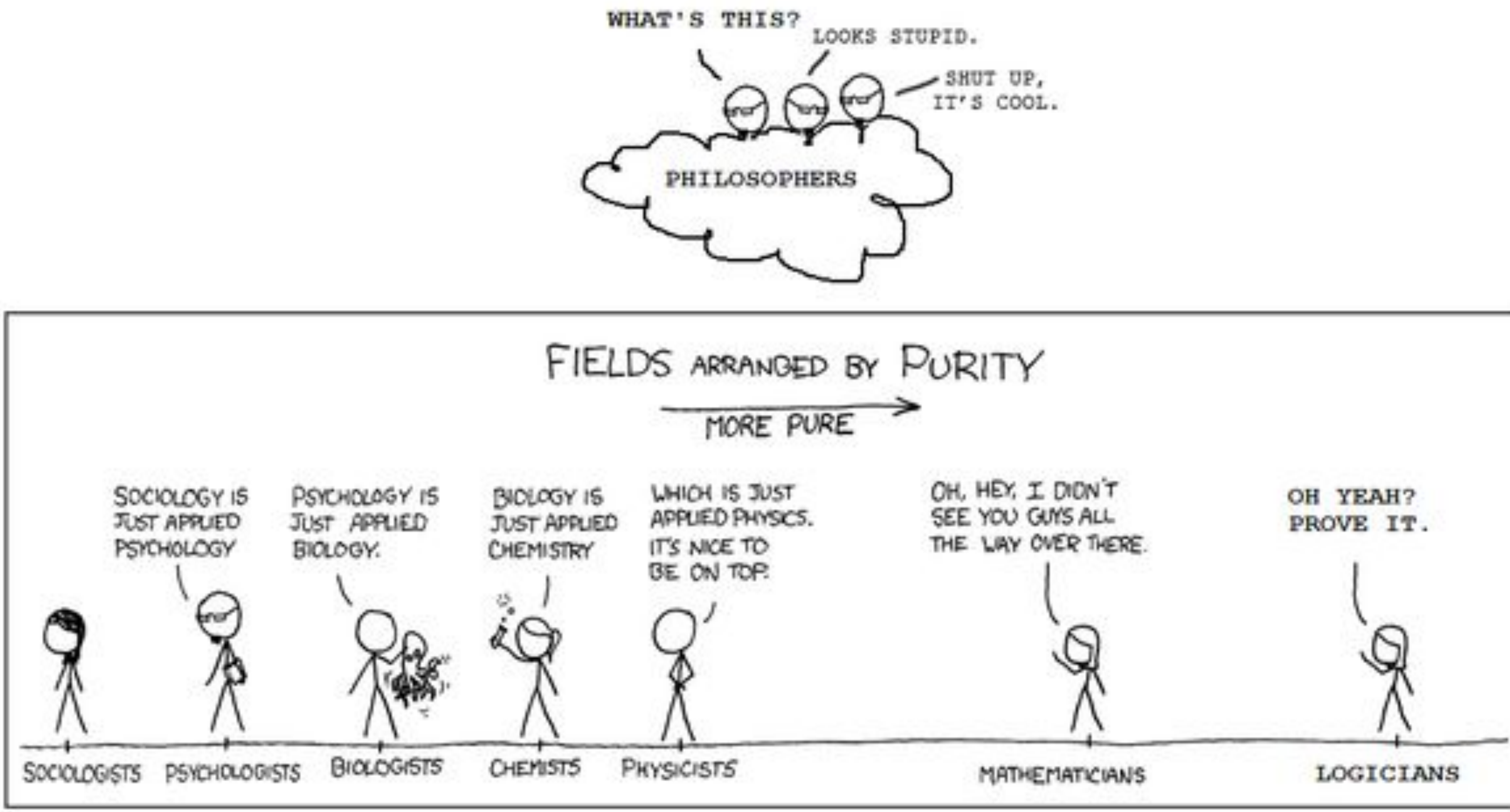
Biology
ES131

Module 2

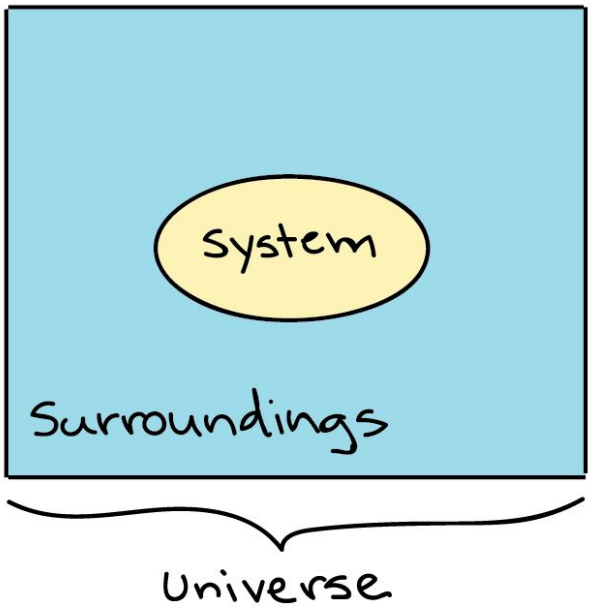
Physics in Biology (Part 1)

Thermodynamics


WHAT'S THIS?
LOOKS STUPID.
SHUT UP, IT'S COOL.
PHILOSOPHERS
FIELDS ARRANGED BY PURITY
MORE PURE
SOCIOLOGY IS JUST APPLIED PSYCHOLOGY
PSYCHOLOGY IS JUST APPLIED BIOLOGY.
BIOLOGY IS JUST APPLIED CHEMISTRY
WHICH IS JUST APPLIED PHYSICS. IT'S NICE TO BE ON TOP.
OH, HEY, I DIDN'T SEE YOU GUYS ALL THE WAY OVER THERE.
OH YEAH? PROVE IT.
SOCIOLOGISTS
PSYCHOLOGISTS
BIOLOGISTS
CHEMISTS
PHYSICISTS
MATHEMATICIANS
LOGICIANS

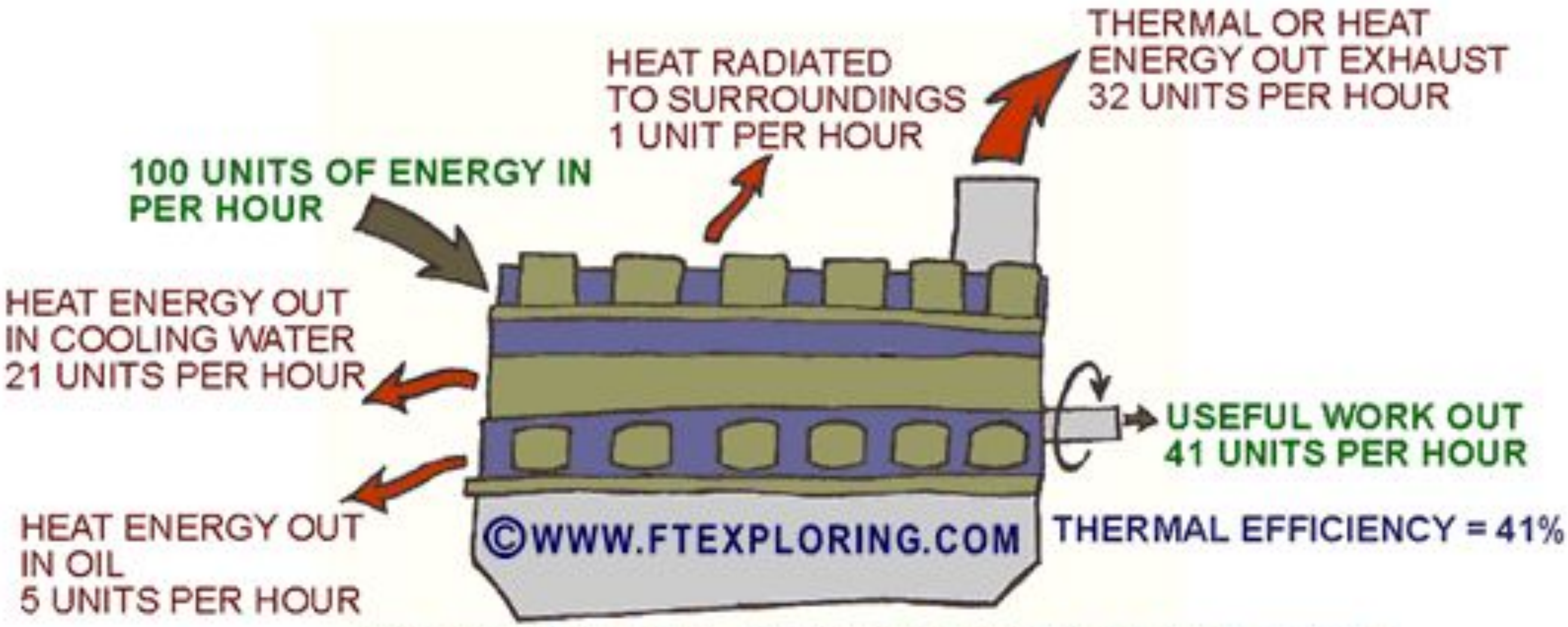
The Laws of Energy Transformation

- **Thermodynamics** is the study of energy transformations
- A isolated system, such as that approximated by liquid in a thermos, is isolated from its surroundings
- In an open system, energy and matter can be transferred betweer the system and its surroundings
- Organisms are open systems



Types of Systems

ENERGY BALANCE IN A BIG EFFICIENT DIESEL ENGINE



100 UNITS OF FUEL POTENTIAL ENERGY INTO ENGINE

100 UNITS OF MECHANICAL & THERMAL ENERGY OUT OF ENGINE

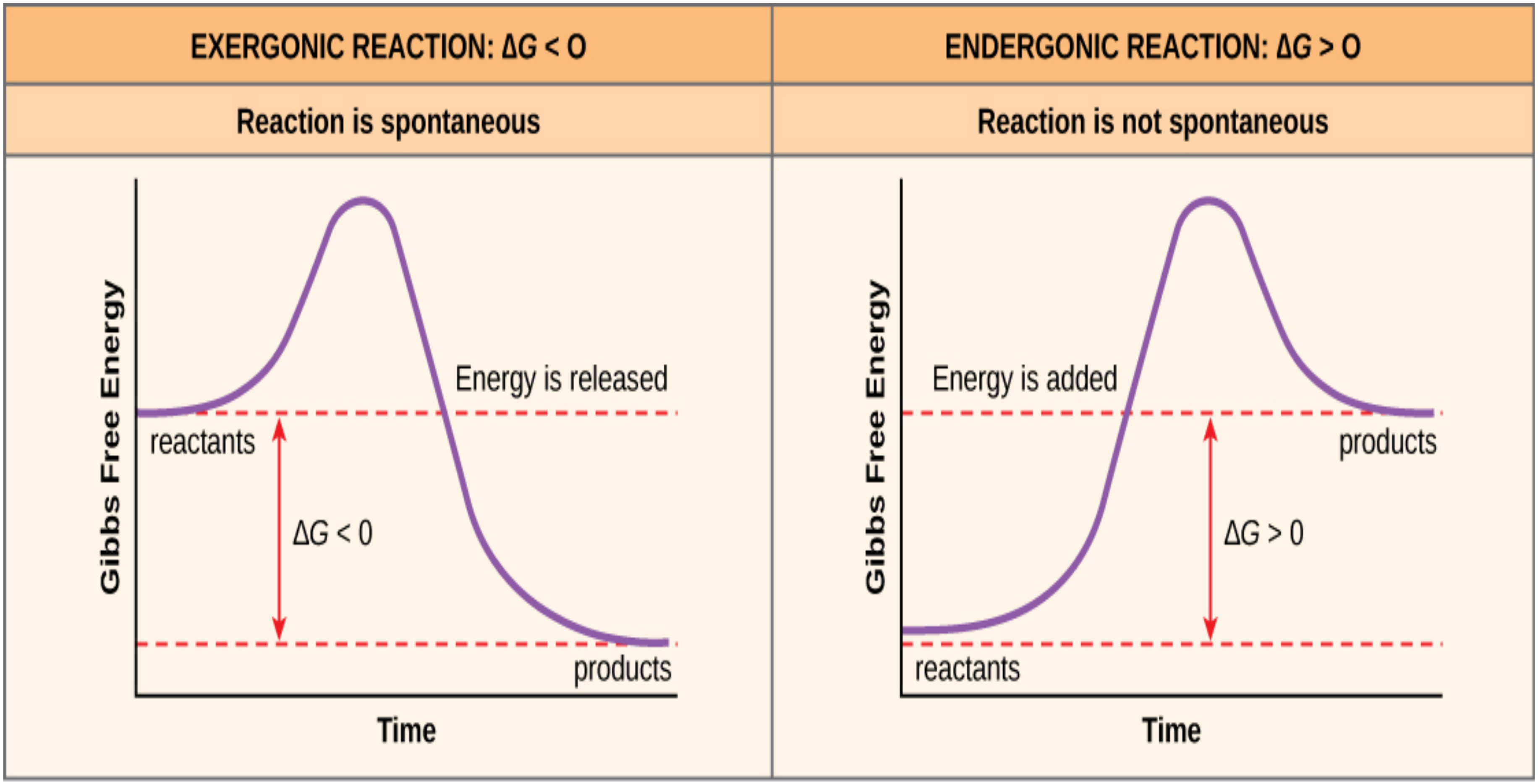
THE CHEMICAL ENERGY STORED IN THE FUEL IS CONVERTED TO MECHANICAL ENERGY AND THERMAL ENERGY. THE TOTAL MECHANICAL ENERGY AND THERMAL (HEAT) ENERGY OUT MUST EQUAL THE ENERGY AVAILABLE IN THE FUEL - FIRST LAW OF THERMODYNAMICS.

Gibbs free energy, G**,** 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, ΔG, has a negative value and the reaction is said to be exergonic. In endergonic reactions, the system gains free energy and ΔG is positive.

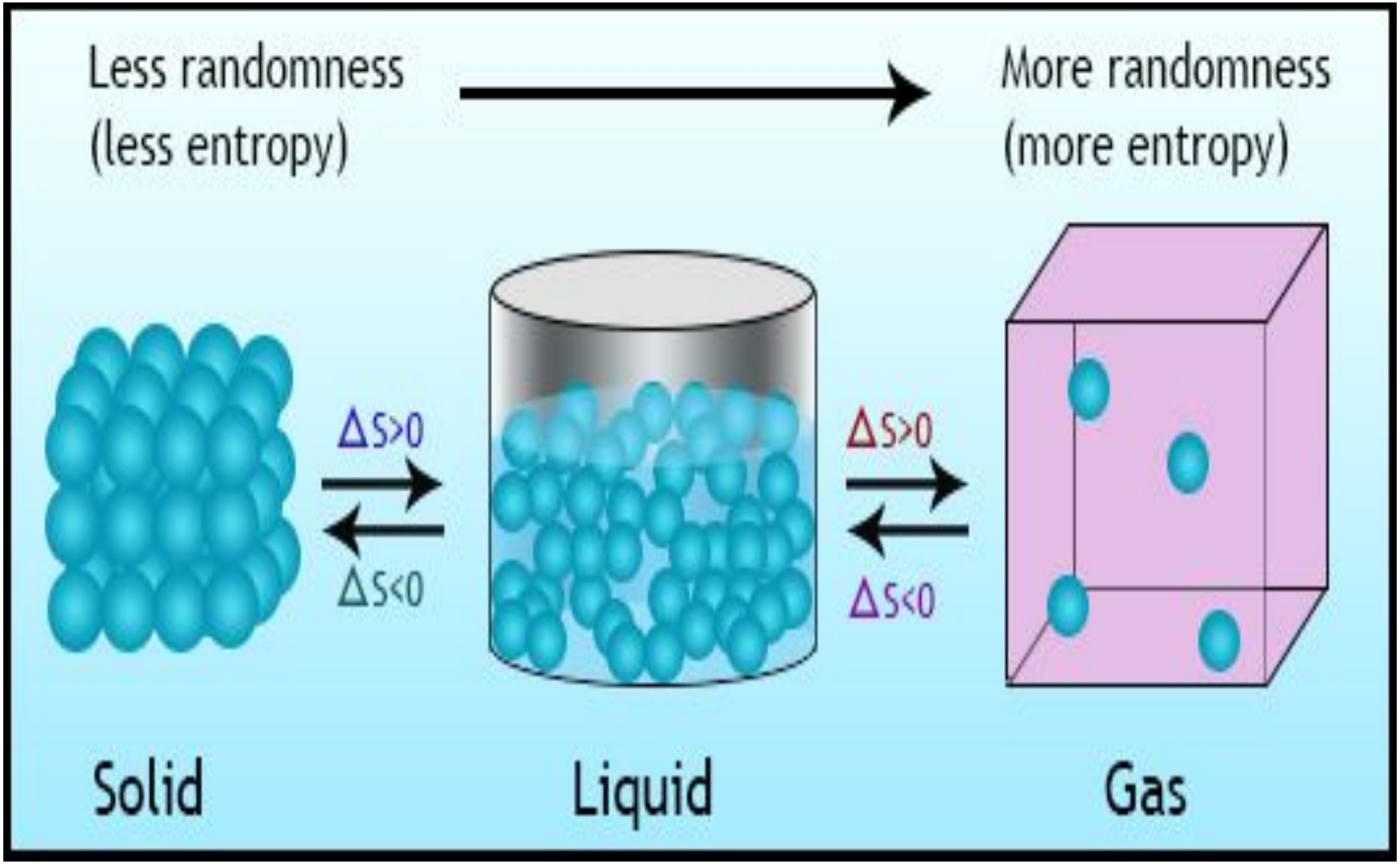
Enthalpy, H**,** is the heat content of the reacting system. It reflects the number and kinds of chemical bonds in the reactants and products. When a chemical reaction releases heat, it is said to be exothermic; the heat content of the products is less than that of the reactants and ΔH has, by convention,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

Entropy, S**,** is a quantitative expression for the randomness or disorder in a system (see Box 1–3). When the products of a reaction are less complex and more disordered than the reactants, the reaction is said to proceed with a gain in entropy.

Enthalpy Change



Randomness - Entropy



The First Law of Thermodynamics

- According to the **first law of thermodynamics**, the energy of the universe is constant

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

- The first law is also called the principle of conservation of energy

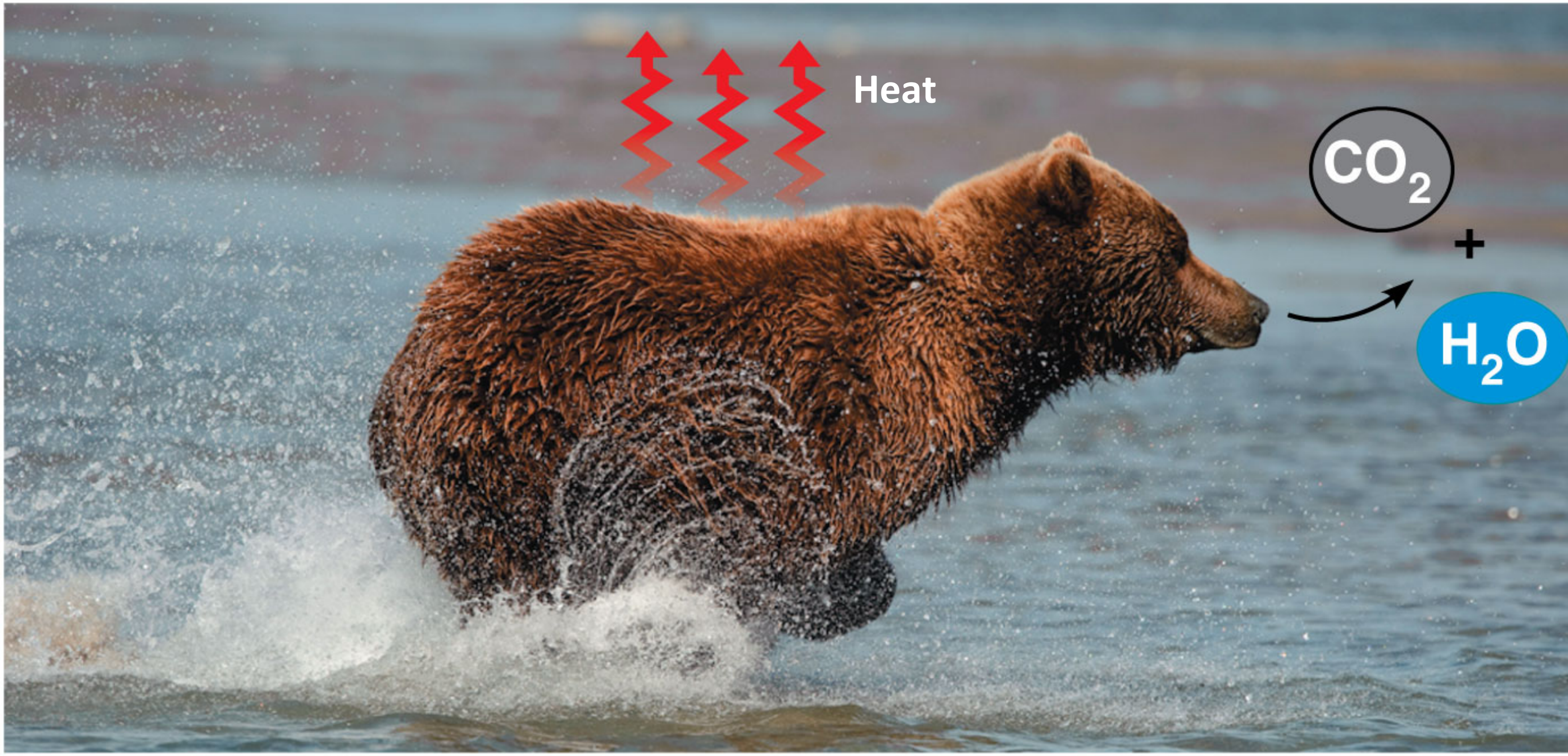
First law of thermodynamics

The Second Law of Thermodynamics

- During every energy transfer or transformation, some energy is unusable, and is often lost as heat

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

  - For a process to occur spontaneously, it must increase the entropy of the universe



Second law of thermodynamics

The 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
- The word ***Spontaneous*** does not imply that such a process would occur quickly; rather, the word signifies that the process is energetically favorable. (In fact, it may be helpful for you to think of the phrase "energetically favorable" when you read the formal term "spontaneous")

Biological Order and Disorder

Biological Order and Disorder

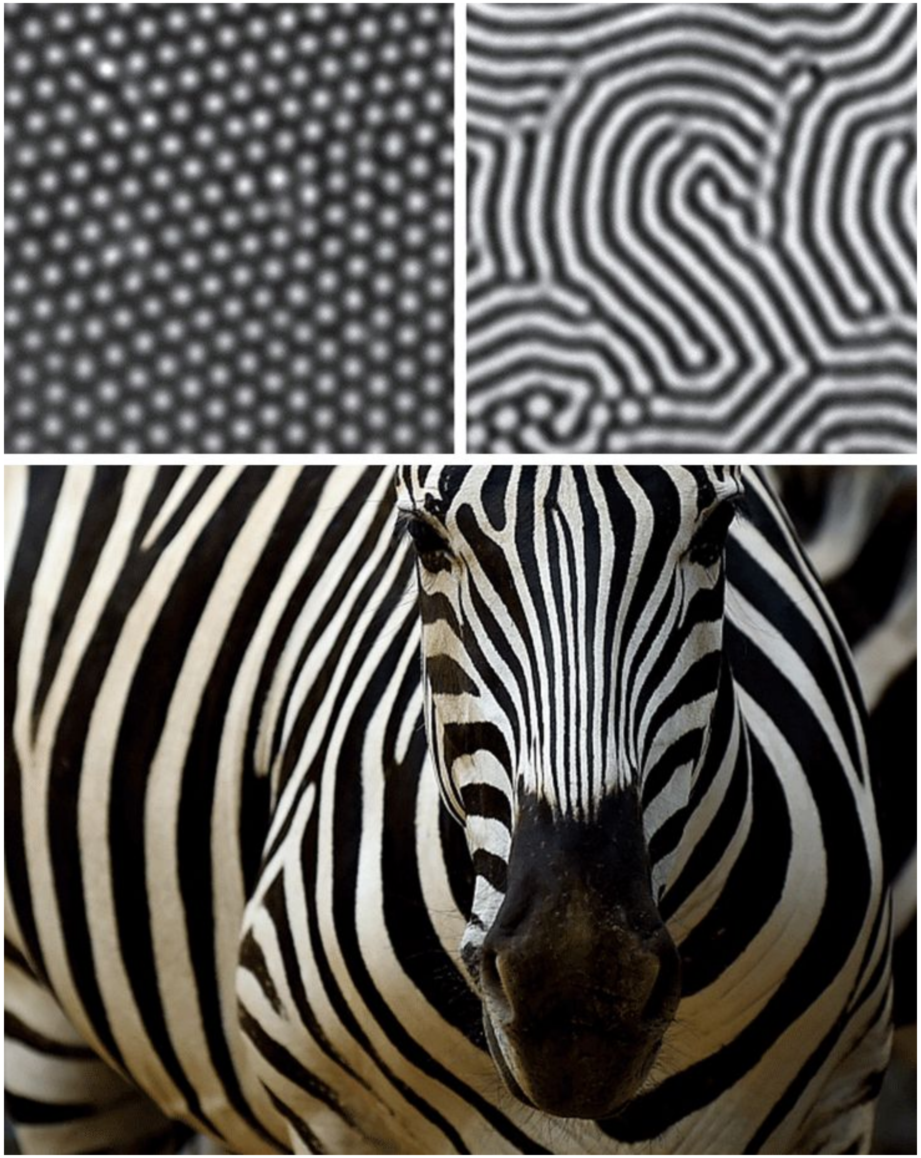
- Cells create ordered structures from less ordered materials
- Organisms also replace ordered forms of matter and energy with less ordered forms
- Energy flows into an ecosystem in the form of light and exits in the form of heat

Biological Order and Disorder

- 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

Biological Order and Disorder



Thermoregulation
Camouflage
Highly Efficient Design
Evolution of millions of years

Free-Energy Change, ΔG

- 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

Free Energy, Stability, and Equilibrium

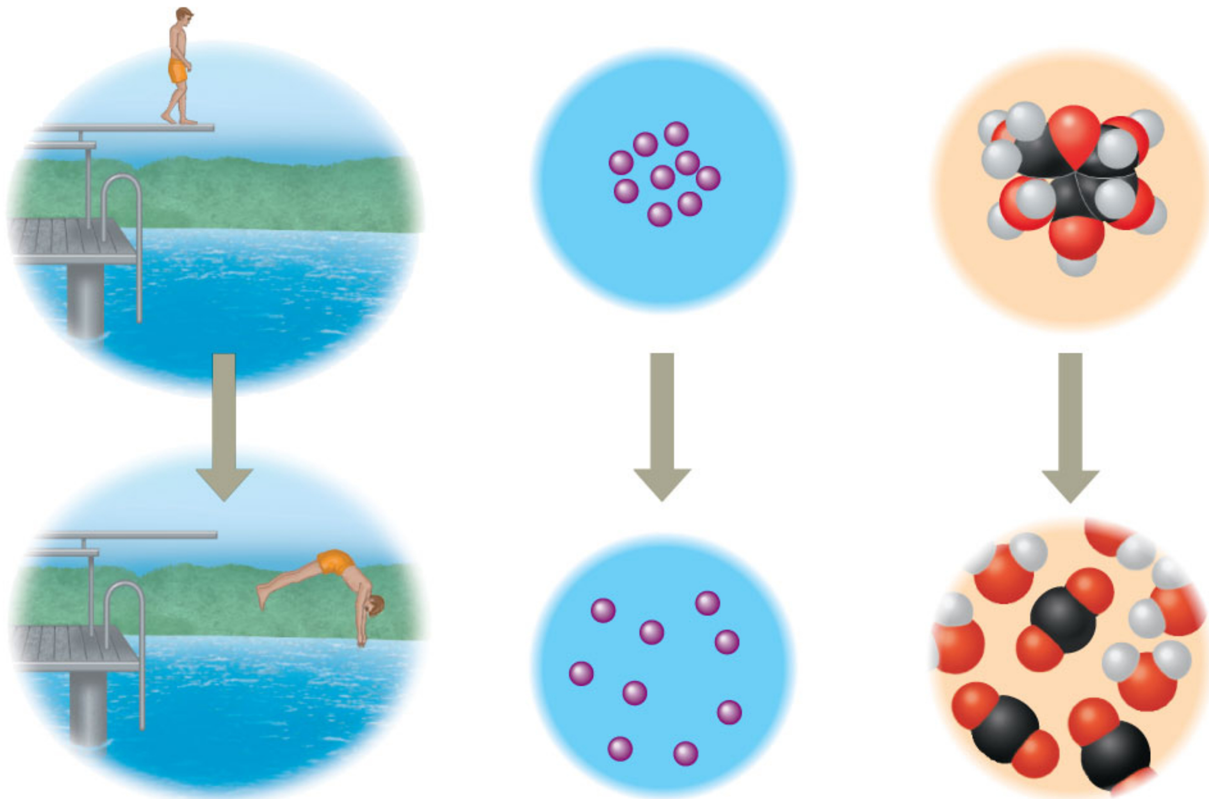
- Free energy is a measure of a system's instability, its tendency to change to a more stable state
- During a spontaneous change, free energy decreases and the stability of a system increases
- Equilibrium is a state of maximum stability
- A process is spontaneous and can perform work only when it is moving toward equilibrium

Free Energy, Stability, and Equilibrium

- More free energy (higher G)
- Less stable
- Greater work capacity

In a spontaneous change
- The free energy of the system decreases ($\Delta G < 0$)
- The system becomes more stable
- The released free energy can be harnessed to do work

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



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

- Living cells constantly perform work. They require energy for maintaining their highly organized structures, synthesizing cellular components, generating electric currents, and many other processes.
- Bioenergetics is the quantitative study of energy relationships and energy conversions in biological systems. Biological energy transformations obey the laws of thermodynamics.
- All chemical reactions are influenced by two forces: the tendency to achieve the most stable bonding state (for which enthalpy, H, is a useful expression) and the tendency to achieve the highest degree of randomness, expressed as entropy, S. The net driving force in a reaction is ΔG, the free-energy change, which represents the net effect of these two factors: $\Delta G = \Delta H - T\Delta S$.

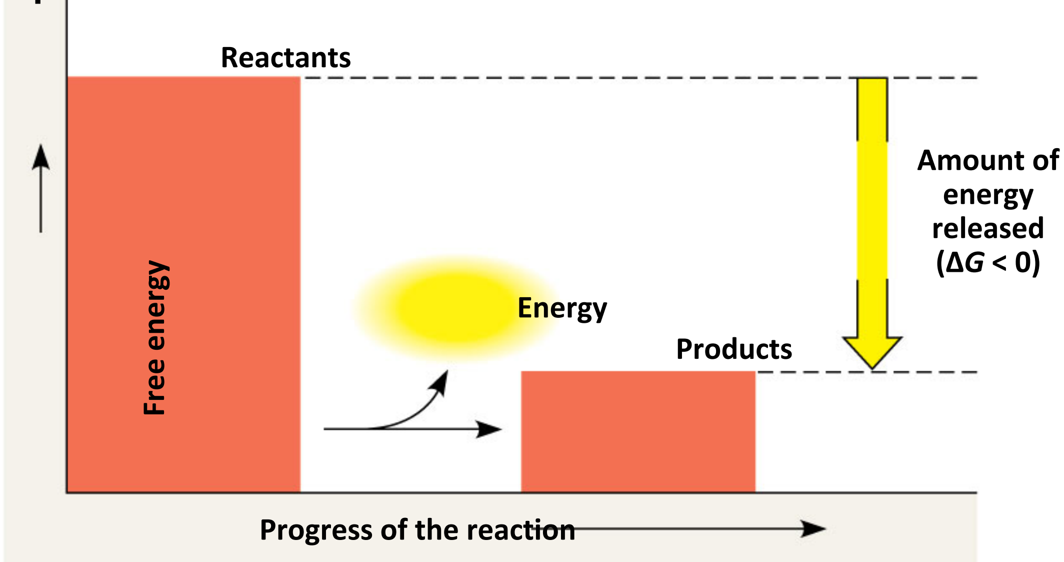
- The standard transformed free-energy change, $\Delta G'^{\circ}$, is a physical constant that is characteristic for a given reaction and can be calculated from the equilibrium constant for the reaction: $\Delta G'^{\circ} = -RT \ln K'_{eq}$.
- The actual free-energy change, ΔG, is a variable that depends on $\Delta G'^{\circ}$ and on the concentrations of reactants and products: $\Delta G = \Delta G'^{\circ} + RT \ln ([\text{products}]/[\text{reactants}])$.
- When ΔG is large and negative, the reaction tends to go in the forward direction; when ΔG is large and positive, the reaction tends to go in the reverse direction; and when $\Delta G = 0$, the system is at equilibrium.
- The free-energy change for a reaction is independent of the pathway by which the reaction 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.

Exergonic and Endergonic Reactions in Metabolism

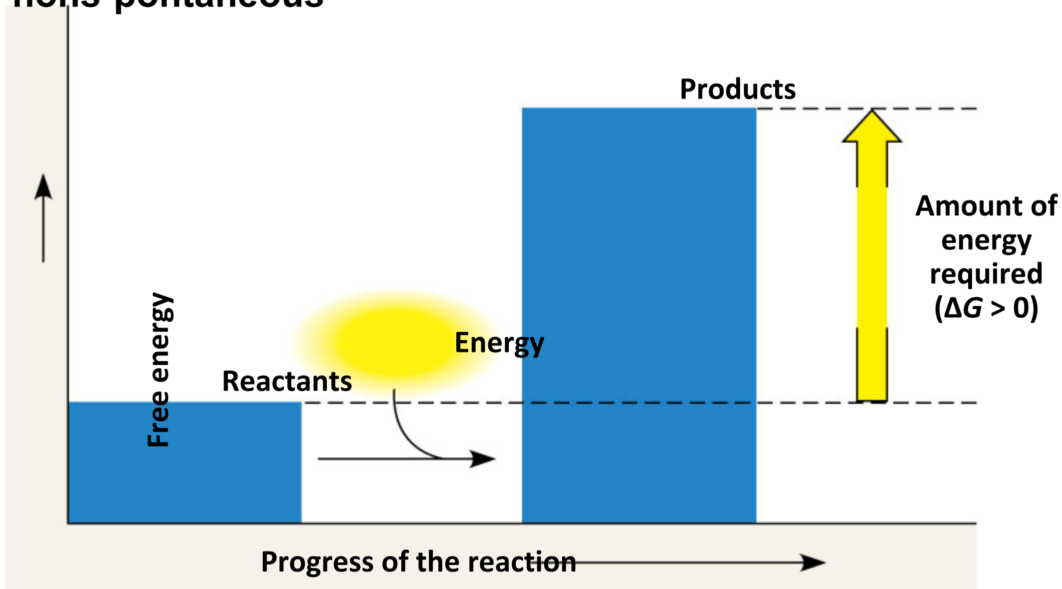
- An Exergonic **reaction** proceeds with a net release of free energy and is spontaneous

- An **Endergonic reaction** absorbs free energy from its surroundings and is non-spontaneous

(a) Exergonic reaction: energy released, spontaneous

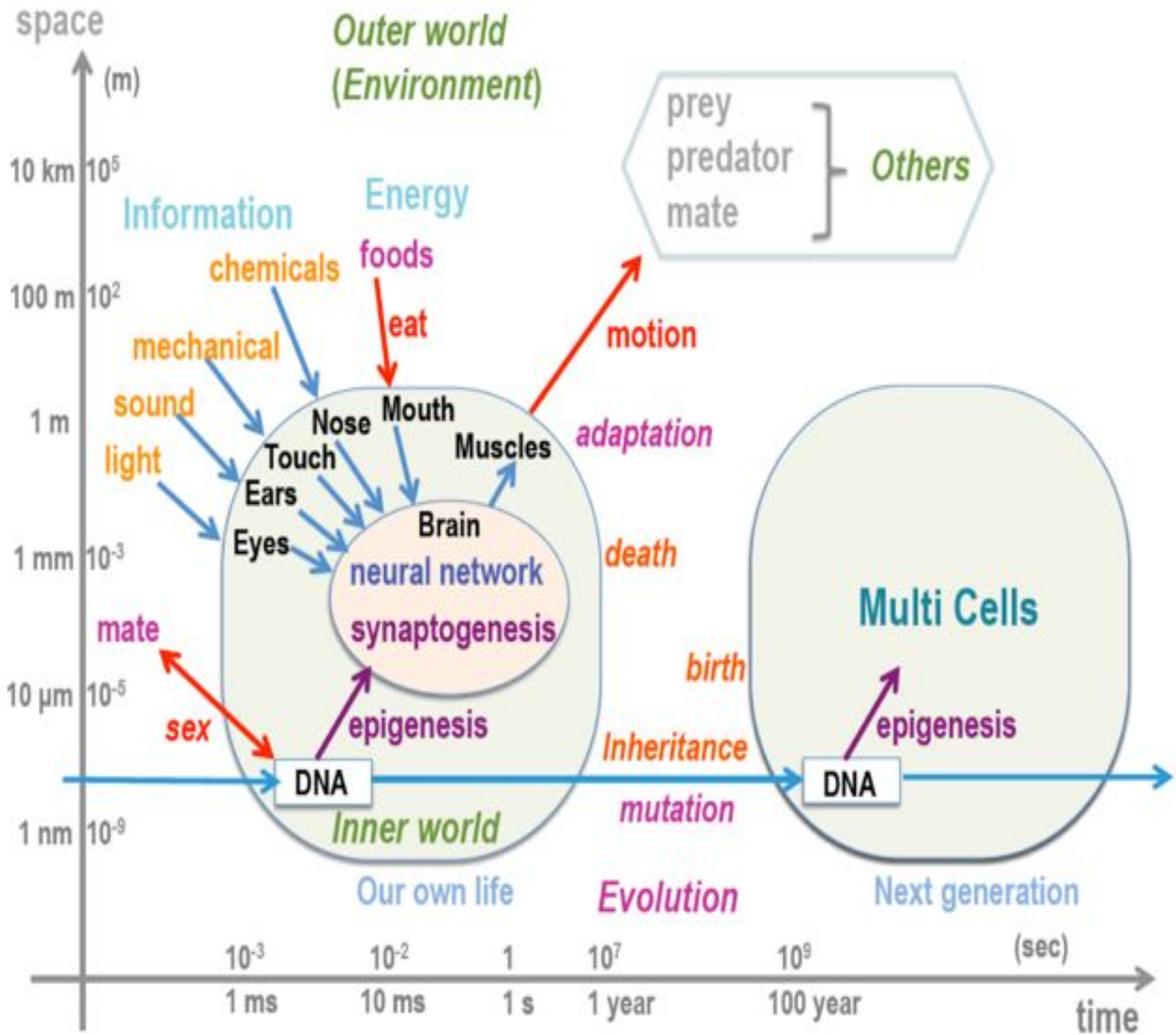


(b) Endergonic reaction: energy required, nons-pontaneous

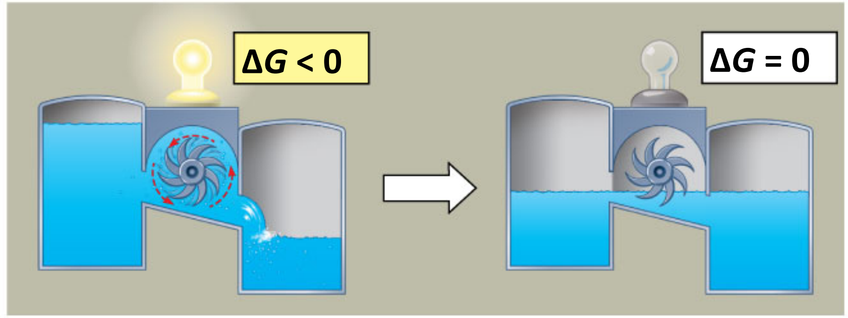


Equilibrium and Metabolism

- Reactions in a <u>closed system</u> 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

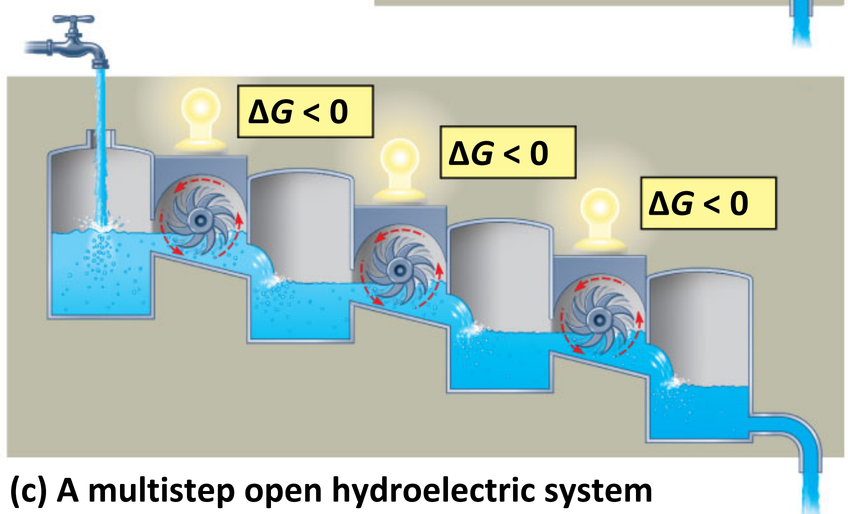


space
(m)
10 km 10^5
100 m 10^2
1 m
1 mm 10^{-3}
10 μm 10^{-5}
1 nm 10^{-9}
Outer world
(Environment)
prey
predator
mate
Others
Information
Energy
chemicals
foods
eat
mechanical
motion
sound
light
Nose
Mouth
Touch
Muscles
adaptation
Ears
Eyes
Brain
neural network
synaptogenesis
death
mate
birth
sex
epigenesis
Inheritance
DNA
mutation
Inner world
Multi Cells
epigenesis
DNA
Our own life
Evolution
Next generation
10^{-3}
10^{-2}
1
10^7
10^9
(sec)
1 ms
10 ms
1 s
1 year
100 year
time

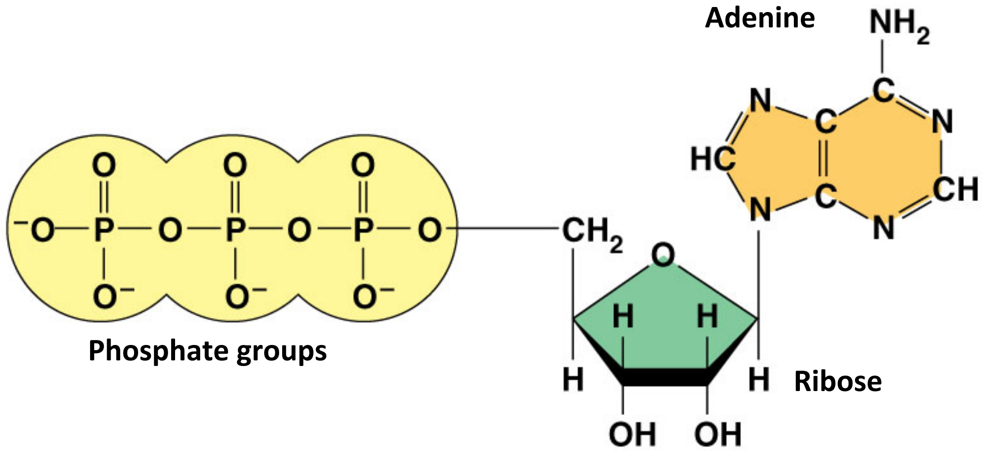


(a) An isolated hydroelectric system

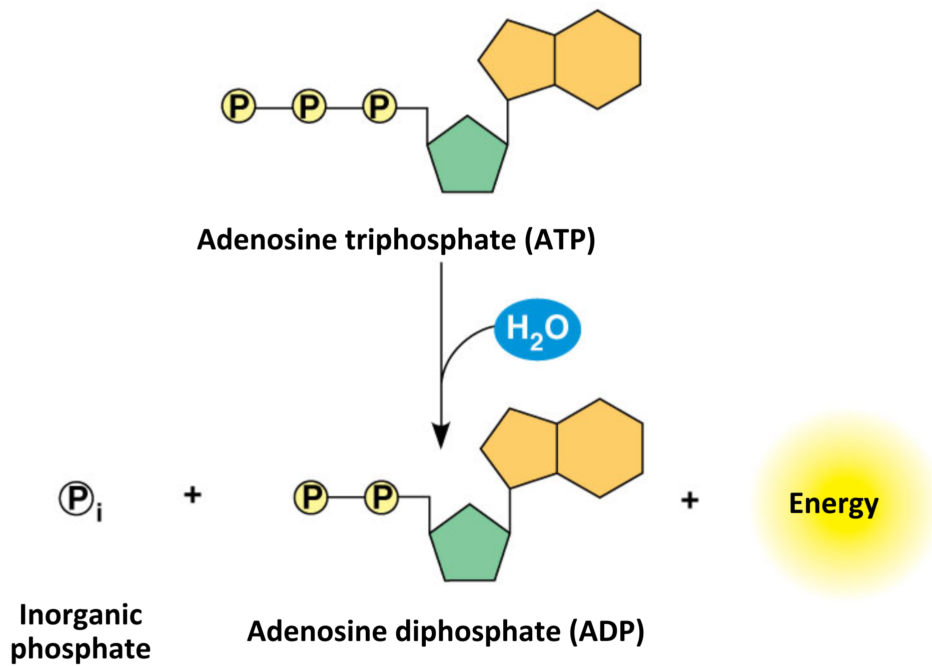
(b) An open hydro-electric system



(c) A multistep open hydroelectric system



(a) The structure of ATP



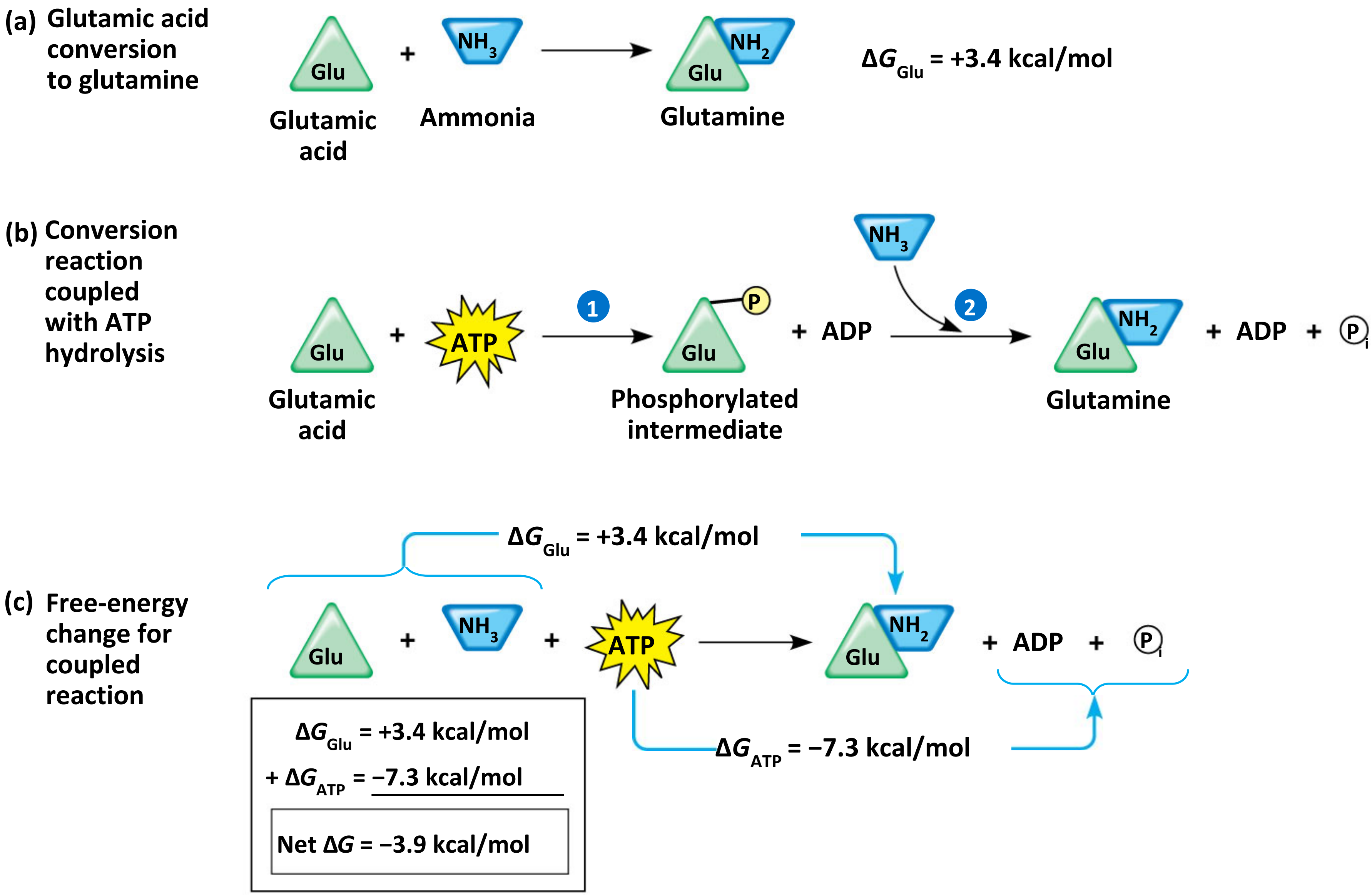
(b) The hydrolysis of ATP

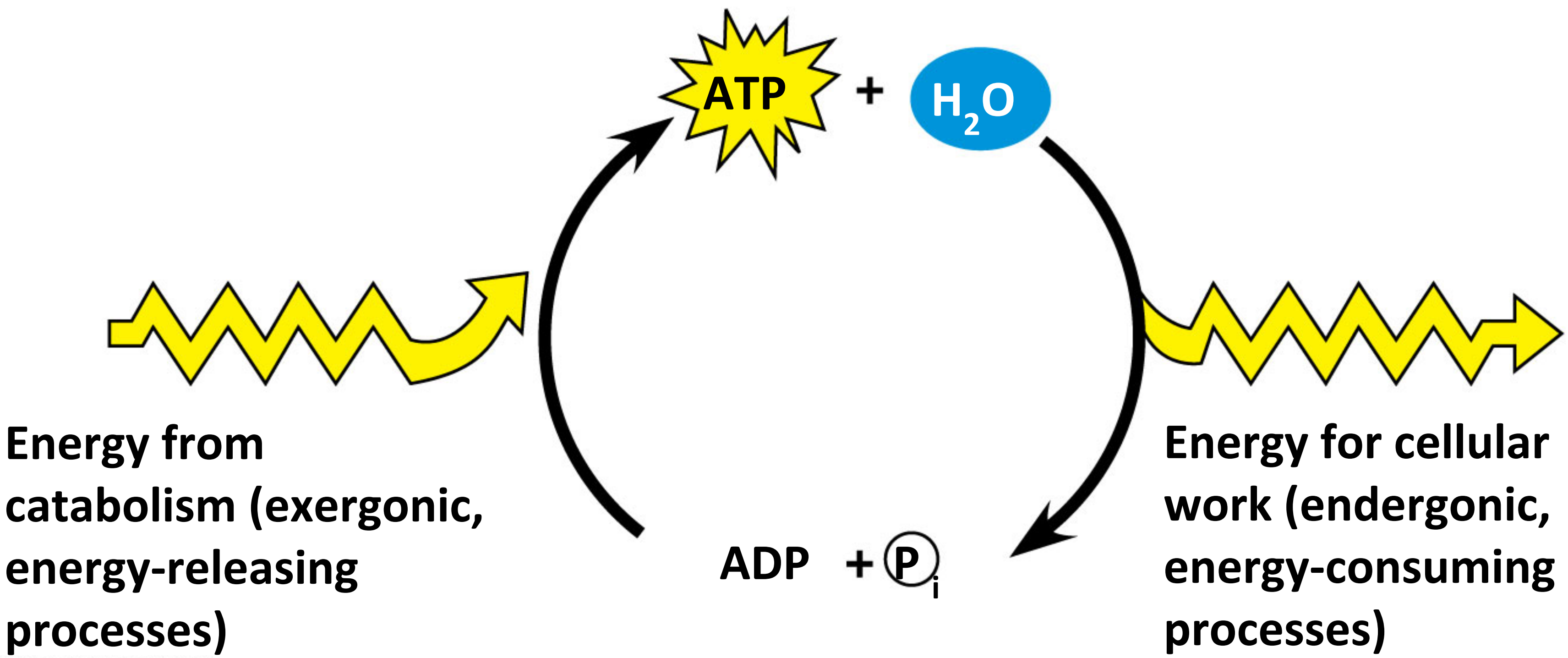
How the Hydrolysis of ATP Performs Work

- 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


(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
Glu
P
+ ADP
NH3
2
Glu
NH2
+ ADP + P i
Glutamic acid
Phosphorylated intermediate
Glutamine
(c) Free-energy change for coupled reaction
ΔG Glu = +3.4 kcal/mol
Glu
+
NH3
+
ATP
Glu
NH2
+ ADP + P i
ΔG Glu = +3.4 kcal/mol
+ ΔG ATP = −7.3 kcal/mol
Net ΔG = −3.9 kcal/mol
ΔG ATP = −7.3 kcal/mol


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

Enzymes speed up metabolic reactions by lowering energy barriers

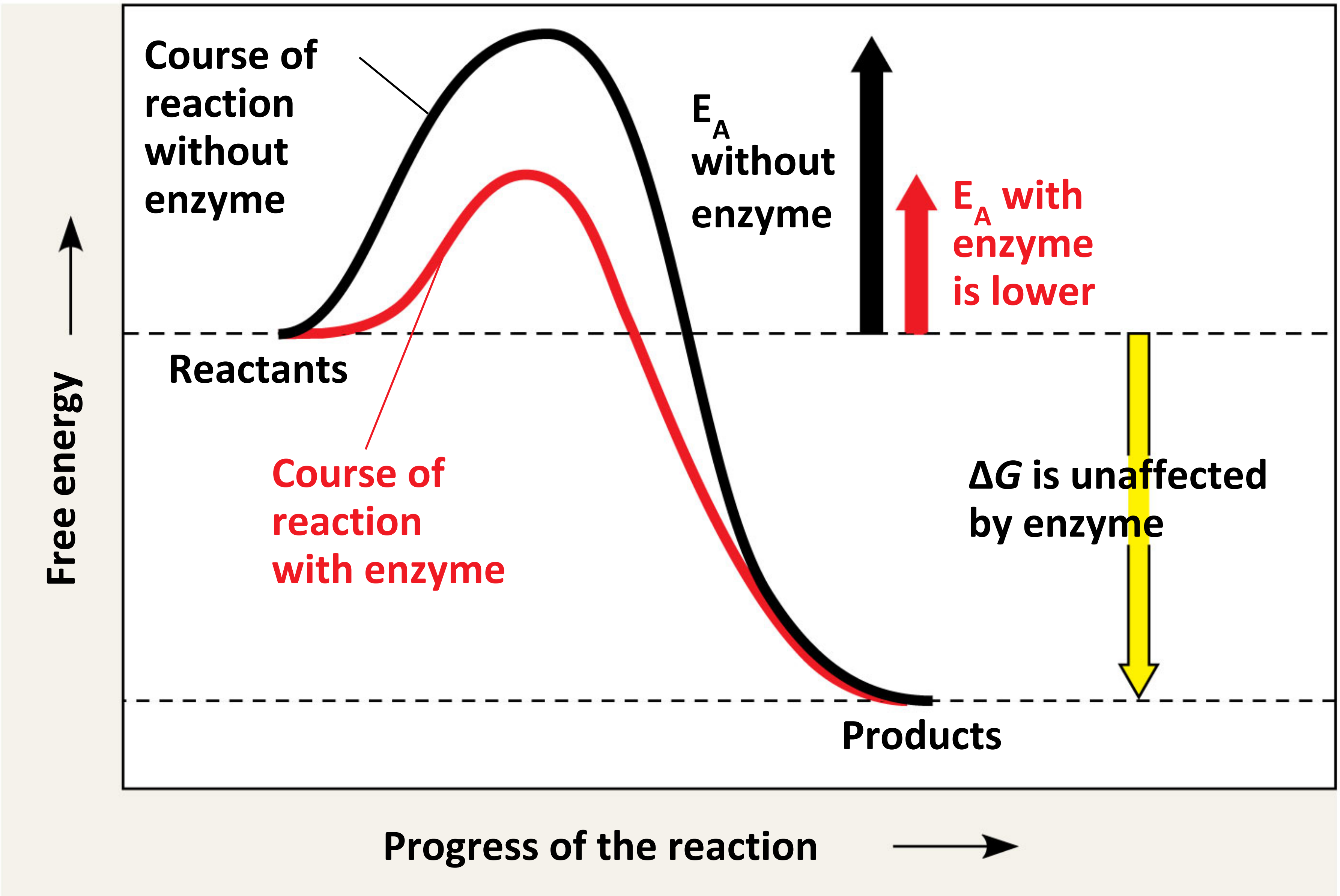
- A **catalyst** is a chemical agent that speeds up a reaction without being consumed by the reaction

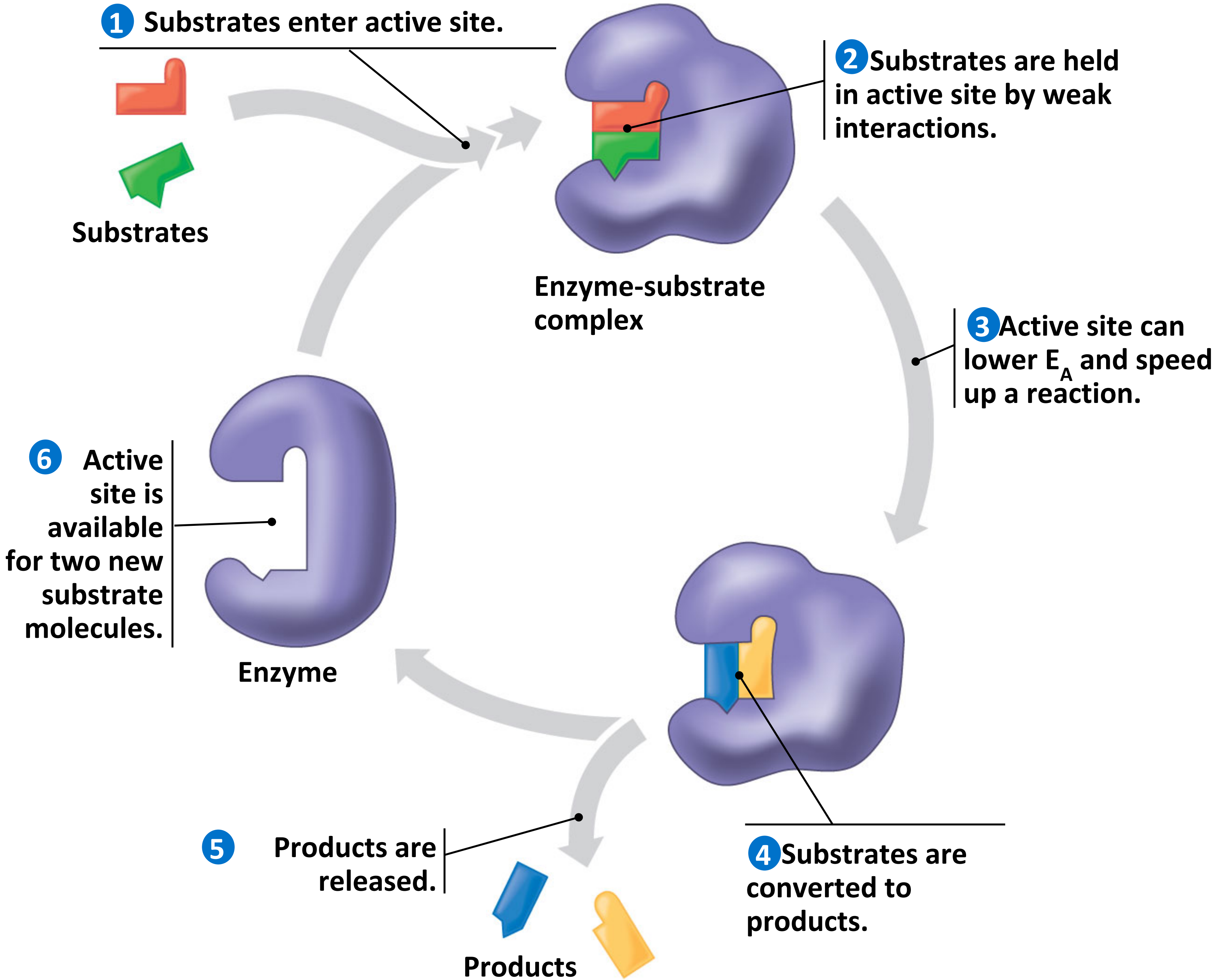
- An **enzyme** is a catalytic protein

- Hydrolysis of sucrose by the enzyme sucrase is an example of an enzyme-catalyzed reaction

The Activation Energy Barrier

- Every chemical reaction between molecules involves bond breaking and bond forming
- The initial energy needed to start a chemical reaction is called the free energy of activation, or **activation energy (E_A)**
- Activation energy is often supplied in the form of thermal energy that the reactant molecules absorb from their surroundings


Course of reaction without enzyme
E_A without enzyme
E_A with enzyme is lower
Reactants
Course of reaction with enzyme
ΔG is unaffected by enzyme
Products
Free energy
Progress of the reaction


1 Substrates enter active site.
Substrates
2 Substrates are held in active site by weak interactions.
Enzyme-substrate complex
3 Active site can lower E_A and speed up a reaction.
4 Substrates are converted to products.
5 Products are released.
Products
6 Active site is available for two new substrate molecules.
Enzyme