Domain 3: Energy

3.1: All living systems require constant input of free energy.

1. Bioenergetic Theory

The First Law of Thermodynamics

Energy cannot be created or destroyed, only transformed.

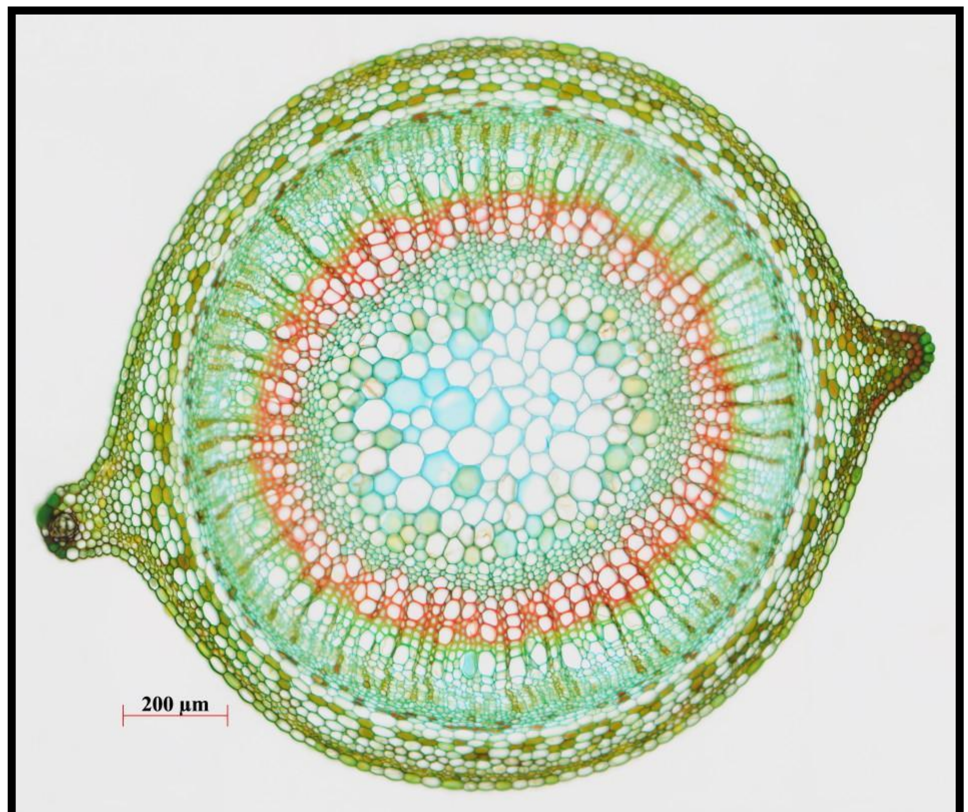
Living systems need to continually acquire and transform energy in order to remain alive.

“Free energy”: The energy available in a system to do work.

The Second Law of Thermodynamics

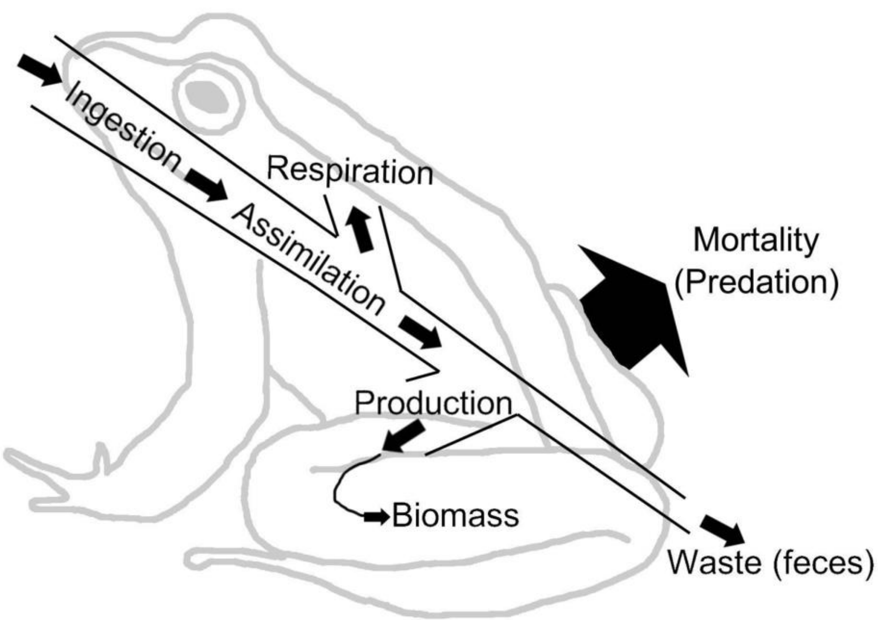
Every time energy is transformed, the **entropy** (“disorder”) of the universe increases.

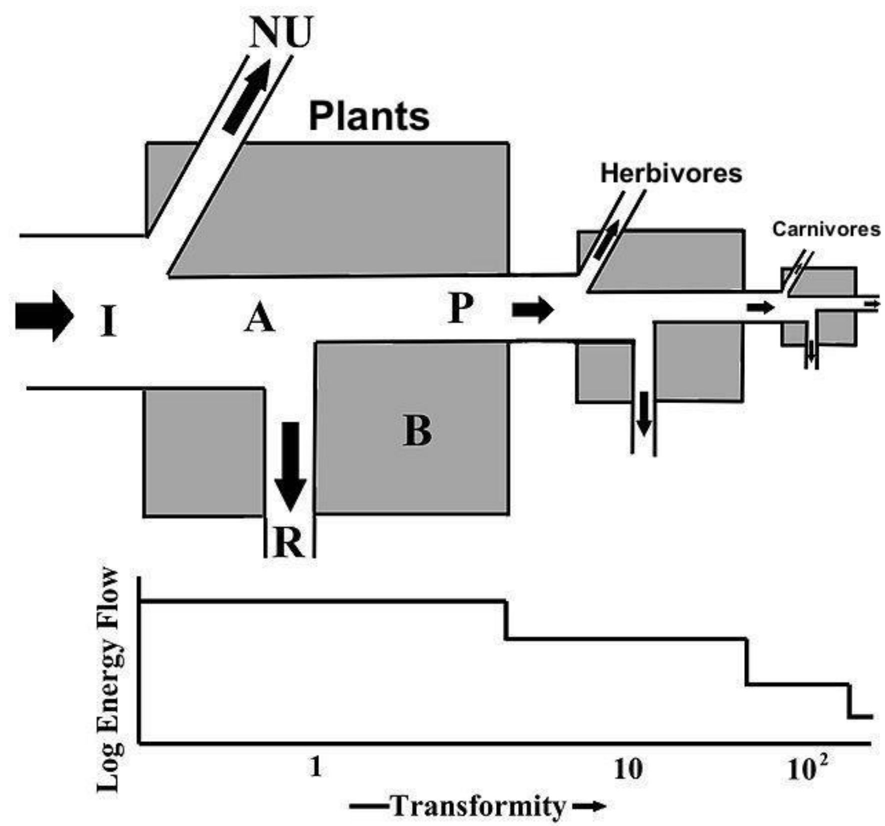
In order to increase/ maintain their internal order, living systems must process more ordered forms of matter in to less ordered ones



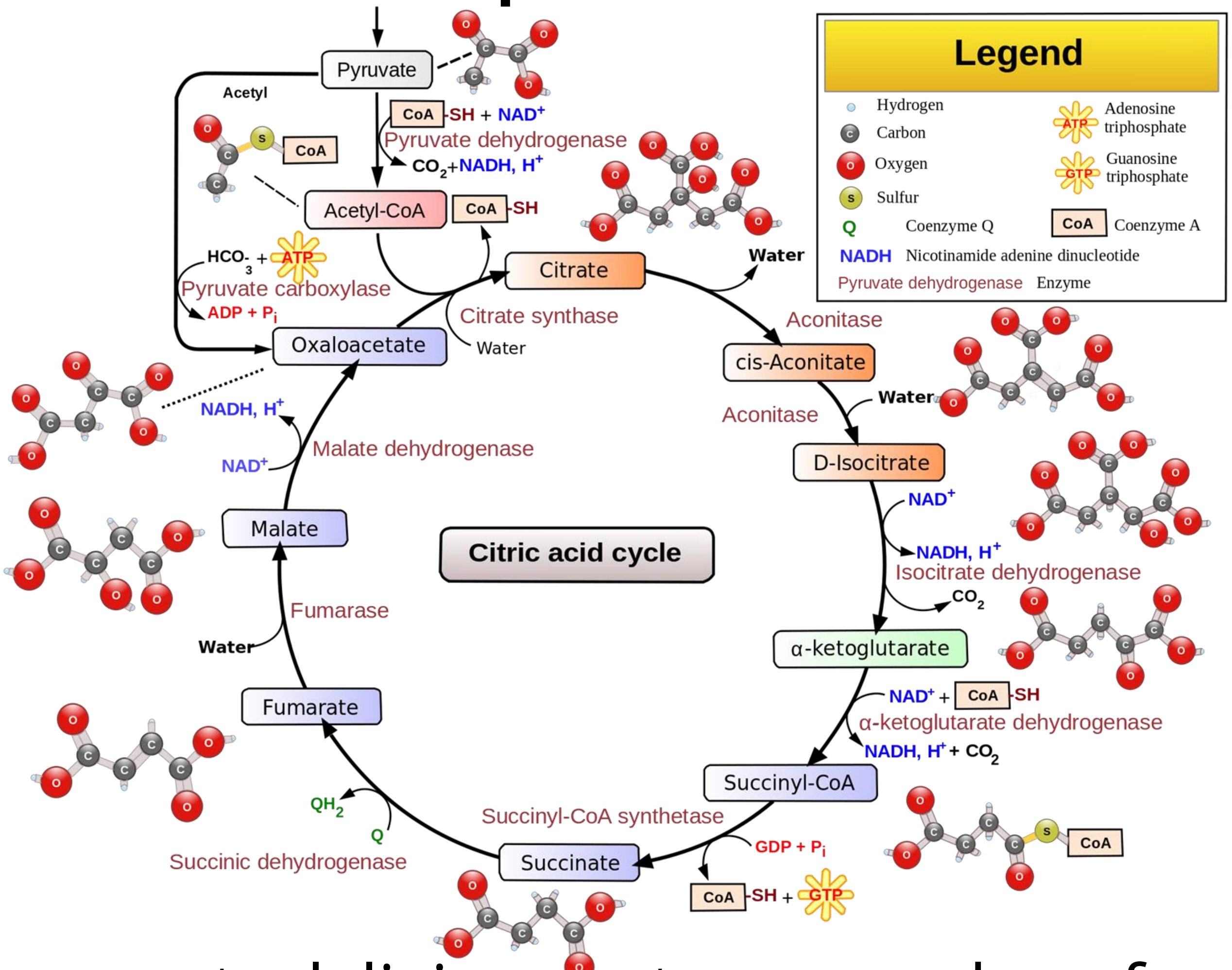
Living Systems are “Open” Systems

Matter and energy move in to living systems from the environment. Living systems transform matter and energy and return it to the environment





Multi-Step Metabolism



To increase control, living systems produce free energy in multiple-step pathways, mediated by enzyme **catalysts**.

3.1: All living systems require constant input of free energy.

2. Math Skills: Gibbs Free Energy

What You Have To Do

Be able to use and interpret the Gibbs Free Energy Equation to determine if a particular process will occur spontaneously or non-spontaneously.

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

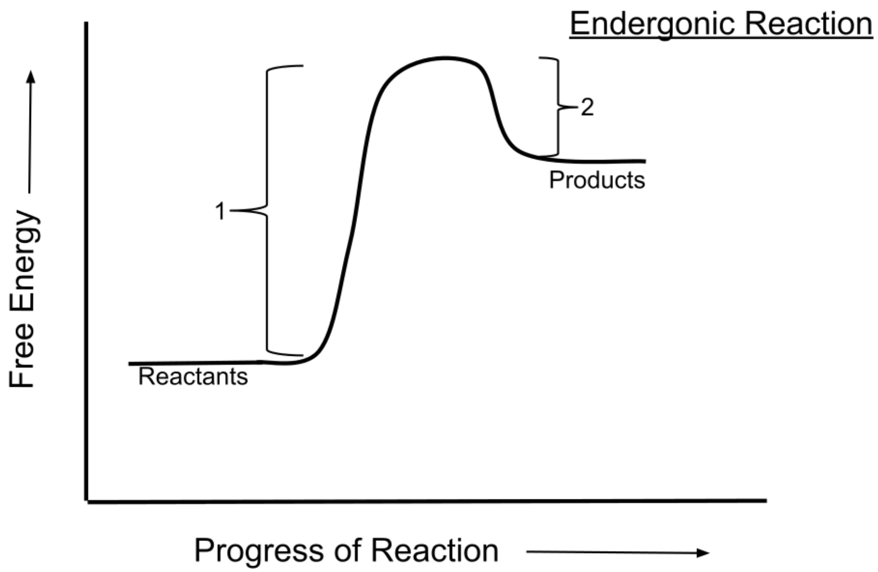
ΔG= change in free energy
(- = **exergonic**, + = **endergonic**)

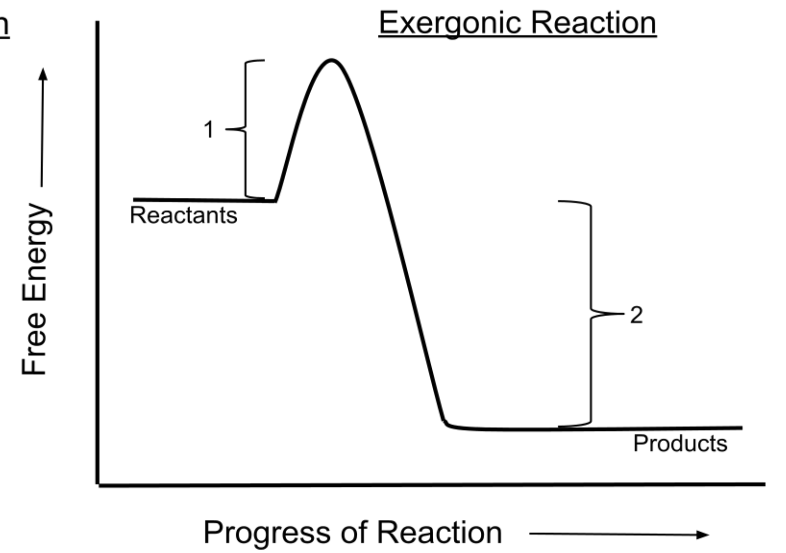
ΔH= change in enthalpy for the reaction
(- = **exothermic**, + = **endothermic**)

T = kelvin temperature

ΔS = change in entropy
(+ = entropy increase, - = entropy decrease)

Spontaneity





Spontaneous reactions continue once they are initiated. **Non-spontaneous** reactions require continual input of energy to continue.

Using the Equation

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

To use the equation, you'll need to be given values.

Exothermic reactions that increase entropy are always spontaneous/exergonic

Endothermic reactions that decrease entropy are always non-spontaneous/endergonic.

Other reactions will be spontaneous or not depending on the temperature at which they occur.

Sample Problem

Determine which of the following reactions will occur spontaneously at a temperature of 298K, justify your answer mathematically:

Reaction 1:

A + B → AB

Δ H: +245 KJ/mol

Δ S: -.02 KJ / K

Reaction 2:

BC → B + C

Δ H: -334 KJ/mol

Δ S: +.12 KJ/K

3.1: All living systems require constant input of free energy.

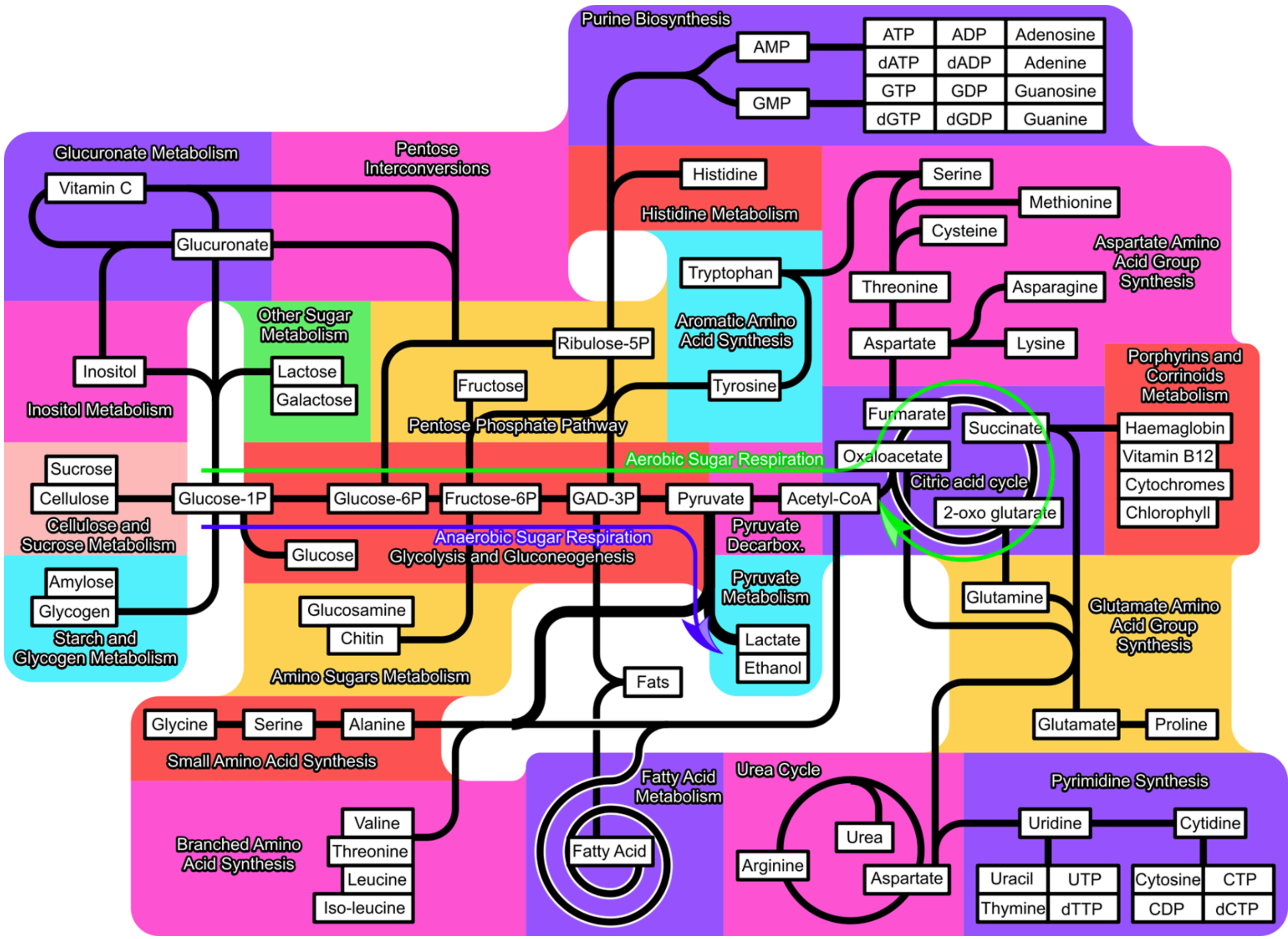
3. Metabolic Strategies

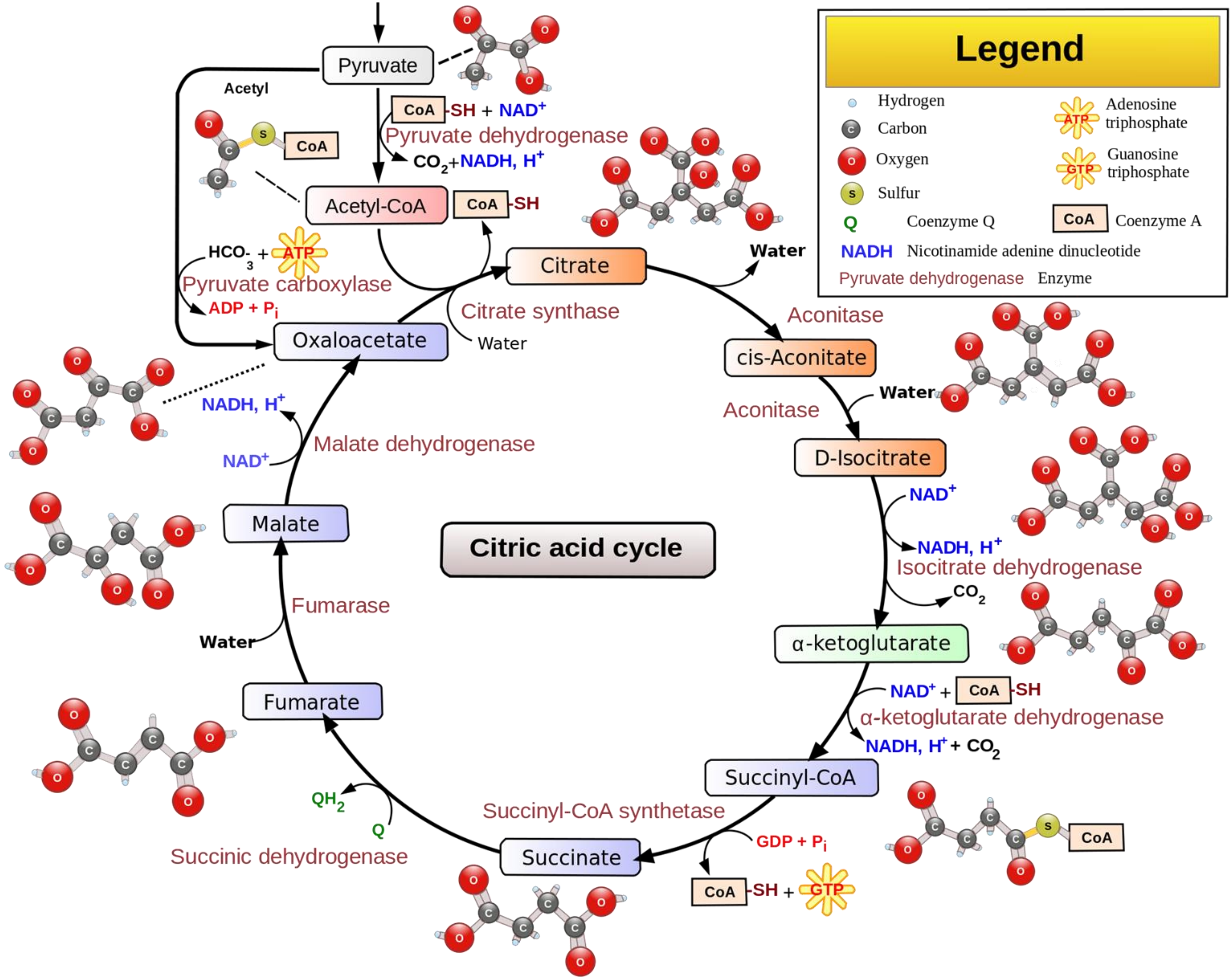
Uses of Biological Free Energy

To accomplish cellular work ("**metabolism**").
Repair, growth, and reproduction.

Catabolism:
Decomposing

Anabolism:
Synthesis



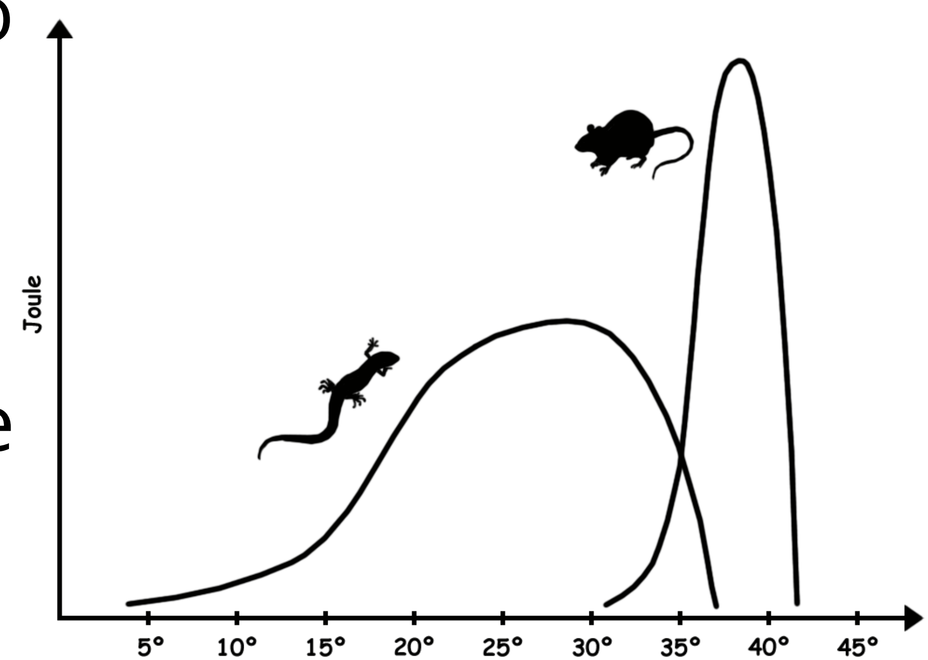


Legend
Hydrogen
Carbon
Oxygen
Sulfur
Q Coenzyme Q
NADH Nicotinamide adenine dinucleotide
Pyruvate dehydrogenase Enzyme
ATP Adenosine triphosphate
GTP Guanosine triphosphate
CoA Coenzyme A
Citric acid cycle
Pyruvate
Acetyl
CoA
CoA-SH + NAD+
Pyruvate dehydrogenase
CO2+NADH, H+
Acetyl-CoA
CoA-SH
HCO3- + ATP
Pyruvate carboxylase
ADP + Pi
Oxaloacetate
Citrate synthase
Water
Citrate
Water
Aconitase
cis-Aconitate
Water
Aconitase
D-Isocitrate
NAD+
NADH, H+
Isocitrate dehydrogenase
CO2
α-ketoglutarate
NAD+ + CoA-SH
α-ketoglutarate dehydrogenase
NADH, H+ + CO2
Succinyl-CoA
Succinyl-CoA synthetase
GDP + Pi
CoA-SH + GTP
Succinate
Succinic dehydrogenase
Q
QH2
Fumarate
Fumarase
Water
Malate
Malate dehydrogenase
NAD+
NADH, H+

Metabolic Strategies

Ectothermy: Conform internal temperature to environmental temperature.

Endothermy: Regulate internal temperature within a narrow range.



Both strategies have advantages and tradeoffs.

Body Size Considerations

Smaller animals need to produce more energy per unit of mass due to increased radiation of heat into the environment.

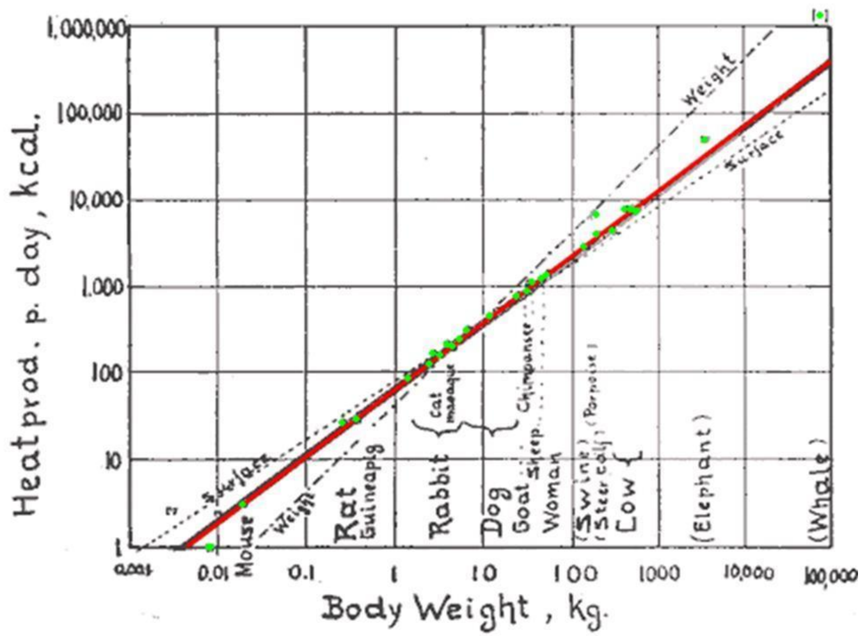
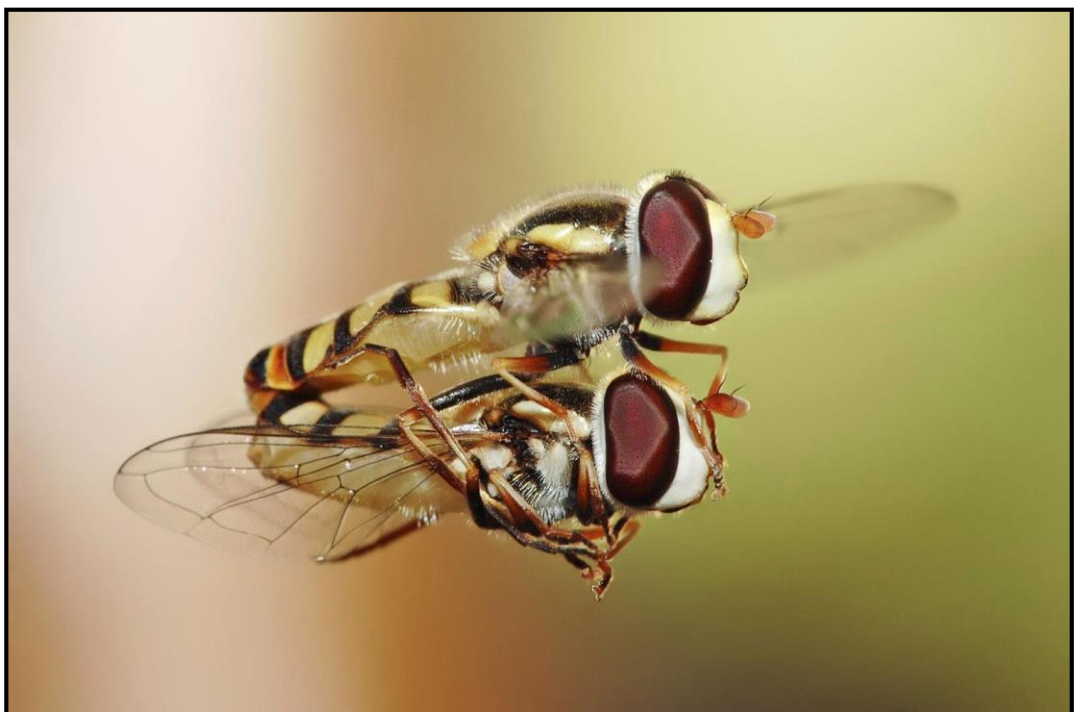


Fig. 1. Log. metabol. rate/log body weight

Free Energy Considerations & Reproduction

Reproductive strategies are optimized for free energy considerations.

Ex. Seasonal Reproduction.

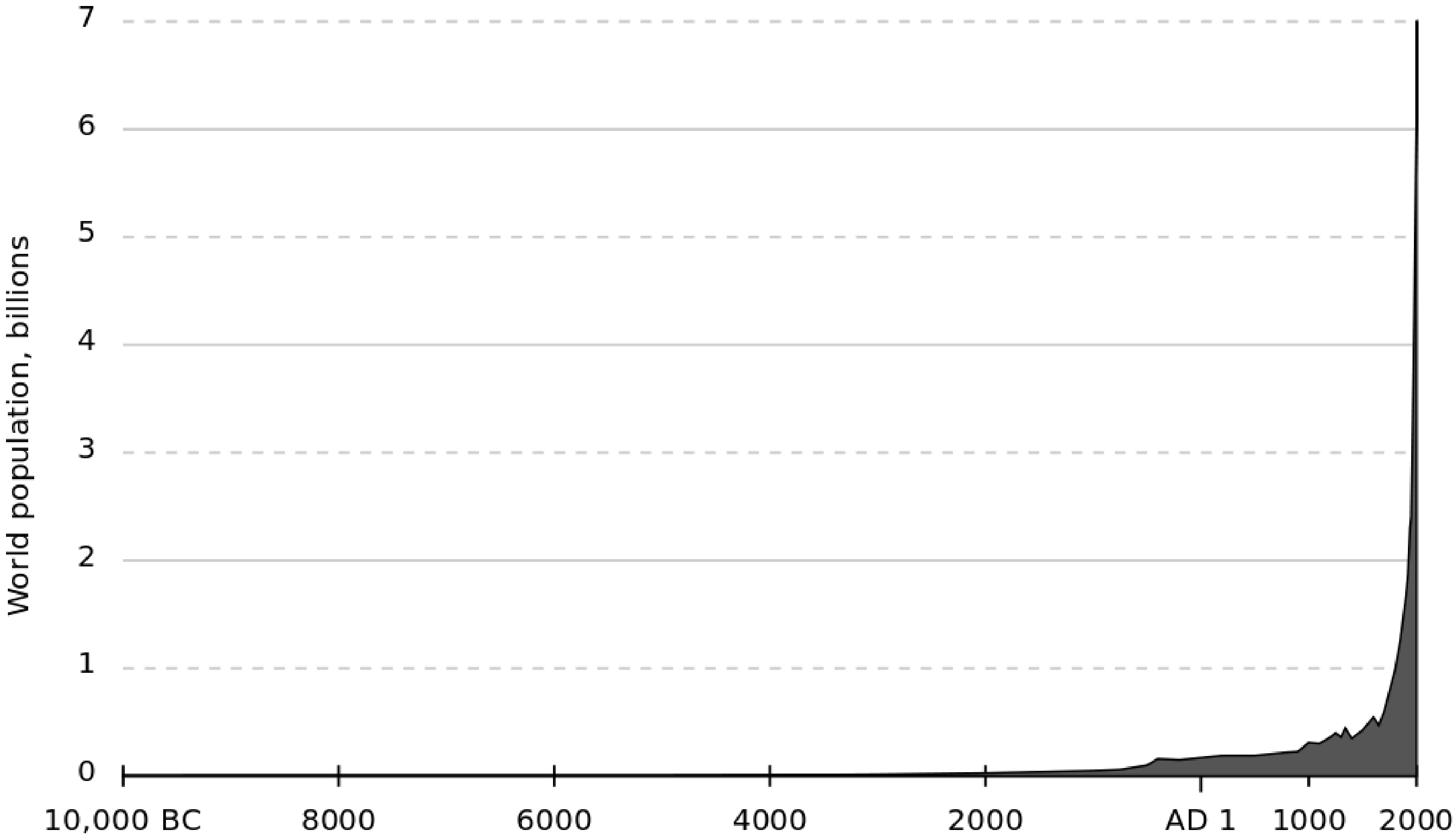


Insufficient Free Energy Production: Individuals

Insufficient free energy production by individuals will lead to disease and death.

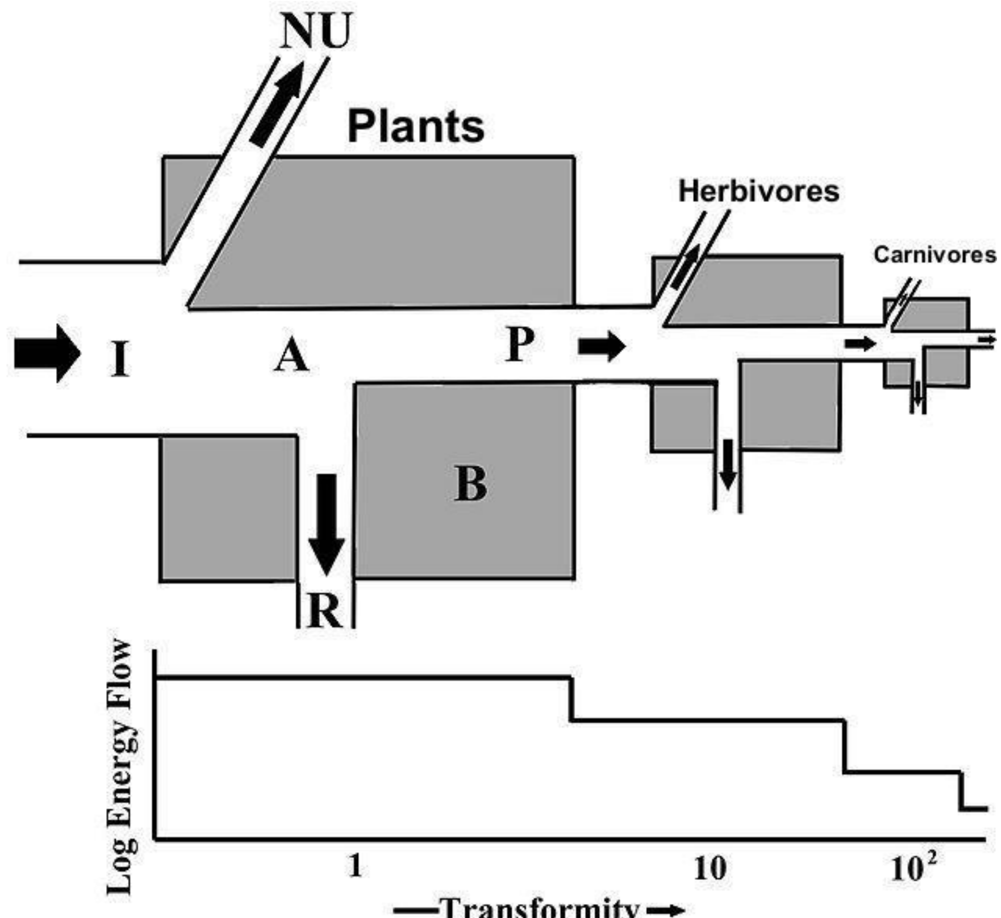
Insufficient Free Energy Production: Populations

If the individuals in the population are unable to survive, the growth rate of the population will decline



Insufficient Free Energy Production: Ecosystems

If the populations in an ecosystem decline, the ecosystems will decrease in complexity



3.1: All living systems require constant input of free energy.

4. Math Skills: Coefficient Q_{10}

What You Have To Do

Be able to use and interpret the Coefficient Q_{10} equation:

$$Q_{10} = \left(\frac{k_2}{k_1} \right)^{\frac{10}{t_2 - t_1}}$$

t_2 = higher temperature
t_1 = lower temperature
k_2= metabolic rate at higher temperature
k_1= metabolic rate at lower temperature
Q_{10} = the factor by which the reaction rate increases when the temperature is raised by ten degrees.

What It Means

$$Q_{10} = \left(\frac{k_2}{k_1}\right)^{\frac{10}{t_2 - t_1}}$$

Q_{10} tells us how a particular process will be affected by a 10 degree change in temperature.

Most biological processes have a Q_{10} value between 2 and 3

Sample Problem

Data taken to determine the effect of temperature on the rate of respiration in a goldfish is given in the table below. Calculate the Q10 value for this data.

Temperature (°C)	Heartbeats per minute
20	18
25	42

3.2: Interactions between molecules affect their structure and function.

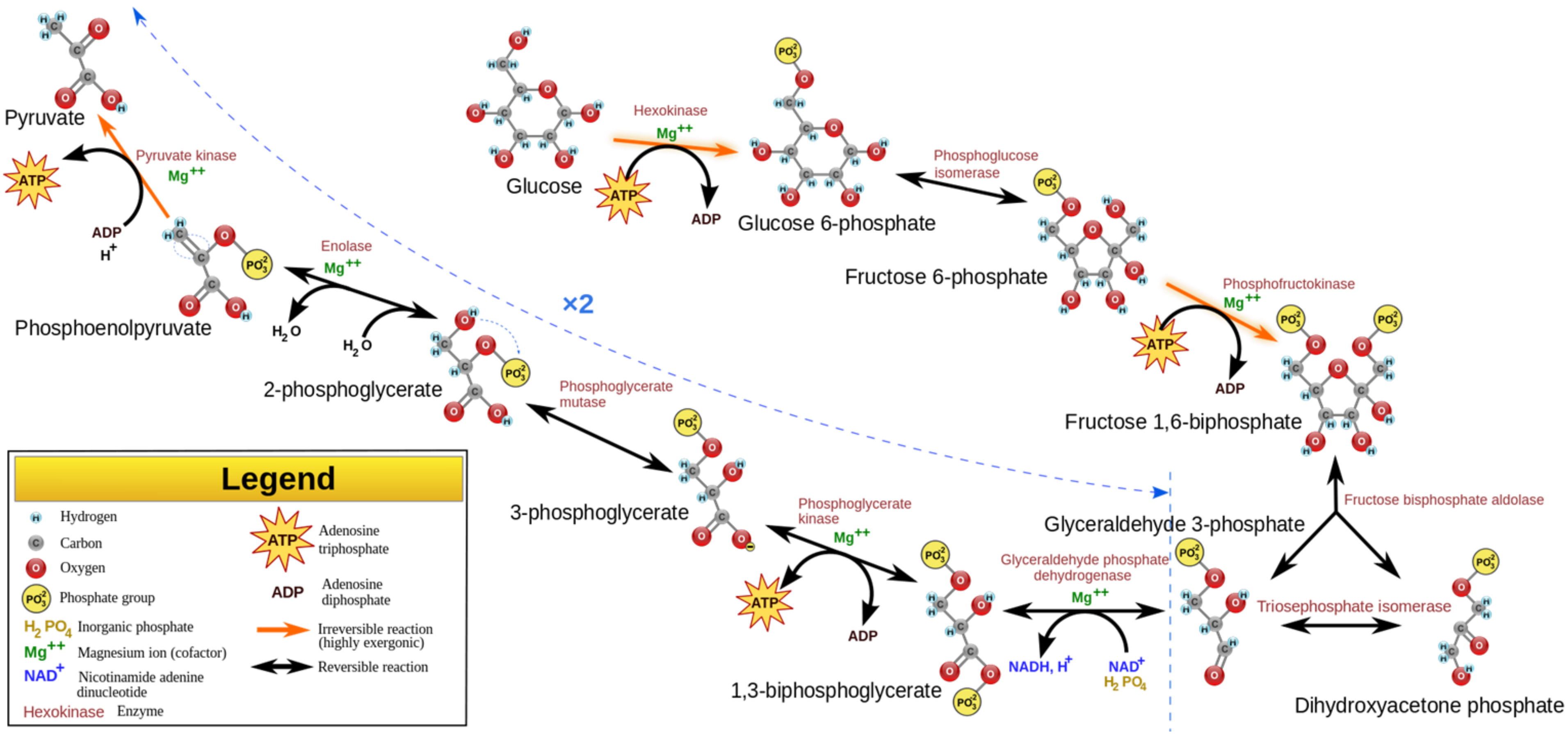
1. Enzyme Structure and Function

Structure and Function

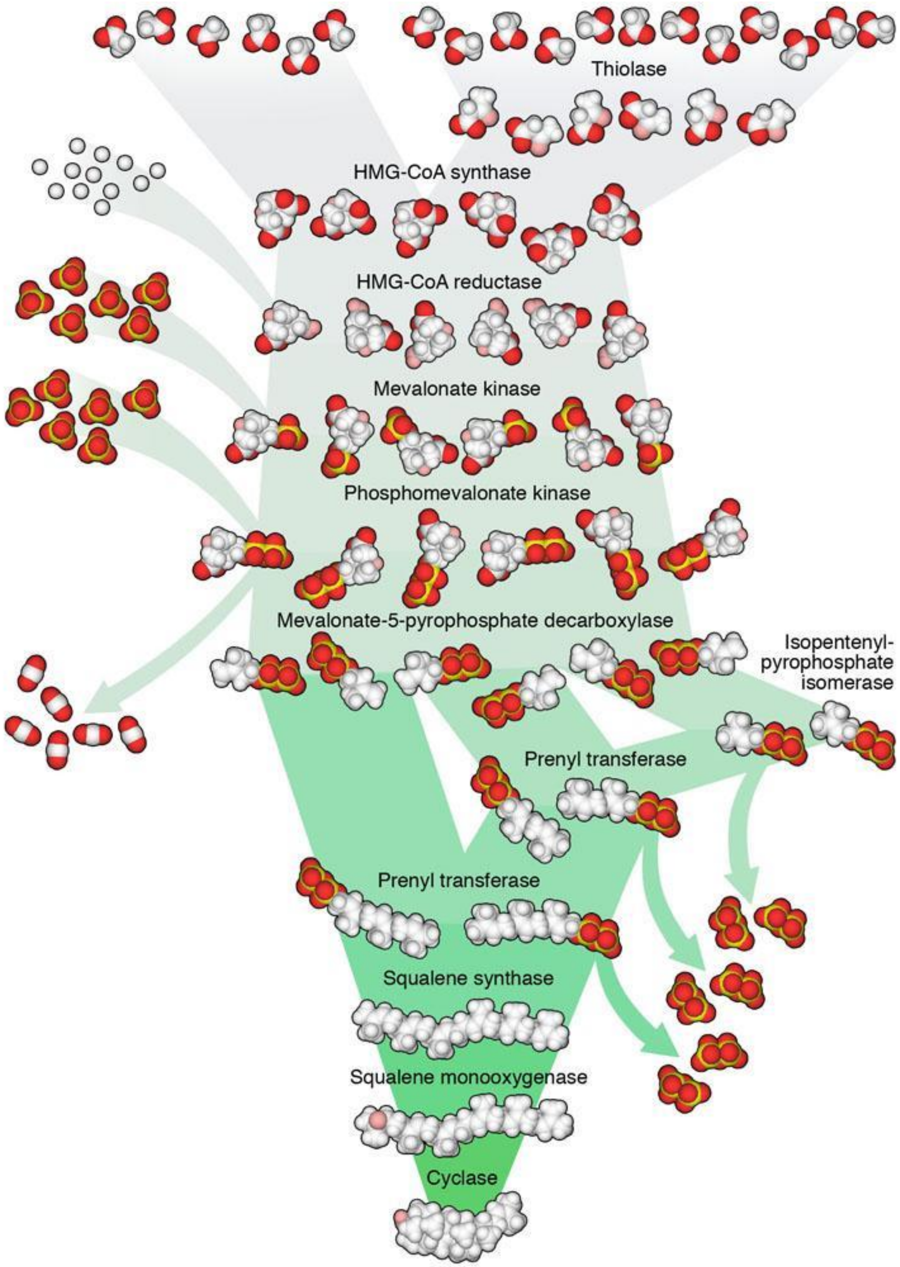
Structure always determines function.

Molecular interactions lead to organism **phenotypes**.

Metabolism is Controlled by Enzymes



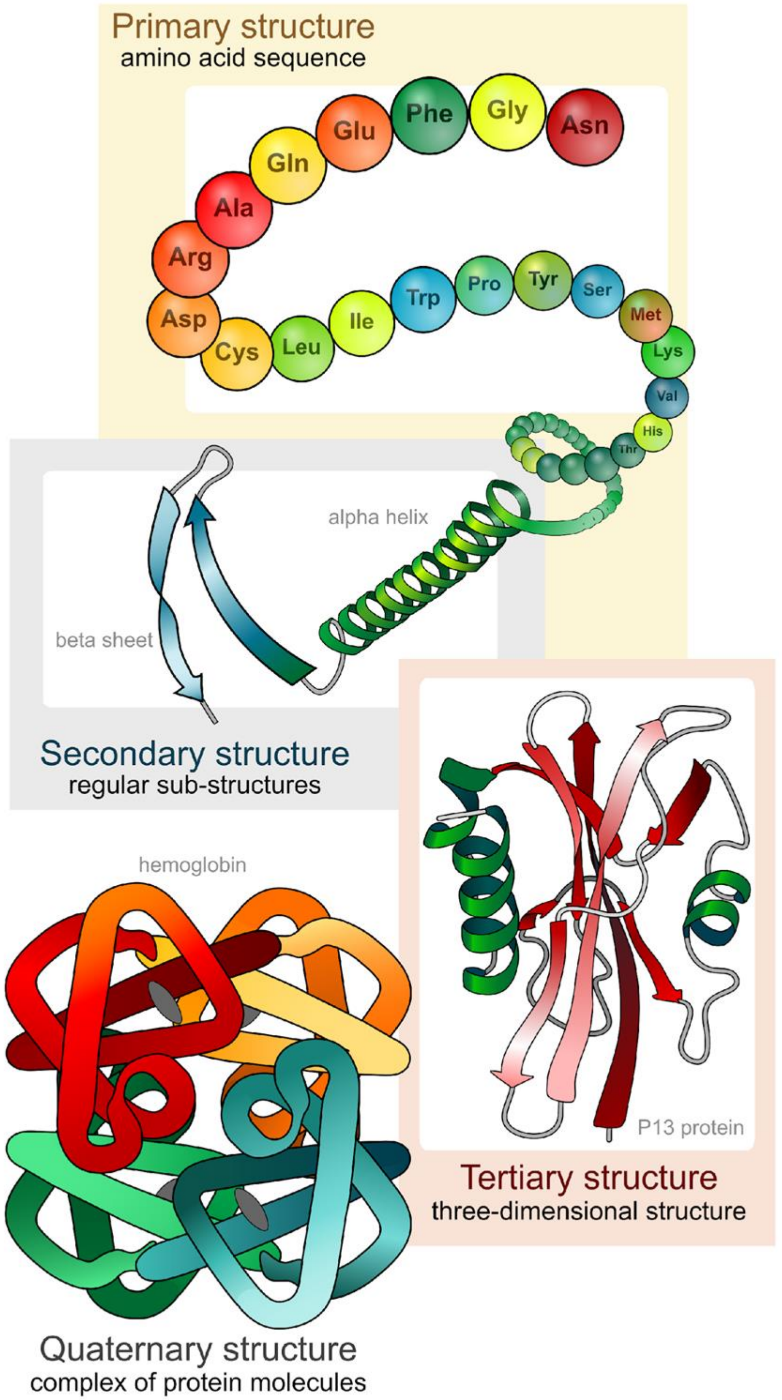
More Steps = More Control = More Complexity



Enzymes are (mostly) Proteins

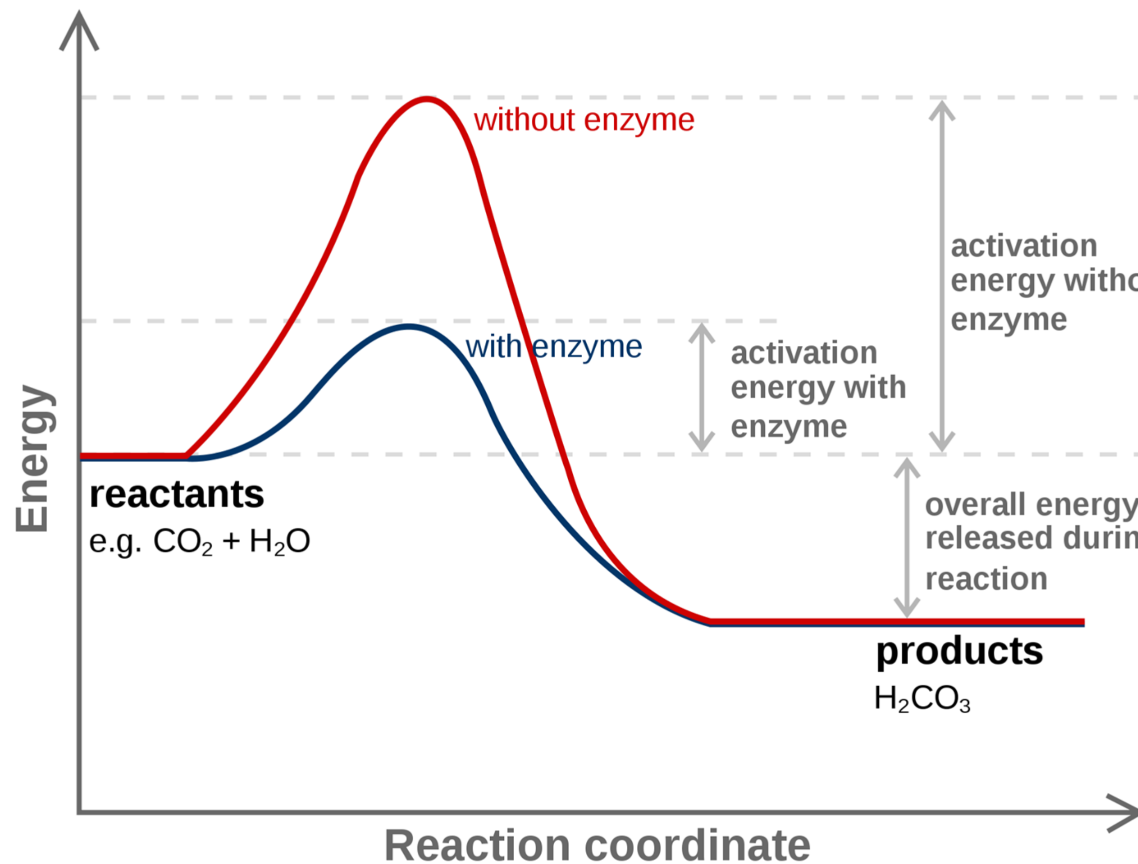
Enzymes are molecules that serve as biological **catalysts**.

Some RNA molecules also have catalytic properties.



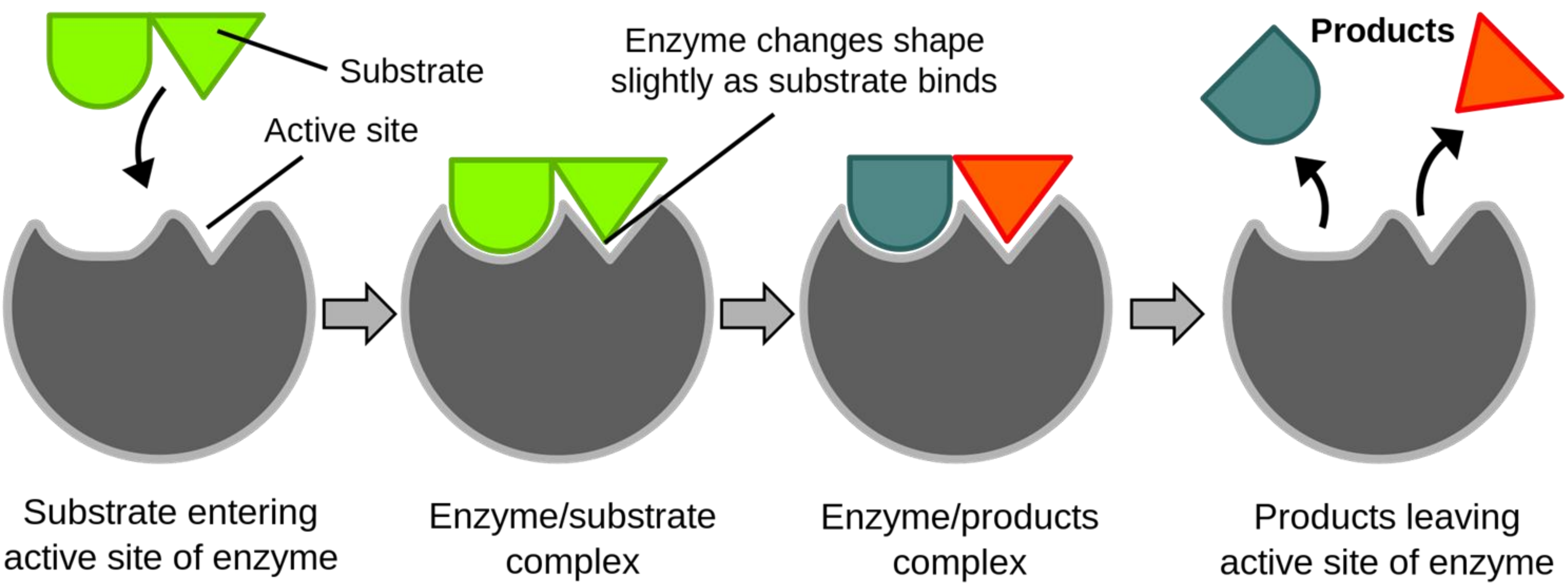
Catalysis

Catalysts: Substances that increase the rate of a chemical reaction by lowering the activation energy of the reaction, without participating in the reaction.



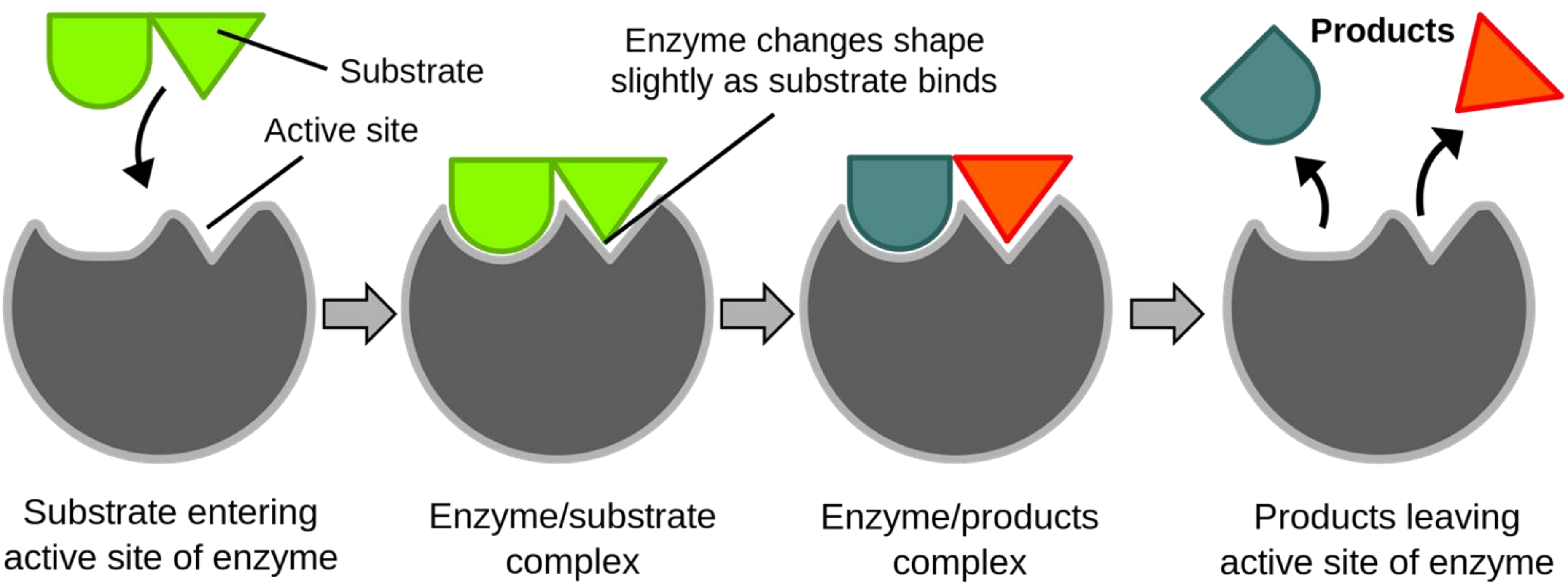
Enzymes work by physically positioning reactants ("**substrate**") in ways that increase the likelihood of chemical bonds being broken or formed.

Enzymes are highly specific for the substrates that they interact with. The name of an enzyme tells you about its substrate in the first part of its name, and ends in **–ase**. (Ex. lipase)



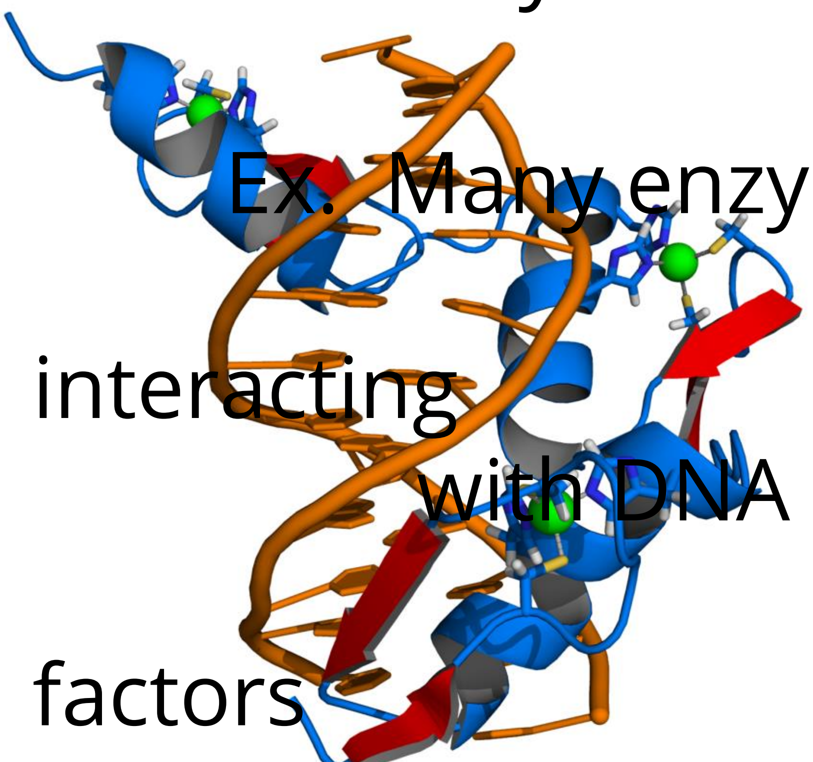
Induced Fit Model:

Substrate molecules physically bind to an area of the enzyme called the "**active site**". The binding causes the conformation of the enzyme to change slightly, catalyzing the reaction.



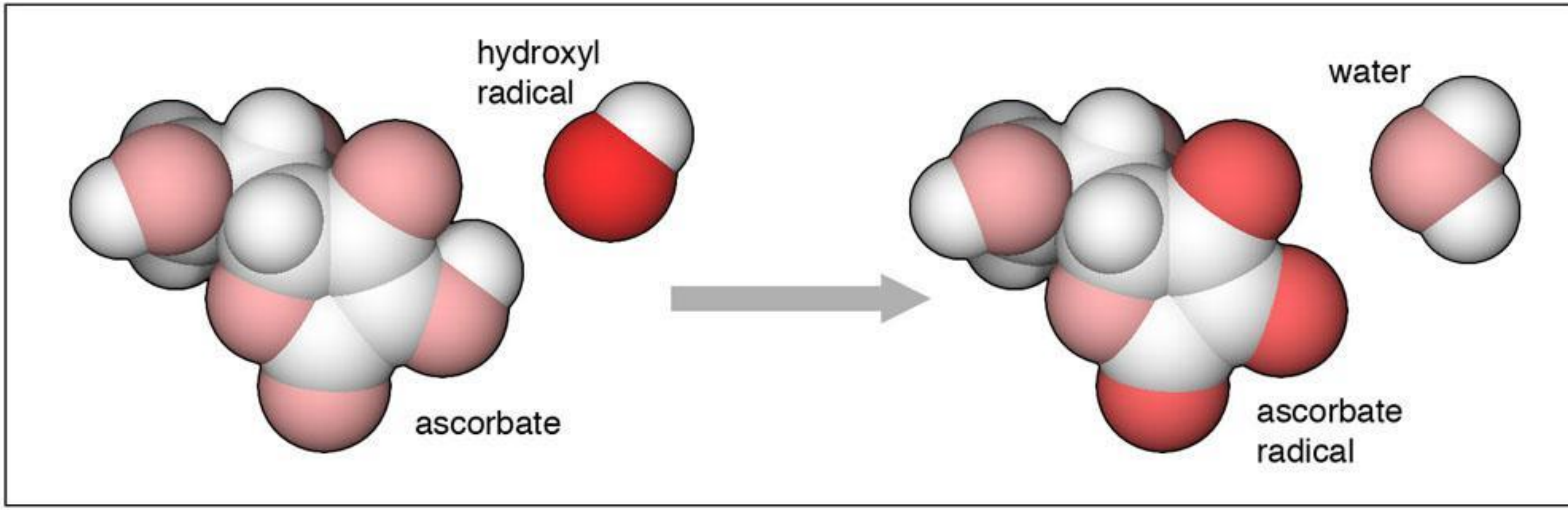
Co-factors/Co-enzymes

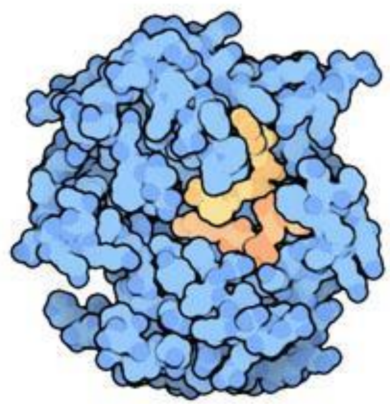
many enzymes require organic (**co-enzymes**: “vitamins”) or inorganic (**co-factors**: “minerals”) groups of atoms to be complexed with the enzyme.



Ex. Many enzymes involved in interacting with DNA require zinc^{2+} ions as co-factors (green spheres)

Ex. Vitamin C


hydroxyl
radical
water
ascorbate
ascorbate
radical

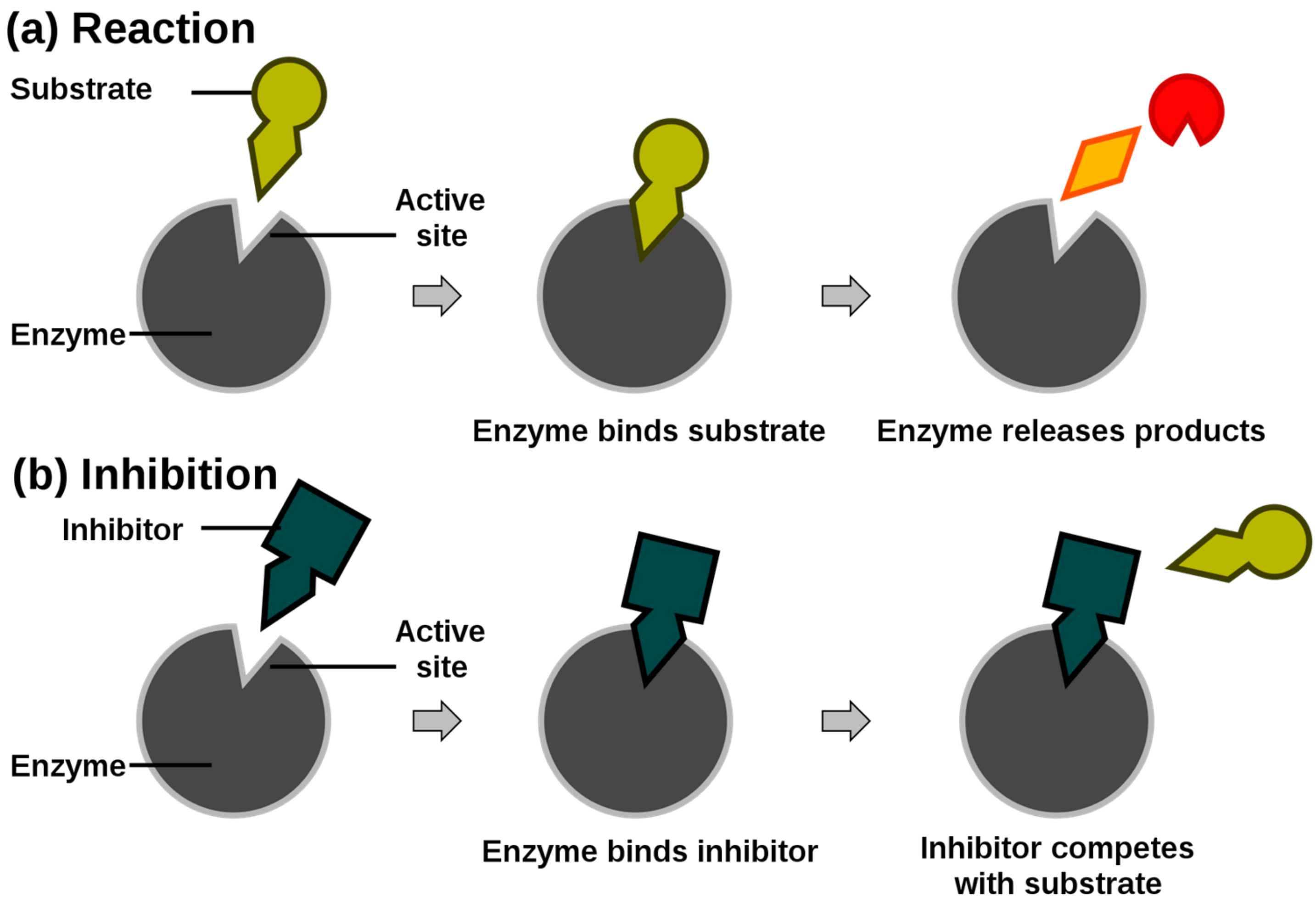

Cytochrome b_5
reductase

3.2: Interactions between molecules affect their structure and function.

2. Regulation of Enzyme Activity

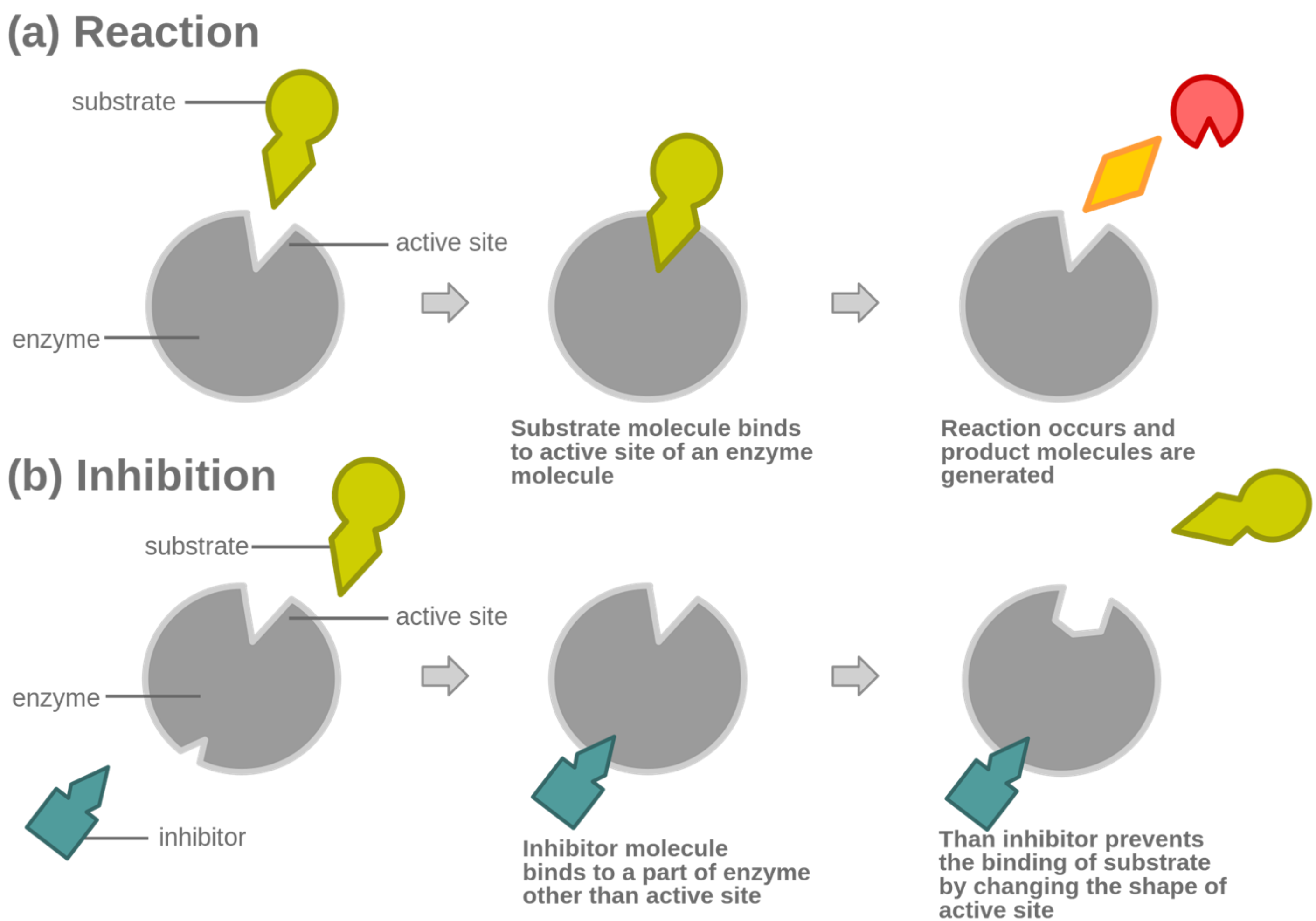
Other Molecules Can Affect Enzyme Structure and Function.

Competitive Inhibition:



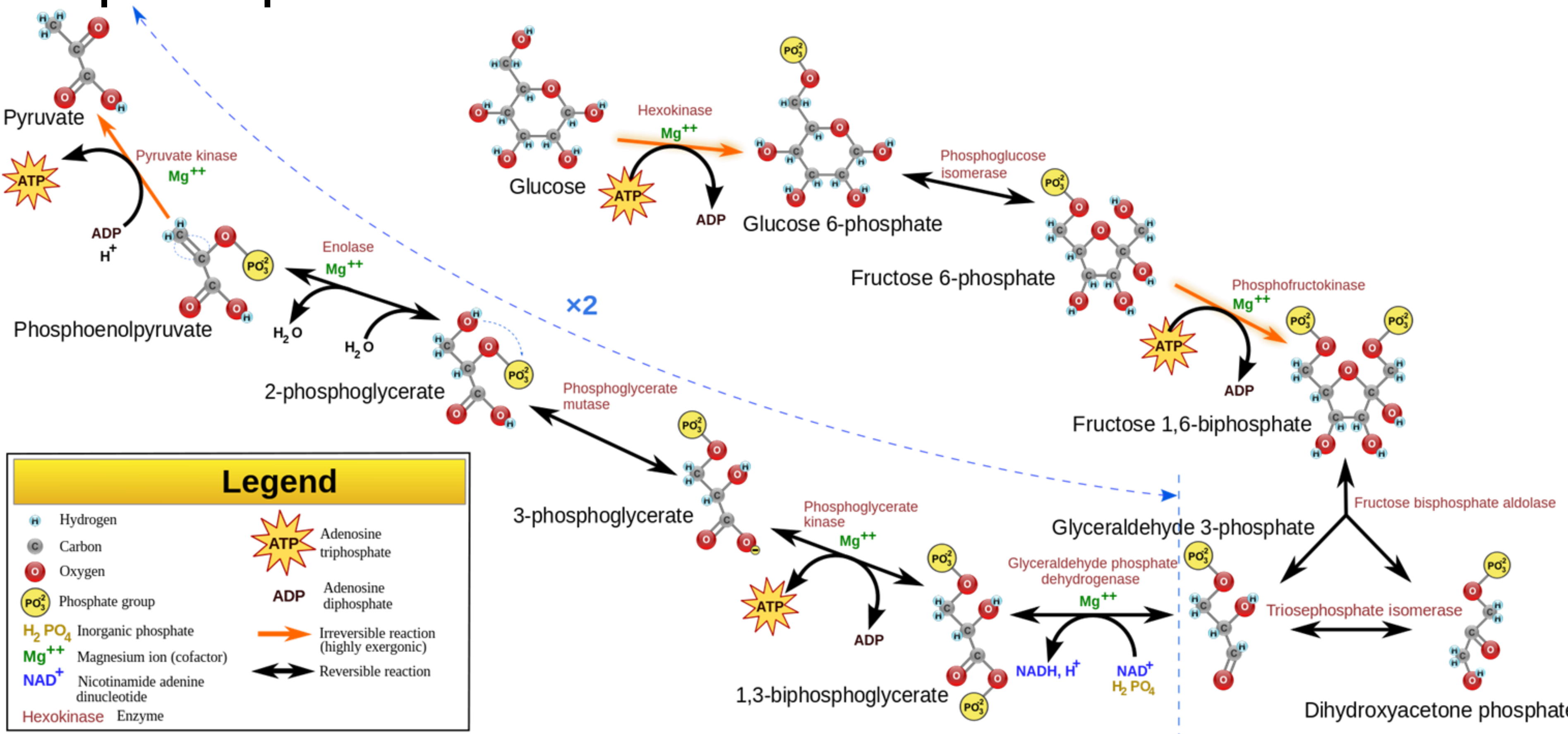
Non-Competitive Inhibition.

“Allosteric Interaction”: Affects enzyme structure through binding away from the active site.



Allosteric Interactions allow for feedback inhibition of metabolism

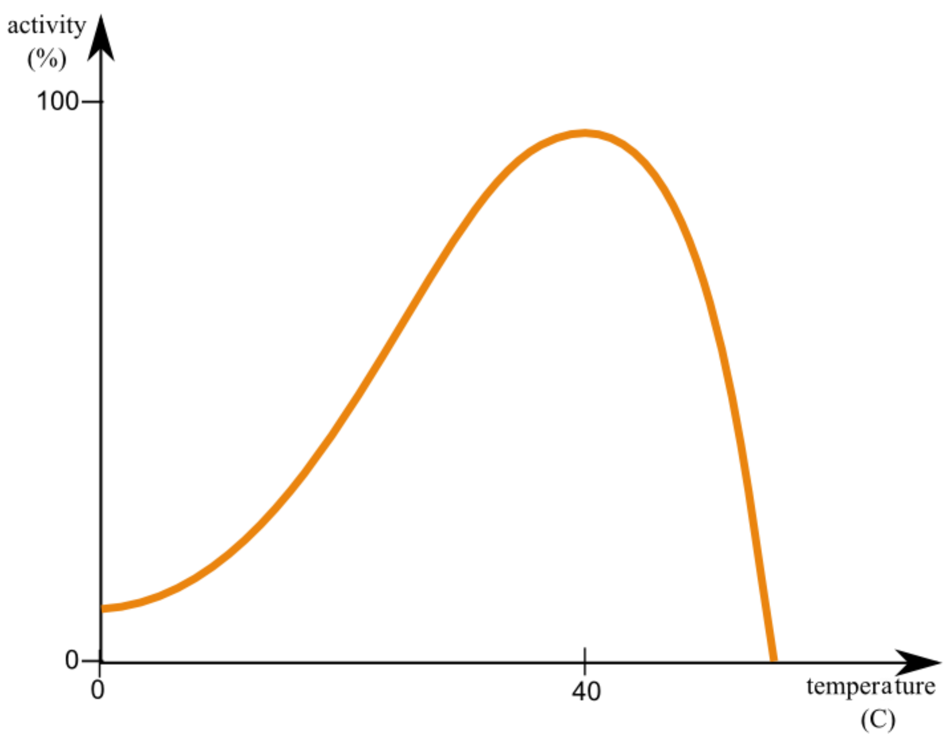
Ex. ATP inhibits the activity of phosphofructokinase.

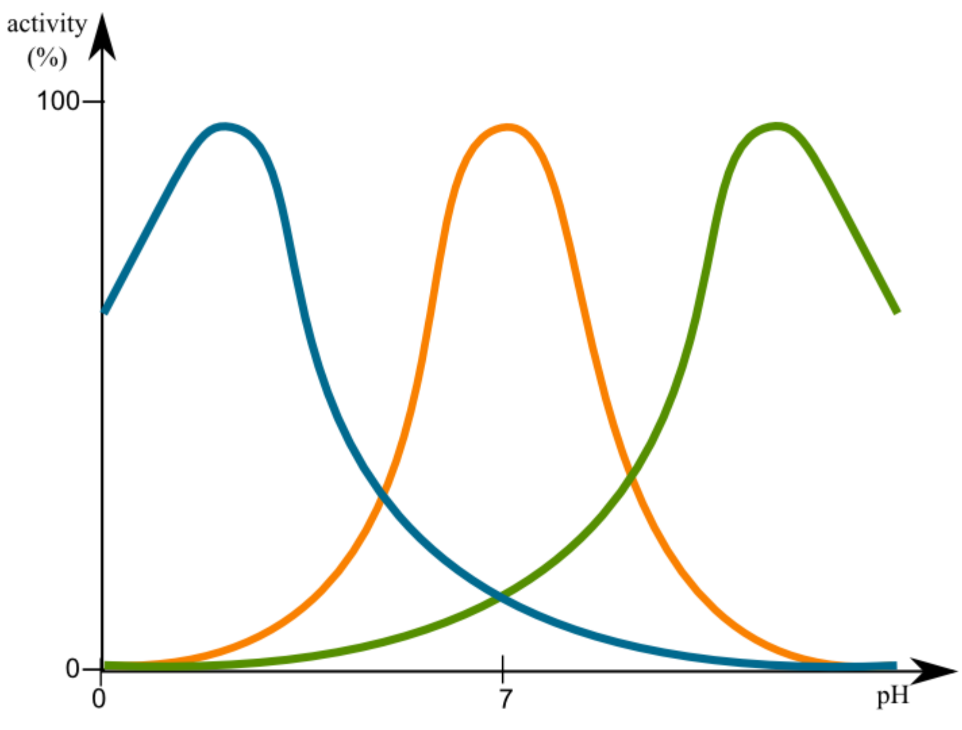


Environmental Influences on Enzyme Function

The local environment can affect the shape of the enzyme, which will affect its function.

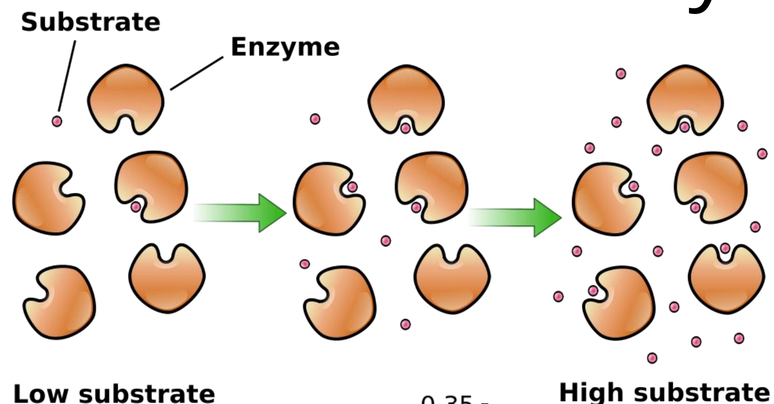
Ex. Temperature and pH.

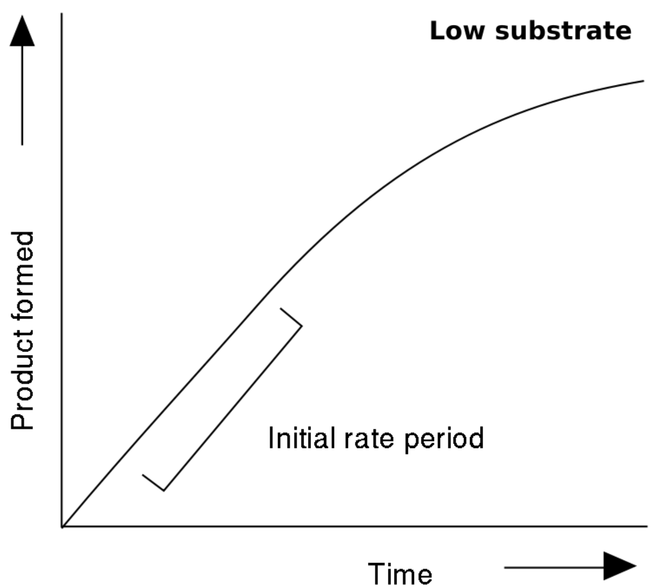


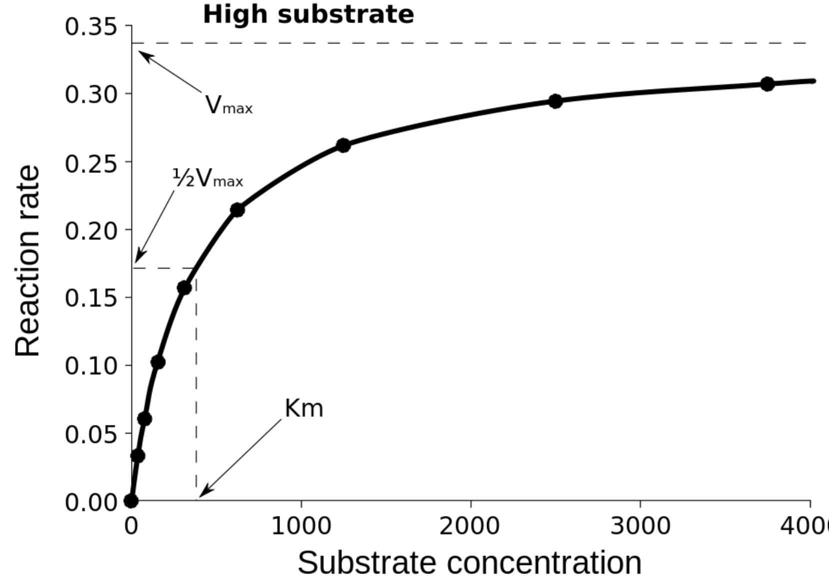


Concentration Influences on Enzyme Function

The concentration of enzyme and substrate will also affect enzyme function.



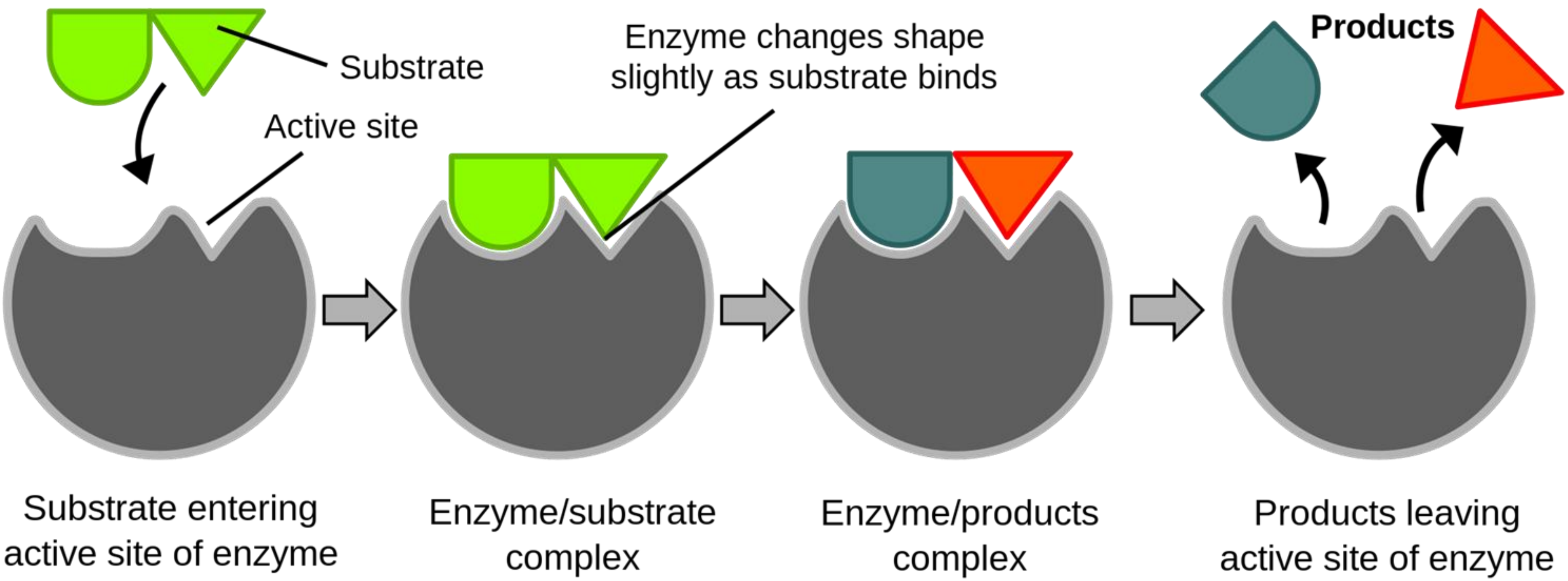




Measuring Enzyme Activity

Enzyme Activity can be measured in different ways:

- Appearance of a product
- Disappearance of a substrate
- Indirect Analogs: Ex. Color Change, Change in Temp.



3.3: Organisms capture and store free energy for use in biological processes.

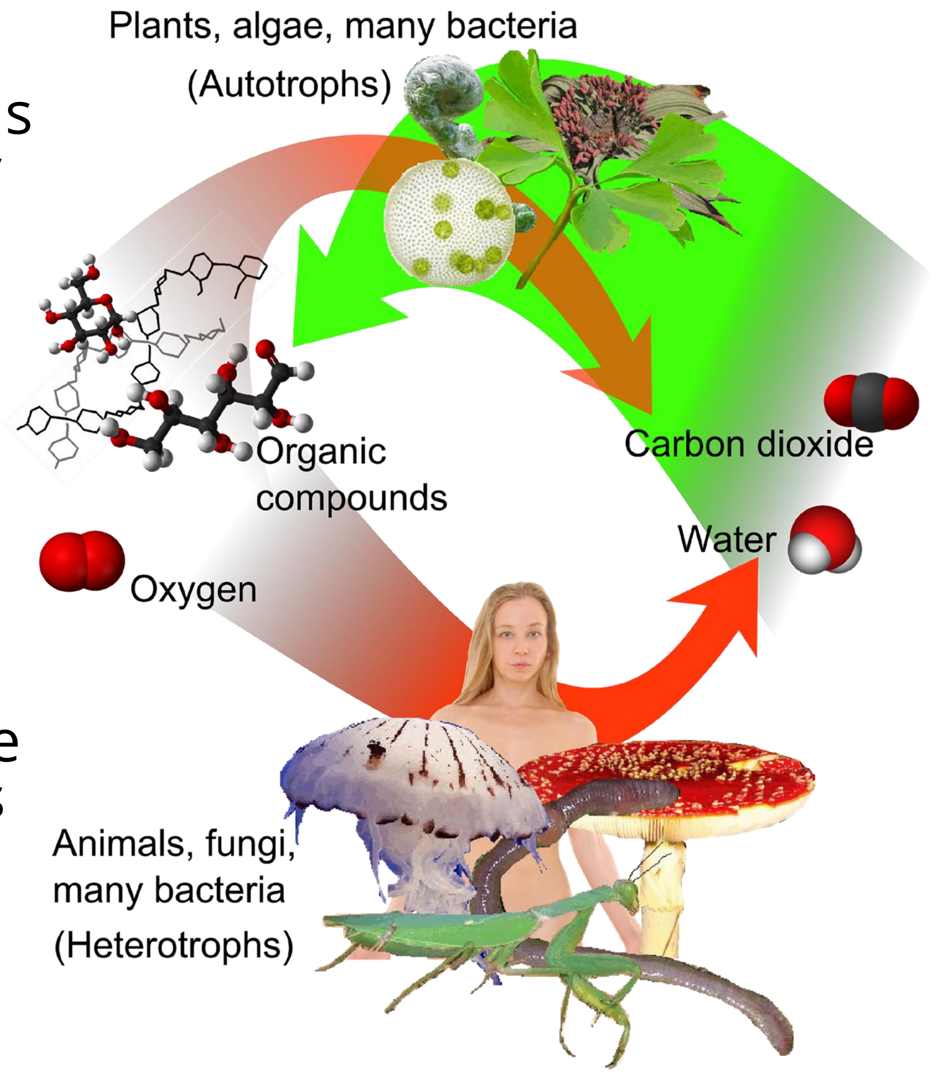
1. Energy Processing

Autotroph Energy Strategies

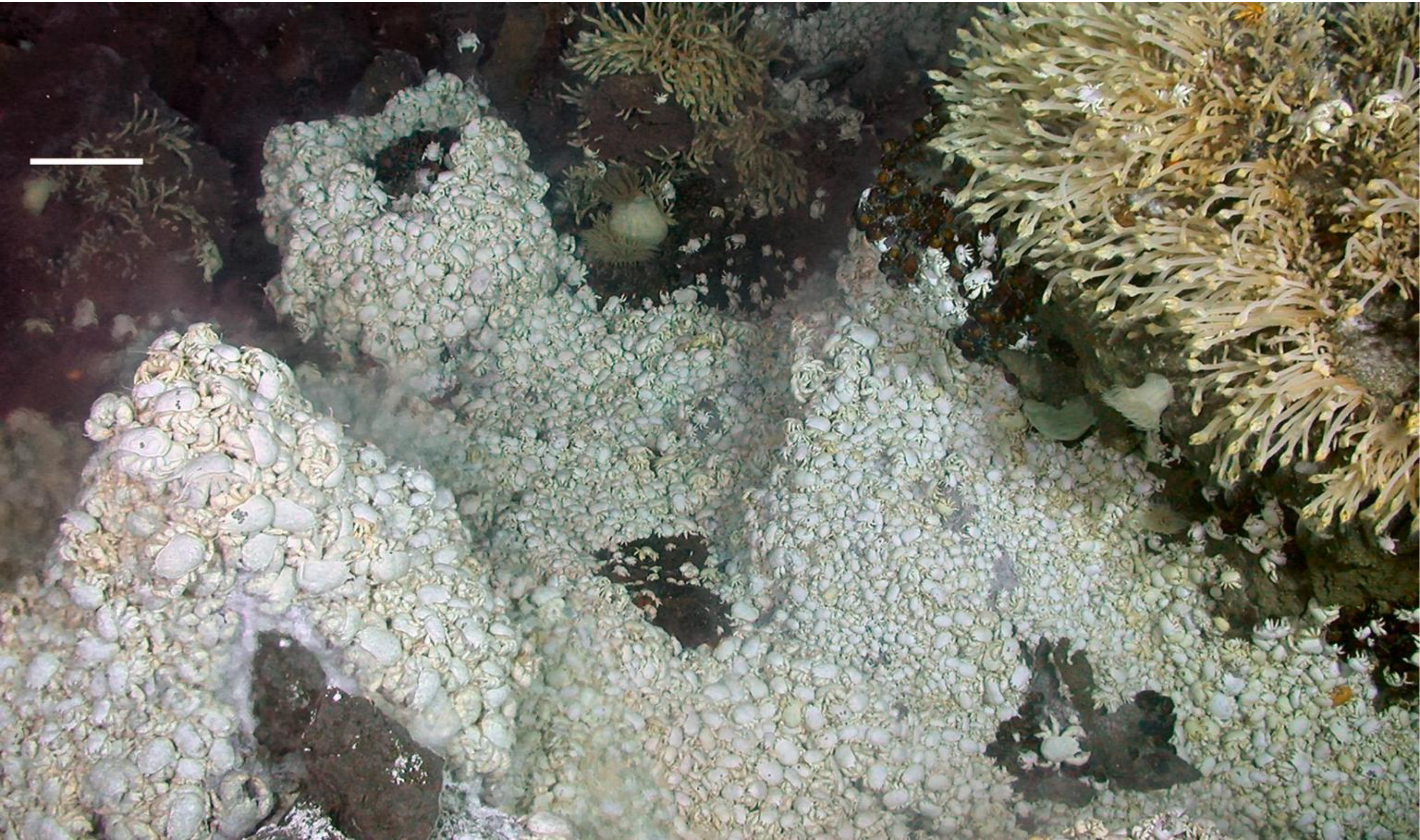
Autotrophs: use energy from the environment to convert inorganic molecules into organic compounds where free energy is stored. They are the producers in all food chains on Earth.

Photosynthetic organisms: Use visible light energy to convert CO_2 and H_2O into sugar precursors
Ex. all plants, and phytoplankton.

Chemosynthetic organisms: Use high energy inorganic compounds
Ex. hydrothermal vent bacteria



Chemosynthetic Hydrothermal Vent Community.

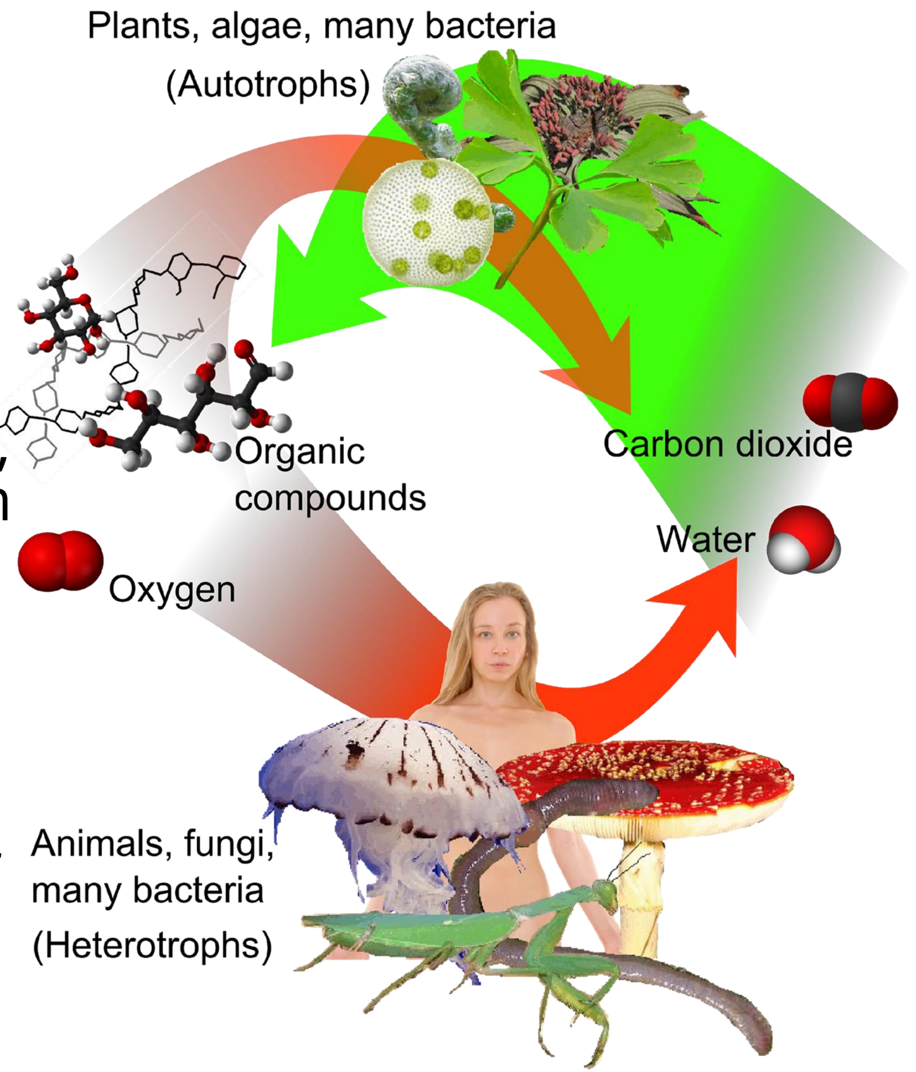


Heterotroph Energy Strategies

Heterotrophs: release free energy from organic compounds (from the food chain, either autotrophs or other heterotrophs), and convert those organic compounds in to inorganic compounds.

Anaerobic heterotrophs: Do not require oxygen. Ex. many bacteria, yeast (**facultative anaerobes**: can do it if they have to).

Aerobic heterotrophs: Use oxygen. Release ~20X more free energy from food molecules than anaerobes do. Ex. all multicellular fungi and animals (plants, too).

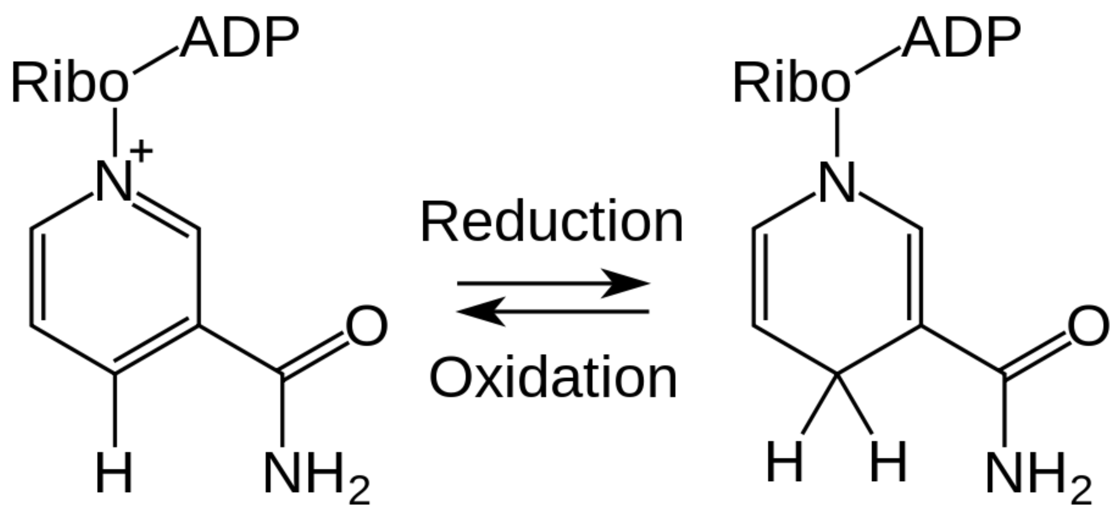


Electron Shuttles

Biological energy production utilizes reduction/oxidation reactions.

The transfer of electrons occurs via "**electron shuttle**" molecules.

Ex. NAD^+/NADH, FAD/$FADH_2$, $NADP^+$/NADPH



$$NAD^+ + H^+ + 2e^- \longrightarrow NADH$$

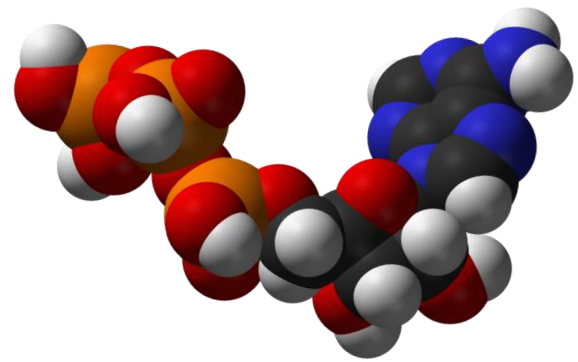
ATP

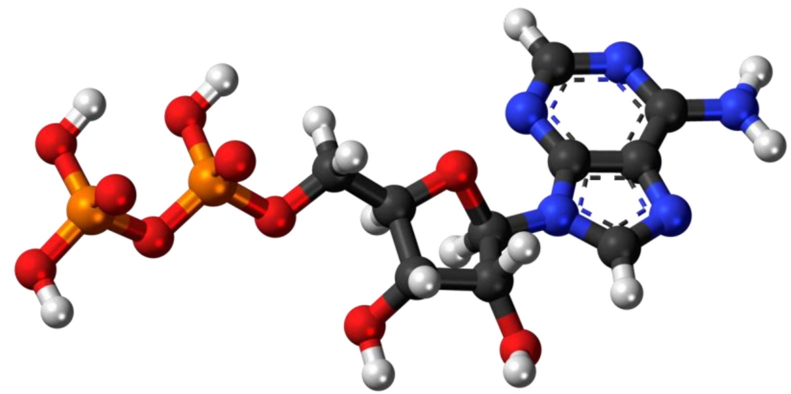
ATP: short-term free energy storage molecule used in all biological systems.

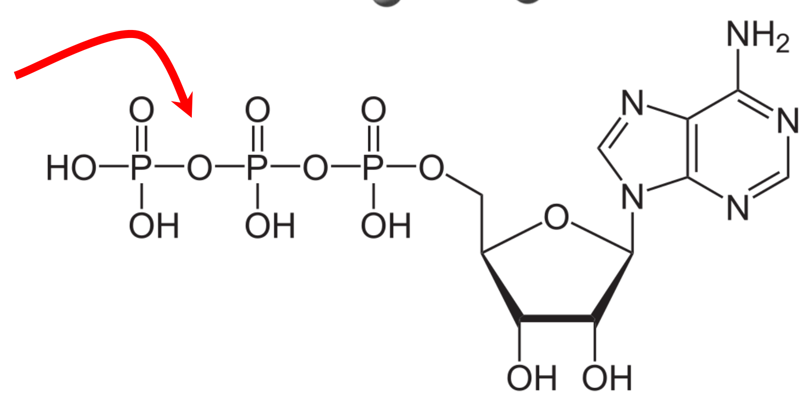
Free energy from metabolism is used to turn a molecule of ADP (2 phosphates) in to a molecule of ATP (3 phosphates).

The bond between the 2nd and 3rd phosphate is easily broken.

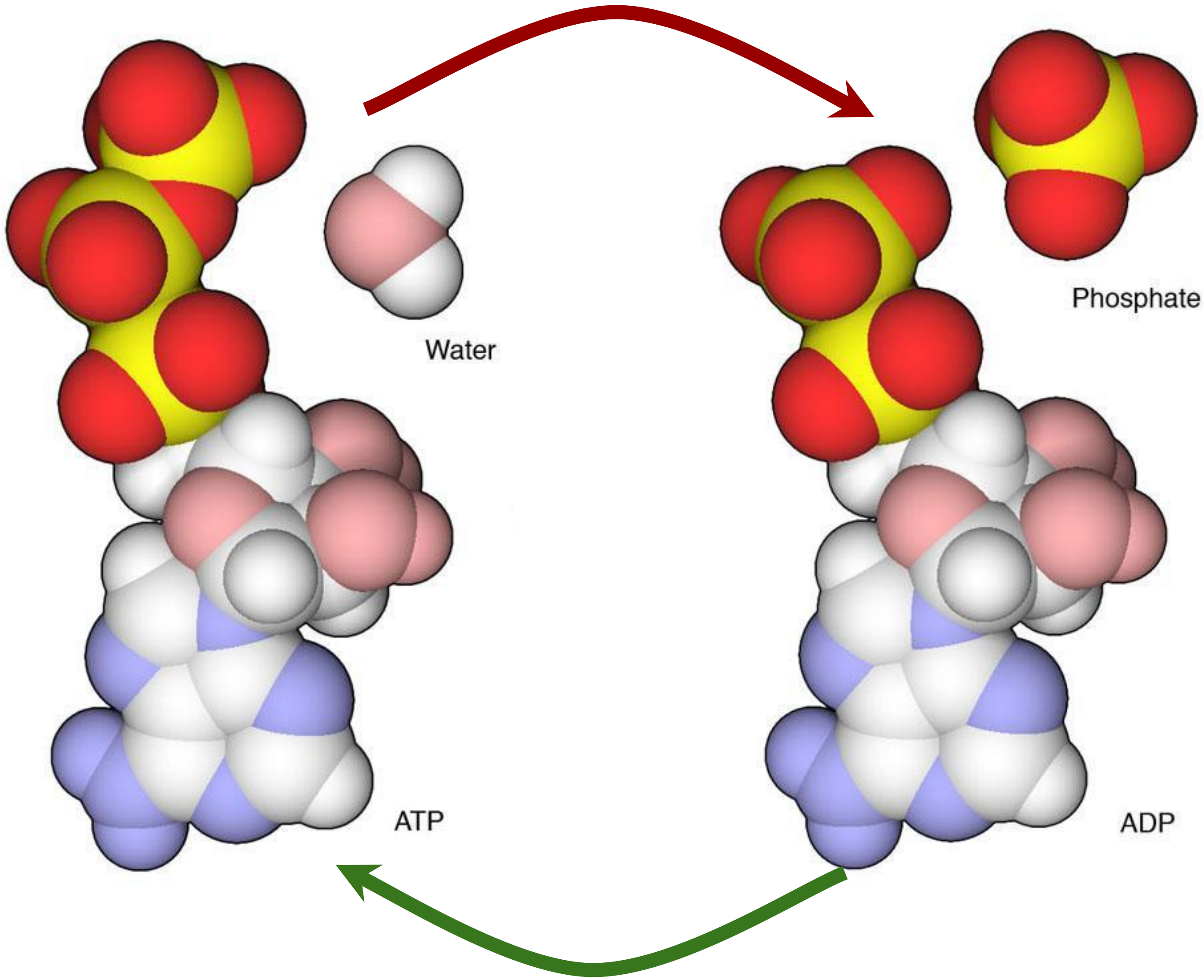
When it is broken, the free energy that is released is used to power cellular work.





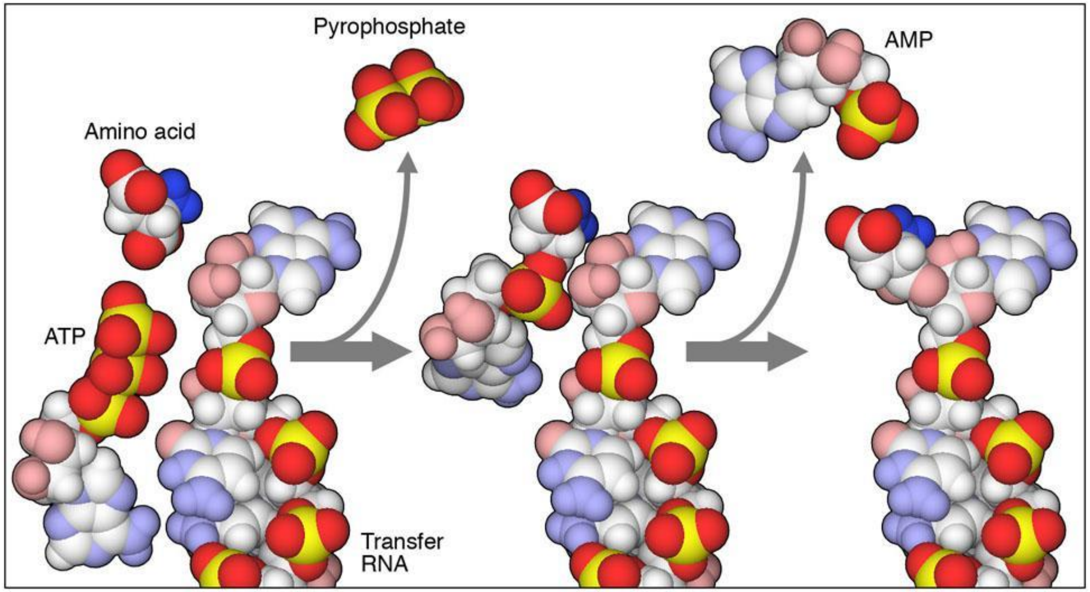


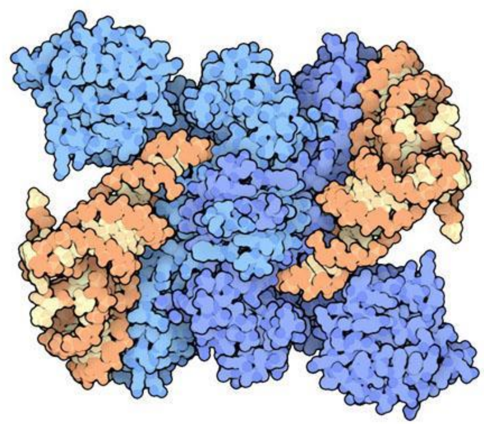
Cellular Work



Cellular Energetics (R & P)

One Example of Cellular Work





"Charging" of tRNA molecules with amino acids.