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.

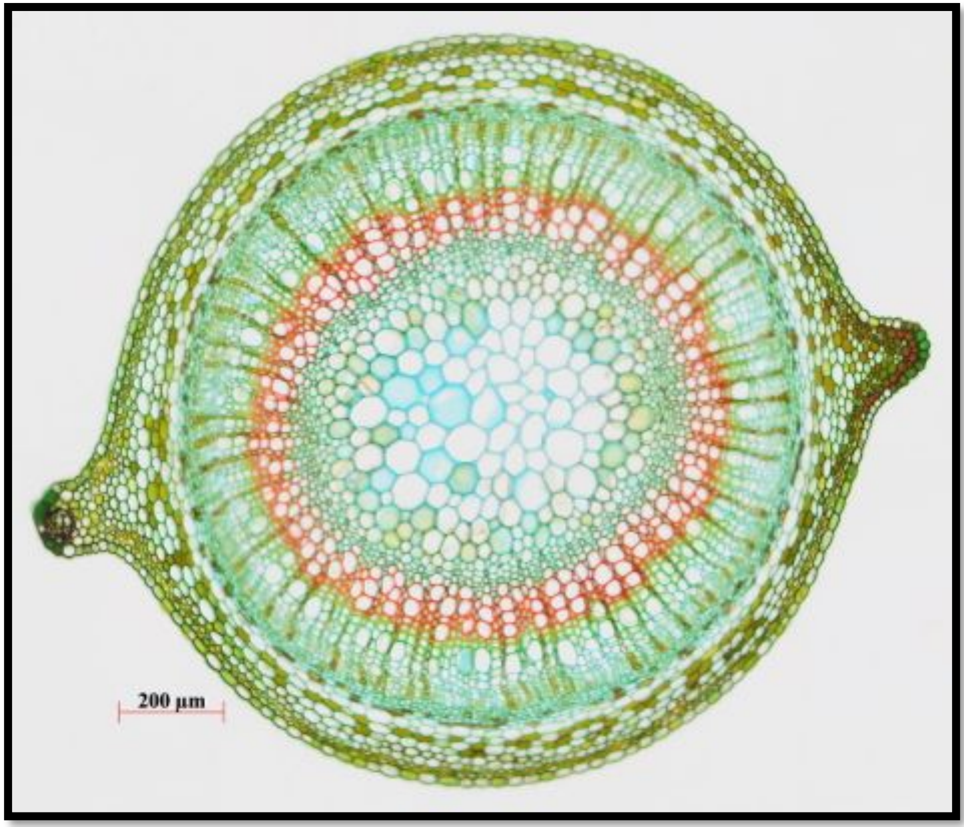
Living systems need to continually acquire and transform energy in order to remain alive.

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

The Second Law of Thermodynamics

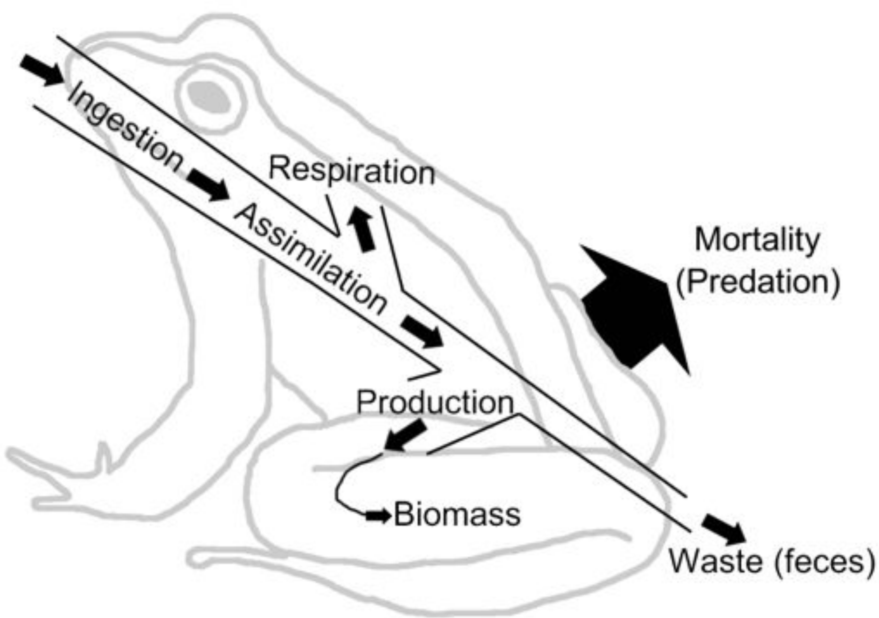
Every time energy is transformed, the **entropy** ("disorder") of the universe increases.

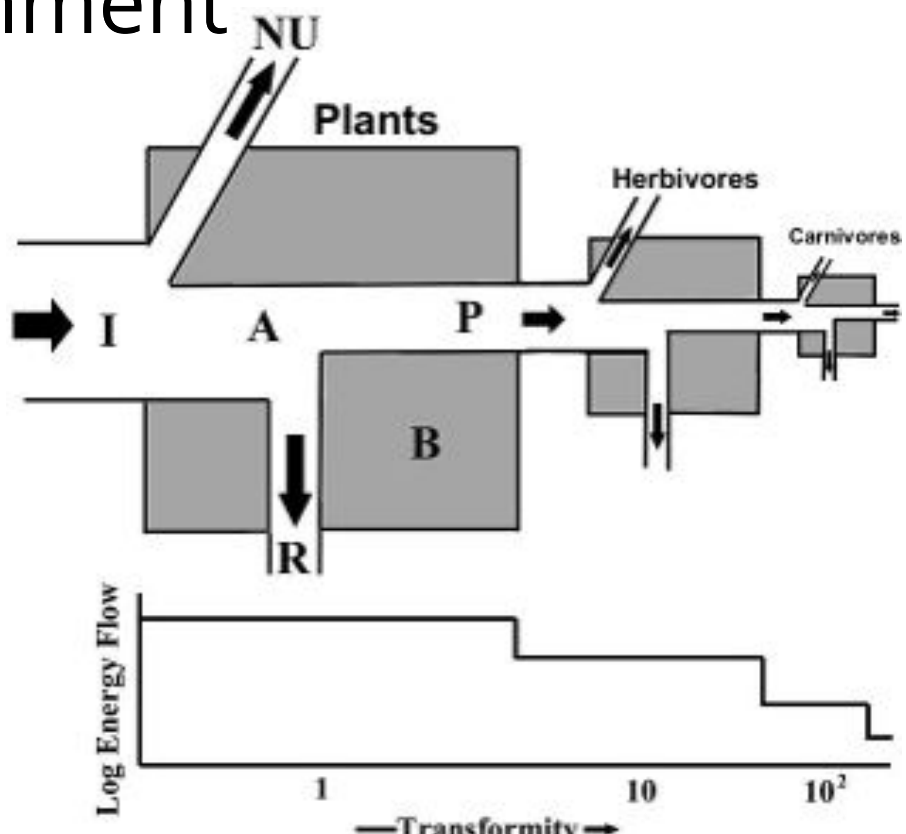
In order to increase/ maintain their internal order, living systems must process more ordered forms of matter in to less ordered ones



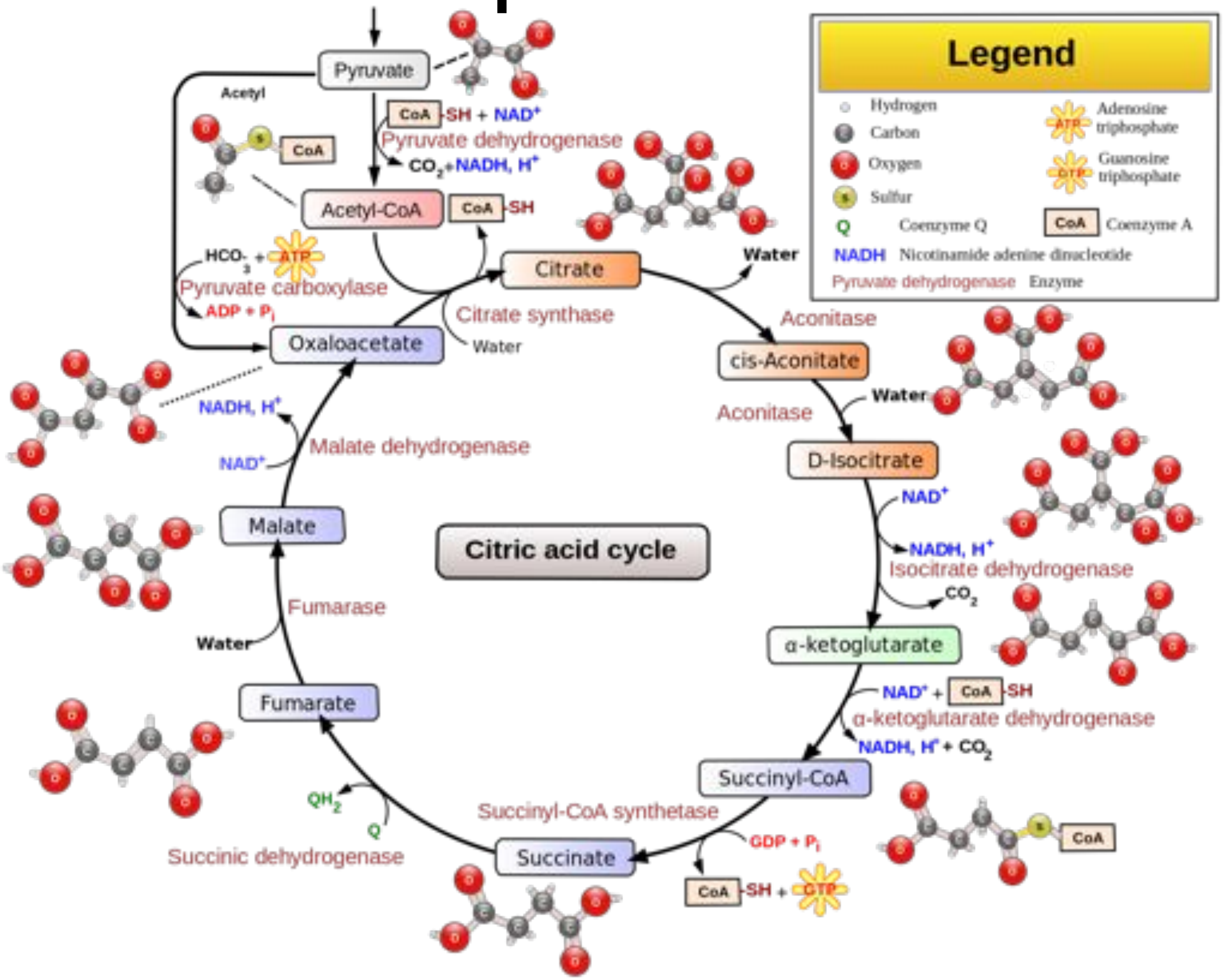
Living Systems are "Open" Systems

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.

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

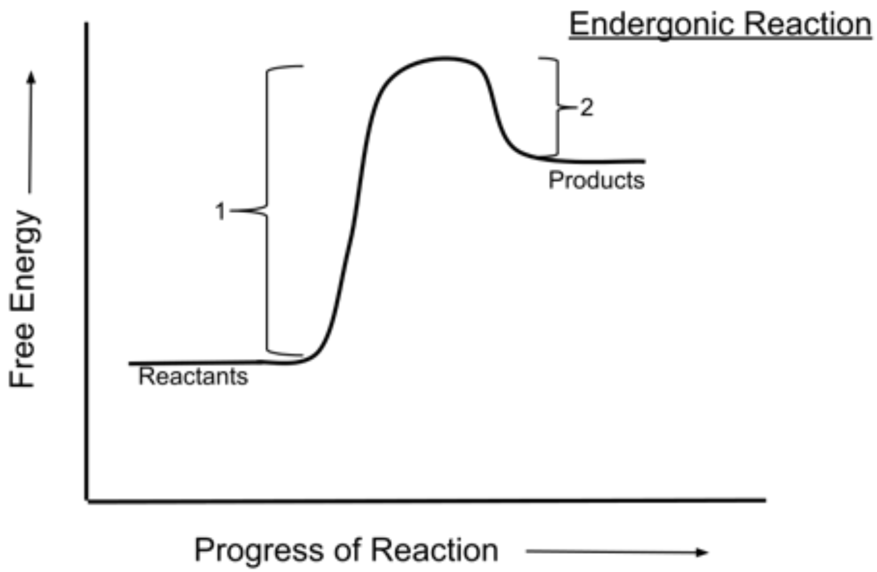
ΔG= change in free energy
(- = **exergonic**, + = **endergonic**)

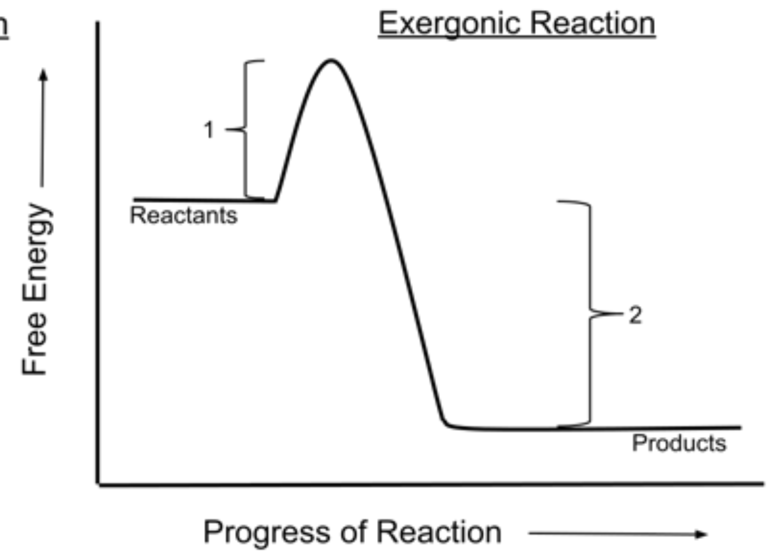
ΔH= change in enthalpy for the reaction
(- = **exothermic**, + = **endothermic**)

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.

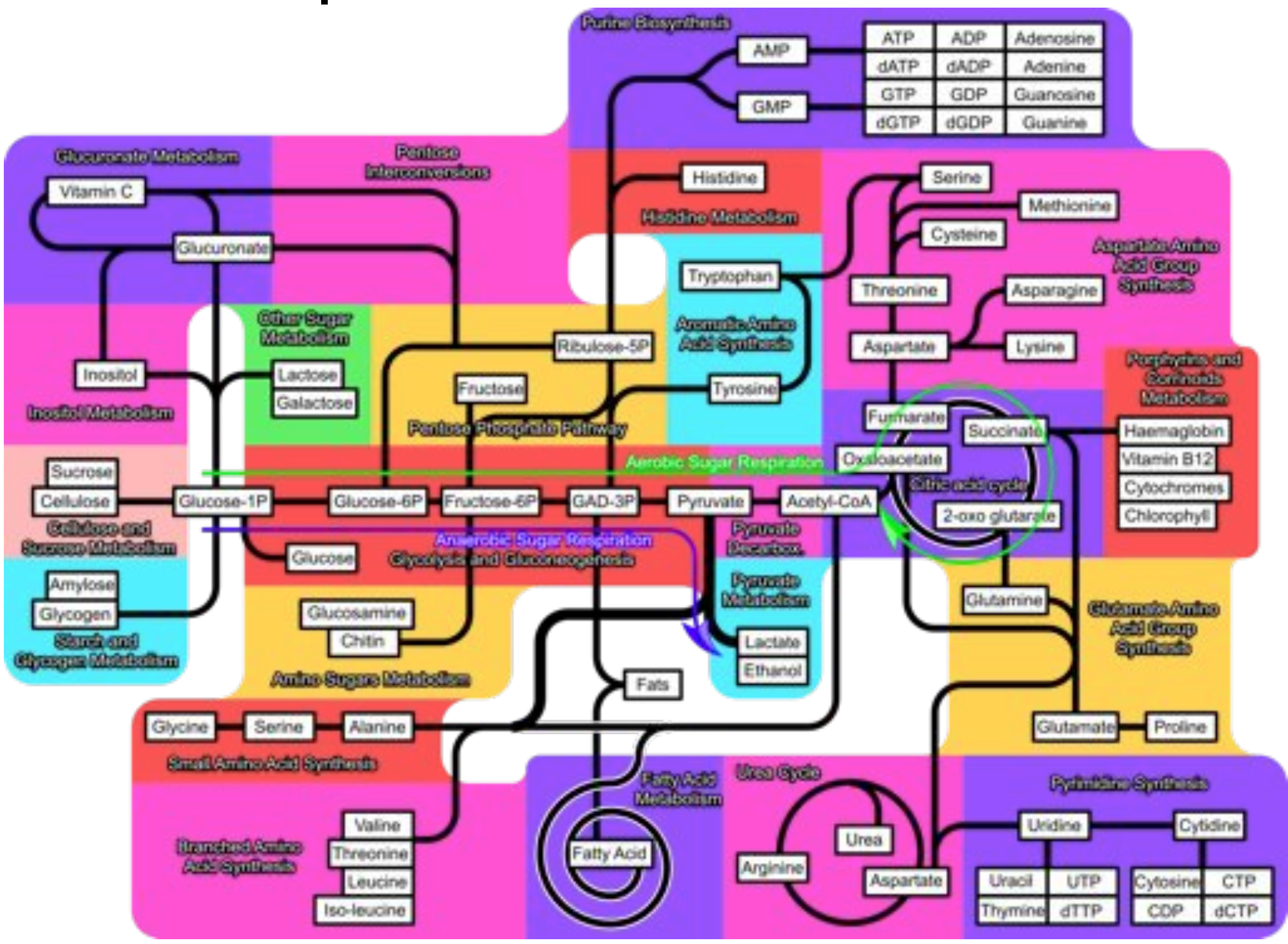
3. METABOLIC STRATEGIES

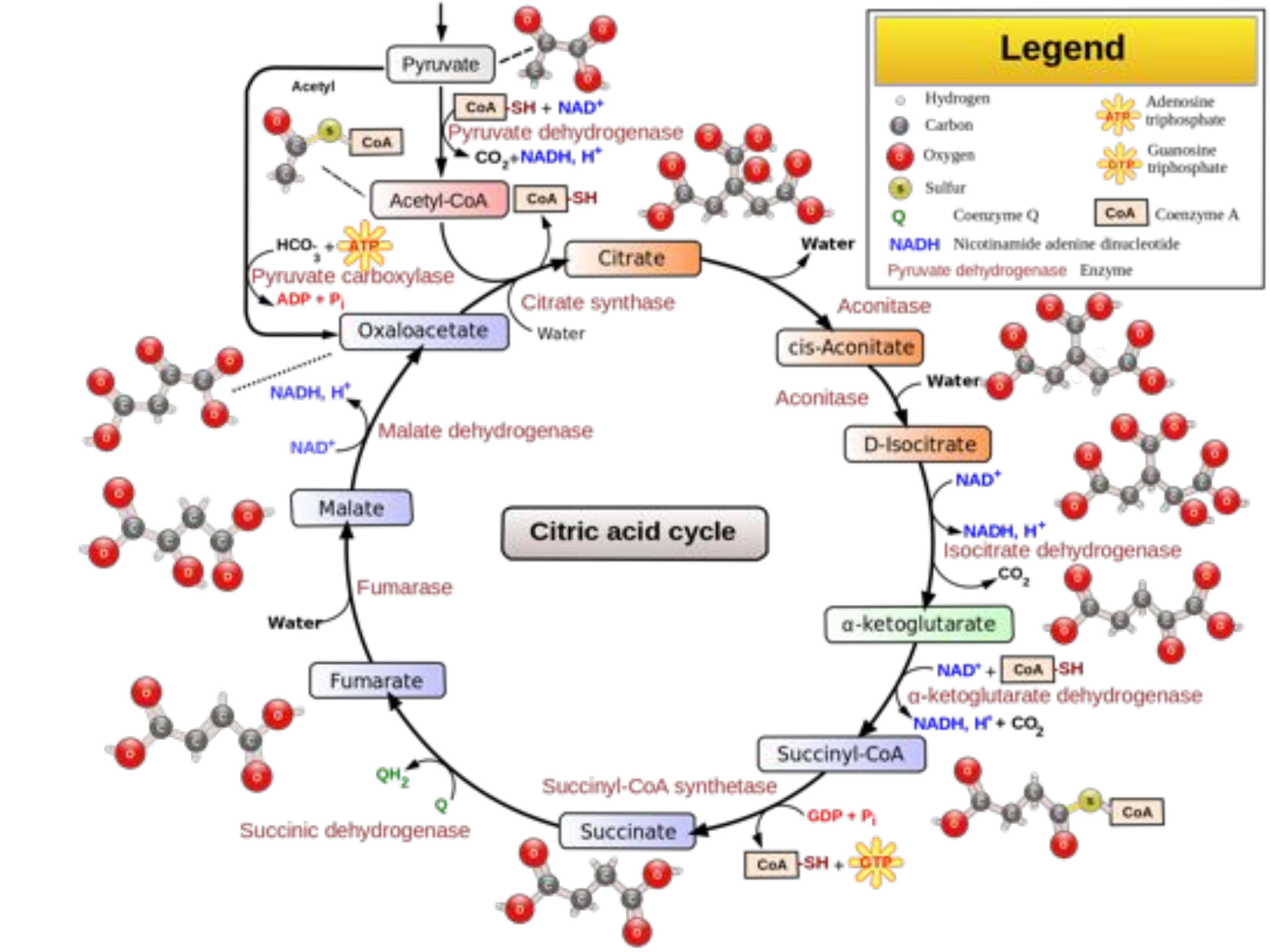
Uses of Biological Free Energy

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

Catabolism:
Decomposing

Anabolism:
Synthesis



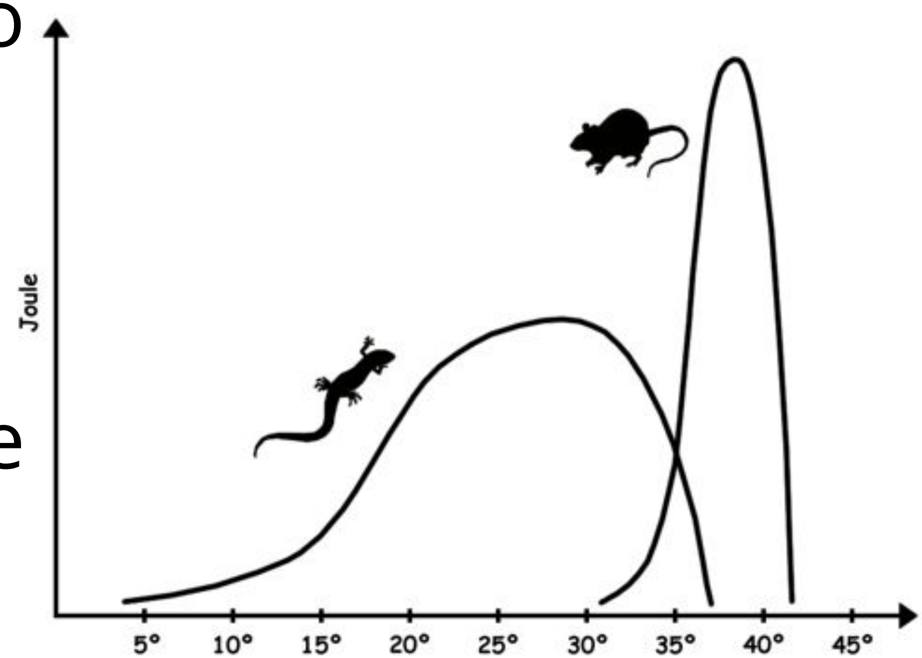


Legend
Hydrogen
Carbon
Oxygen
Sulfur
Q Coenzyme Q
NADH Nicotinamide adenine dinucleotide
Pyruvate dehydrogenase Enzyme
Adenosine triphosphate
Guanosine triphosphate
CoA Coenzyme A
Citric acid cycle
Pyruvate
Acetyl
CoA-SH + NAD+
Pyruvate dehydrogenase
CO2+NADH, H+
Acetyl-CoA
CoA-SH
HCO3- + ATP
Pyruvate carboxylase
ADP + Pi
Oxaloacetate
Citrate
Citrate synthase
Water
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.

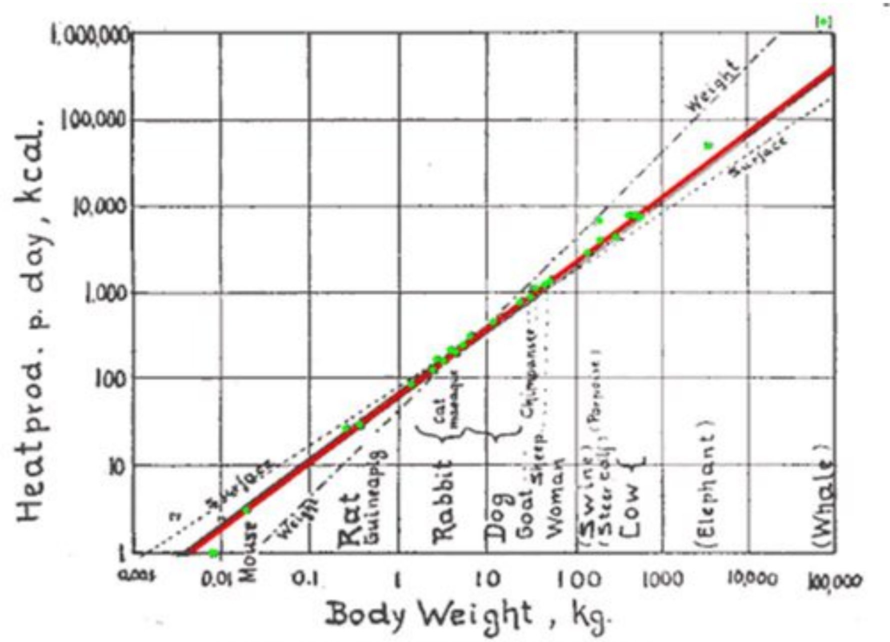


Fig. 1. Log. metabol. rate/log body weight

Free Energy Considerations & Reproduction

Reproductive strategies are optimized for free energy considerations.

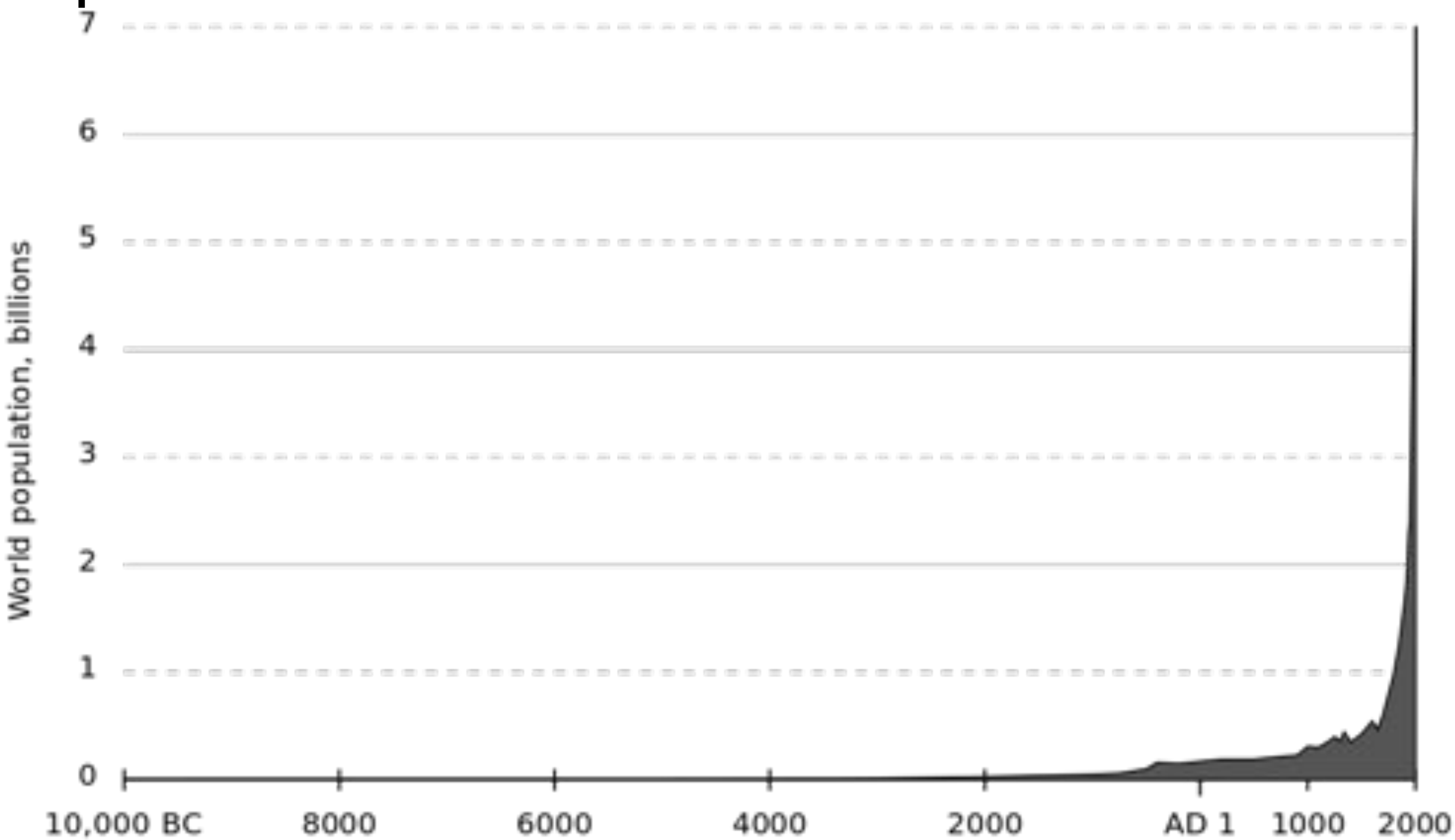
Ex. Seasonal Reproduction.

Insufficient Free Energy Production: Individuals

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

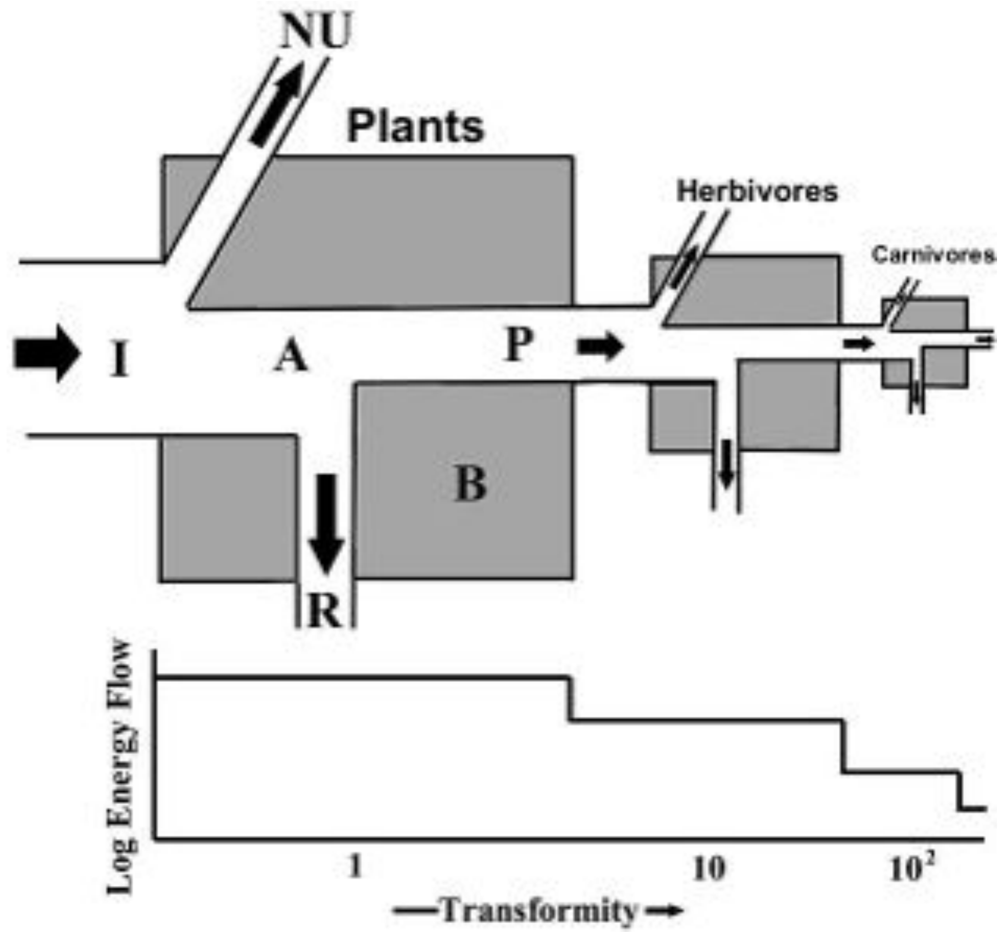
Insufficient Free Energy Production: Populations

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.

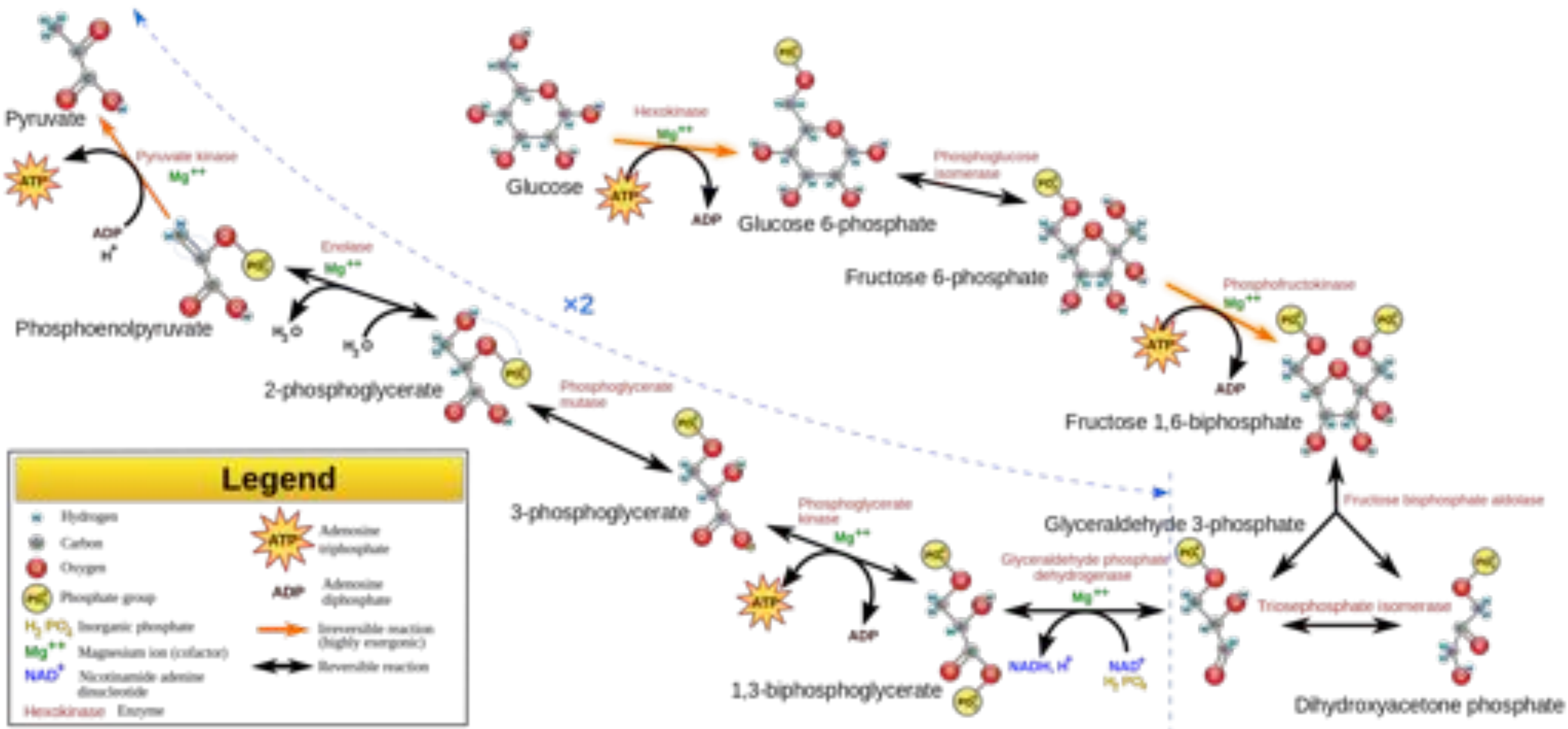
1. ENZYME STRUCTURE AND FUNCTION

Structure and Function

Structure always determines function.

Molecular interactions lead to organism **phenotypes**.

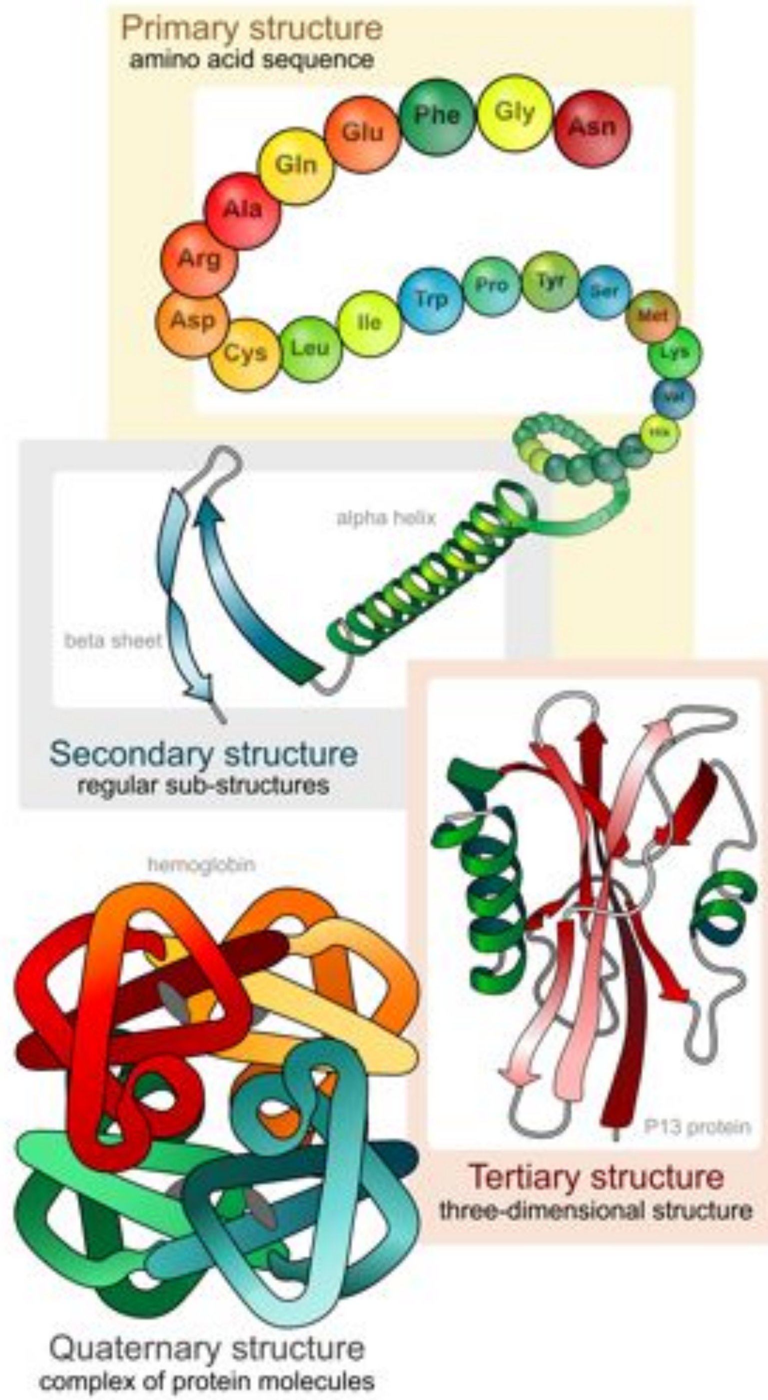
Metabolism is Controlled by Enzymes



Enzymes are (mostly) Proteins

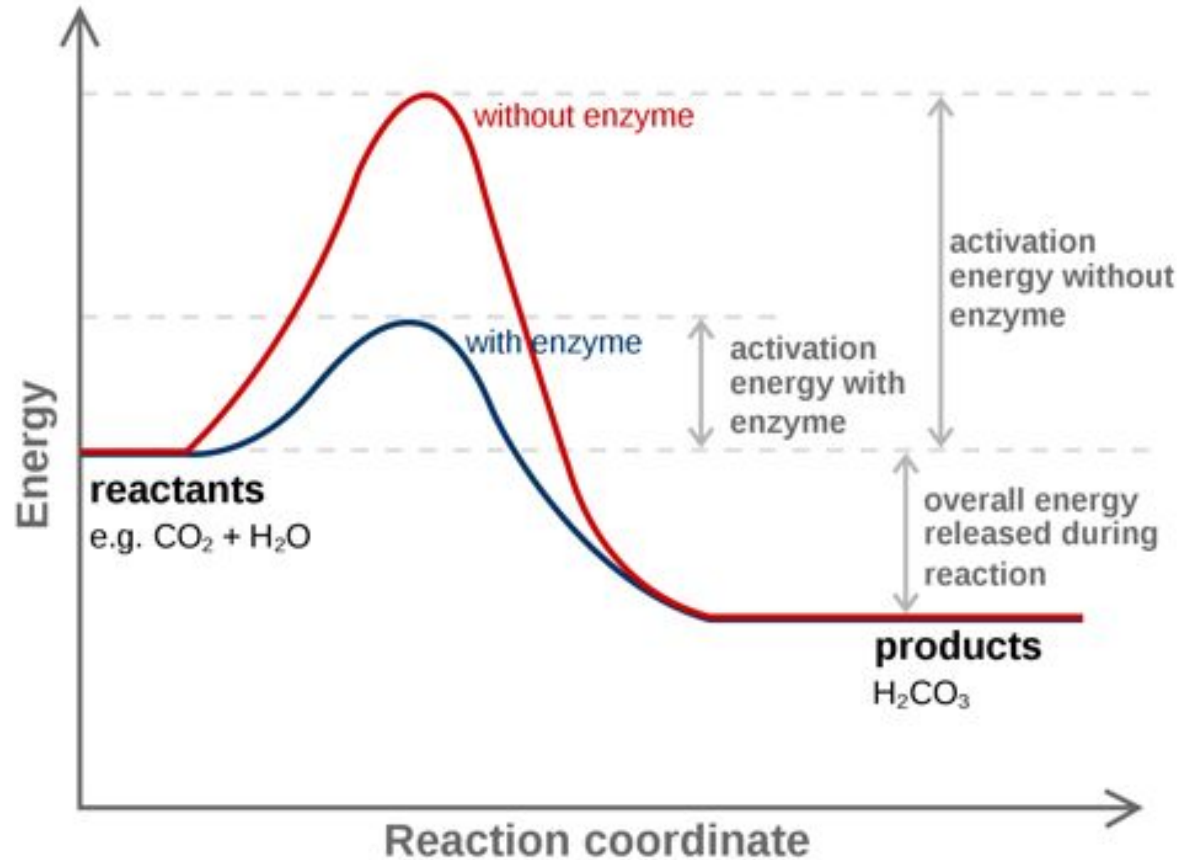
Enzymes are molecules that serve as biological **catalysts**.

Some RNA molecules also have catalytic properties.



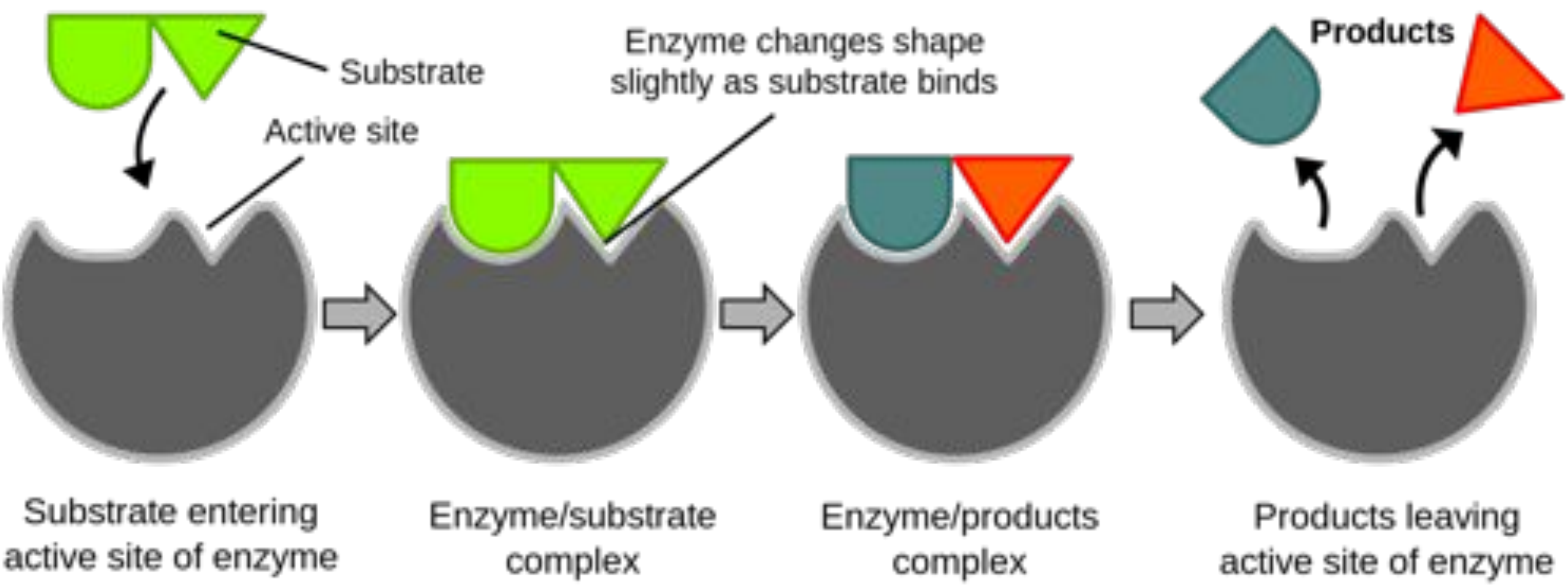
Catalysis

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



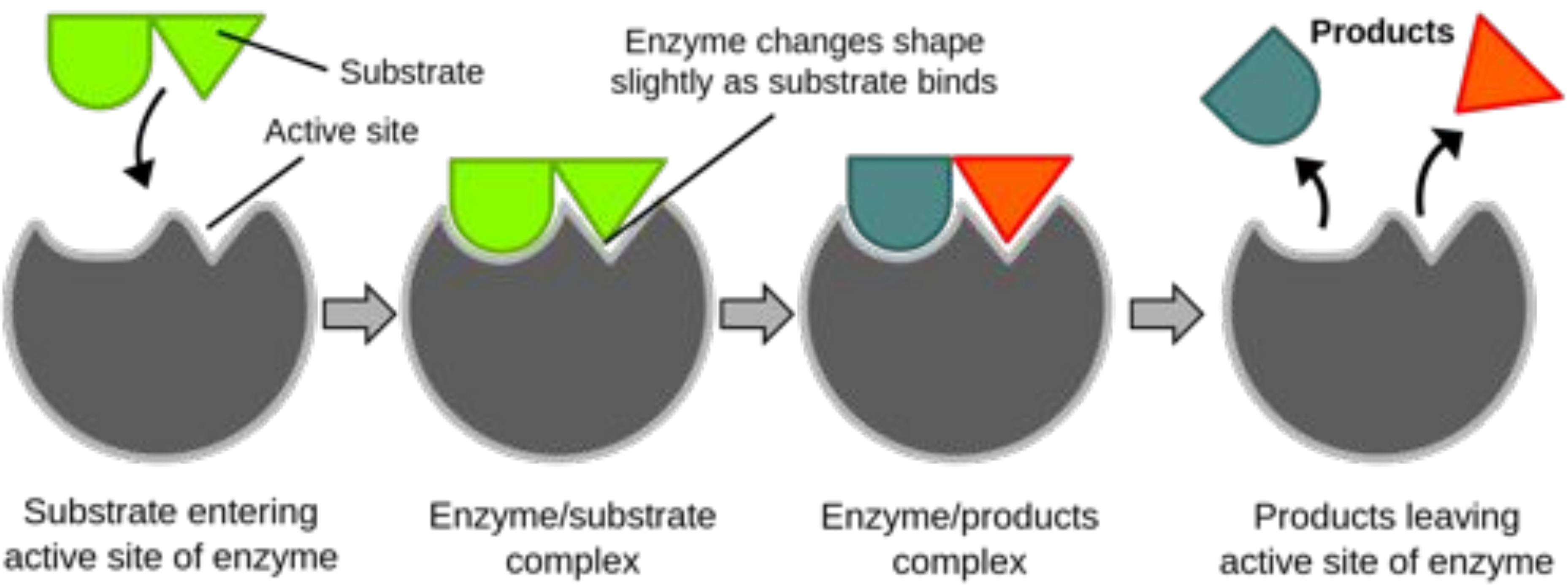
Enzymes work by physically positioning reactants ("**substrate**") in ways that increase the likelihood of chemical bonds being broken or formed.

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)



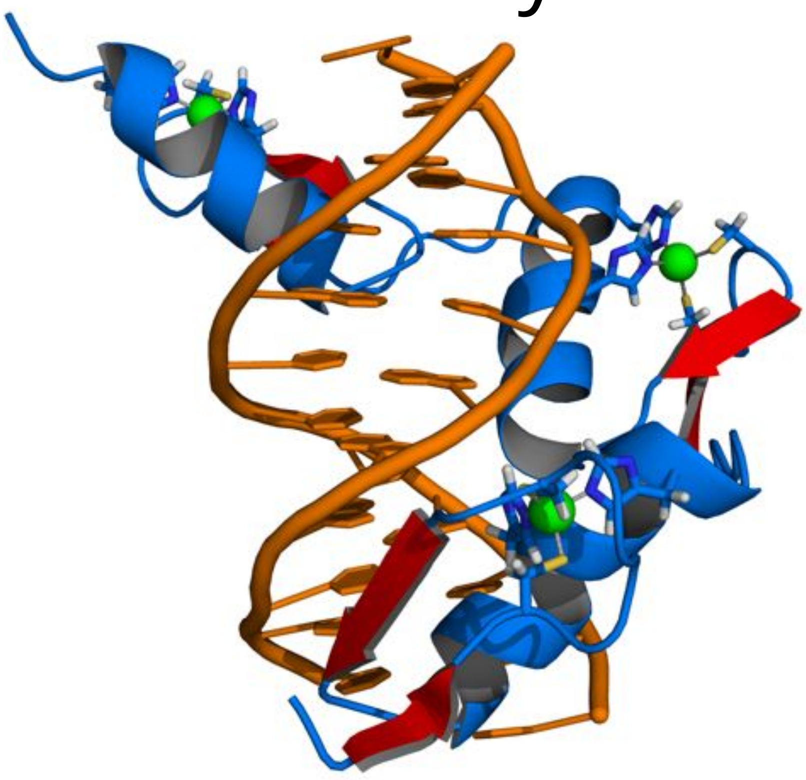
Induced Fit Model:

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.



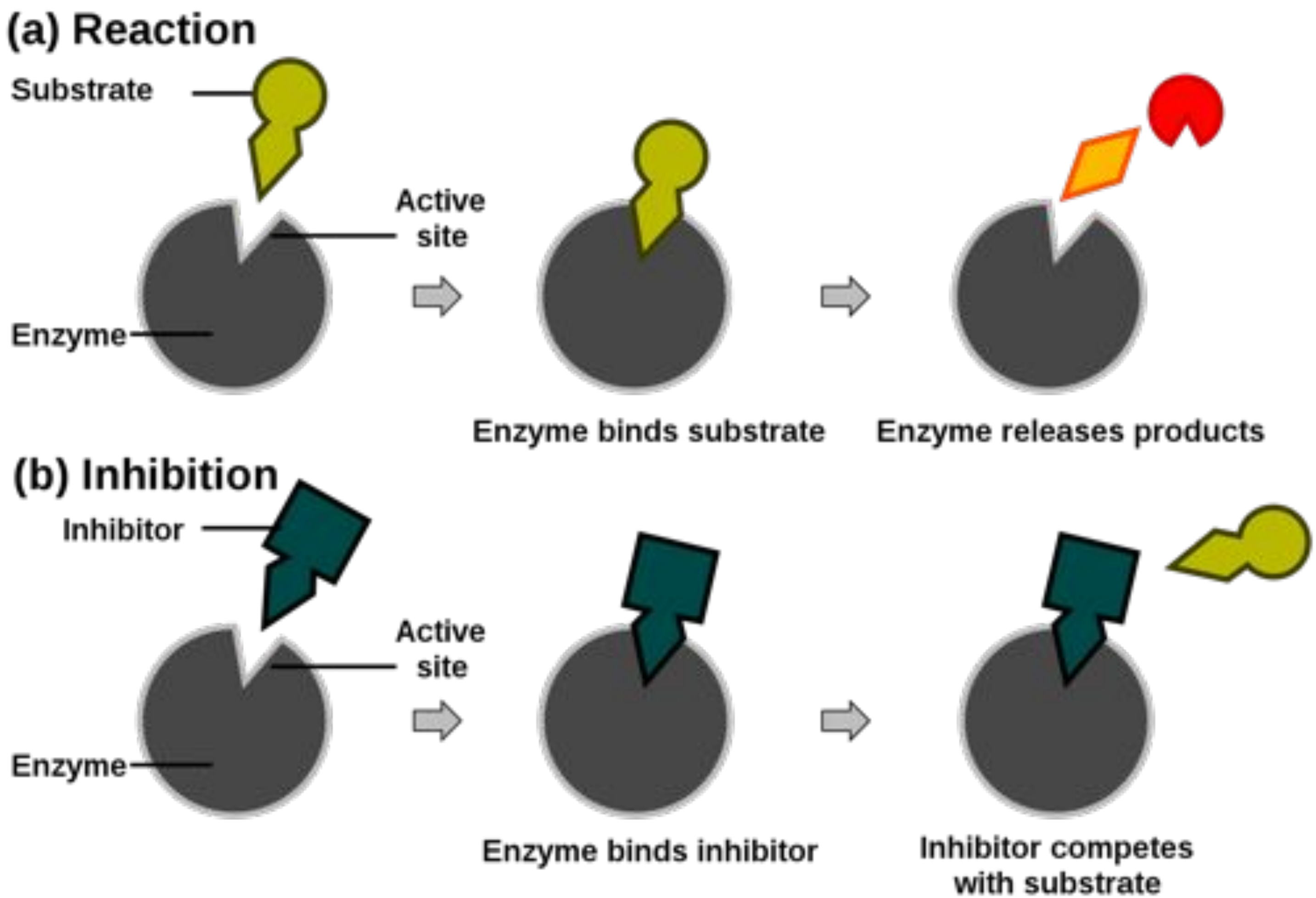
Ex. Many enzymes involved in interacting with DNA require $zinc^{2+}$ ions as co-factors (green spheres).

3.2: Interactions between molecules affect their structure and function.

2. REGULATION OF ENZYME ACTIVITY

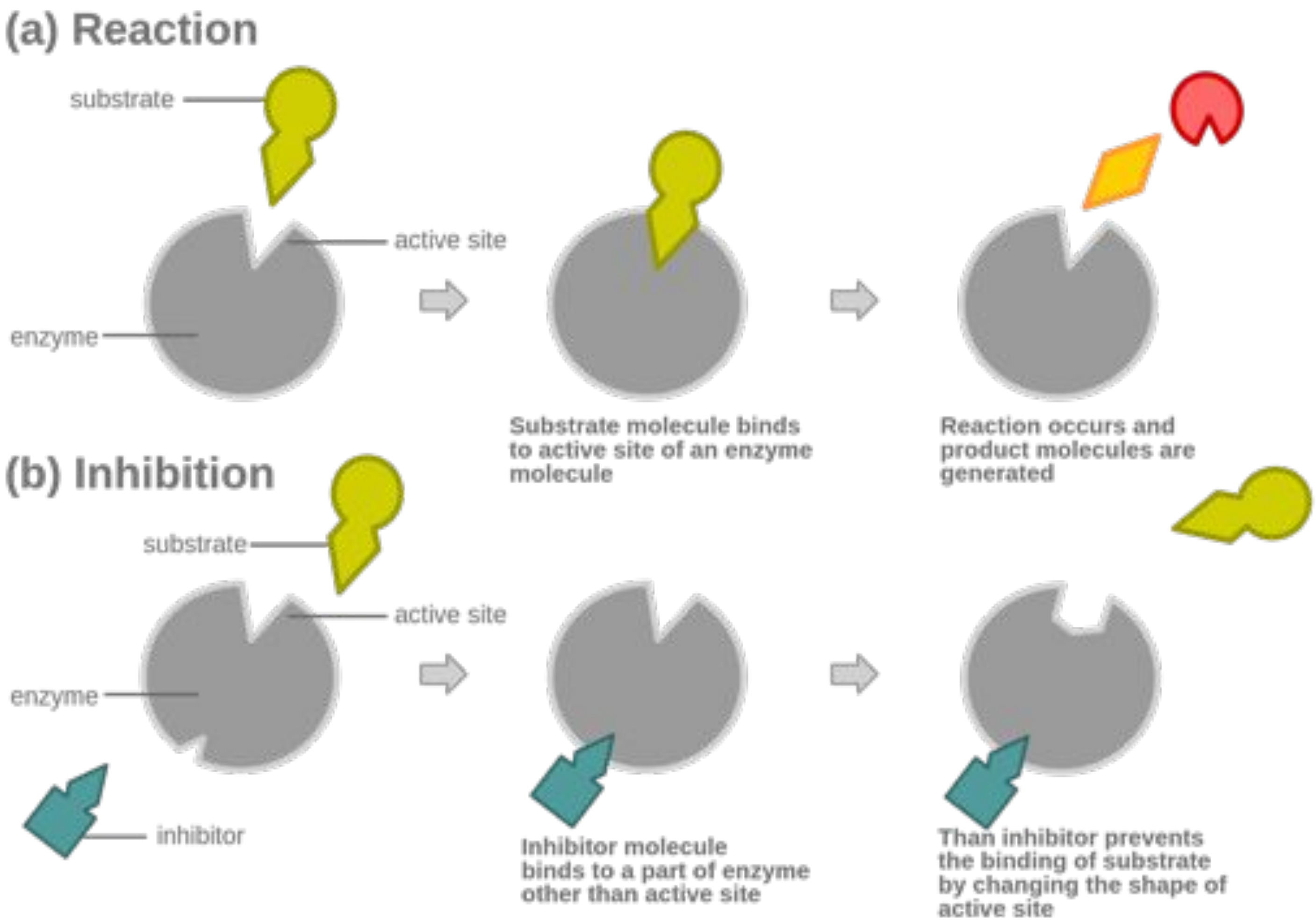
Other Molecules Can Affect Enzyme Structure and Function.

Competitive Inhibition:



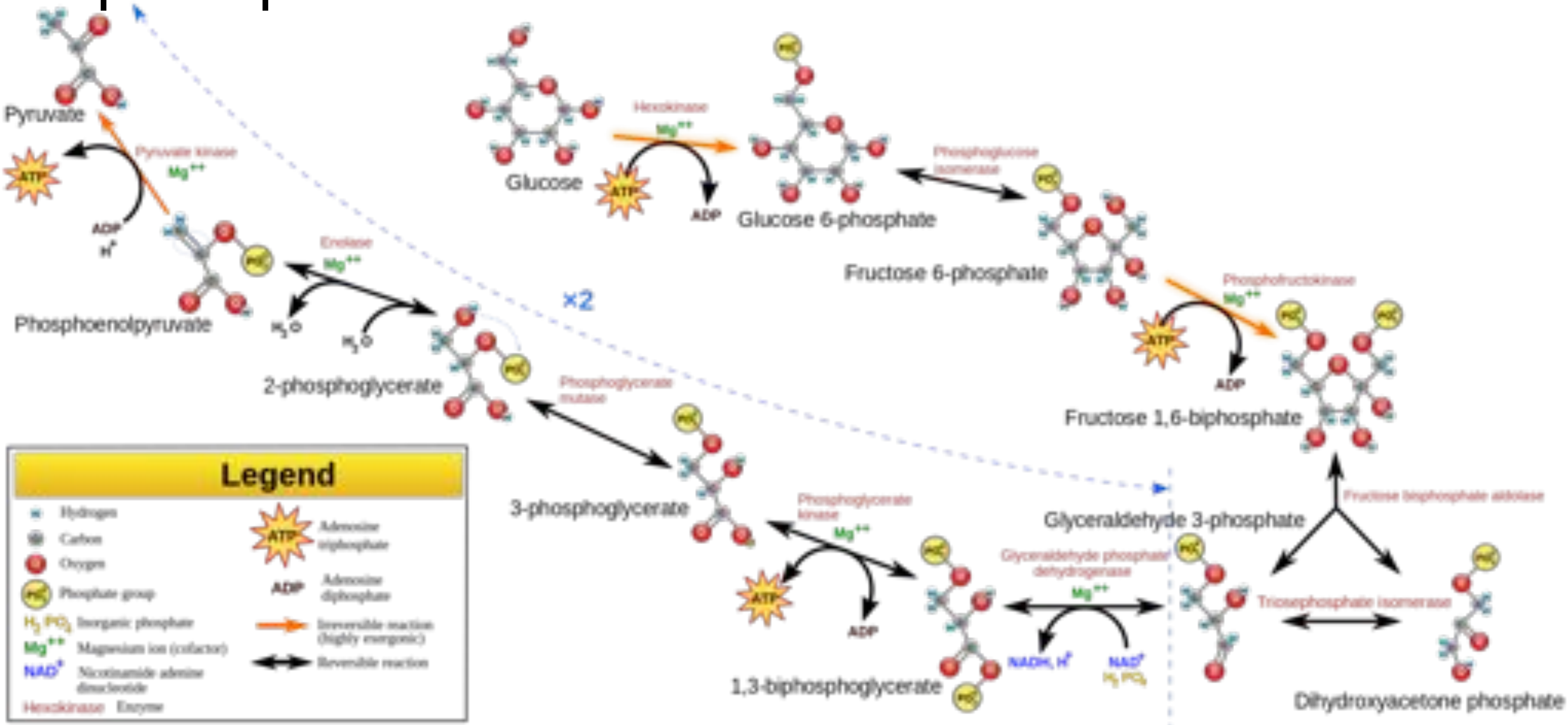
Non-Competitive Inhibition.

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



Allosteric Interactions allow for feedback inhibition of metabolism

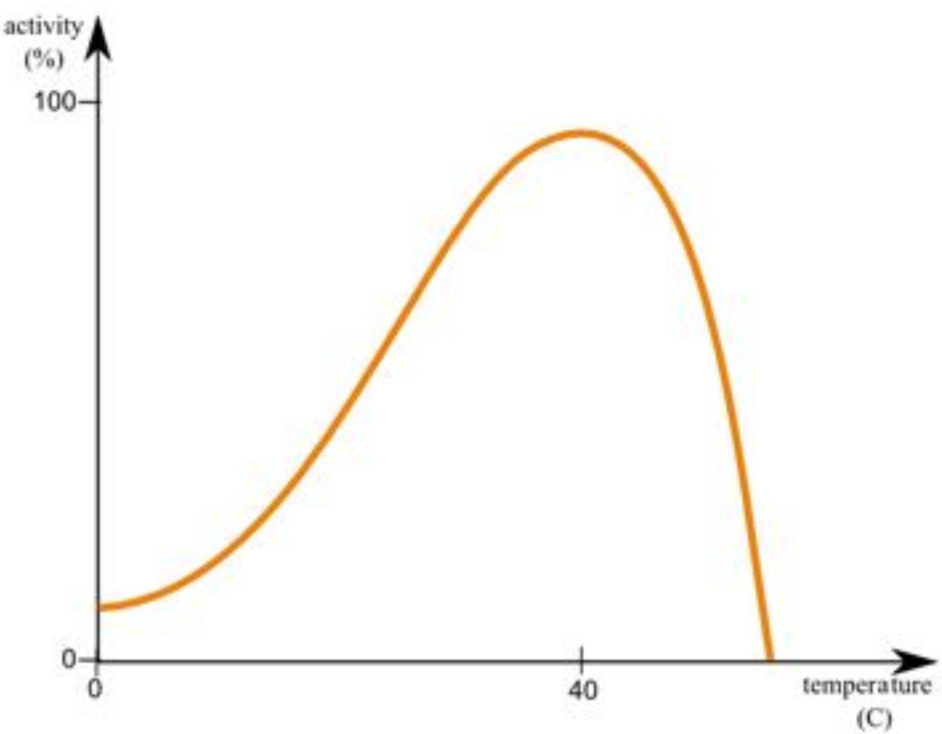
Ex. ATP inhibits the activity of phosphofructokinase.

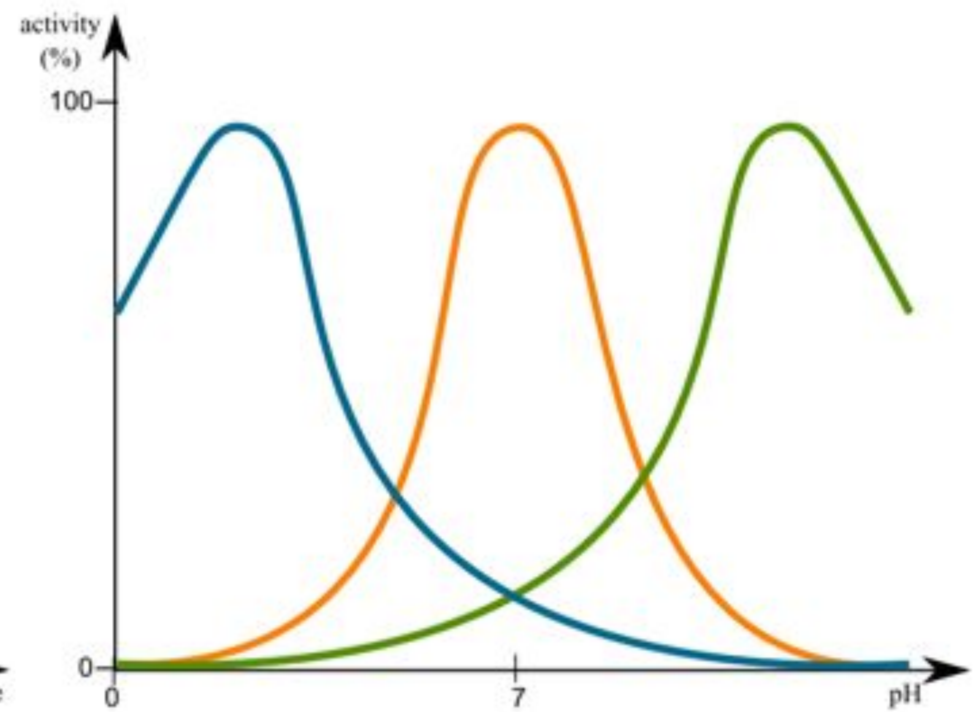


Environmental Influences on Enzyme Function

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

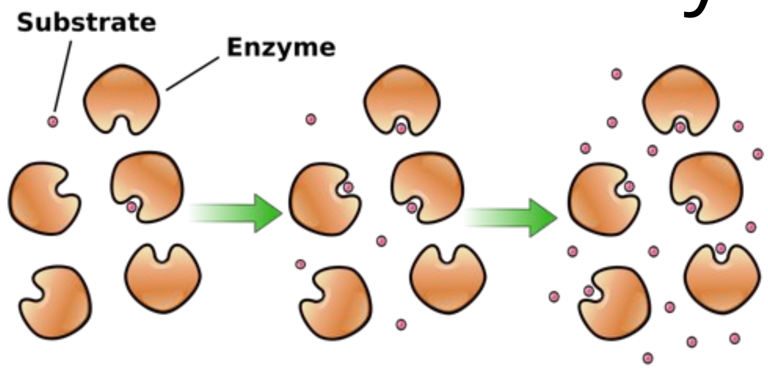
Ex. Temperature and pH.

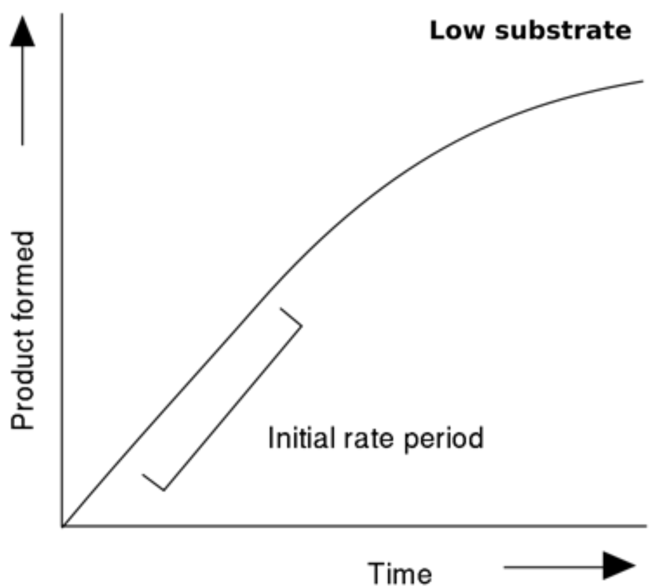


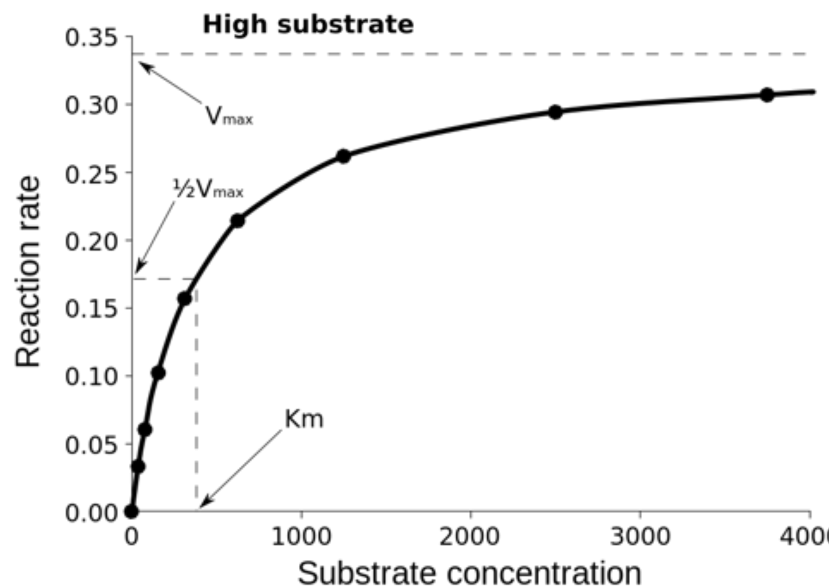


Concentration Influences on Enzyme Function

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



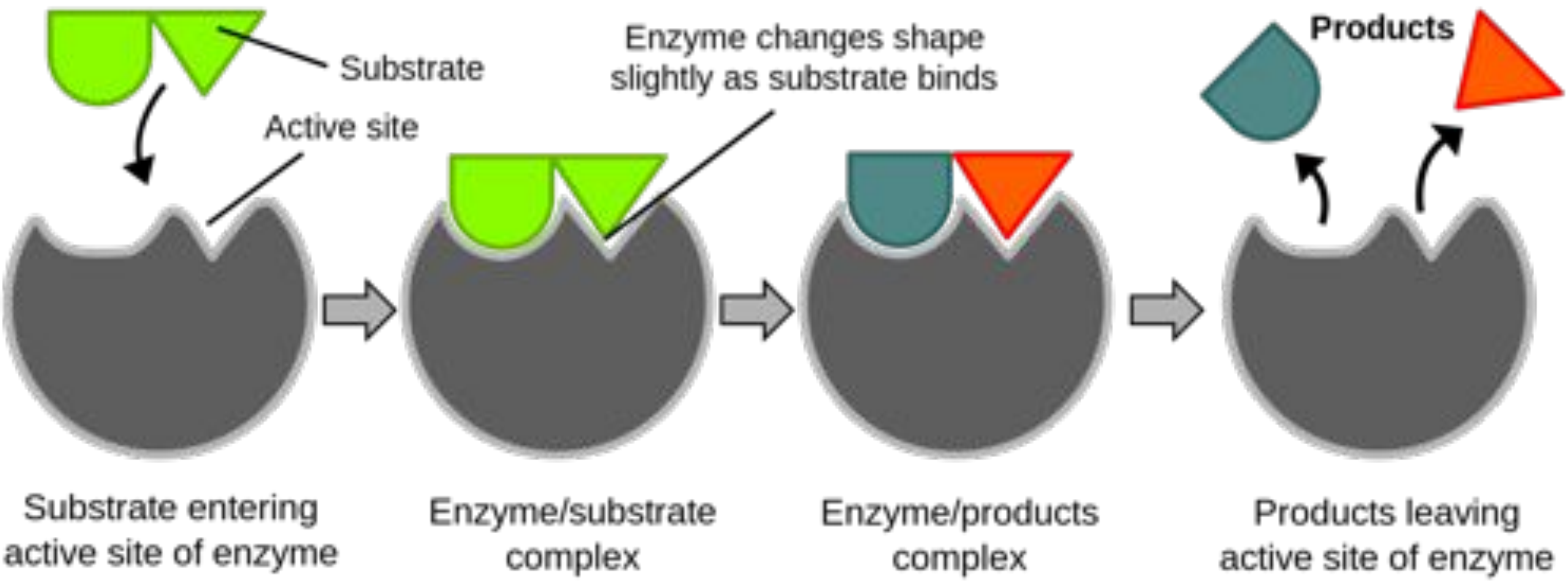




Measuring Enzyme Activity

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.

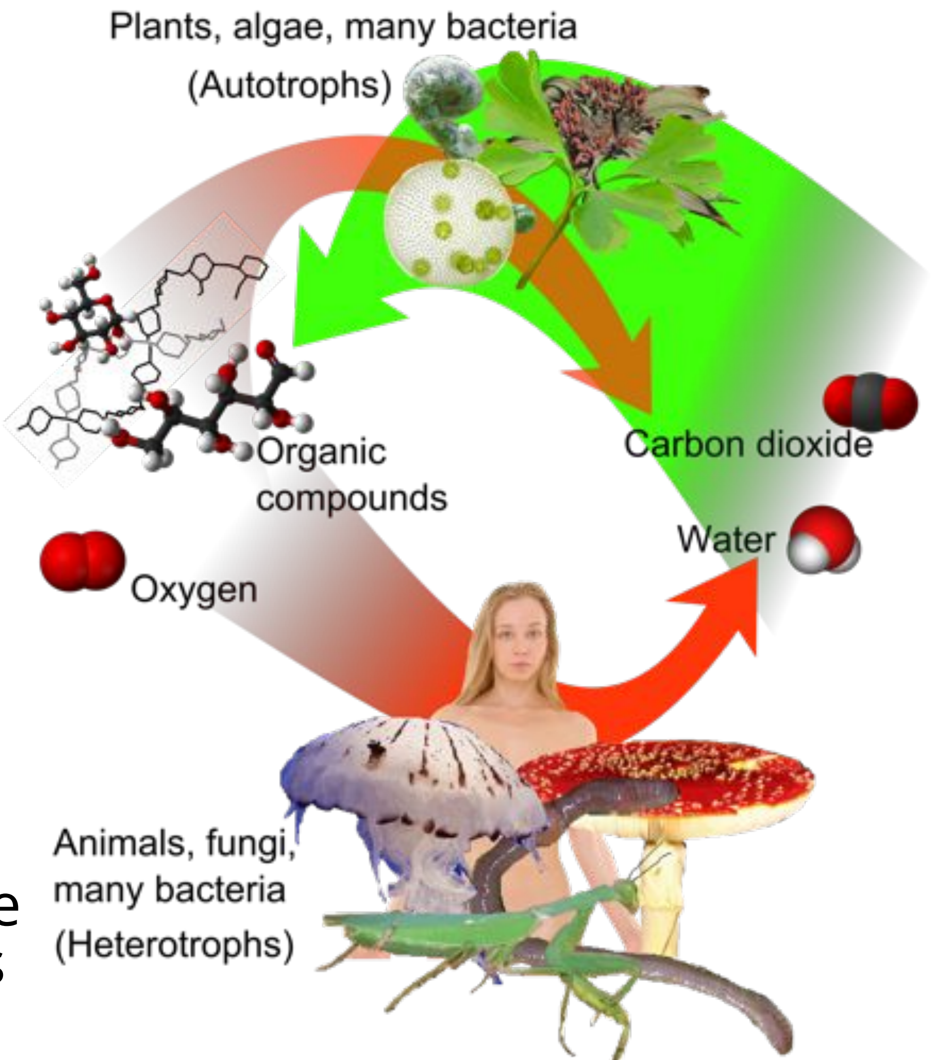
1. ENERGY PROCESSING

Autotroph Energy Strategies

Autotrophs: use energy from the environment to convert inorganic molecules in to 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 water and carbon dioxide in to oxygen gas (waste product) and organic compounds (sugar precursor molecules). Ex. all plants, and phytoplankton.

Chemosynthetic organisms: Use high energy inorganic compounds to convert carbon dioxide and water in to organic compounds. Ex. hydrothermal vent producers



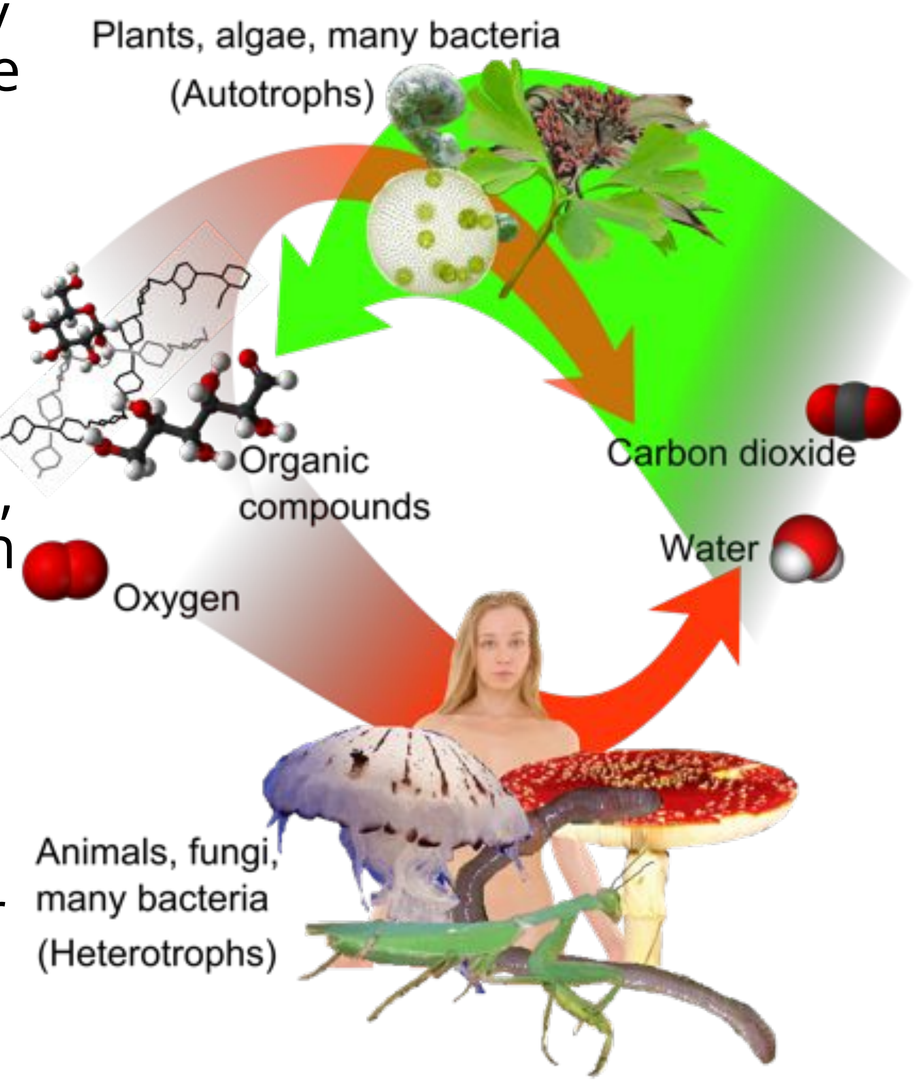
Chemosynthetic Hydrothermal Vent Community.

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.

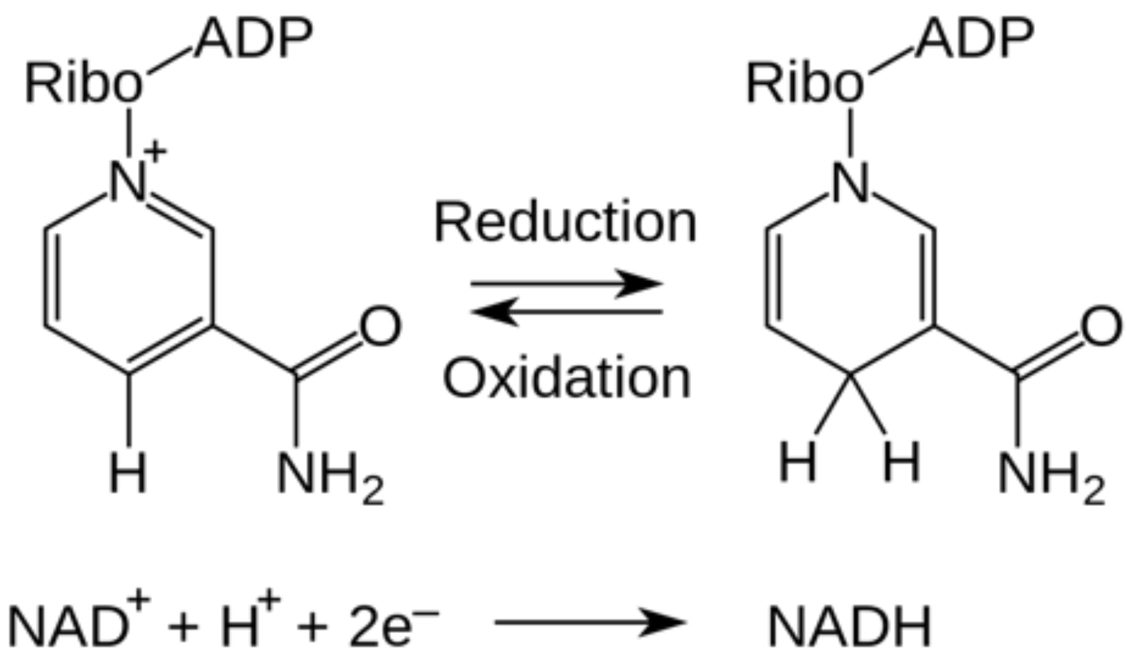


Electron Shuttles

Biological energy production utilizes reduction/oxidation reactions.

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

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



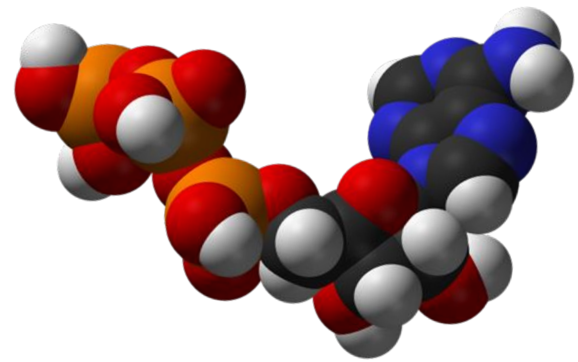
ATP

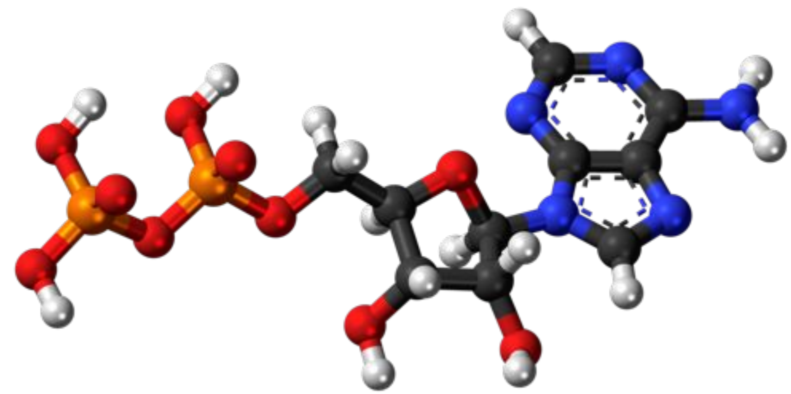
ATP: short-term free energy storage molecule used in all biological systems.

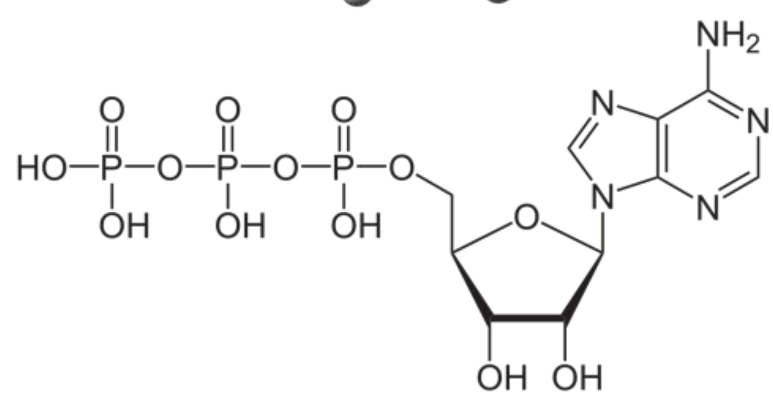
Free energy from metabolism is used to turn a molecule of ADP (2 phosphates) in to a molecule of ATP (3 phosphates).

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.







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

2. PHOTOAUTOTROPHIC NUTRITION-LIGHT REACTIONS

Photosynthesis

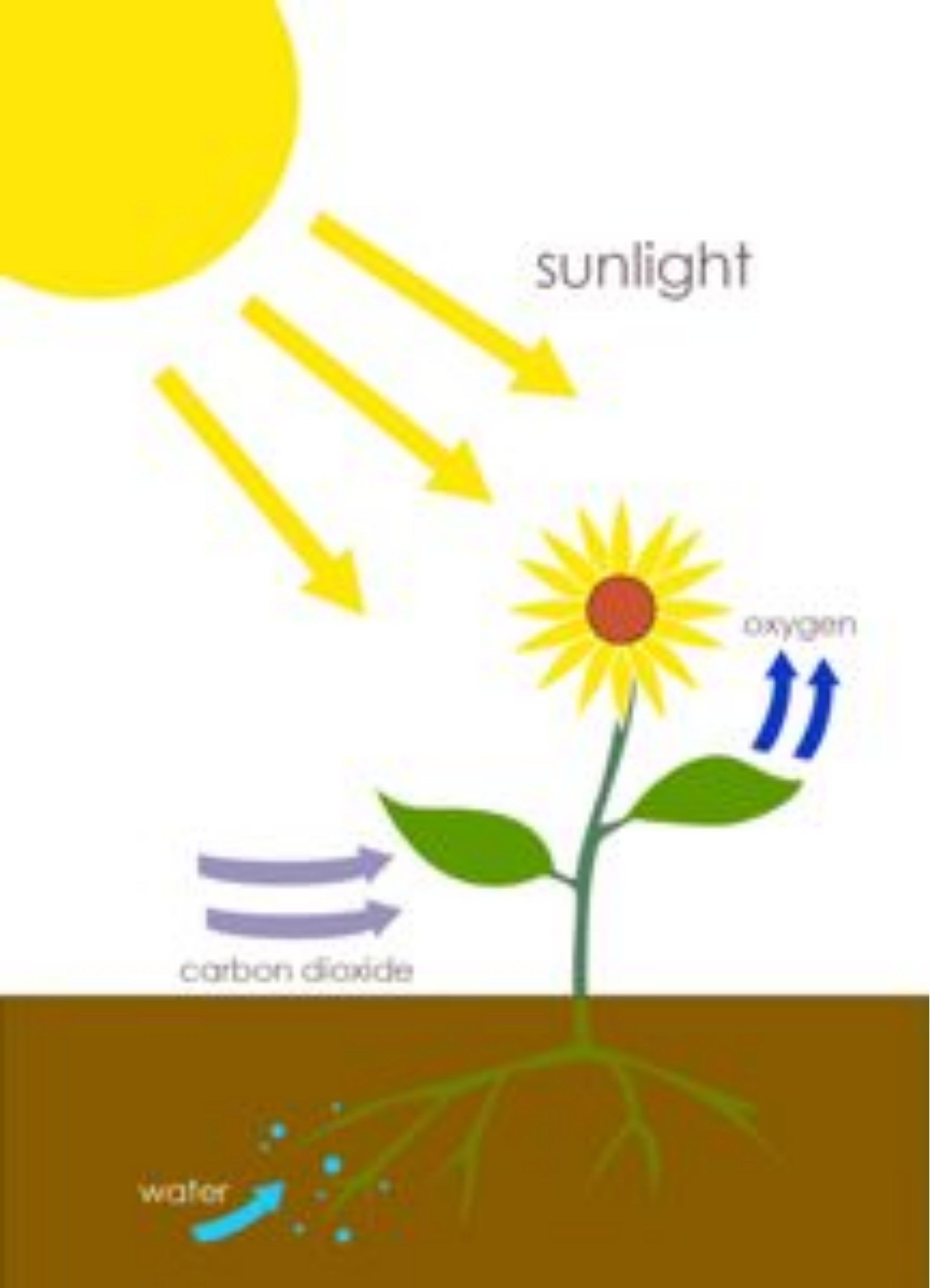
$$6CO_2 + 6H_2O \xrightarrow{\text{Light}} C_6H_{12}O_6 + 6O_2$$

Carbon dioxide + Water → Sugar + Oxygen

Photosynthesis is a two-part process.

1. The Light Reactions

2. Carbon Fixation (aka “The Calvin Cycle”)



Light is Energy

Photons of specific wavelengths of light are used in the light reactions.

Light Reactions: Overview

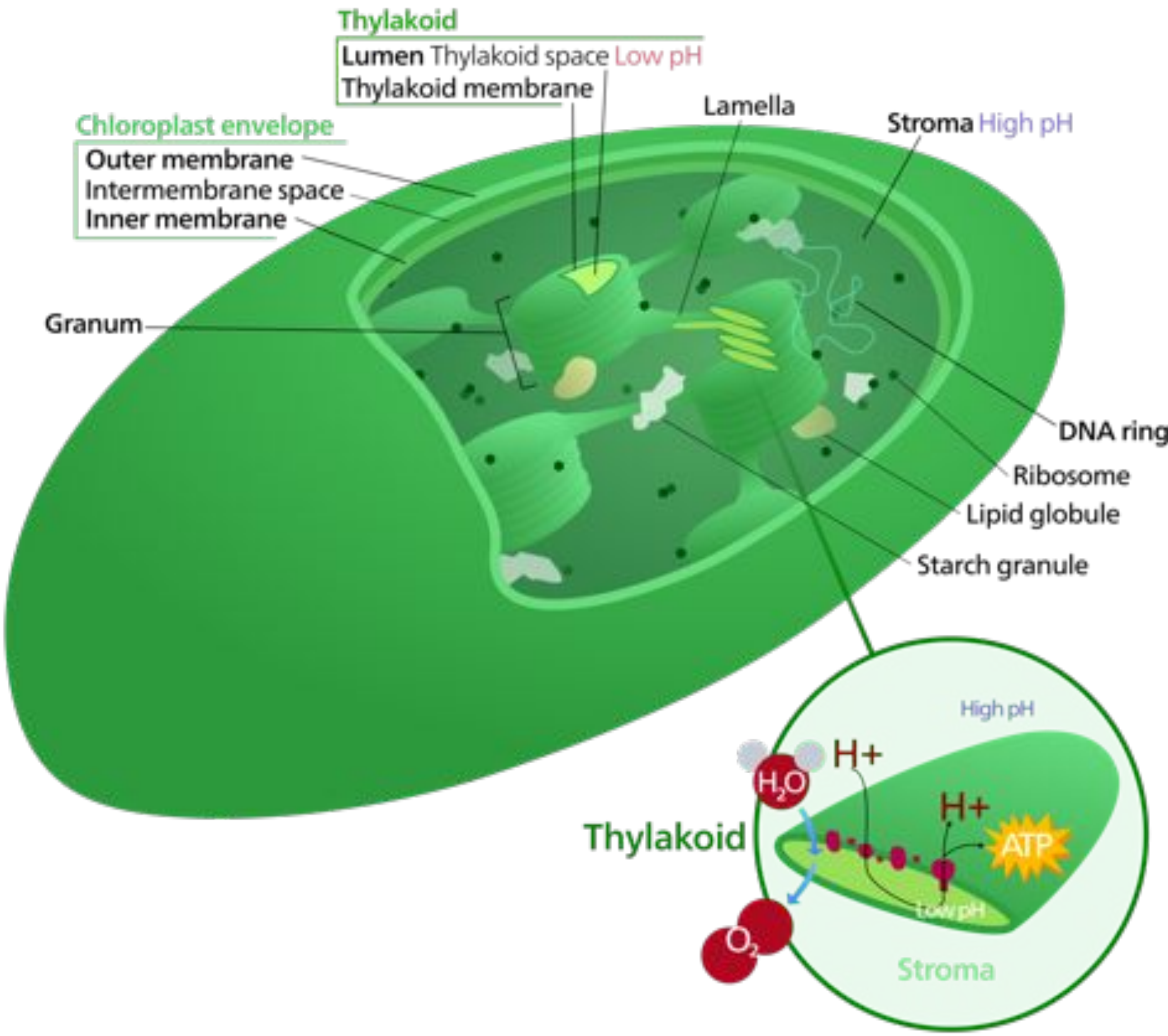
Occurs: in photosystems in the thylakoid membrane of chloroplasts.

Uses: Water, light, $NADP^+$, and ADP

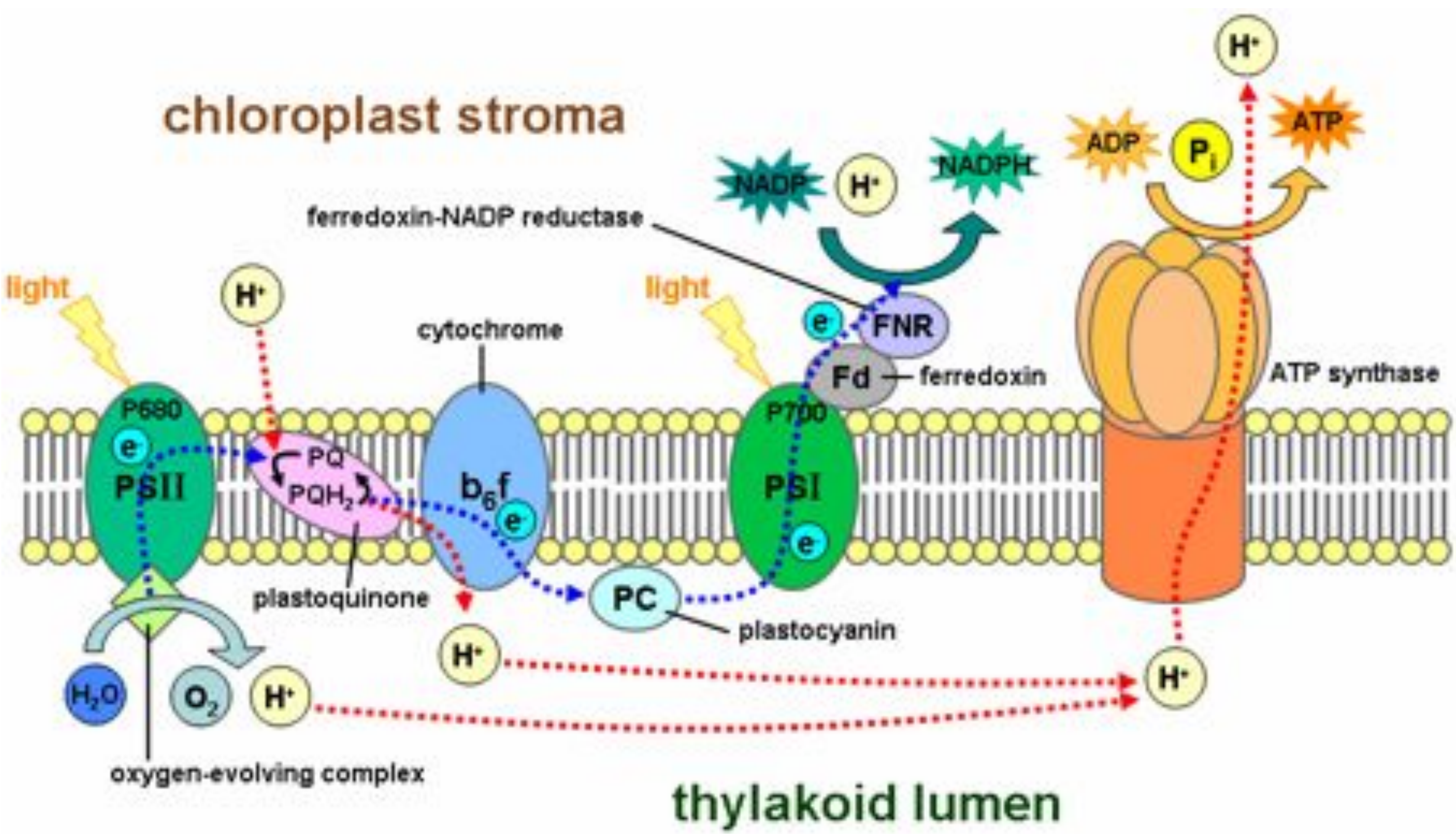
Produces: O_2 (waste), NADPH, and ATP

Chloroplasts are adapted to separate the light reactions from carbon fixation.

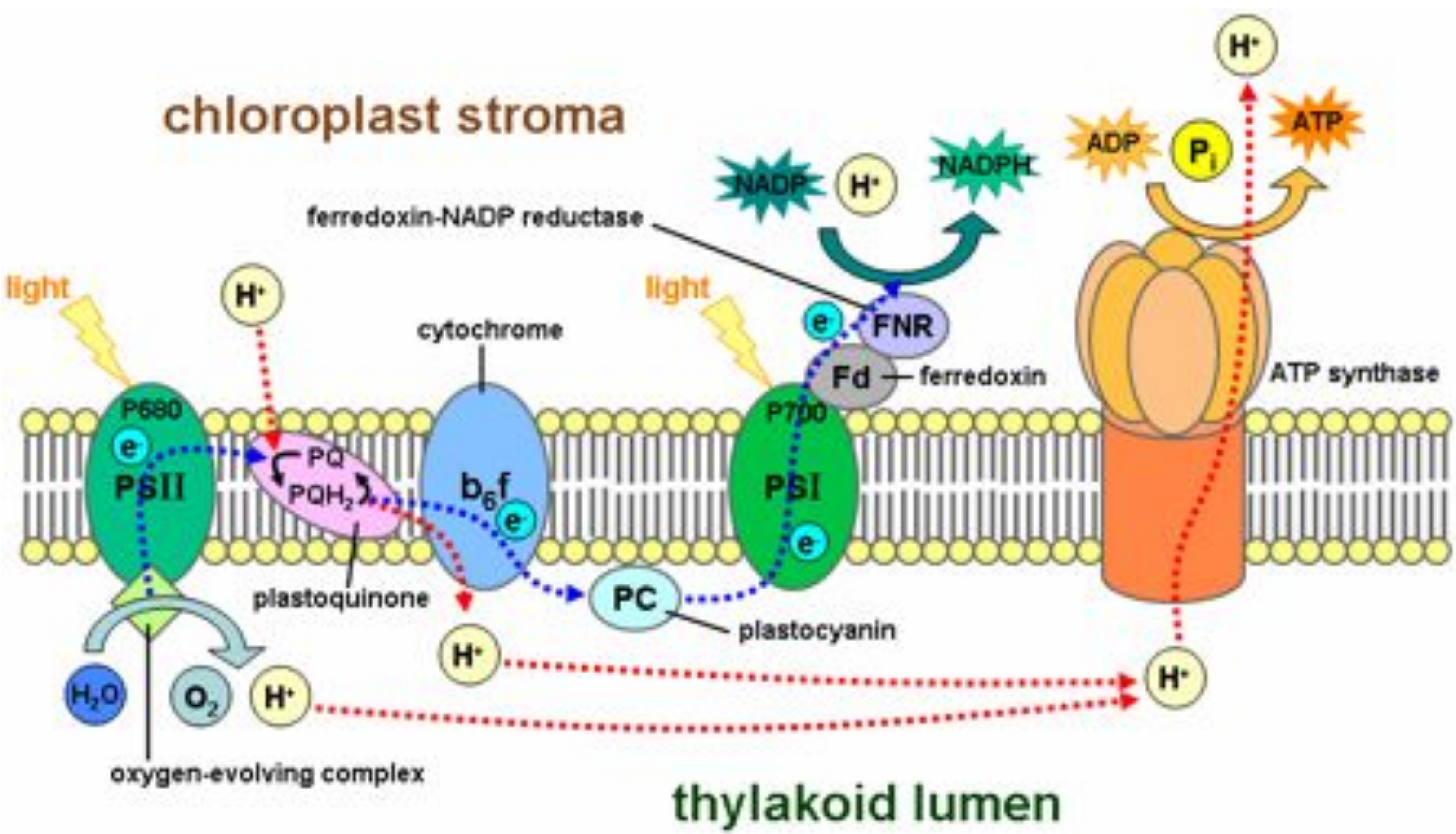
The light reactions occur at the **thylakoid membrane**.



Chlorophyll molecules in **photosystems** produce high energy electrons when exposed to photons.

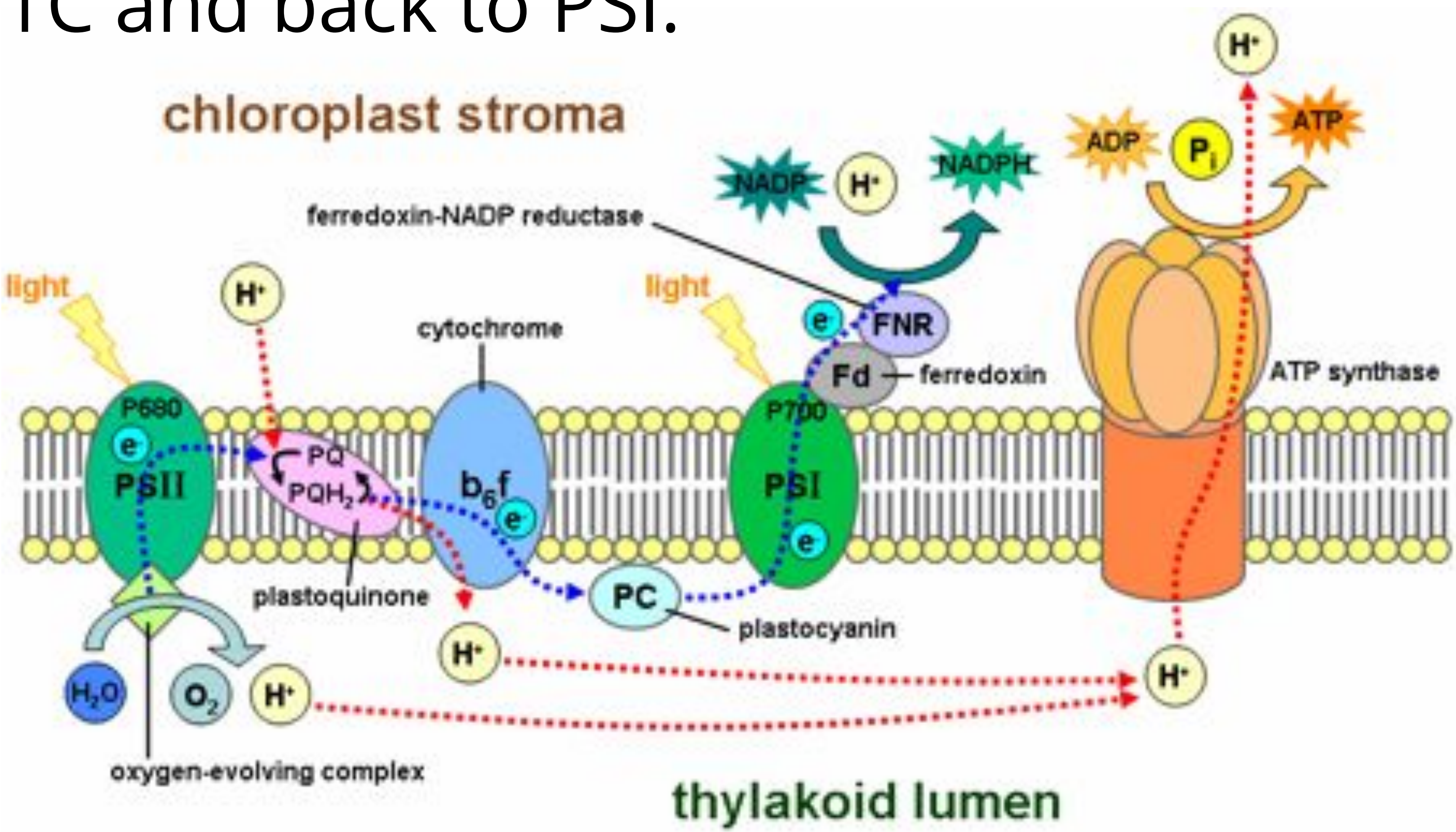


Electrons move through **electron transport chains** between photosystems. This releases free energy used to move protons across the thylakoid membrane.



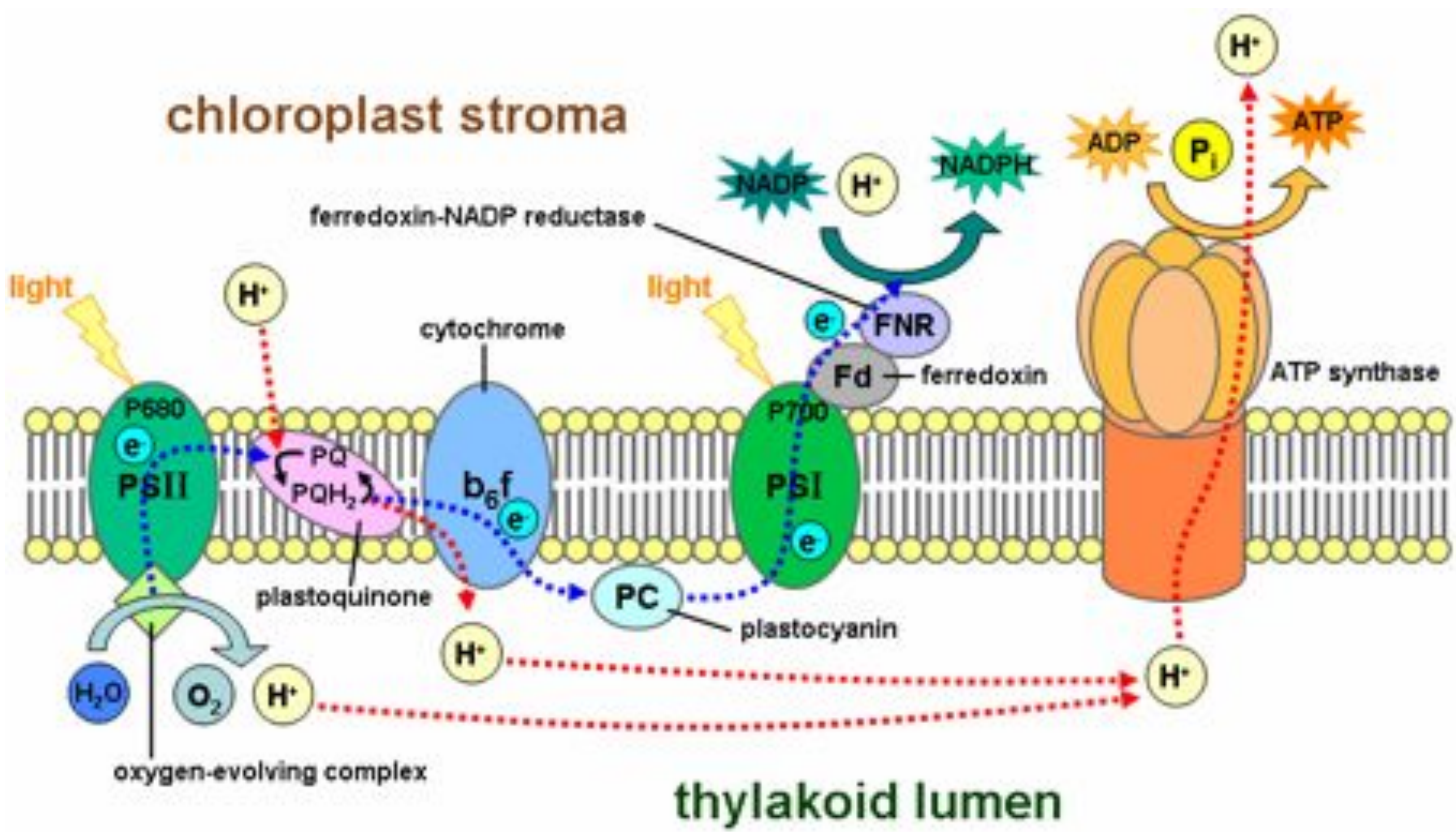
Non-Cyclic e⁻ flow: e⁻'s move from PSII to PS1, and are incorporated into **NADPH**.

Cyclic e- flow: e⁻'s move from PSI into the ETC and back to PSI.

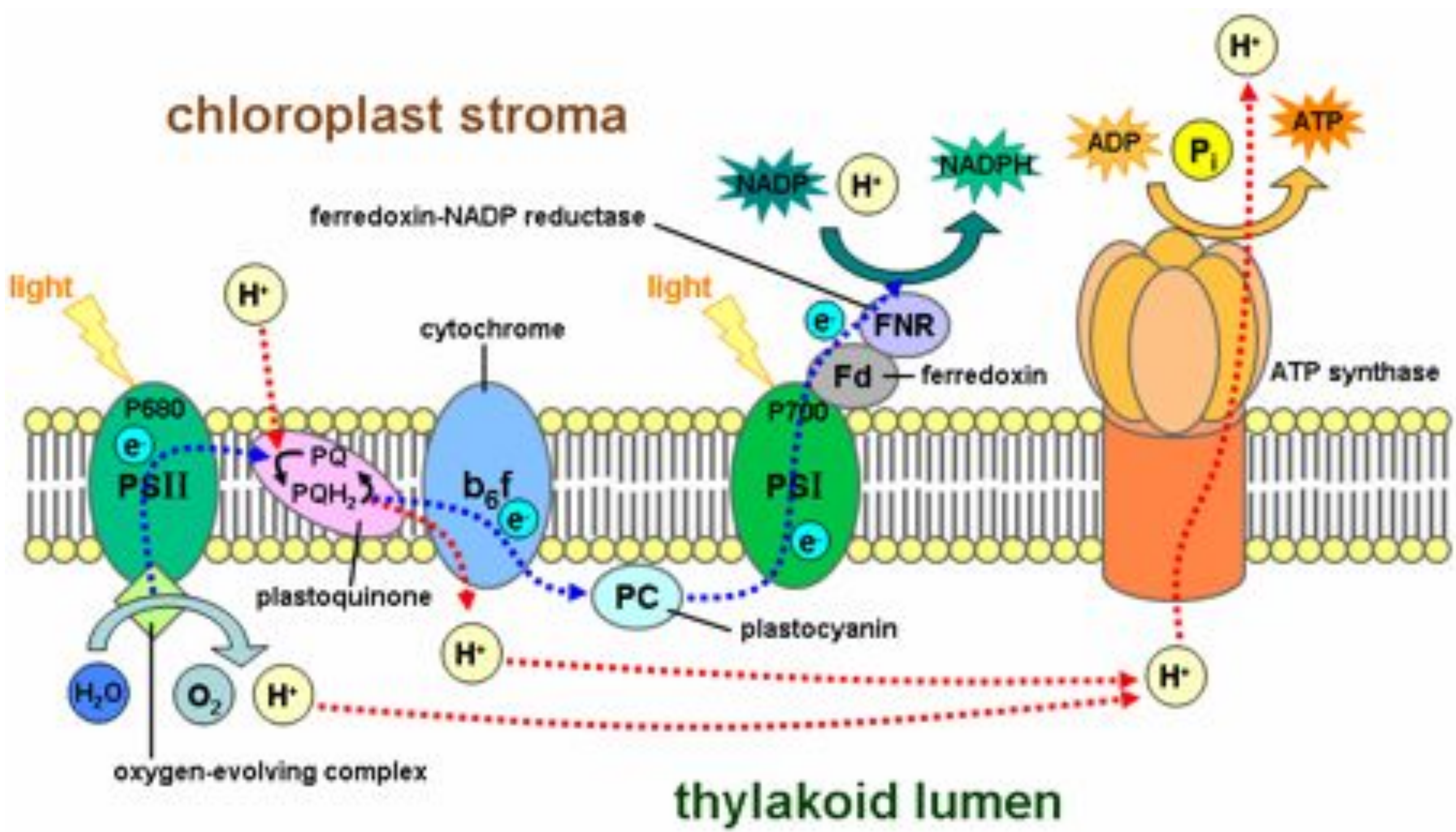


Water is decomposed at PSII to supply chlorophyll with replacement e⁻'s.

This produces **waste O_2**



The high concentration of H^+ in the thylakoid space is used to produce ATP through **chemiosmosis**

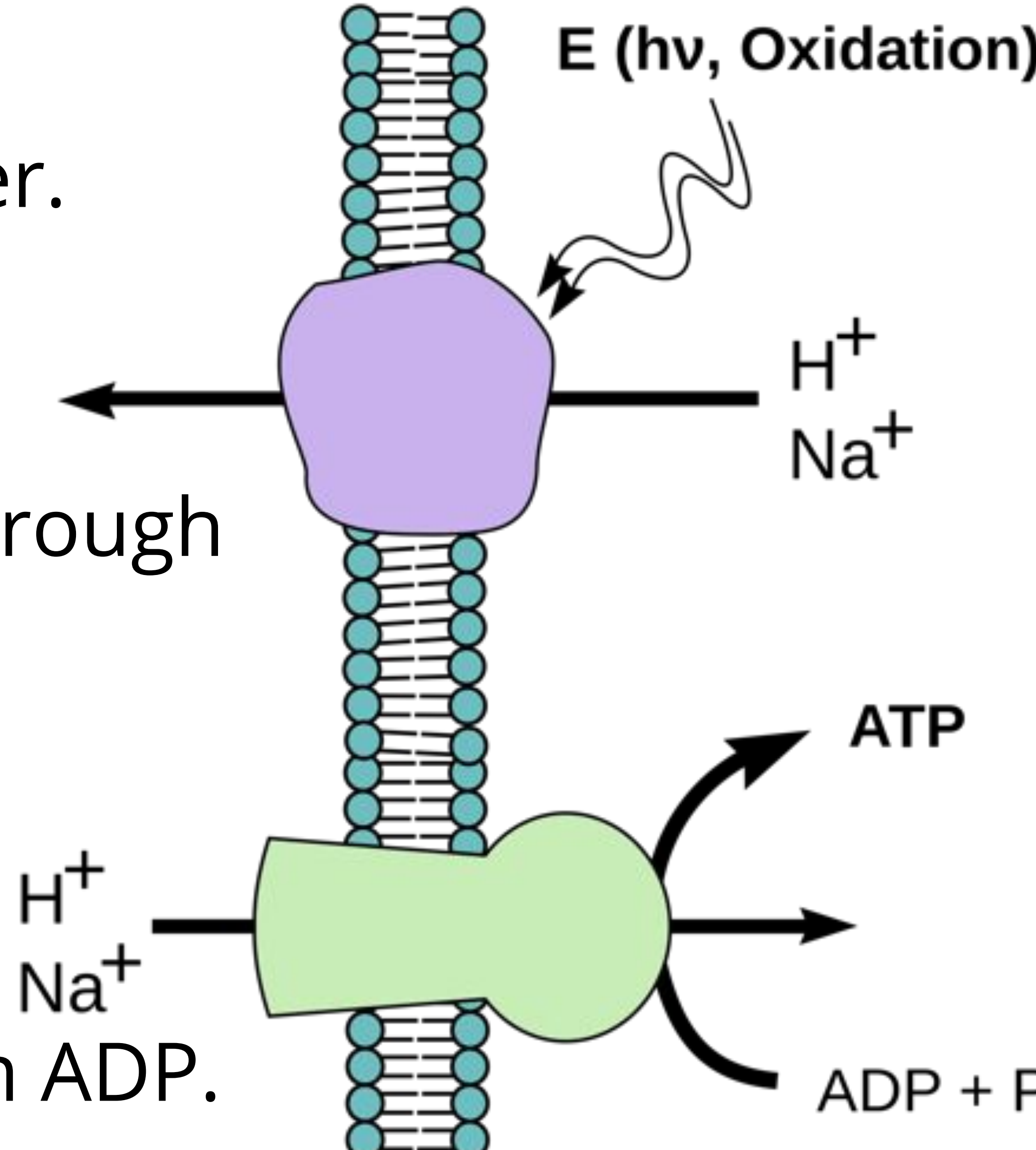


Chemiosmosis

H^+ can not diffuse through the bi-layer.

The only way that H^+ can diffuse is through the **ATP synthase** enzyme.

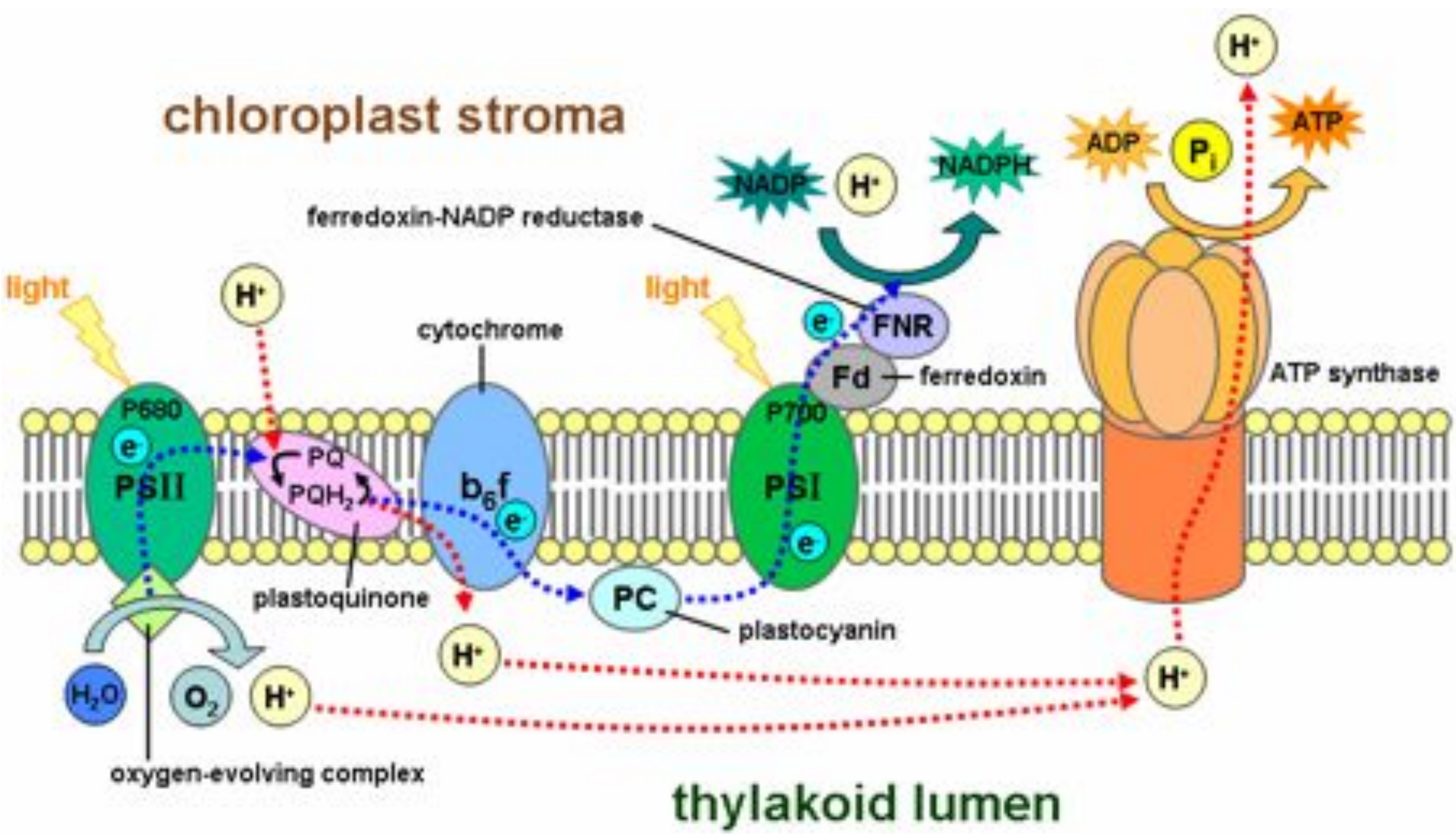
This diffusion produces ATP from ADP.



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

3. PHOTOAUTOTROPHIC NUTRITION- CARBON FIXATION

Review: The light reactions produced ATP and NADPH at the Thylakoid Membrane.



Carbon Fixation: Overview

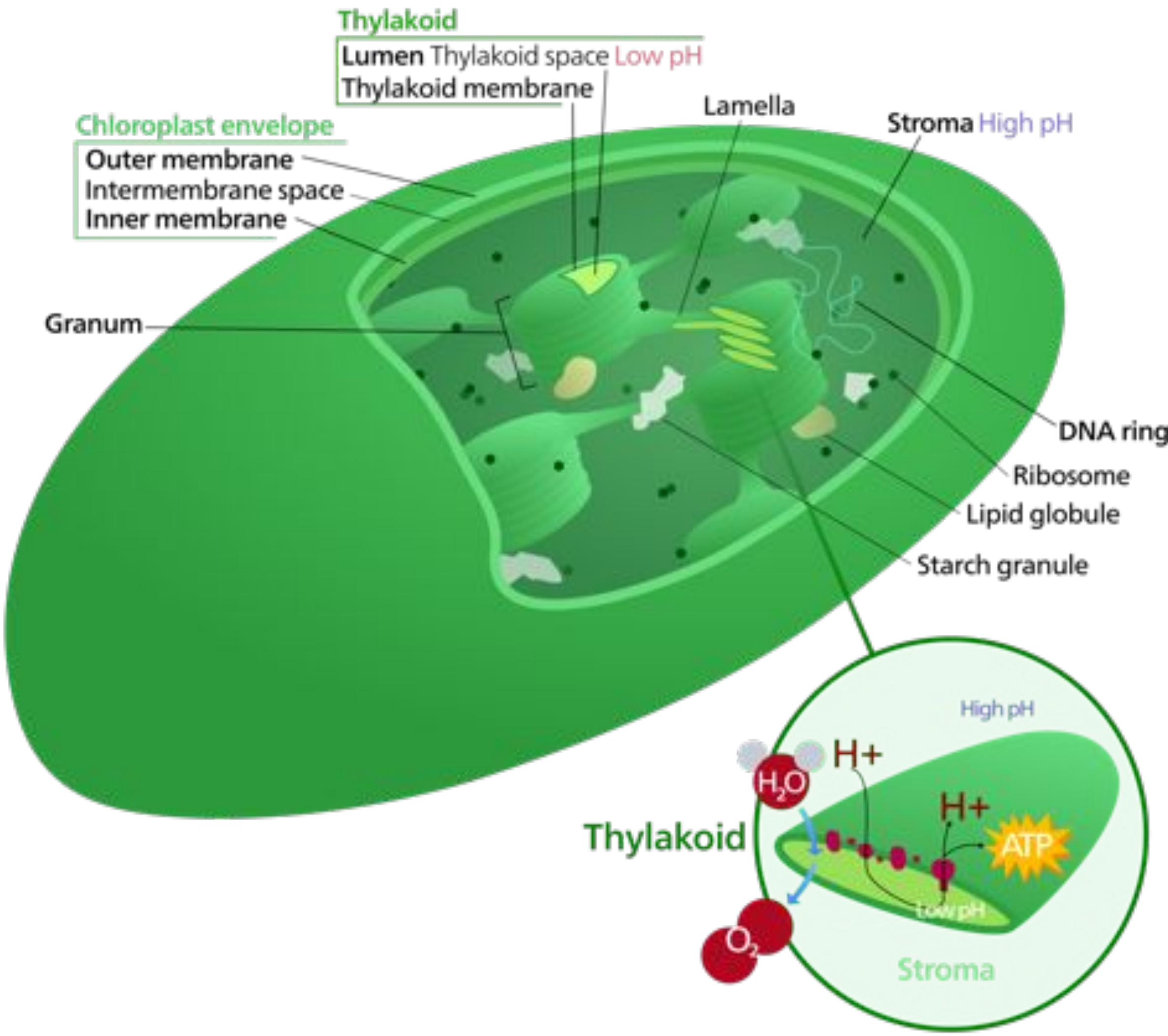
Occurs: in the stroma of the chloroplast.

Uses: CO_2, NADPH, and ATP

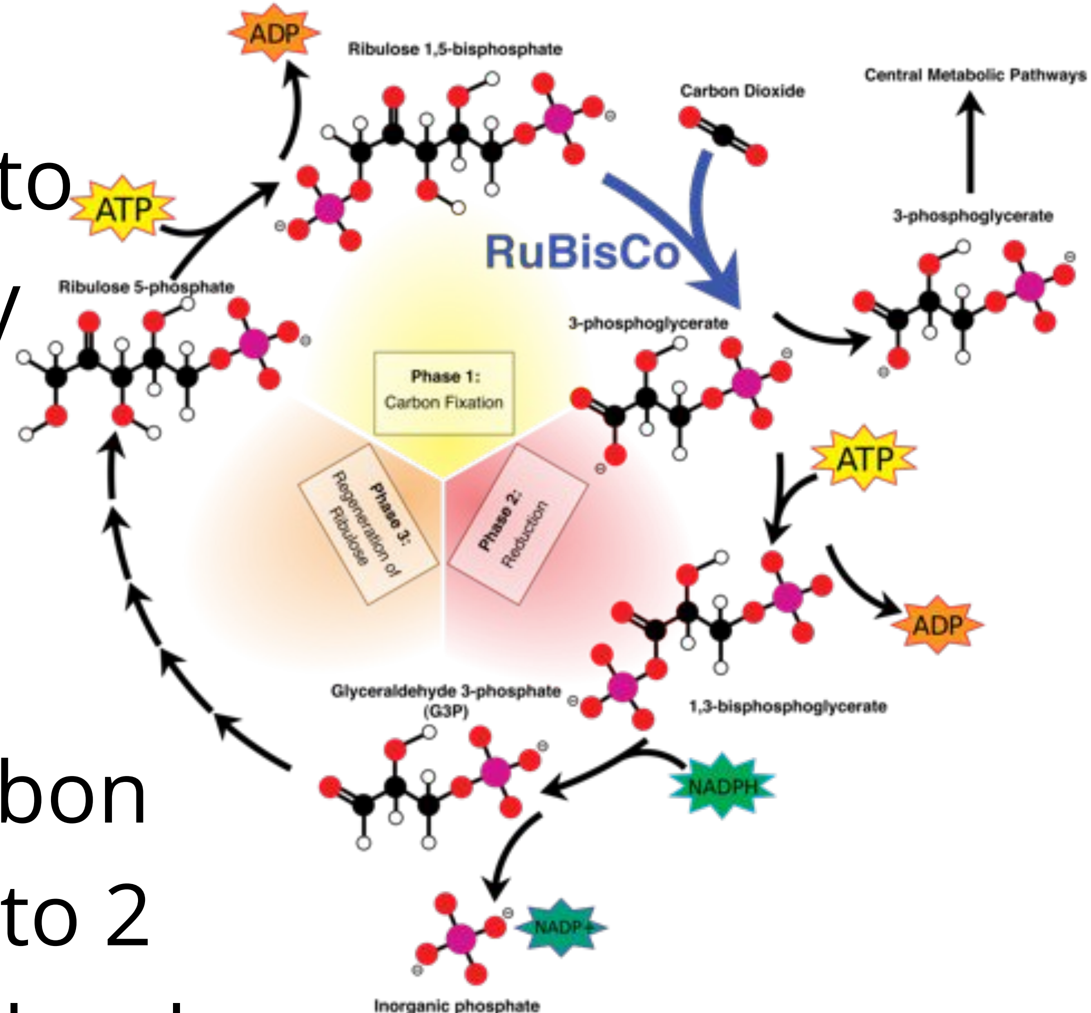
Produces: Organic Molecules (G3P), NADP, and ADP

Chloroplasts are adapted to separate the light reactions from carbon fixation.

Carbon fixation occurs in the **stroma**.

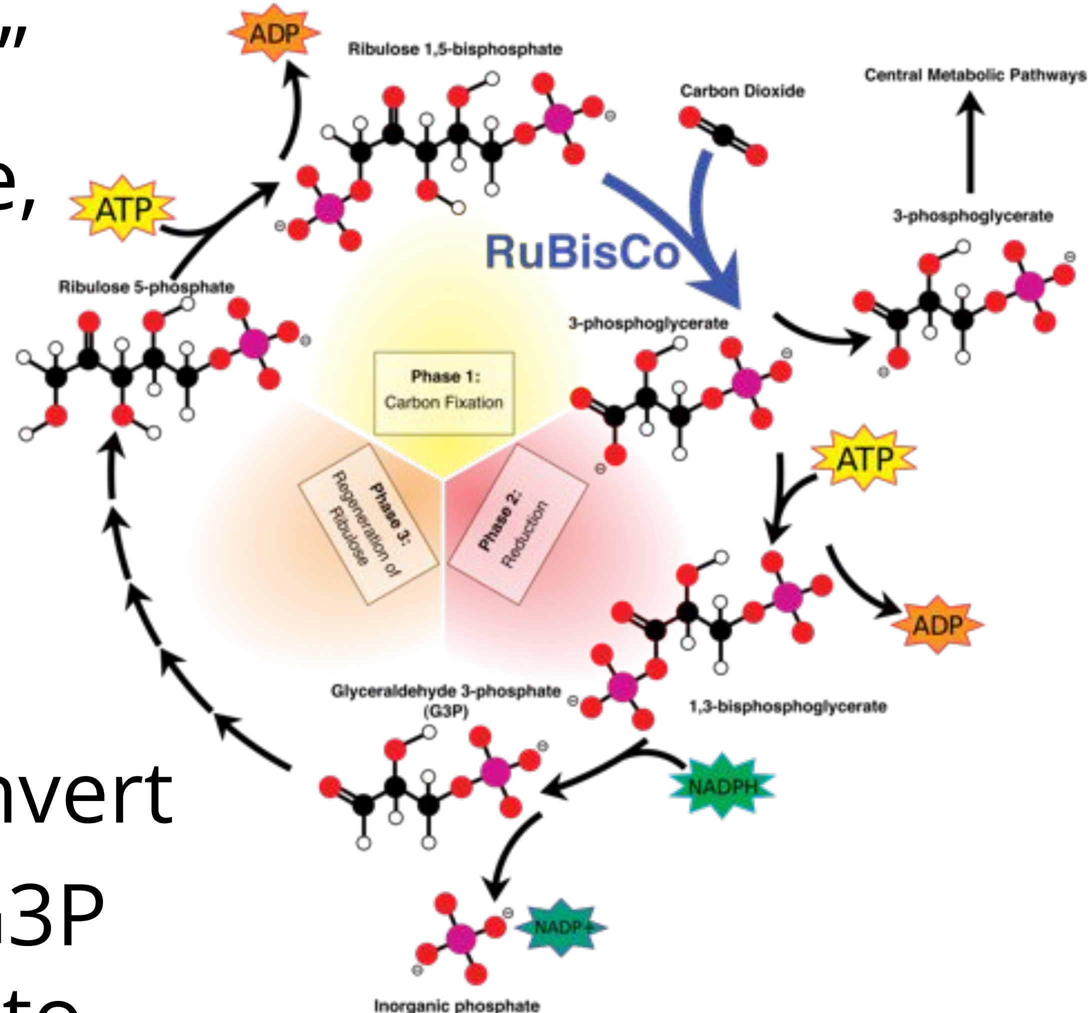


Carbon Dioxide is incorporated into the Calvin cycle by the enzyme **RuBisCo**.



This turns a 5-Carbon **RuBP** molecule into 2 3-Carbon **G3P** molecules (through a series of reactions NOT shown) using ATP and NADPH.

For every 3 “turns” of the Calvin Cycle, 1 net molecule of **G3P** is produced.



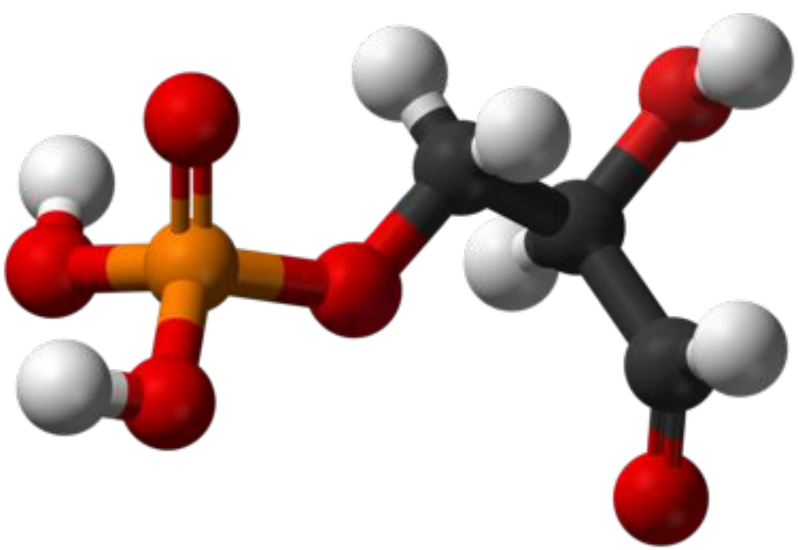
ATP is used to convert the remaining 5 G3P molecules back into 3 RuBP molecules.

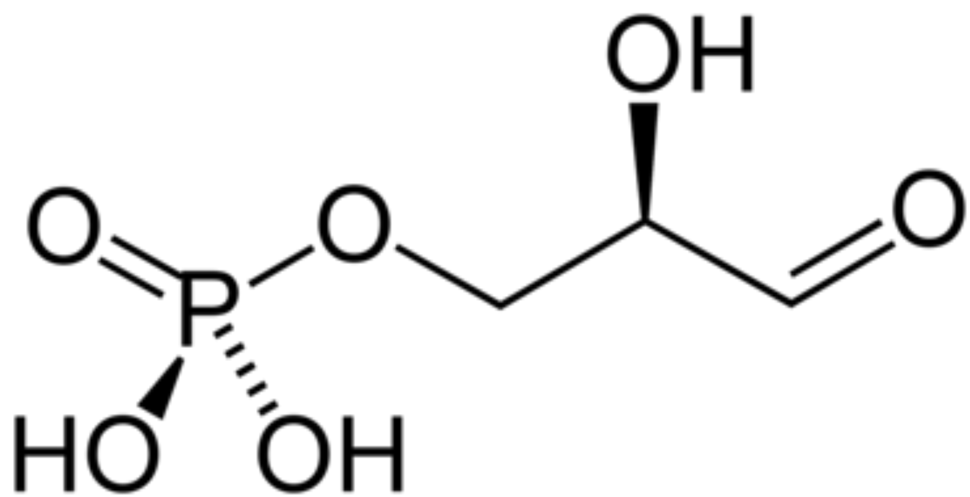
1 Net G3P requires 3 CO_2, 6 NADPH, & 9 ATP

G3P

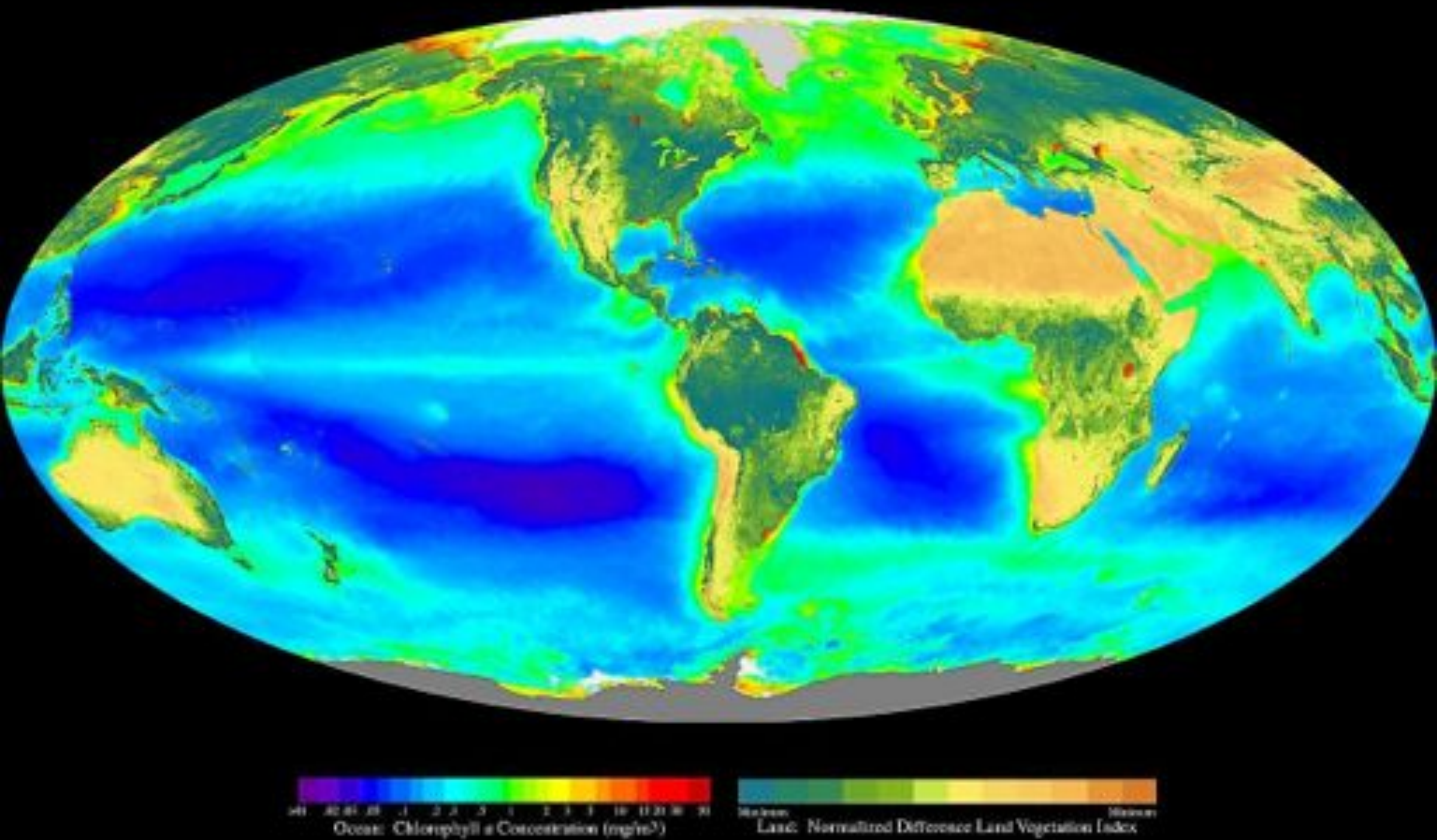
G3P is a sugar precursor.

2 G3P can make 1 glucose.





Photosynthesis determines **global productivity**.



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

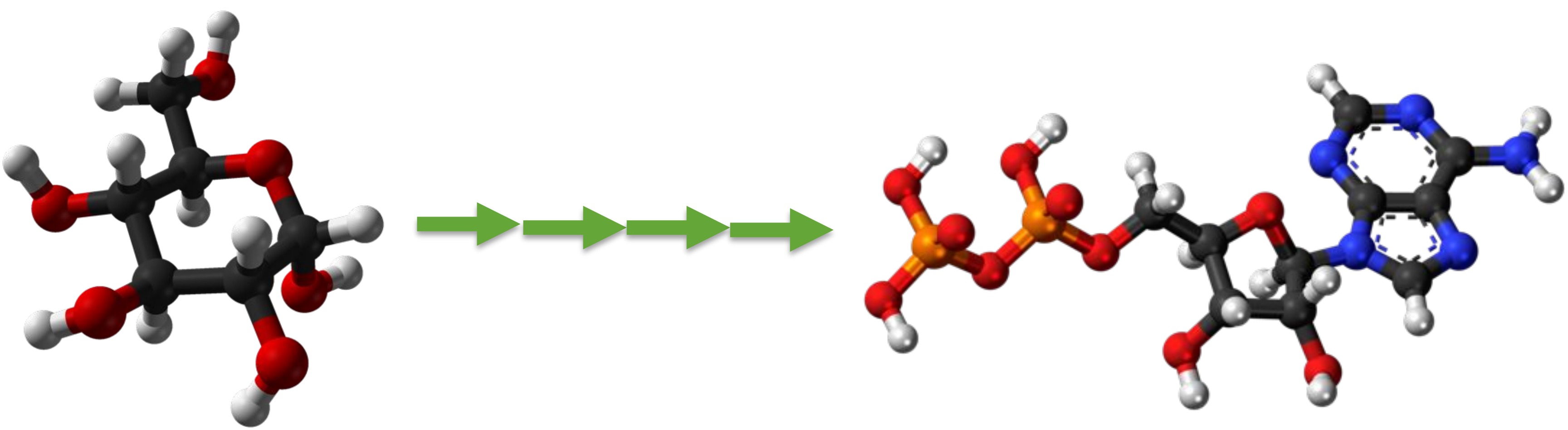
4. CHEMOHETEROTROPHIC NUTRITION- ANAEROBIC CELLULAR RESPIRATION

Energy Transfer

Respiration pathways involve the transfer of energy from complex organic molecules (we look at glucose) into ATP.

This happens in a series of enzymatically controlled reactions that can require oxygen (**aerobic**) or not (**anaerobic**).

Both start the same way.



Glycolysis: Overview

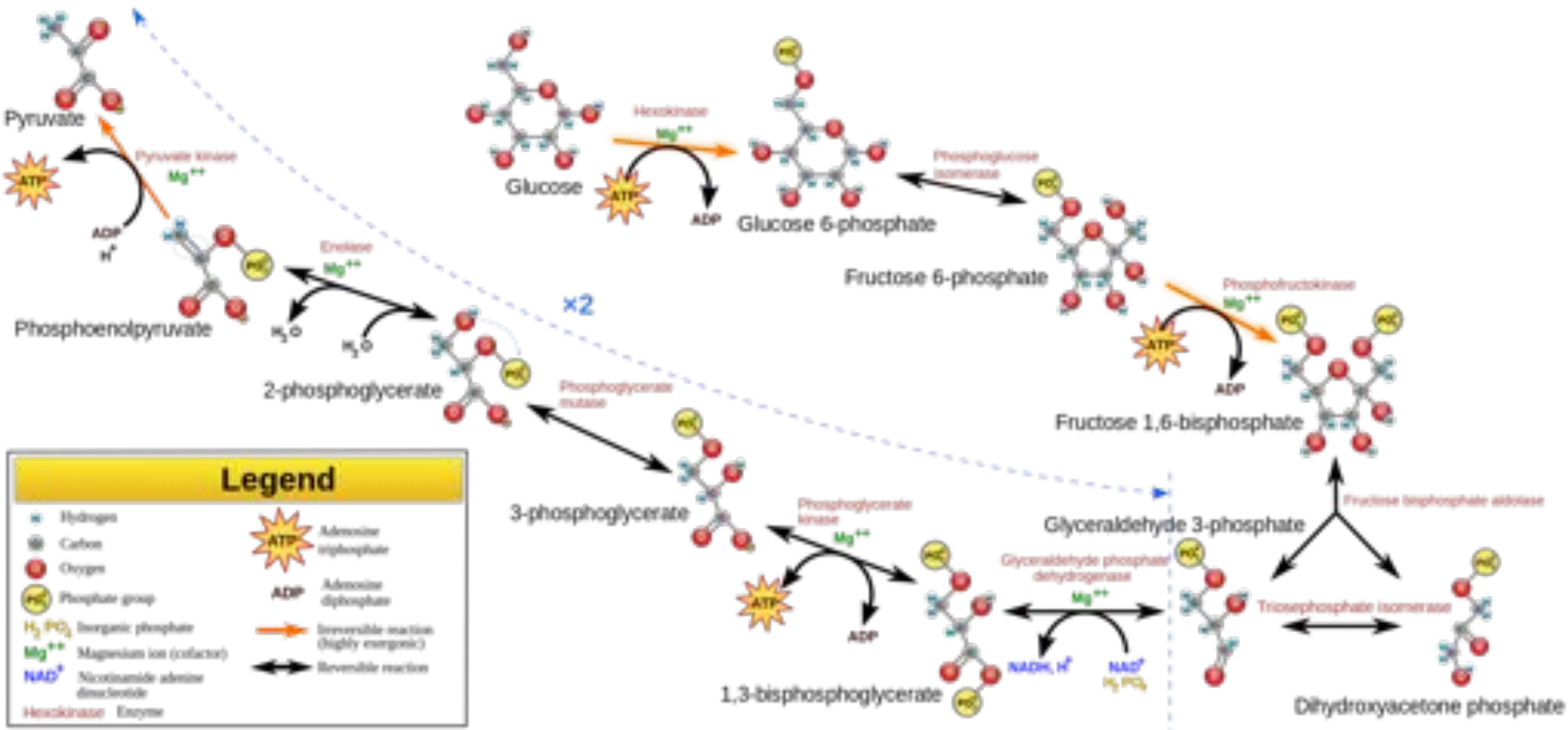
Occurs: in the cytoplasm of all cells on the planet

Uses: Glucose (6 Carbon), 2 ATP, $2NAD^+$

Produces: 2 Pyruvate (3 Carbon), 4 ATP, 2 NADH

Glycolysis is universal among all living things.

2 ATP are invested, but 4 are produced.

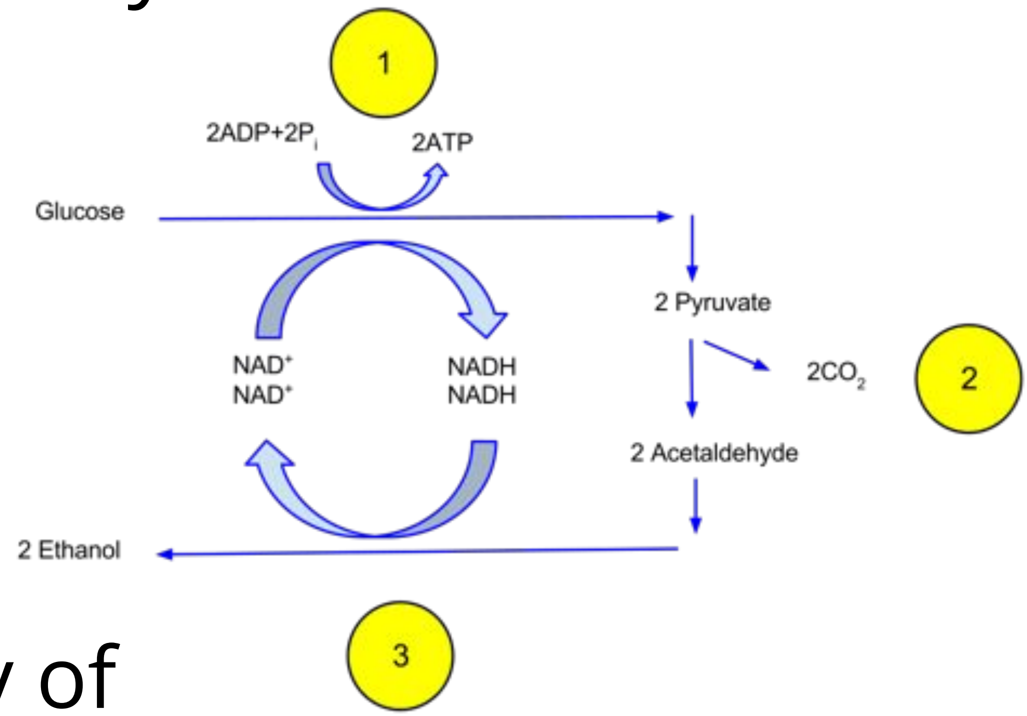


Fermentation

If a cell stops at glycolysis, it will run out of NAD^+.

Fermentation pathways allow cells to oxidize NADH back to NAD^+ in order to continue anaerobic cellular respiration.

Pyruvate is reduced into one of a variety of molecules.



Fermentation: Overview

Occurs: in the cytoplasm of all anaerobically respiring cells

Uses: 2 Pyruvate, 2 NADH

Produces: A variety of organic molecules, and 2 NAD^+

2 Examples: Yeast – ethanol (2 Carbon) and CO_2

Mammalian Muscle – Lactic Acid (3 Carbon)

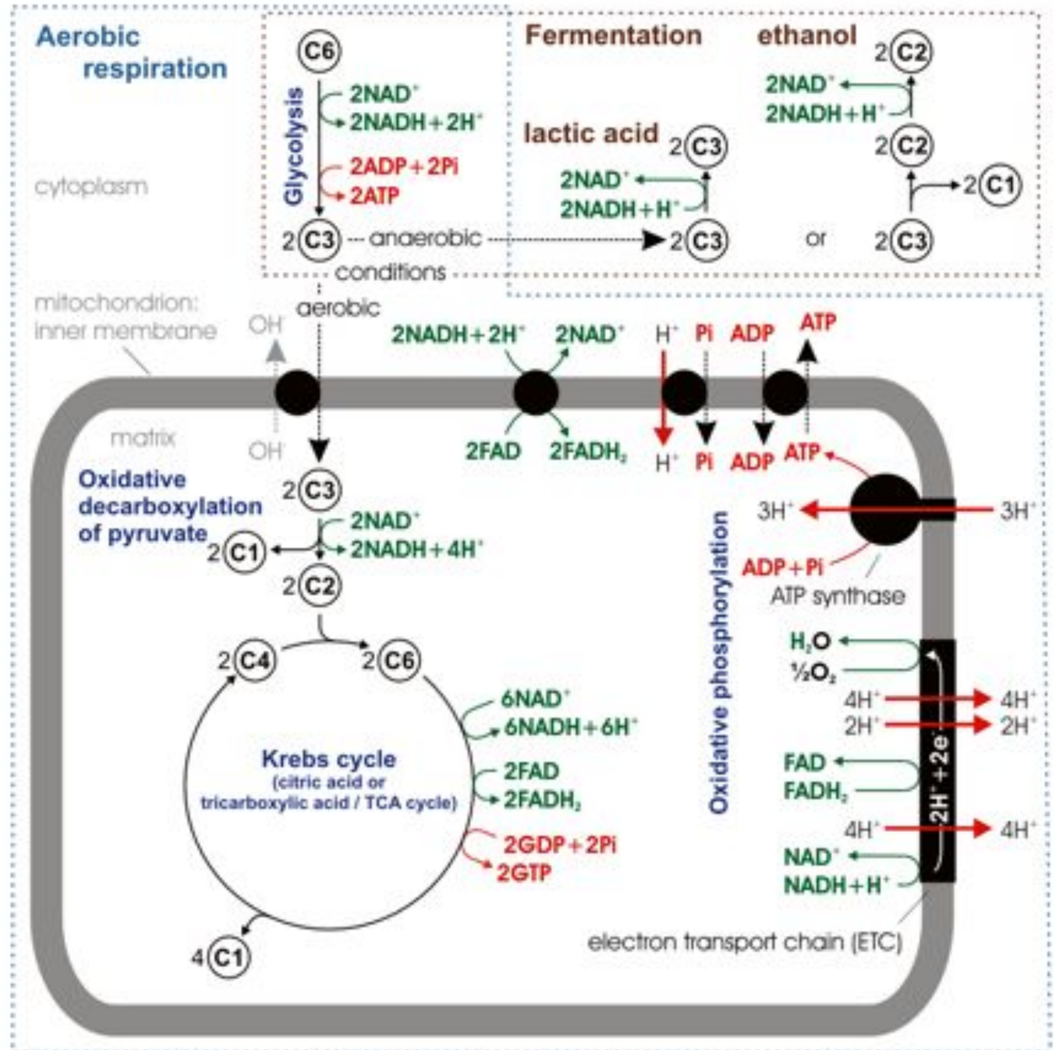
3.3: Organisms capture and store free energy for use in biological processes.

5. CHEMOHETEROTROPHIC NUTRITION- AEROBIC CELLULAR RESPIRATION

Aerobic Cellular Machinery

Cells that carry out Aerobic Respiration need **mitochondria** or similar membrane compartments.

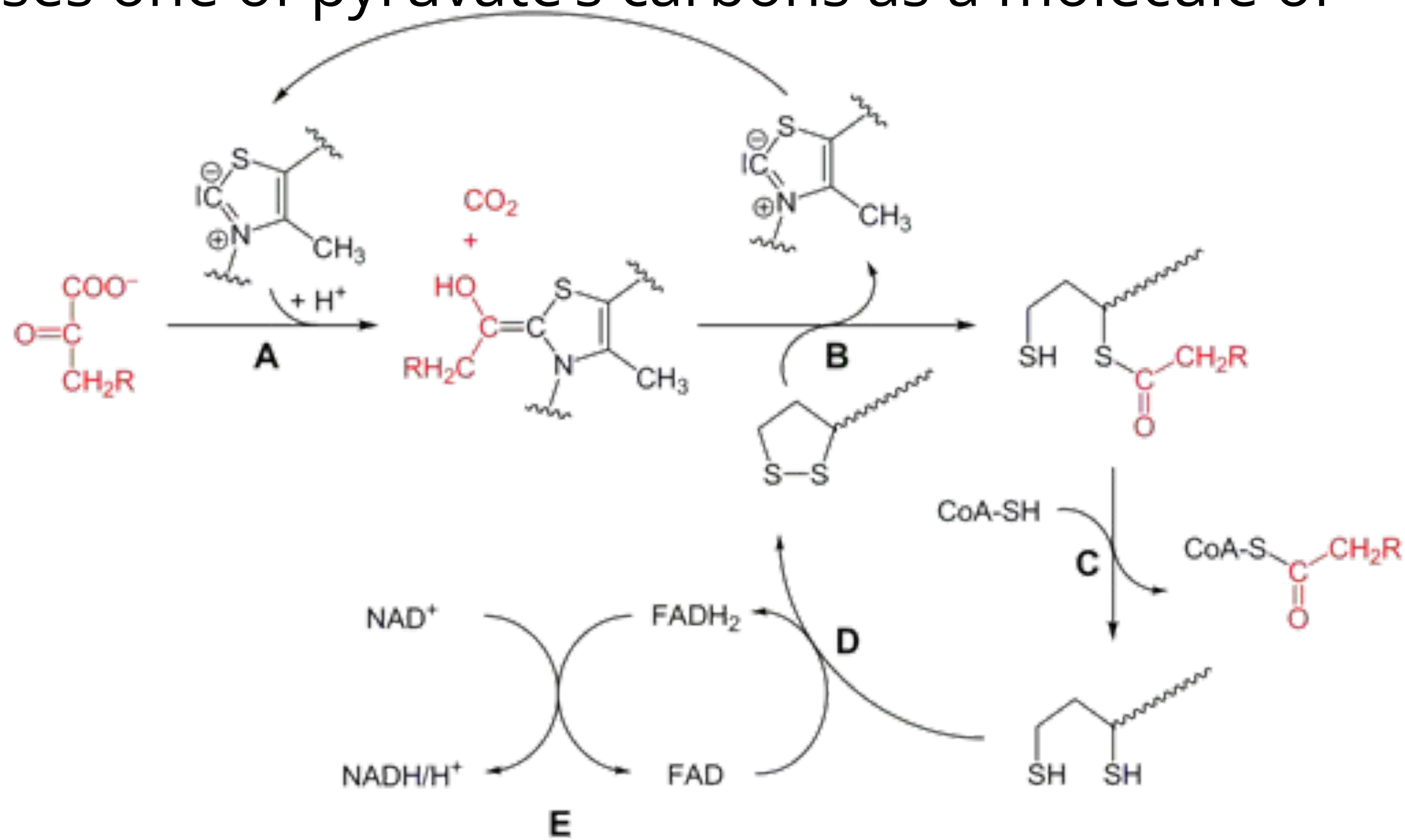
Aerobic Respiration is a 2-part process: **The Citric Acid Cycle**, followed by **Oxidative Phosphorylation**



But First…

Pyruvate is converted into a molecule of **acetyl-CoA**.

This process produces **1 NADH** per pyruvate, and also releases one of pyruvate's carbons as a molecule of **CO_2**



Citric Acid Cycle: Overview

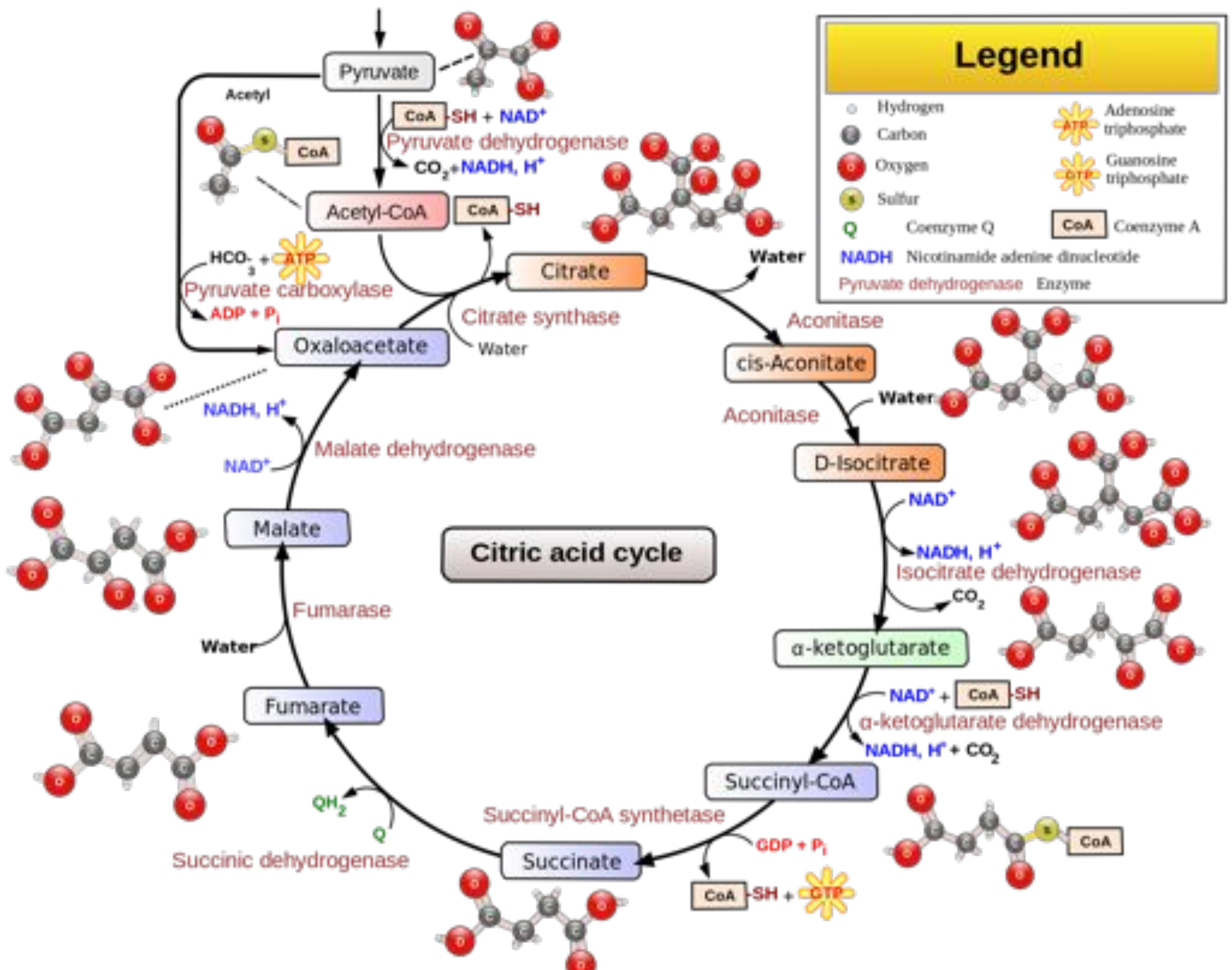
Occurs: In the matrix of the mitochondria.

Uses: A molecule of Acetyl-CoA (2 Carbon), 3 NAD^+, 1 FAD, and 1 ADP

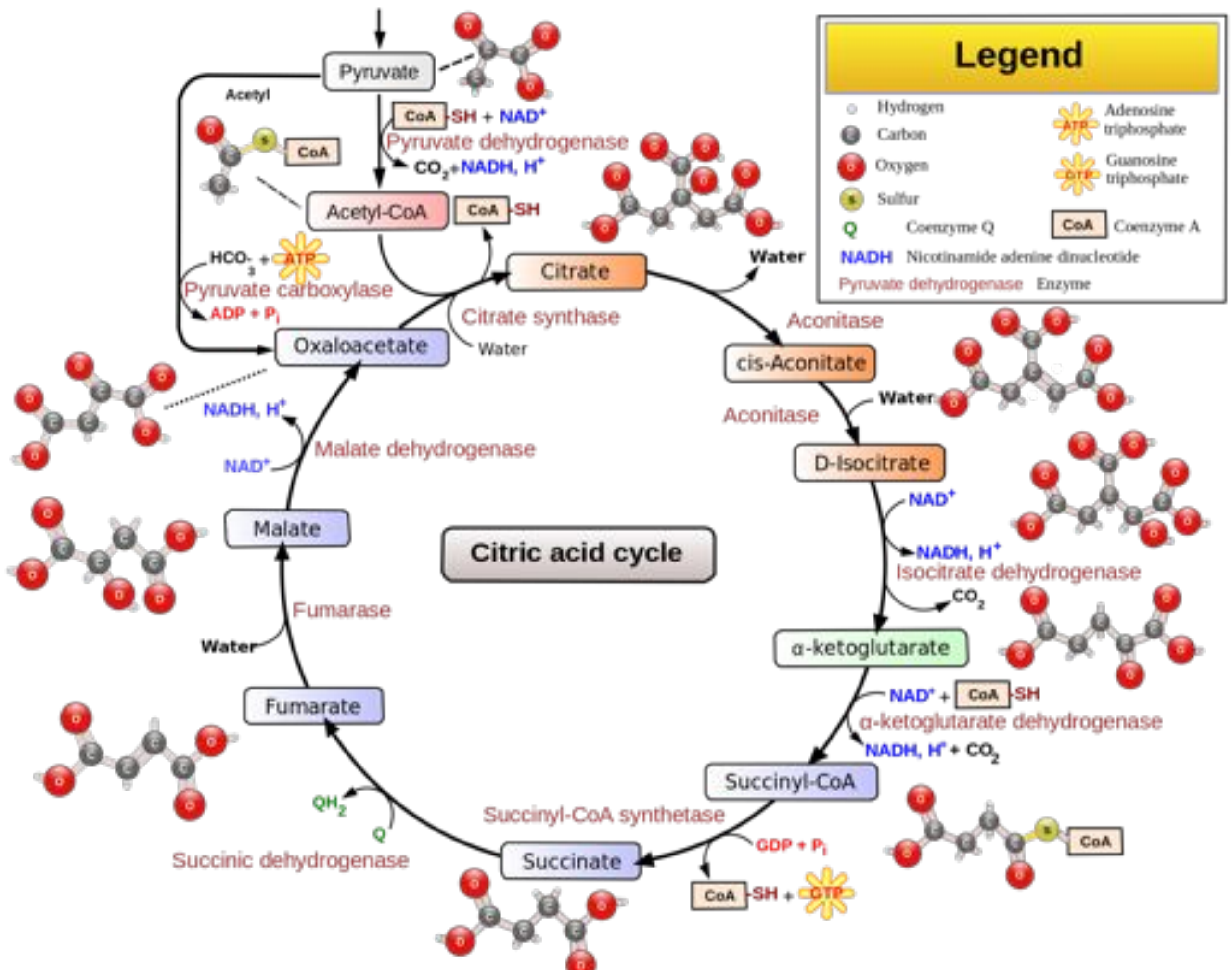
Produces: 2 CO_2, 3 NADH, 1 $FADH_2$, 1 ATP

Note: This happens twice per every 1 glucose.

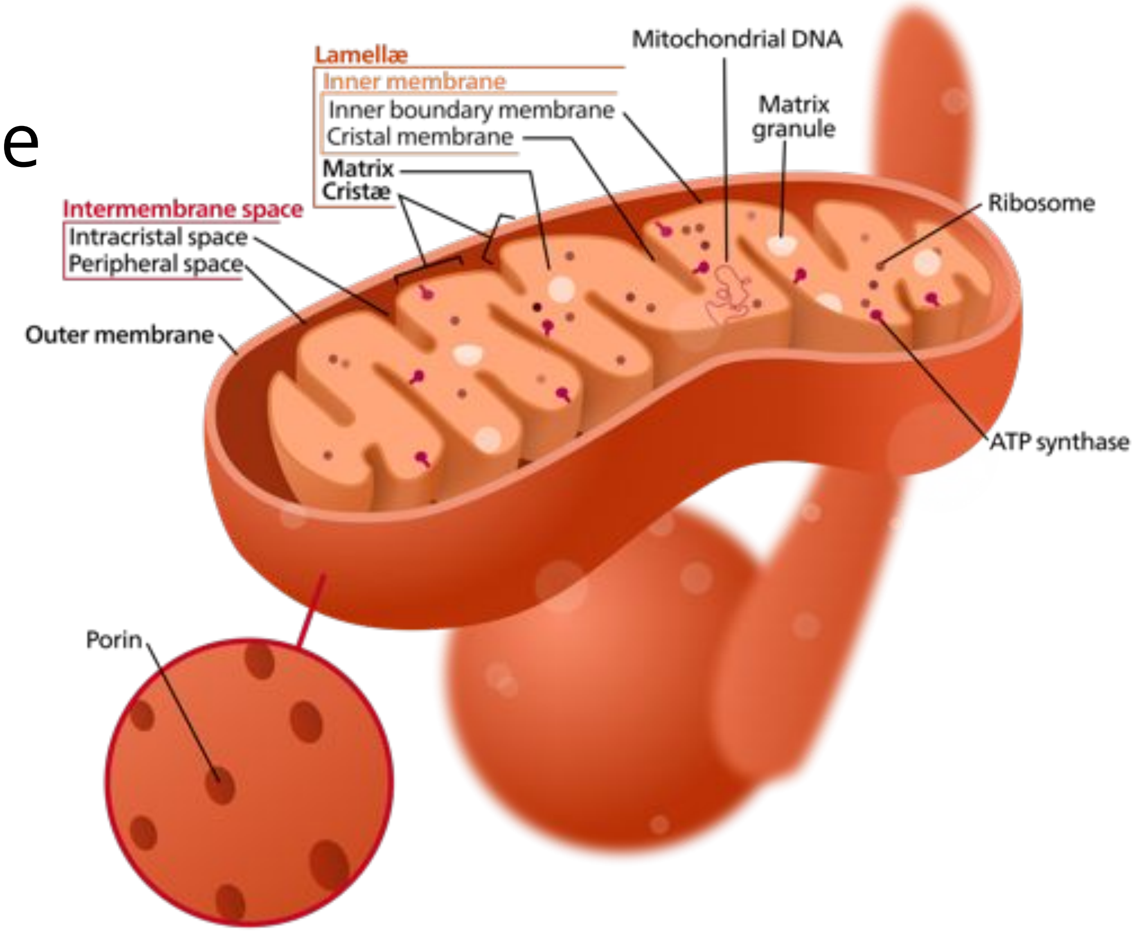
Though it doesn't use oxygen, the citric acid cycle stores more of the energy from glucose in electron shuttles (**NADH, FADH$_2$**). These will be used in the next step (Oxidative Phosphorylation)



The remaining 4 carbons from the original glucose will be released as CO_2 during this process.



Mitochondria are adapted to separate the citric acid cycle from oxidative phosphorylation.



The citric acid cycle occurs in the **mitochondrial matrix.**

Oxidative Phosphorylation occurs at the **inner membrane.**

Oxidative Phosphorylation: Overview

Occurs: At the inner membrane of the mitochondria

Uses: Oxygen, and all NADH and $FADH_2$ produced in glycolysis (2 NADH), acetyl-CoA conversion (2 NADH per glucose), and the citric acid cycle (6 NADH and 2 $FADH_2$ per glucose)

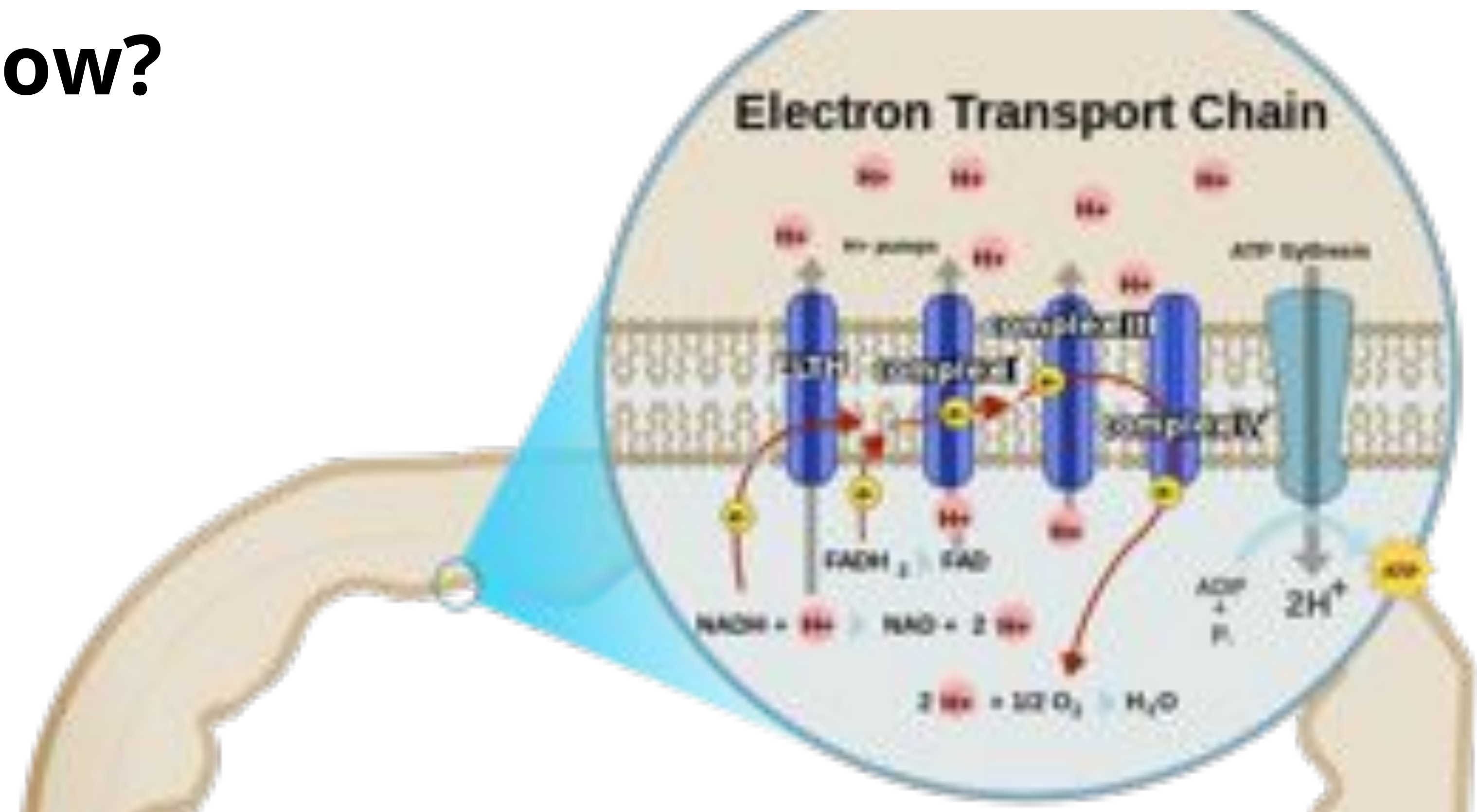
Produces: Water, NAD^+, FAD, and >30 ATP

Oxidative Phosphorylation

What's oxidized: NADH and $FADH_2$

What's produced: ATP and Water

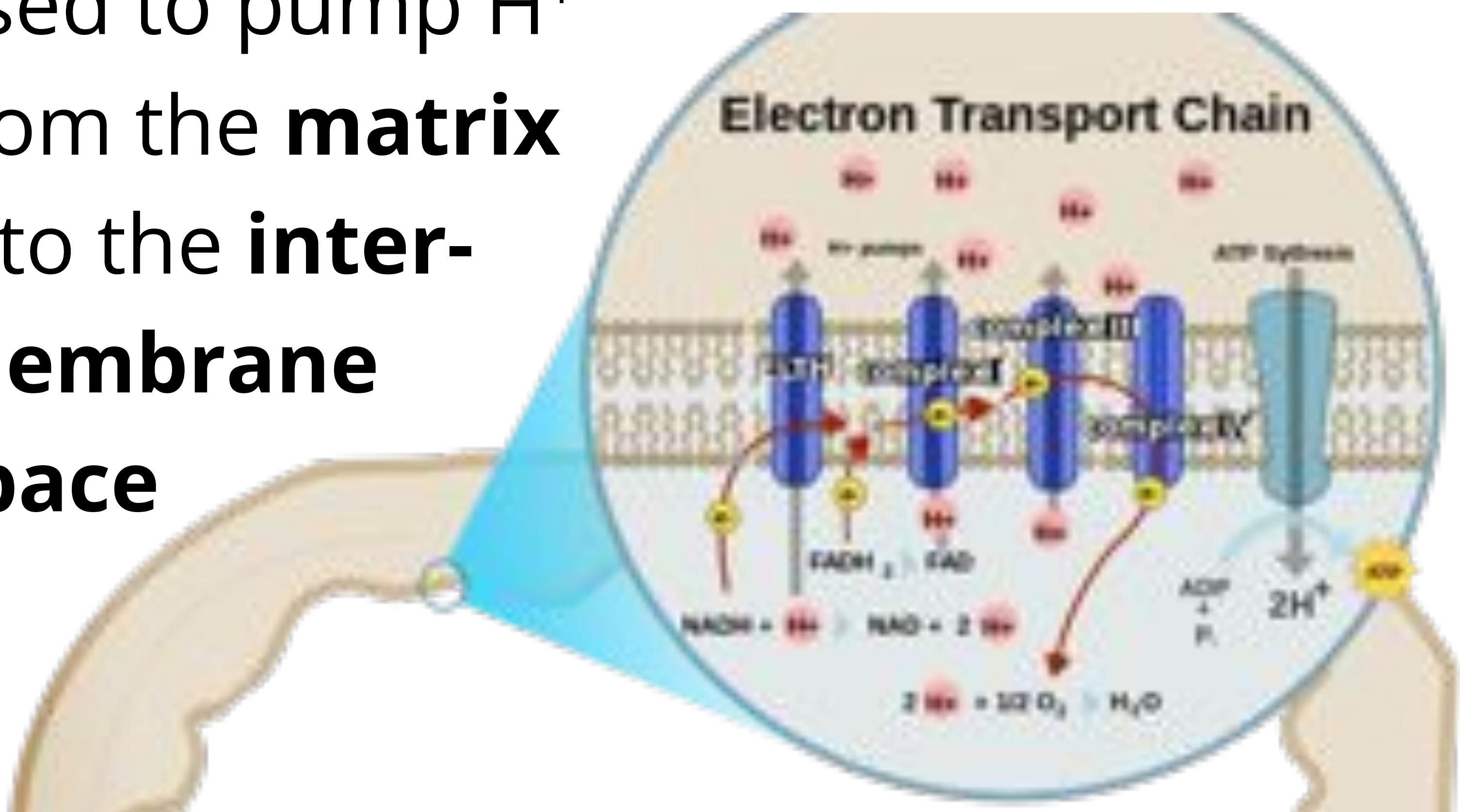
How?



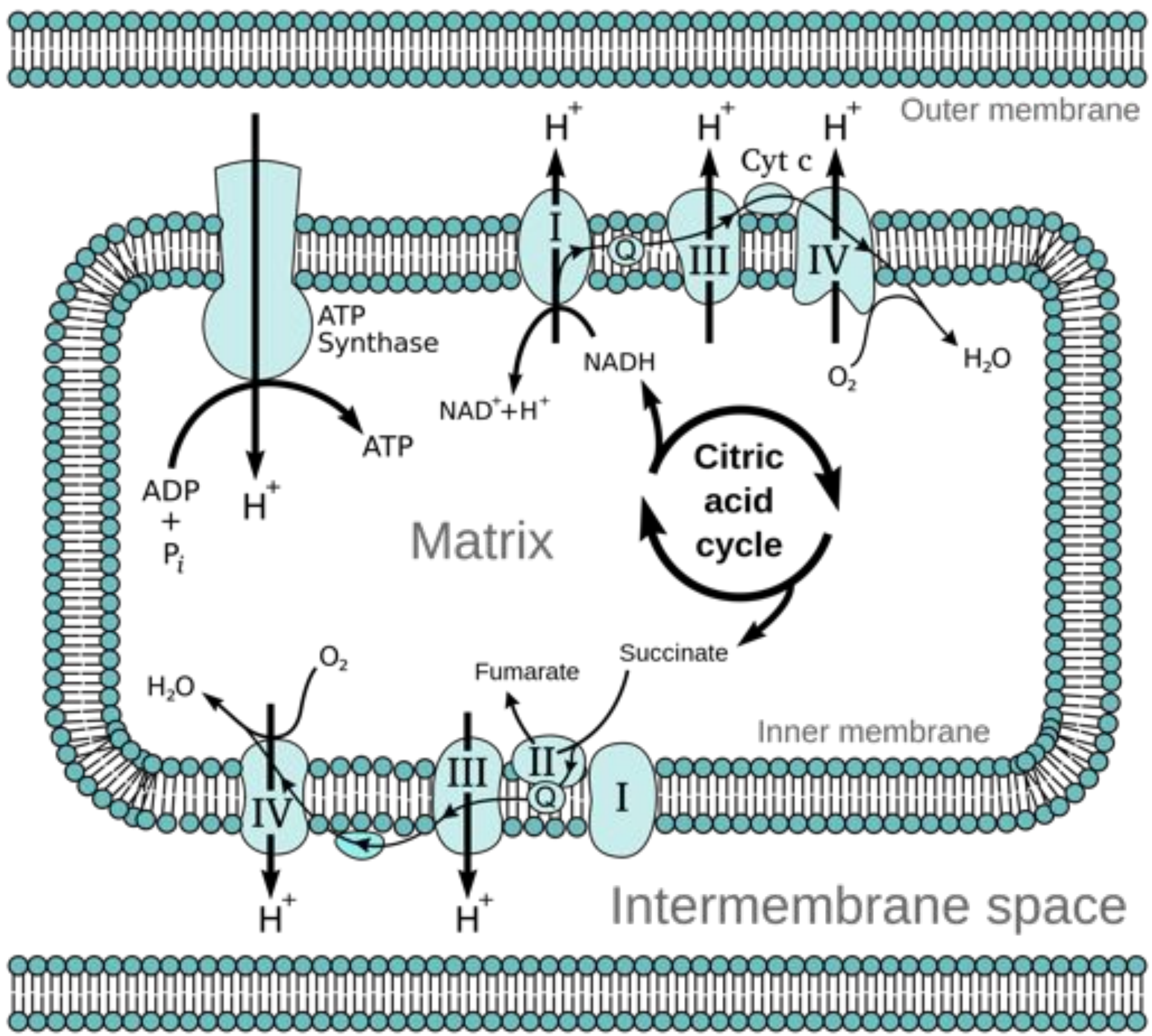
Chemiosmosis

Similar to the light reactions.

The electrons move through an **electron transport chain**. The energy released is used to pump H^+ from the **matrix** into the **inter-membrane space**



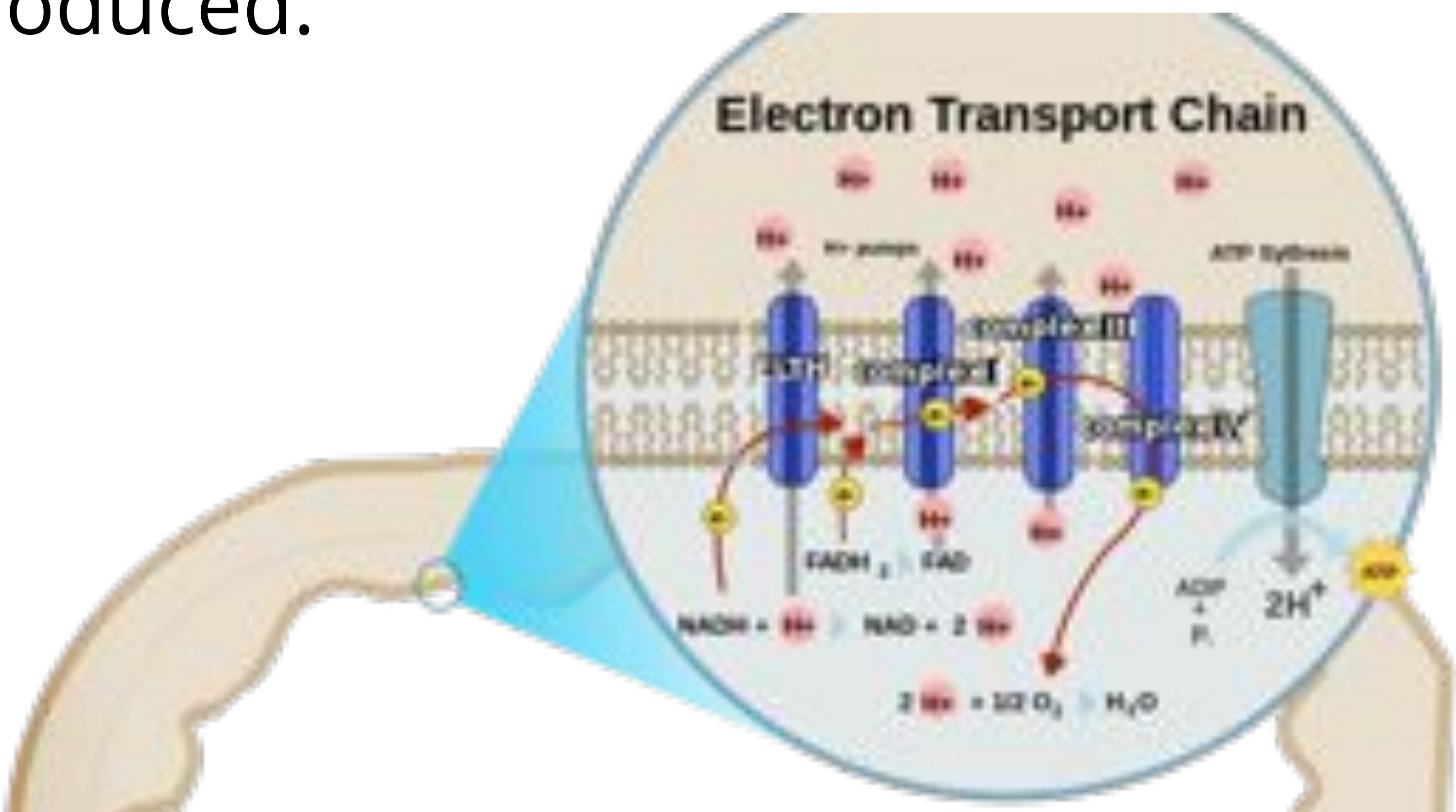
The only way for H^+ to diffuse back into the matrix is through **ATP Synthase**.



Where's Water?

Water is produced when electrons reach the end of the Electron Transport Chain.

They combine with oxygen, and water is produced.



Why >30 ATP?

We can't give an exact number because ATP synthesis and oxidation of electron carriers are not directly coupled.

~ 3 ATP per NADH, ~2 ATP per $FADH_2$

Certainly **MUCH MORE ATP** than in anaerobic cellular respiration.

Other Metabolites

All biological molecules are able to be metabolized through respiration pathways.

They are either converted in to glucose, or enter the process “downstream” of glycolysis, depending on the molecule.

3.4: Cooperative interactions within organisms promote efficiency in the use of energy and matter.

Compartmentalization in Energy Processing

Compartmentalization allows for increased cellular efficiency.

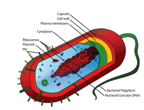
Different metabolic pathways can occur in different cellular compartments, at different conditions, and not interfere with each other.

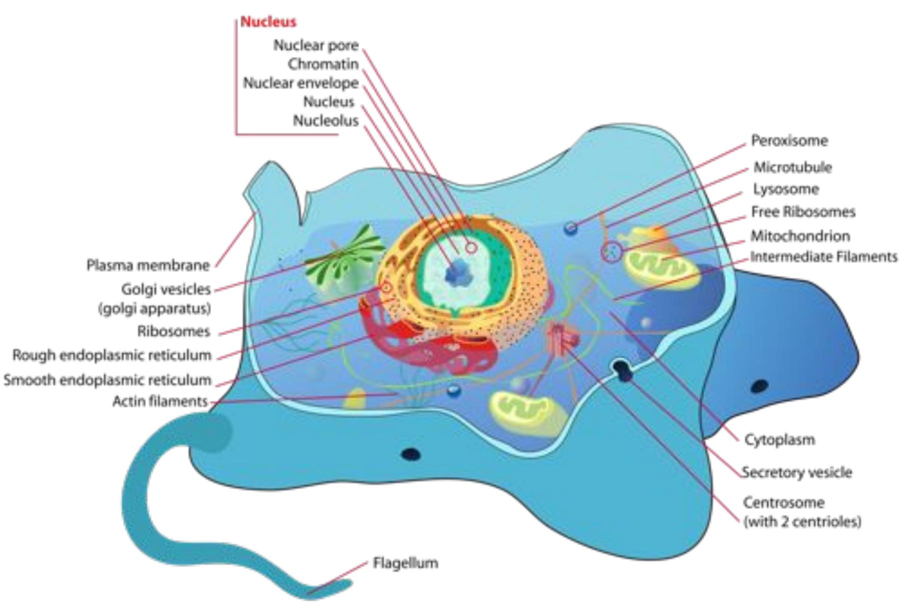
Groups of related enzymes can also be localized to particular areas.

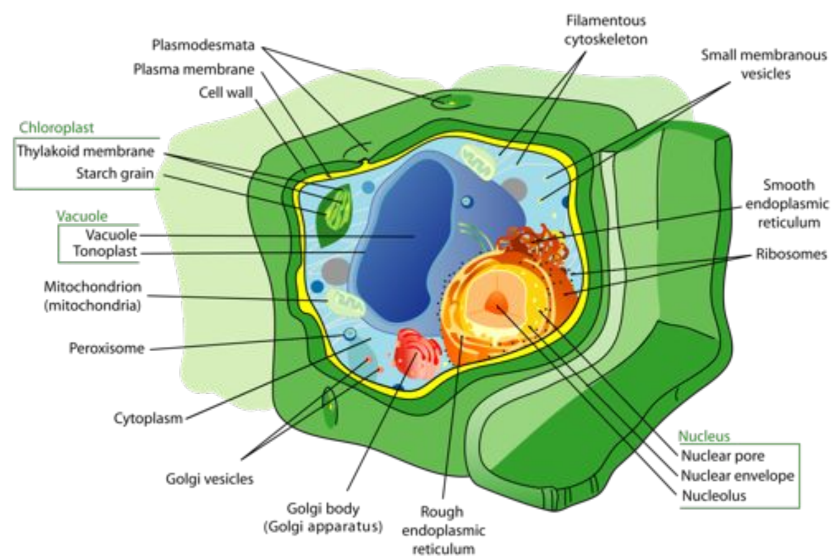
Prokaryotes vs. Eukaryotes

The increased compartmentalization of eukaryotes leads to increased complexity and efficiency.

Note: To Scale.

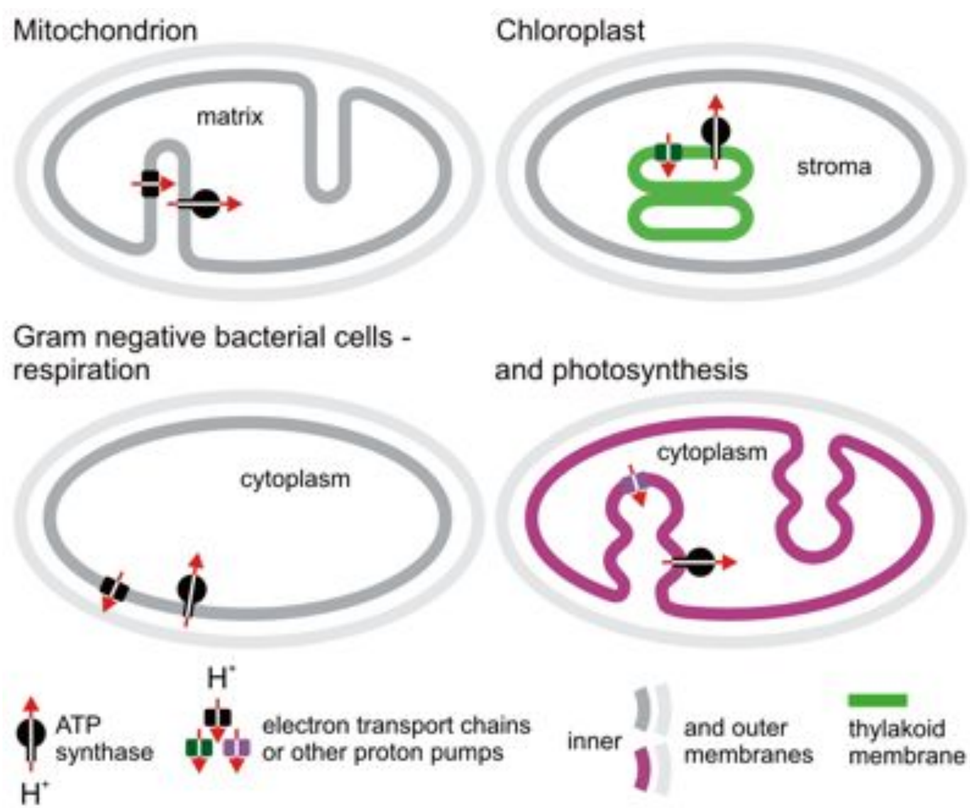






But Don't Forget!

Some prokaryotes are able to carry out aerobic cellular respiration, and photosynthesis. They have adapted their cell membrane into quasi-compartments.



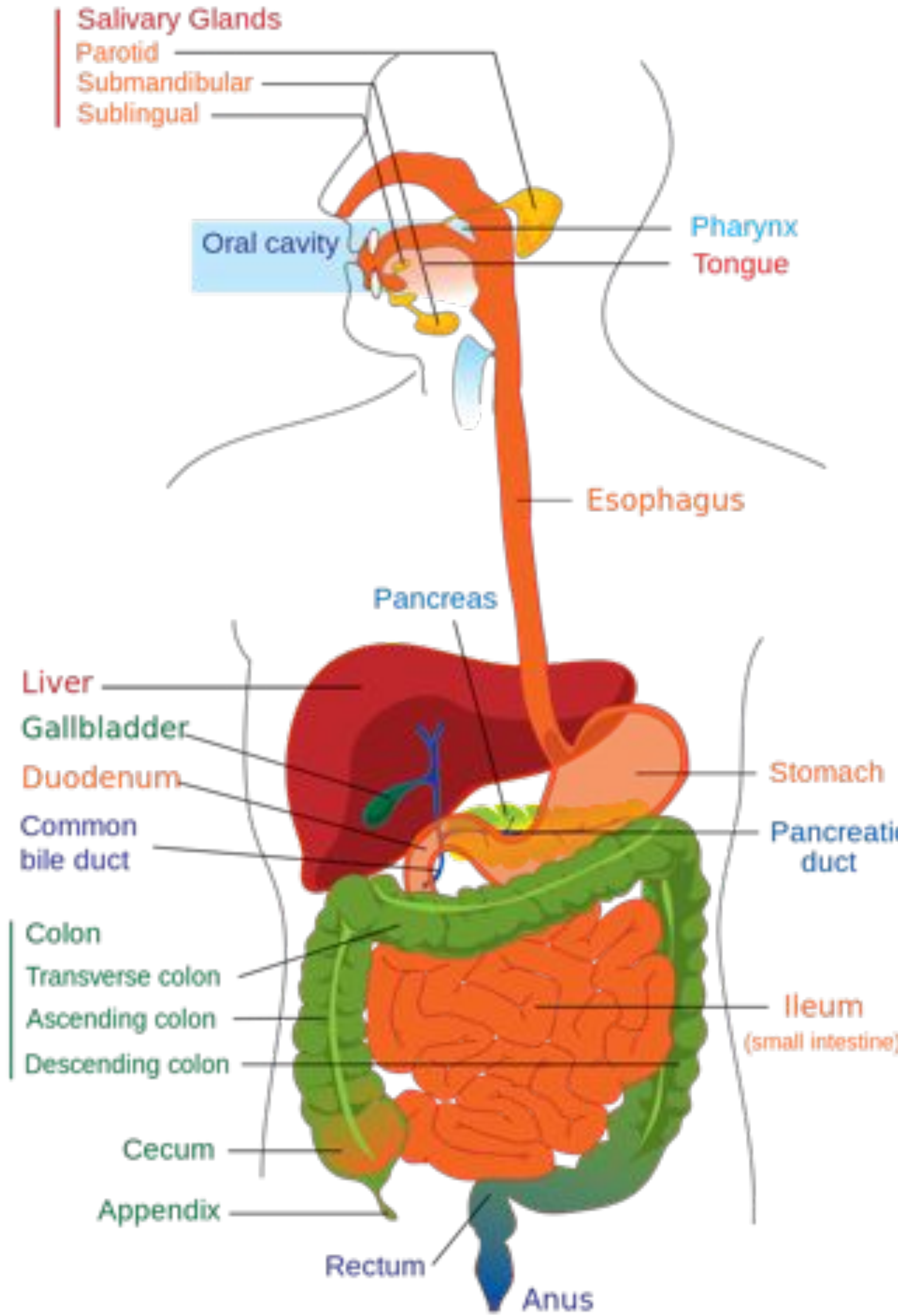
Multicellular Compartmentalization

Multicellular organisms have compartmentalized **organs** and **organ systems** to increase their efficiency.

All systems work together to accomplish tasks, including metabolism.

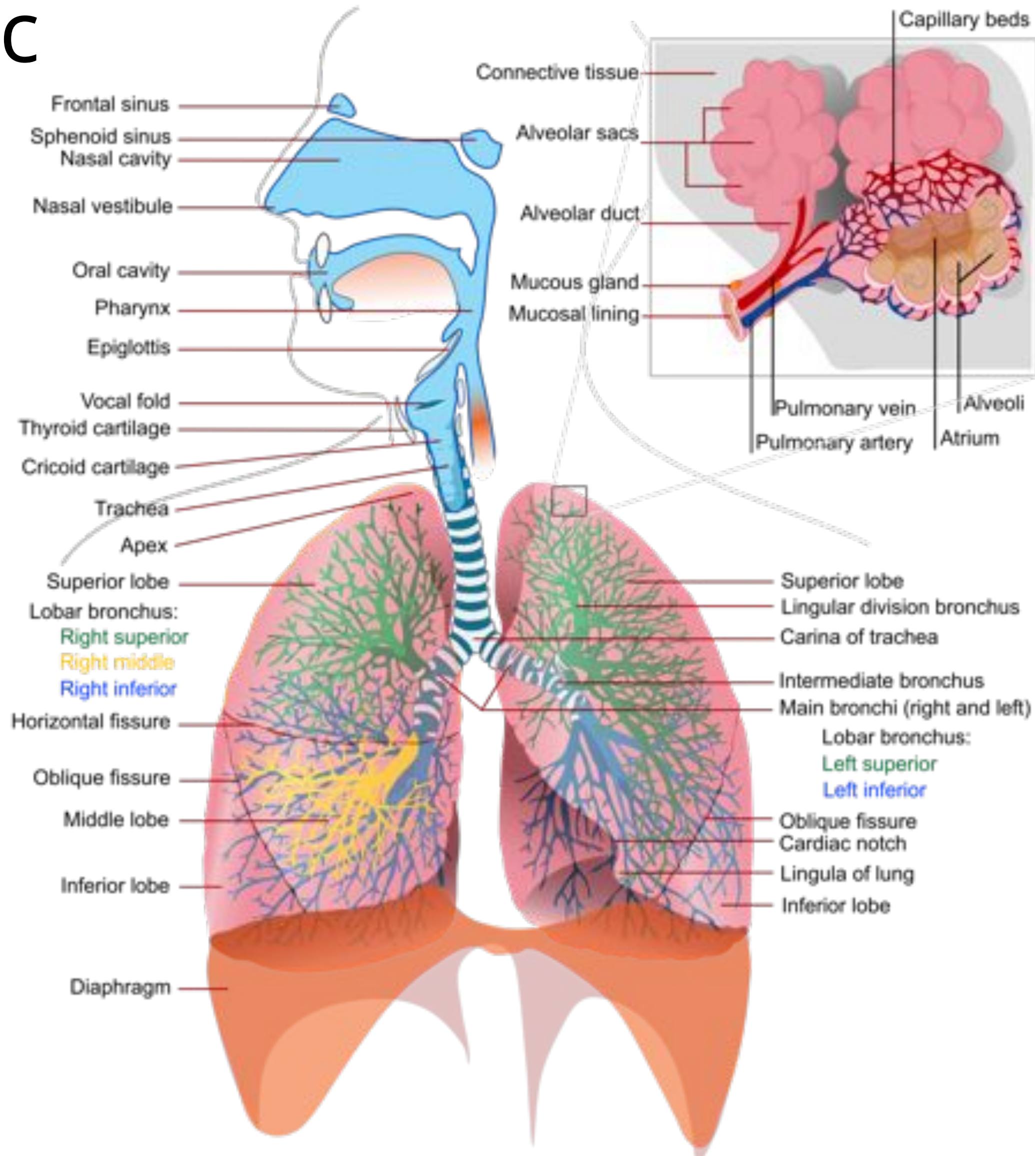
Digestive System

Converts and absorbs complex food molecules in to metabolic inputs (ex. starch into glucose)



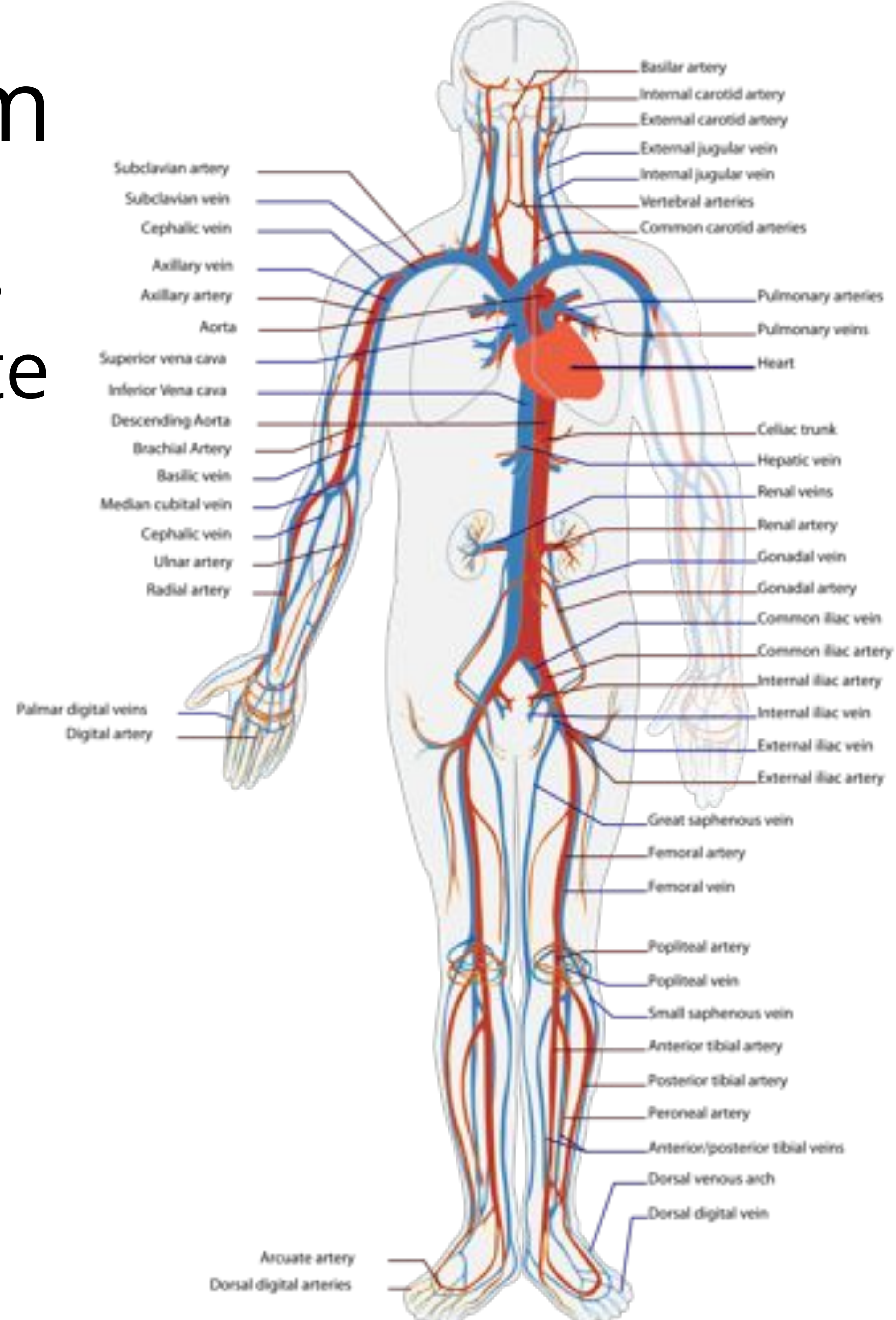
Respiratory System

Exchanges metabolic gases (oxygen and carbon dioxide)



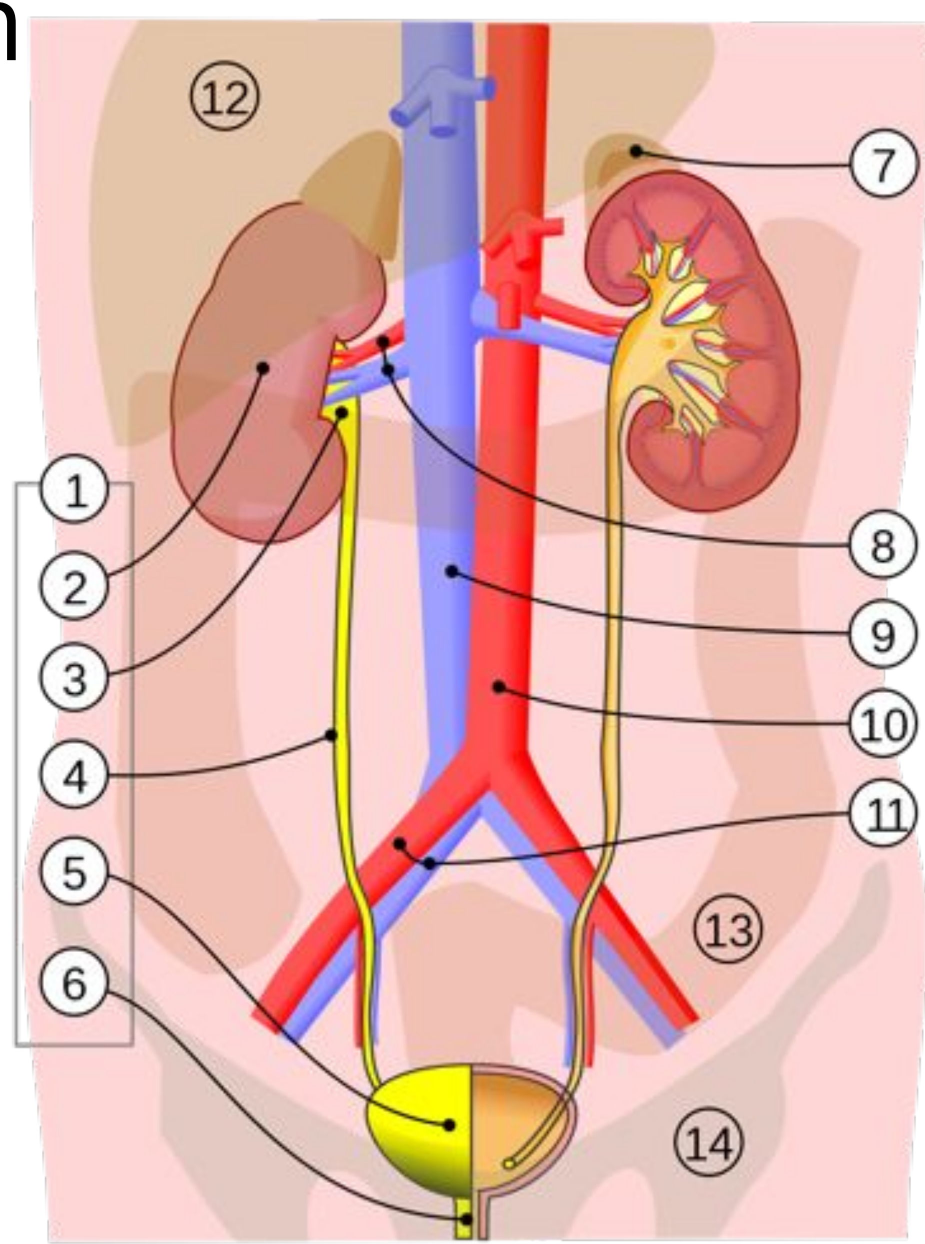
Circulatory System

Delivery of nutrients and removal of waste products from the cells of the body



Excretory System

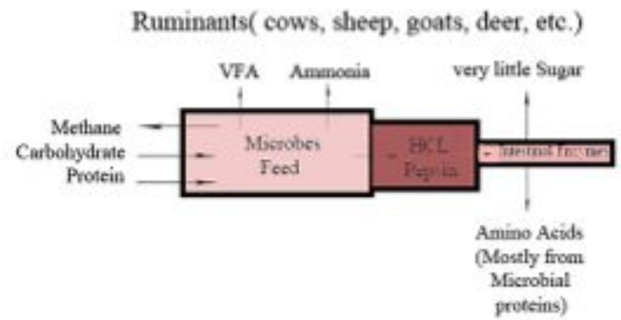
Removal of metabolic waste products (water and nitrogenous wastes) from the body.

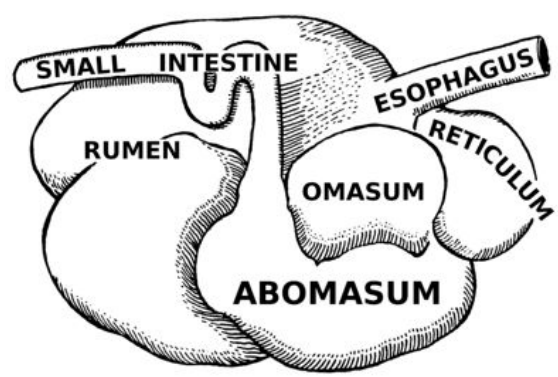


Microbial Cooperation

Communities of microbes will use a diversity of functions to cooperatively accomplish metabolic tasks.

Ex. Animal Rumen Communities





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