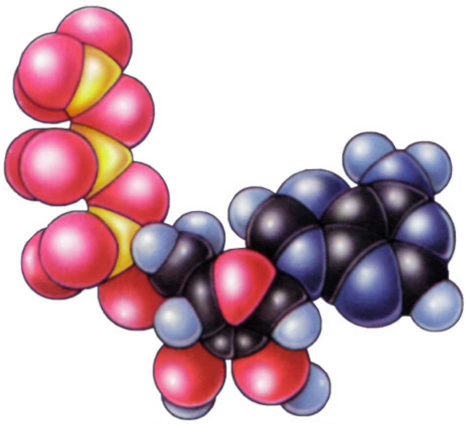
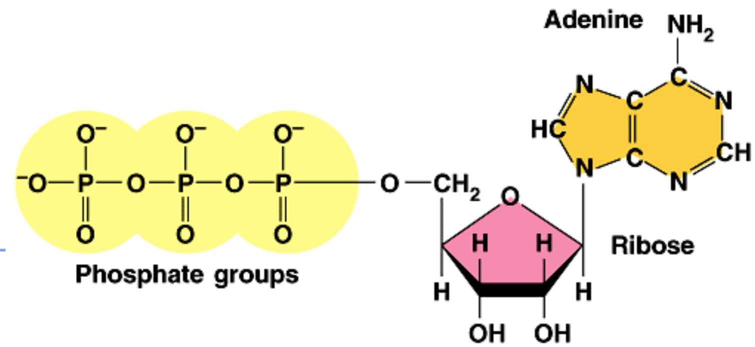
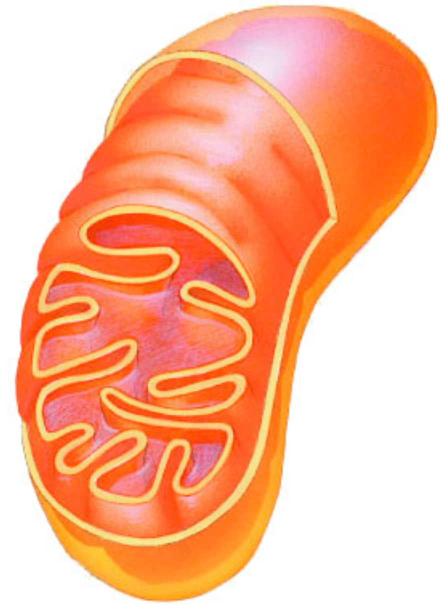
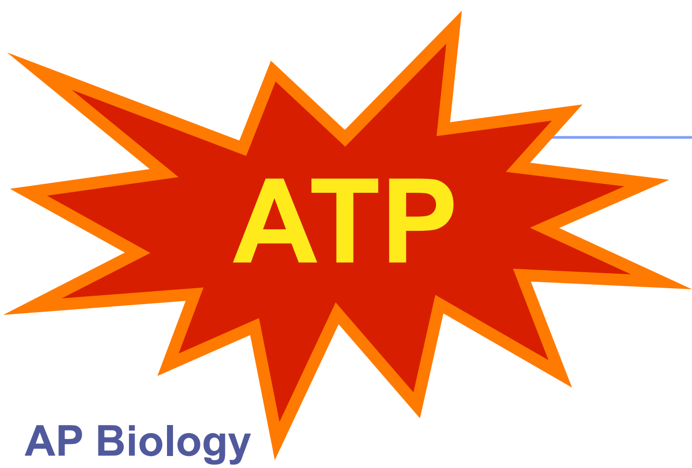




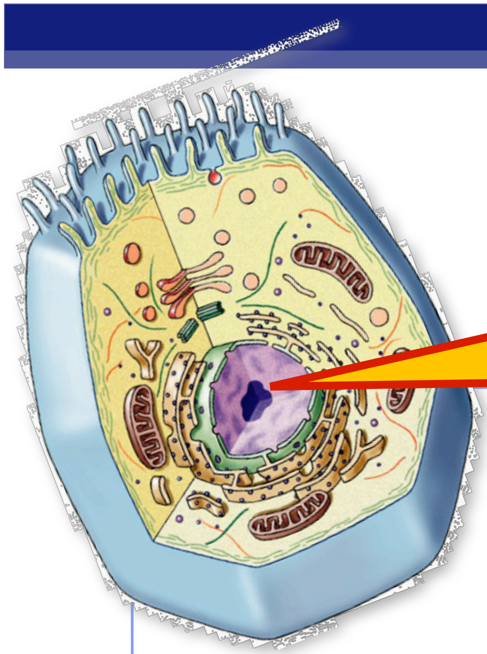


Ch.9: Cellular Respiration

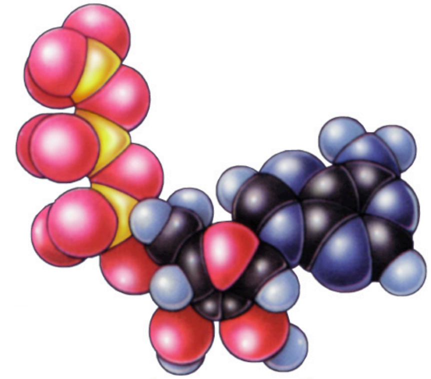
Harvesting Chemical Energy



AP Biology

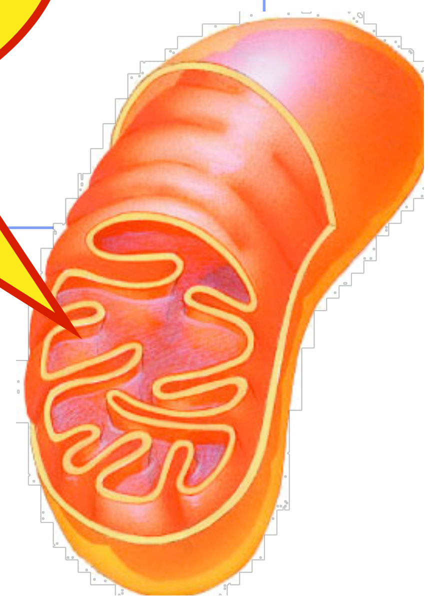


What's the point of Cellular Respiration?



The point is to make ATP!

ATP



Living Organisms Process Energy

- **Living cells require energy from outside sources to perform work.**
  - **The three types of work cells perform include:**
    1. **Transport work:** **Pumping *(actively transporting)* solutes against their concentration gradients across membranes**
    2. **Mechanical work:** **Moving objects in the cell such as moving chromosomes during cell division, beating cilia/flagella, transporting transport and secretory vesicles along microtubule and actin fibers, contracting the protein fibers in muscle cells etc..**
    3. **Chemical work:** **Anabolic *(synthesis)* processes like building macromolecules and other higher energy molecular products in chemical reactions**

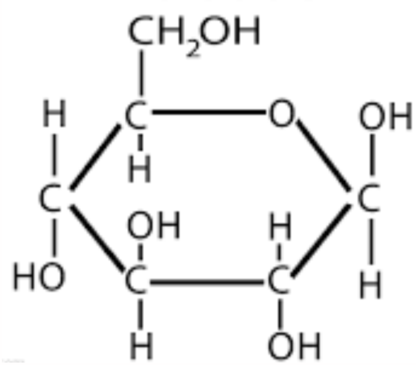
Living Organisms Process Energy

energy

- **Potential energy, known as chemical energy, is stored in <u>high-energy organic molecules</u>:**
  - **<u>Carbohydrates</u>, including monosaccharides like glucose and polysaccharides like starch and glycogen, both made up of glucose**
  - **<u>Lipids</u>, including fats, which are made up of a glycerol and three fatty acids**
    - **High-energy organic molecules contain multiple <u>high energy carbon-to-carbon and carbon-to-hydrogyen covalent bonds</u> that store chemical energy due to the location of electrons in the bond**
      - **As we will see carbon-to-oxygen bonds are <u>low</u> in stored potential "chemical" energy**

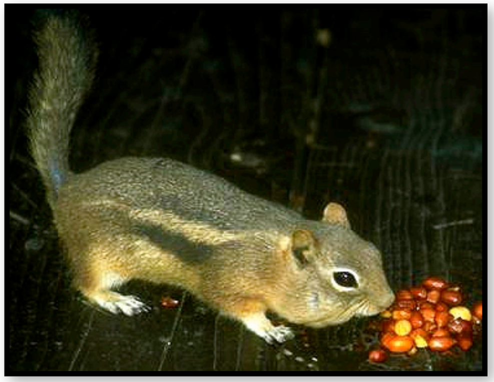
Fat

Glucose



Harvesting stored chemical energy

- Energy is stored in (high-energy) organic molecules
  - Ex: carbohydrates, fats, proteins
- Chemoheterotrophs (often called *heterotrophs or consumers*) are organism that...
  1. cannot conduct photosynthesis (to make glucose) and
  2. get their carbon (and other elements) AND their needed energy from organic compounds
     - Organic molecules made up part of the nutrients consumed in their food *(other nutrients include necessary ions and H_2O)*



The energy stored in organic molecules *ultimately* come from the SUN!

- During the biochemical process known as photosynthesis, high-energy, organic sugars (glucose, $C_6H_{12}O_6$) and O_2 (a waste product) are generated from CO_2 and H_2O.

$$6\,CO_2 + 6\,H_2O \longrightarrow C_6H_{12}O_6 + 6O_2$$

$6\,CO_2$	$6\,H_2O$	$C_6H_{12}O_6$	$6O_2$
Carbon dioxide from the atmosphere	Water	Organic matter	Oxygen

- During photosynthesis:
  - RADIANT ENERGY is converted into CHEMICAL ENERGY
    - Chemical energy is stored in the covalent bonds of the high energy organic molecules made

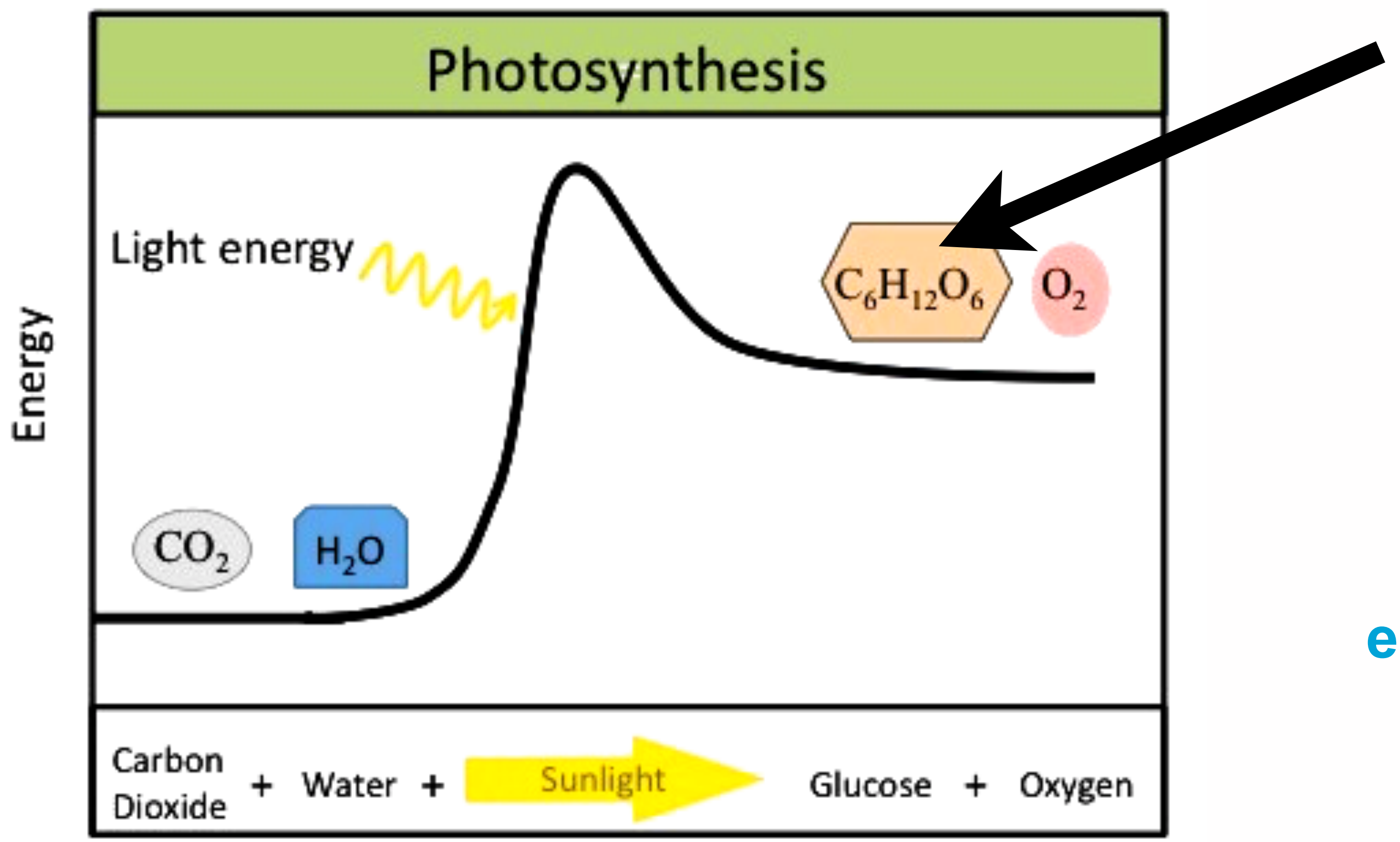
Photosynthetic Organisms are Called Producers

- In Photosynthetic Bacteria (like Cyanobacteria)
  - Photosynthesis takes place in the cytoplasm and extensions of the plasma membrane

- In Photosynthetic Eukaryotes (like Plants and some Protists, like Algae)
  - Photosynthesis takes place in the chloroplast organelle
- Photosynthesis is anabolic: it results in synthesis of glucose.
  - It is an endergonic process since the products combined (the sugar and oxygen) have more Gibbs free energy stored in their chemical bonds than the reactants (the carbon dioxide and water) did $(G_{final} - G_{initial} = +\Delta G)$

Photosynthesis is an Endergonic Process

- The energy needed to drive <u>photosynthesis</u> is obtain from the <u>sun</u> (from radiant/solar energy)



<u>Glucose</u> is a High Energy Organic Product (contains stored potential energy called <u>chemical energy</u>)

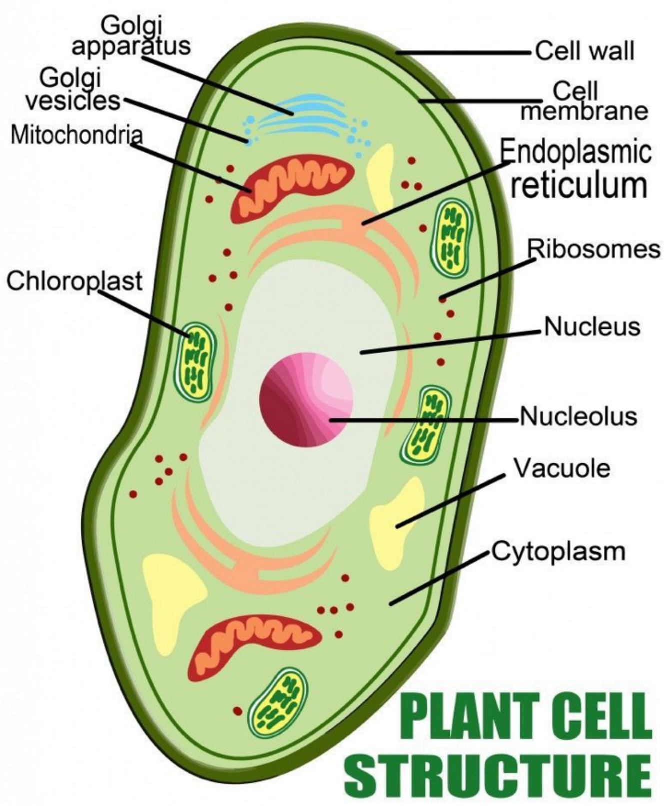
Chemical Energy Is Transferred from High-Energy Organic Molecules onto ATP through Cellular Respiration

- Cells release the **ENERGY** stored high-energy organic molecules (like glucose) and transfer it onto ATP (ATP provides the cell with the energy needed for doing work).
  - Energy stored in organic molecules is released (and stored on ATP) using the biochemical pathway known as cellular respiration
    
    - In some species/cells, cellular respiration chemistry uses O_2 (aerobic respiration)
    
    - In other species/cells, it can be done without O_2 (either via anaerobic respiration or fermentation)

AP Bio

Energy is Stored on ATP as a Result of Cellular Respiration

- In prokaryotes, cellular respiration takes place in the cytoplasm and plasma membrane
- In eukaryotes, cellular respiration takes place in the cytoplasm and mitochondria
  - Plants, fungi, animals, & protists all have mitochondria and engage in cellular respiration.
    - Photosynthetic organisms do cellular respiration too!
      - Including organisms like plants, cyanobacteria, algae (protist)



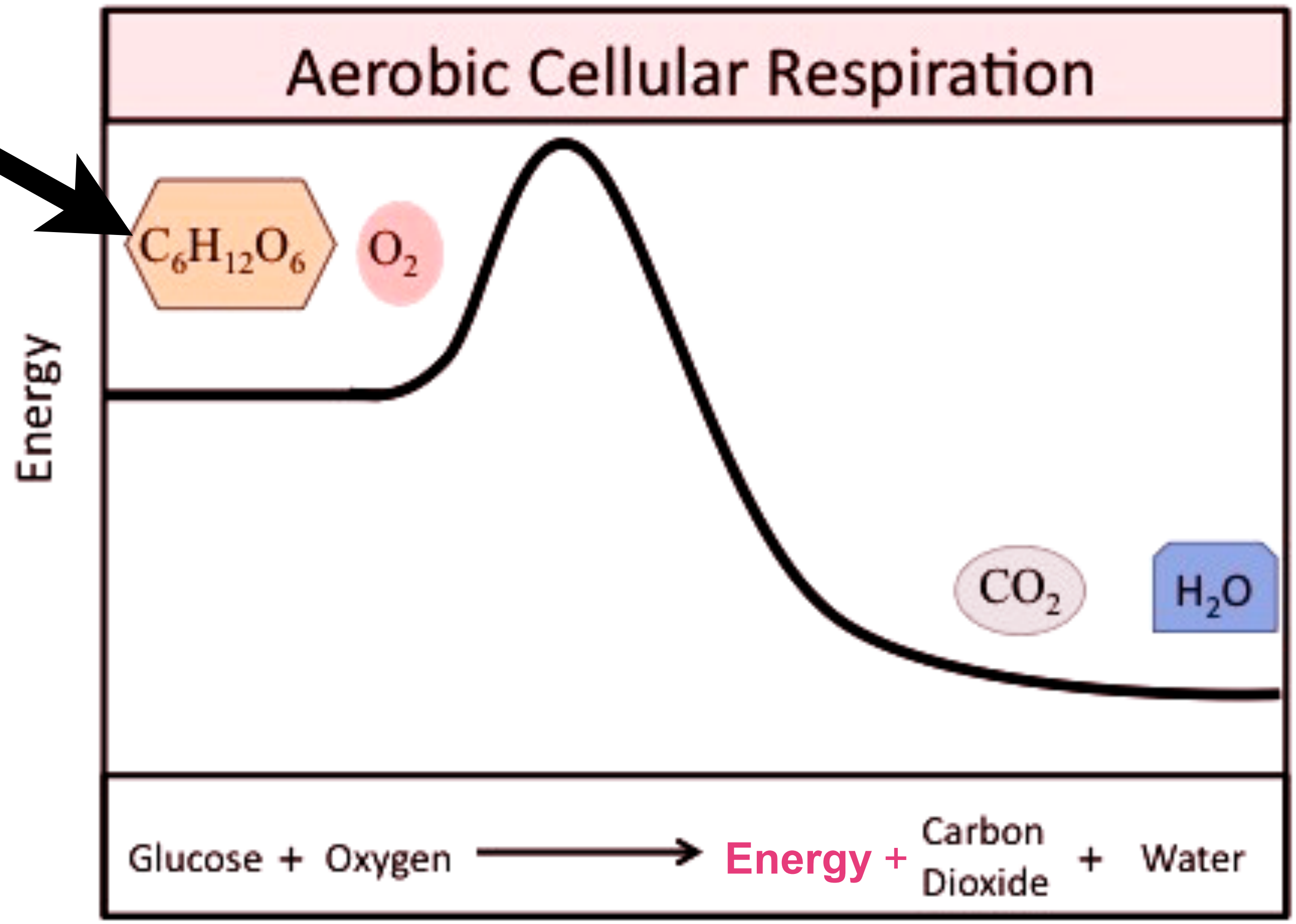
Cellular Respiration is an Exergonic Process

- **During (aerobic) cellular respiration, high-energy, organic molecules are broken down (oxidized) with the help of O_2 into low energy CO_2 and H_2O.**
  - **<u>Cellular Respiration is catabolic</u>: it results in breakdown of glucose (a high-energy organic molecule).**
    - **It is an <u>exergonic process</u> since the products (carbon dioxide and water) have less Gibbs free energy stored in their chemical bonds than the reactants combined (organic molecule and oxygen) did ($G_{final} - G_{initial} = -\Delta G$)**

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

Cellular Respiration is an Exergonic Process

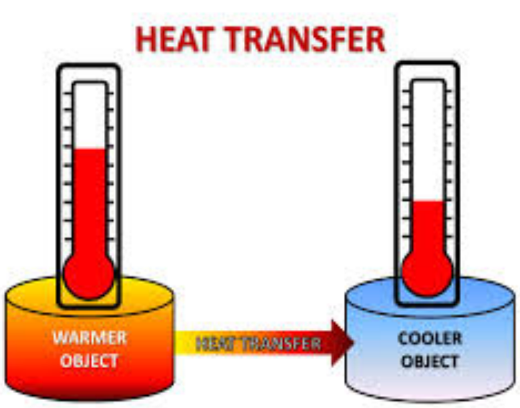
High Energy Organic Reactant (contains potential energy that will be used to build ATP molecules from ADP + Phosphate)



The energy released through cellular respiration will be stored on ATP, some being lost as heat

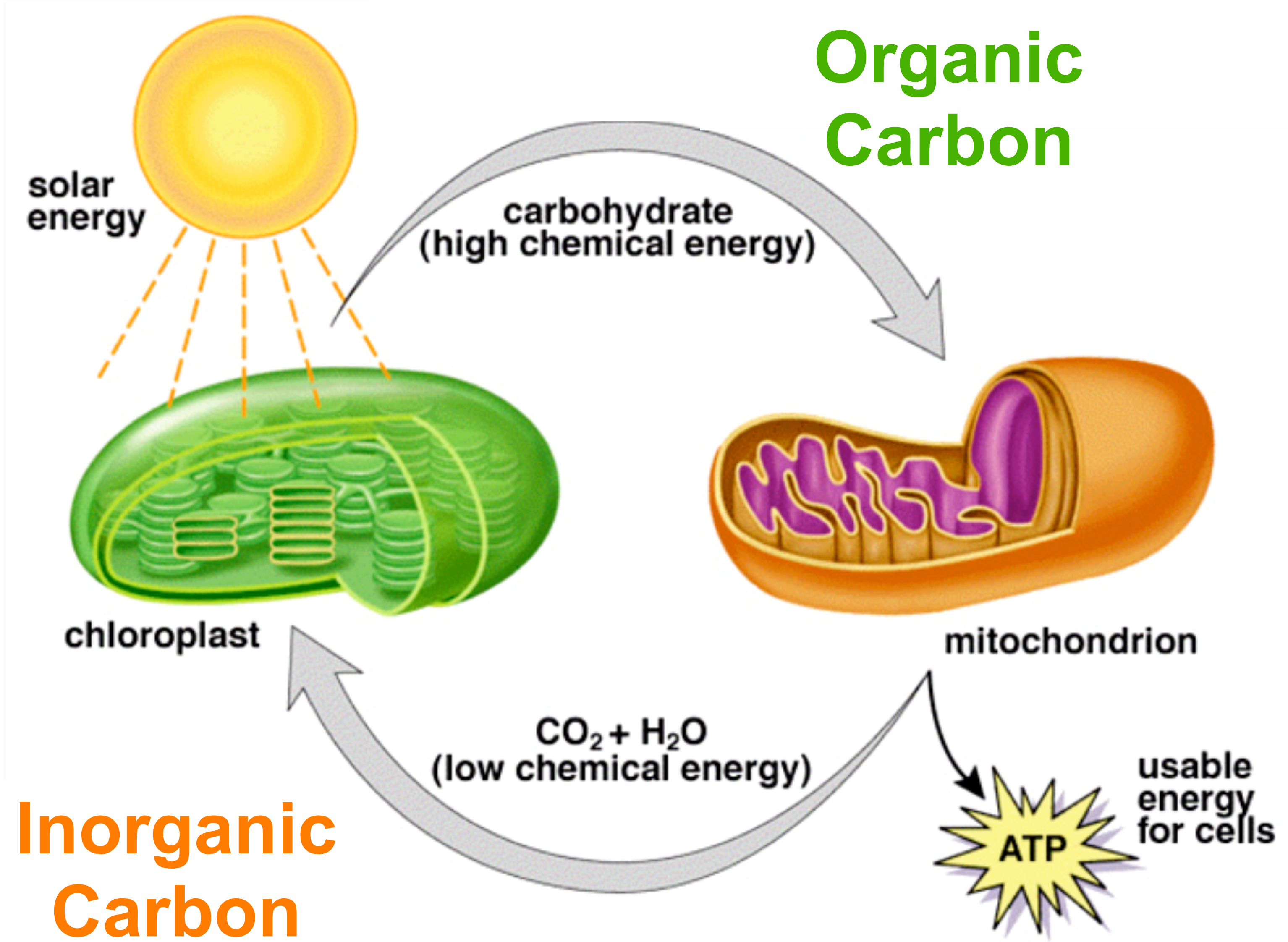
Carbon Continually Cycles Between Inorganic & Organic Forms

- **Photosynthesis** converts **carbon dioxide** and water into oxygen and **glucose**.
  - O_2 is a waste product of photosynthesis, which is later used by cellular respiration
- **Cellular respiration** converts oxygen and **glucose** into water and **carbon dioxide**.
  - H_2O and CO_2 are waste products of cellular respiration

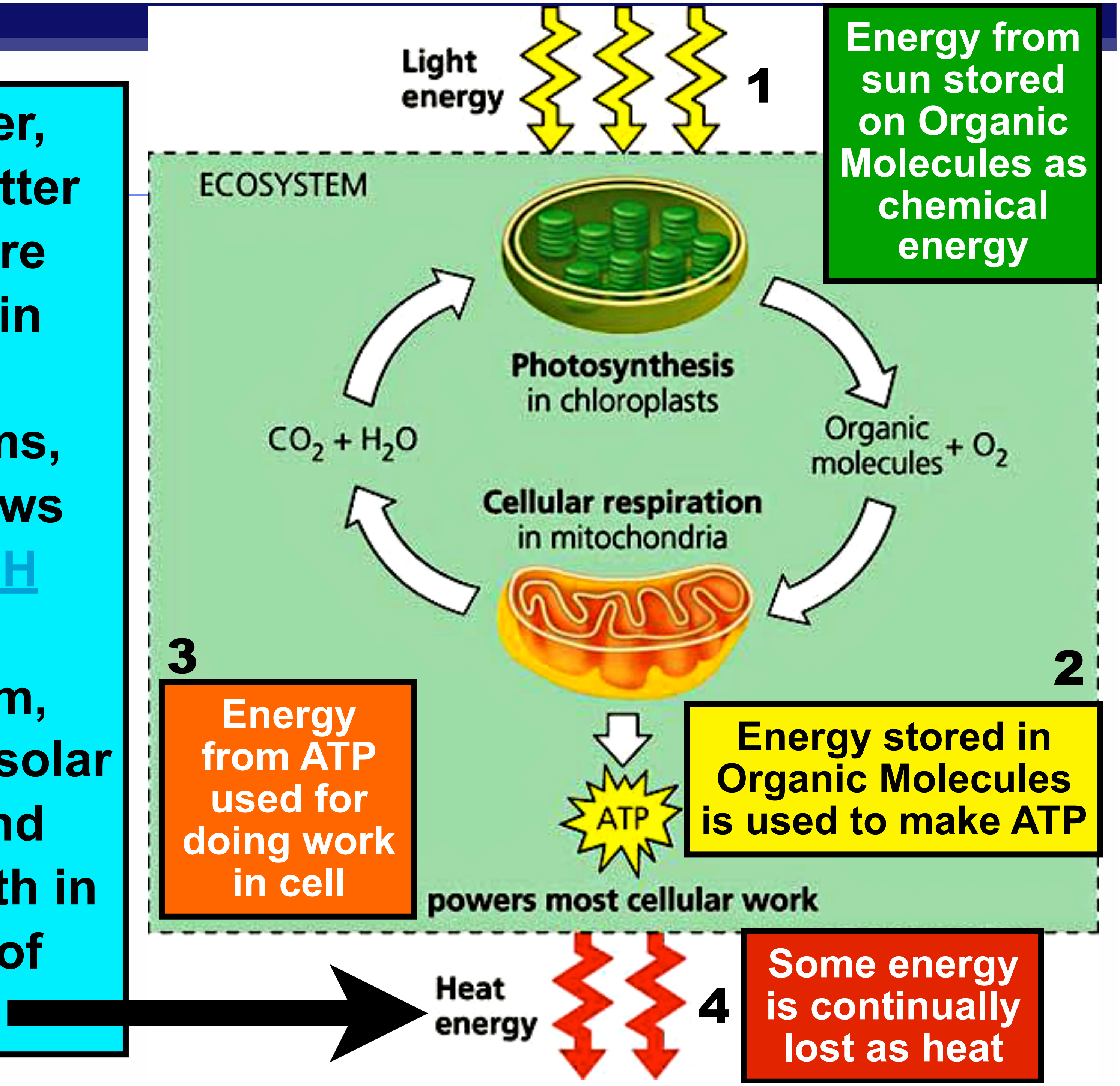


Though some energy that gets released from organic molecules is lost to the cell, and eventually environment surrounding the cell, as **HEAT**, the rest of the energy will get stored on **ATP**

Carbon Continually Cycles Between Inorganic & Organic Forms



Remember, though matter *(atoms)* are recycled in Earth's ecosystems, energy flows THROUGH Earth's ecosystem, entering as solar energy and leaving Earth in the form of HEAT.



Cellular Respiration is an Exergonic Process

- During cellular respiration, the chemical energy that is released from the organic molecule is stored on ATP molecules
  - Making ATP from ADP + Phosphate (either inorganic or organic phosphate) is an endergonic process
    - The chemical energy released from breaking down an organic molecule during cellular respiration drives the endergonic process of phosphorylating ADP into ATP, which has more Gibbs Free energy than ADP + P had.

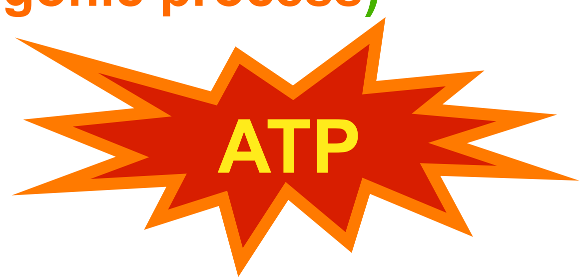
$$\text{energy} + \text{ADP} + \text{P}_i \leftrightharpoons \text{ATP} + \text{H}_2\text{O}$$

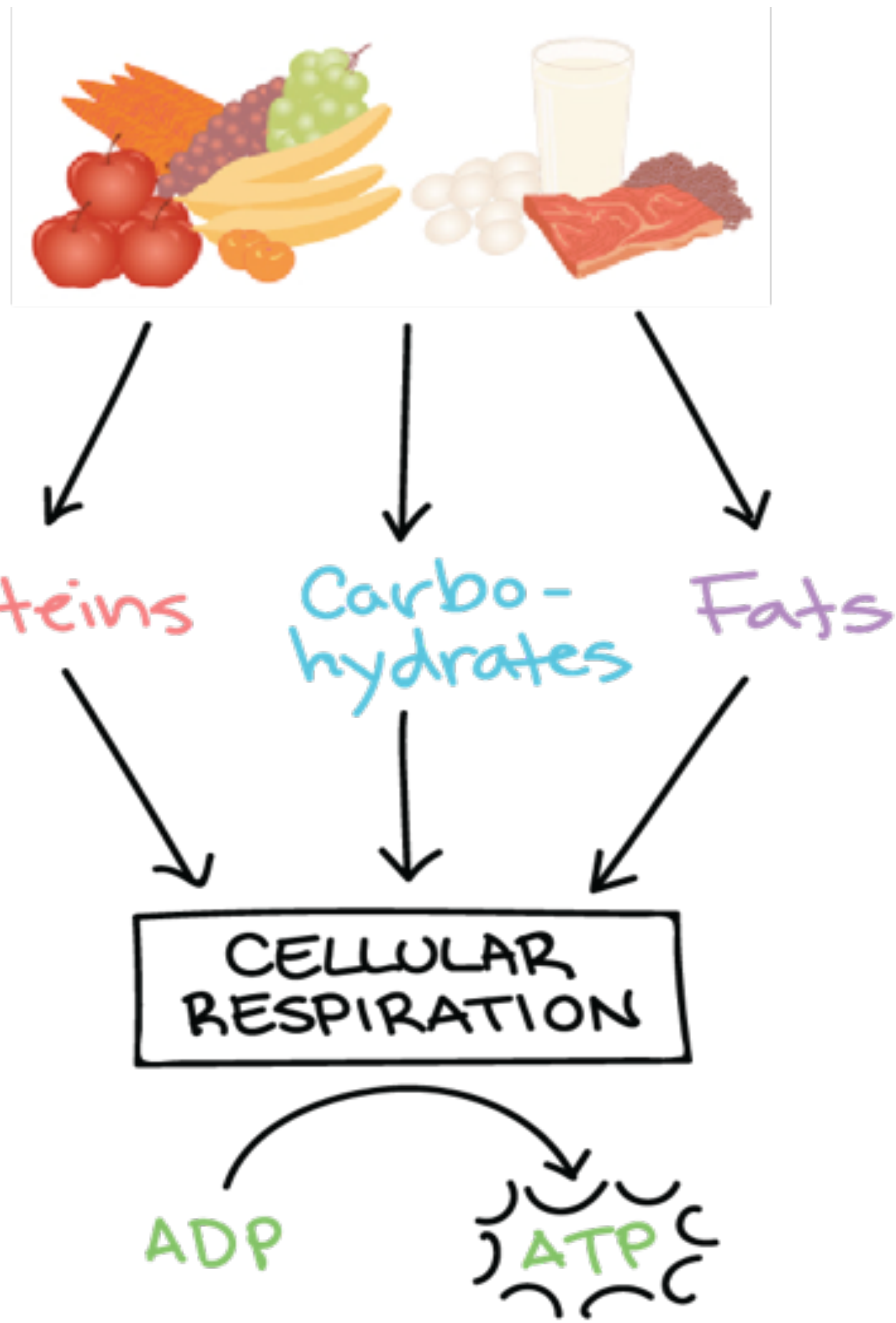
- The ATP is made by ENERGY COUPLING the exergonic cellular respiration to the endergonic ATP synthesis

The Energy Currency in Cells

- To gain the energy needed for work:
  - Animals ingest high-energy high-energy organic molecules
    - carbohydrates, lipids, (proteins) - macromolecules in food are digested and monomers absorbed into cells
  - Plants produce high-energy high-energy organic molecules
    - convert light energy into stored chemical energy by building high-energy organic molecules like sugars via photosynthesis
  - Next, cells break down high-energy organic molecules to release the stored energy and transfer it to molecules (ATP) that are easy to use in the cell.
    - Cellular Respiration (catabolic, exergonic process) is coupled to the ATP synthesis (an anabolic, endergonic process)

- ATP is the short term energy storage molecule in the cell



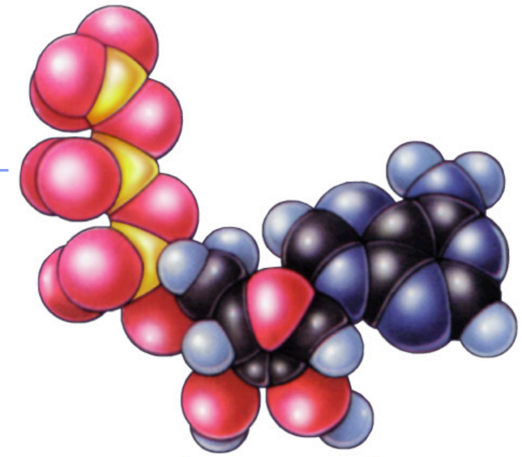

Proteins
Carbo-
hydrates
Fats
CELLULAR
RESPIRATION
ADP
ATP

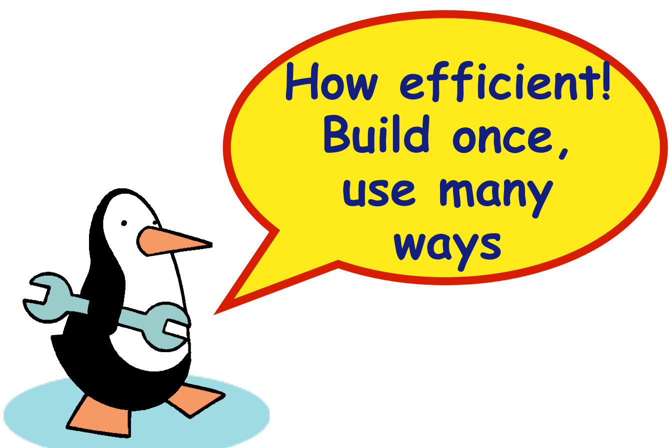
The energy stored on reactive ATP molecules is used for doing work

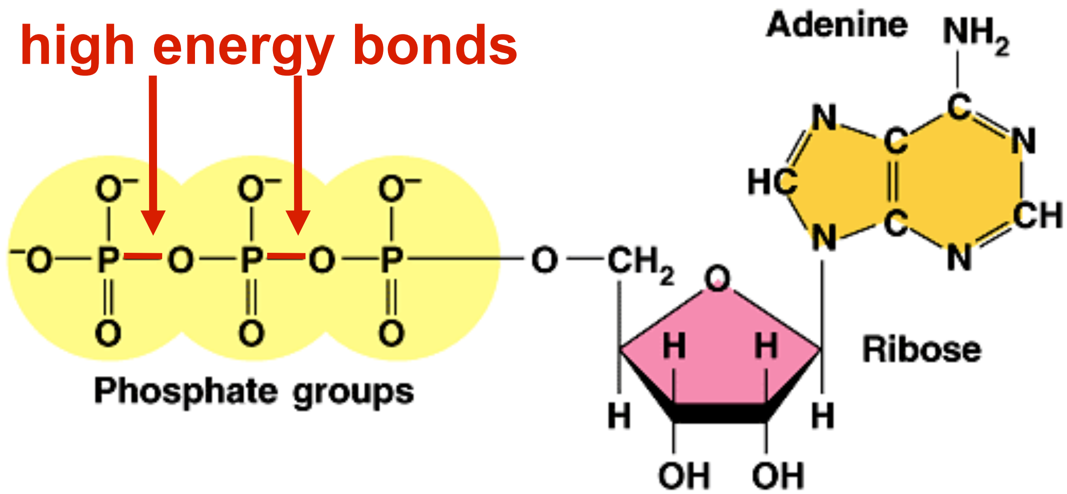
- What do organisms need energy for?
  - synthesis
  - reproduction
  - body and cellular movement
  - active transport in cells
  - temperature regulation
  - growth and repair etc...

ATP

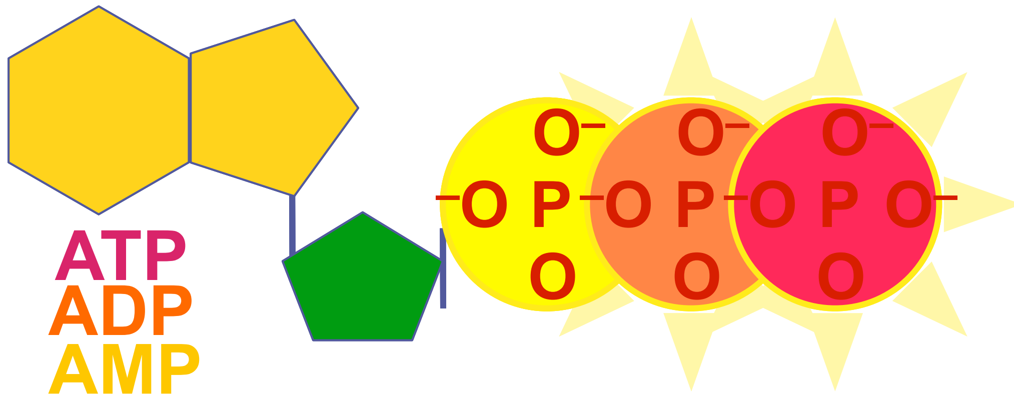
- <u>Adenosine Triphosphate</u>
  - modified RNA nucleotide
    - nucleotide =
      adenine + ribose + P_i → <u>AMP</u>
    - AMP + P_i → <u>ADP</u>
    - ADP + P_i → <u>ATP</u>
  - Adding phosphates is an <u>endergonic process</u>







How does ATP store energy?

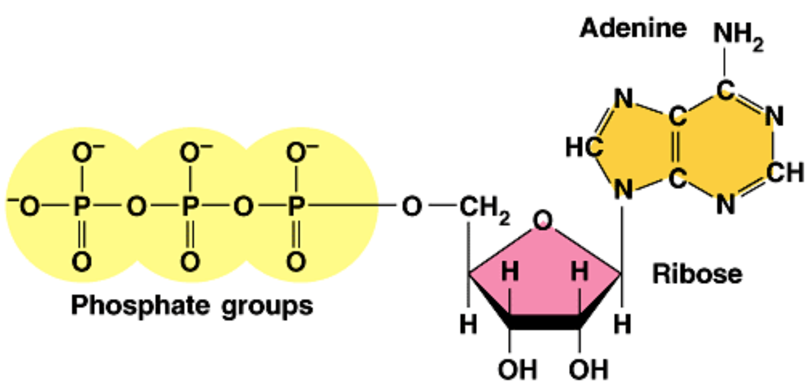


- Each negative PO_4 is more difficult to add
  - stored potential energy is found in each unstable Phosphate-to-Phosphate bond
    - the most energy is stored in last (terminal) P-P bond
    - the 3rd Phosphate is hardest to keep bonded to molecule
- Bonding of negative P_i groups is unstable
  - P_i groups can be removed easily by hydrolysis, releasing ENERGY

Instability of its P-P bonds makes ATP an excellent energy donor

Energy is Stored on ATP

- Organic compounds possess potential energy as a result of the arrangements of atoms and the location of electrons.
- Compounds capable of exergonic reactions can act as fuels (sources of energy for the cell).
  - In cellular respiration, cells break down complex molecules rich in chemical energy into simpler waste product with less energy.
    - The energy released, stored on ATP, can be used to do work.

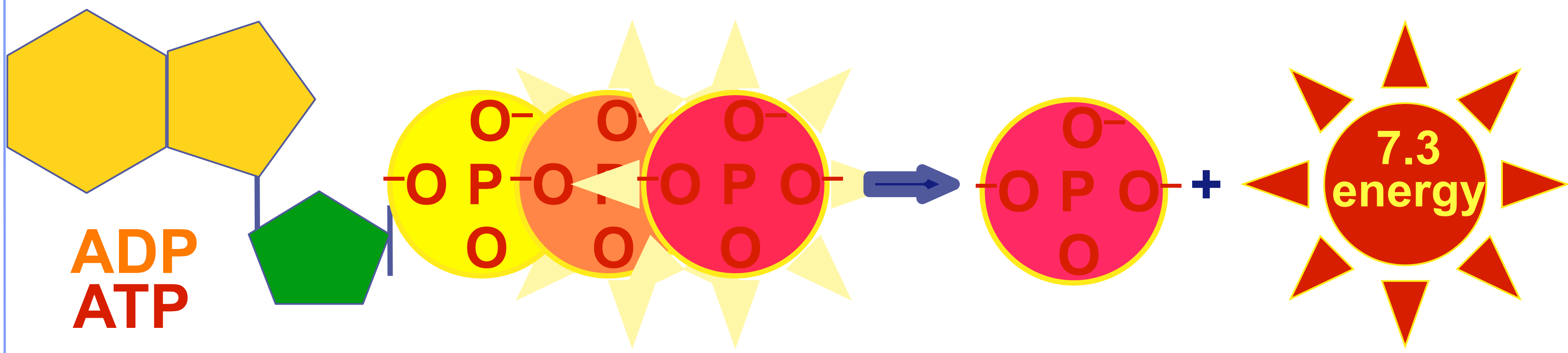


respiration

glucose + oxygen → water + carbon dioxide (+ ENERGY)

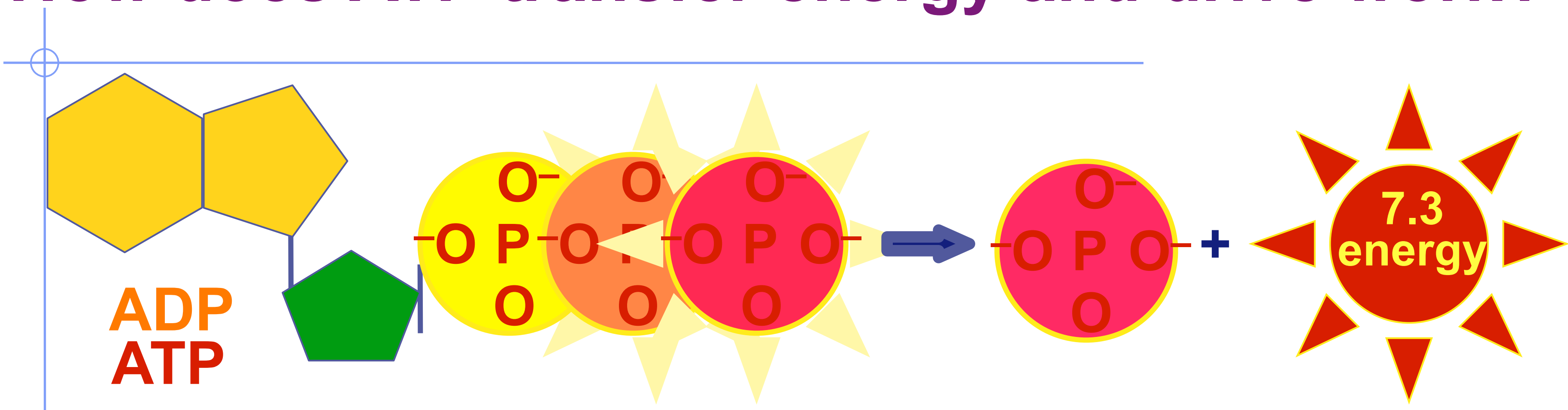
$C_6H_{12}O_6$ + $6O_2$ → $6H_2O$ + $6CO_2$ (ATP + HEAT)

How does ATP transfer energy and drive work?



- Each phosphate group is negatively charged.
  - Because like charges repel, the crowding of negative charge in the ATP tail contributes to the potential energy stored in ATP.
- Hydrolysis of ATP → ADP + P_i
  - releases energy
    - $\Delta G = -7.3$ kcal/mol
- This energy can fuels other reactions (provides the energy needed to make endergonic reactions take place)

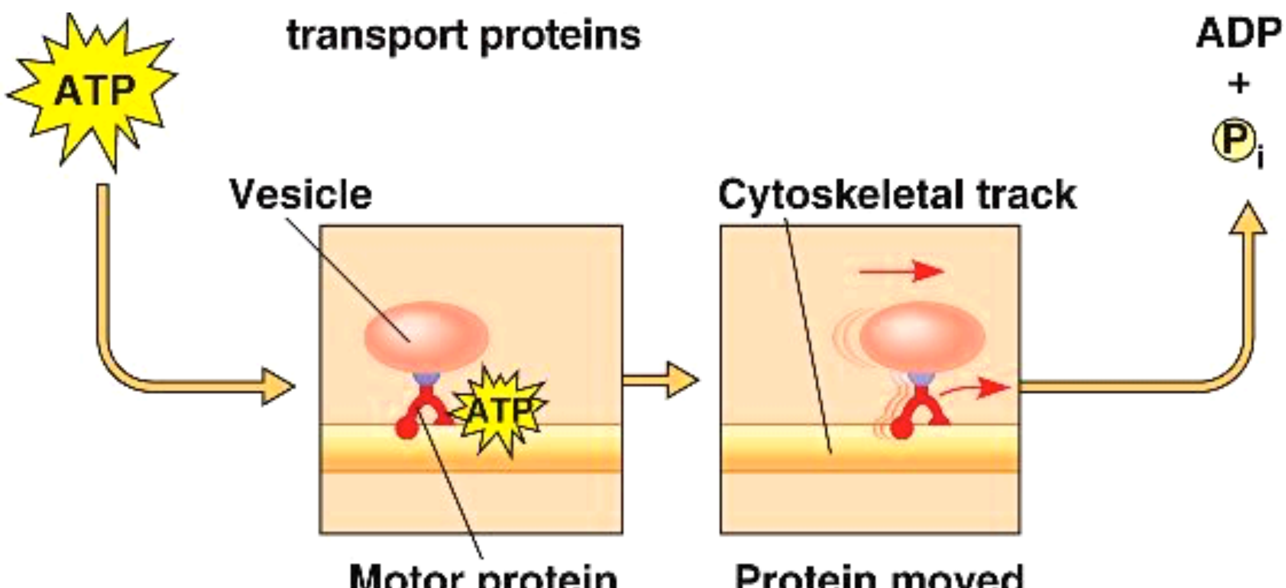
How does ATP transfer energy and drive work?



1. **Hydrolyzing ATP temporarily non-covalently attached to a nearby proteins can cause the protein to change shape and thus change its activity/function, driving work.**
2. **Other times, doing work utilizing the energy stored on ATP involves protein phosphorylation**
   - **The released P_i from ATP can be temporarily covalently bonded (transferred) to another protein causing the protein to change shape and thus change their activity/function, driving work.**
     - **Specific enzymes (kinases) enable this transfer to occur.**

Doing cellular mechanical work involves non-spontaneous processes that need energy to proceed

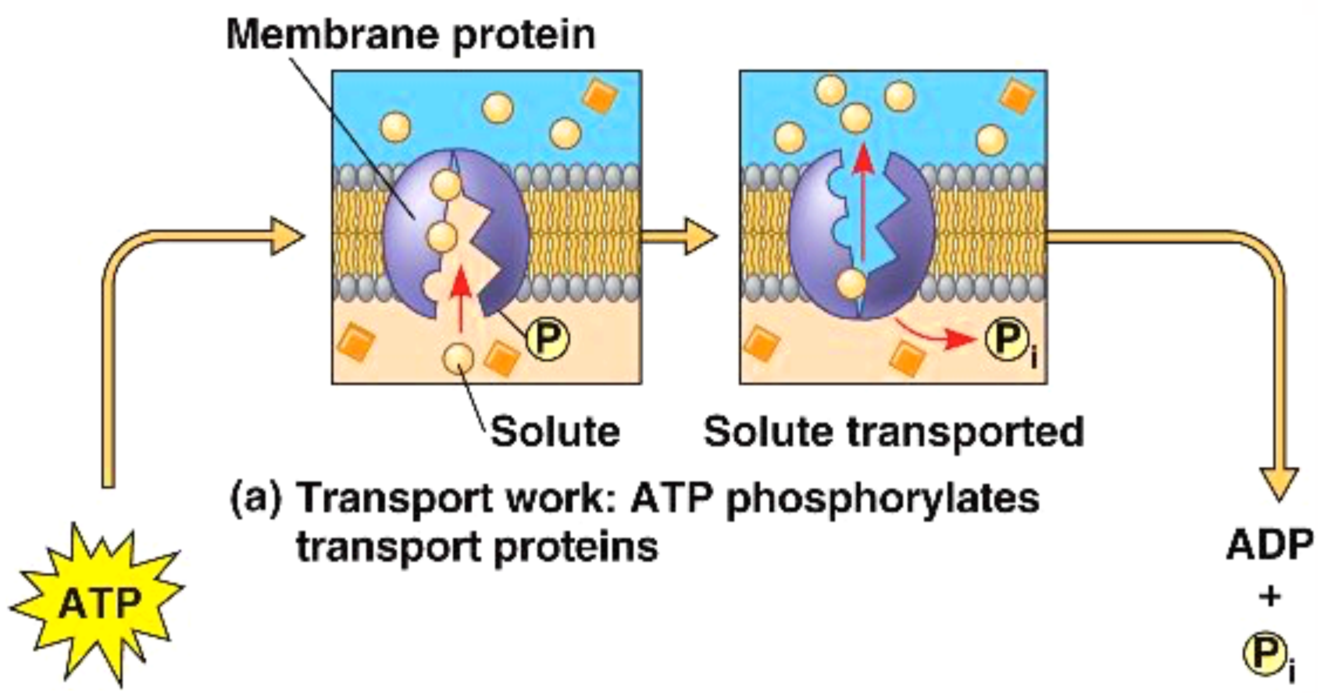
- When ATP non-covalently docks onto a motor protein, (like kinesin, which is a motor protein that pulls transport vesicles along microtubules), the motor protein may change shape.
- ATP, now docked onto the protein, is subsequently hydrolyzed into ADP and an Inorganic Phosphate (P_i), the ADP eventually falling off the motor protein.
  - This process helps motor proteins undergo shape changes that allow them to "walk" down microtubules while puling transport vesicles along.



(b) Mechanical work: ATP binds noncovalently to motor proteins, then is hydrolyzed

Doing cellular active transport work involves non-spontaneous processes that need energy to proceed

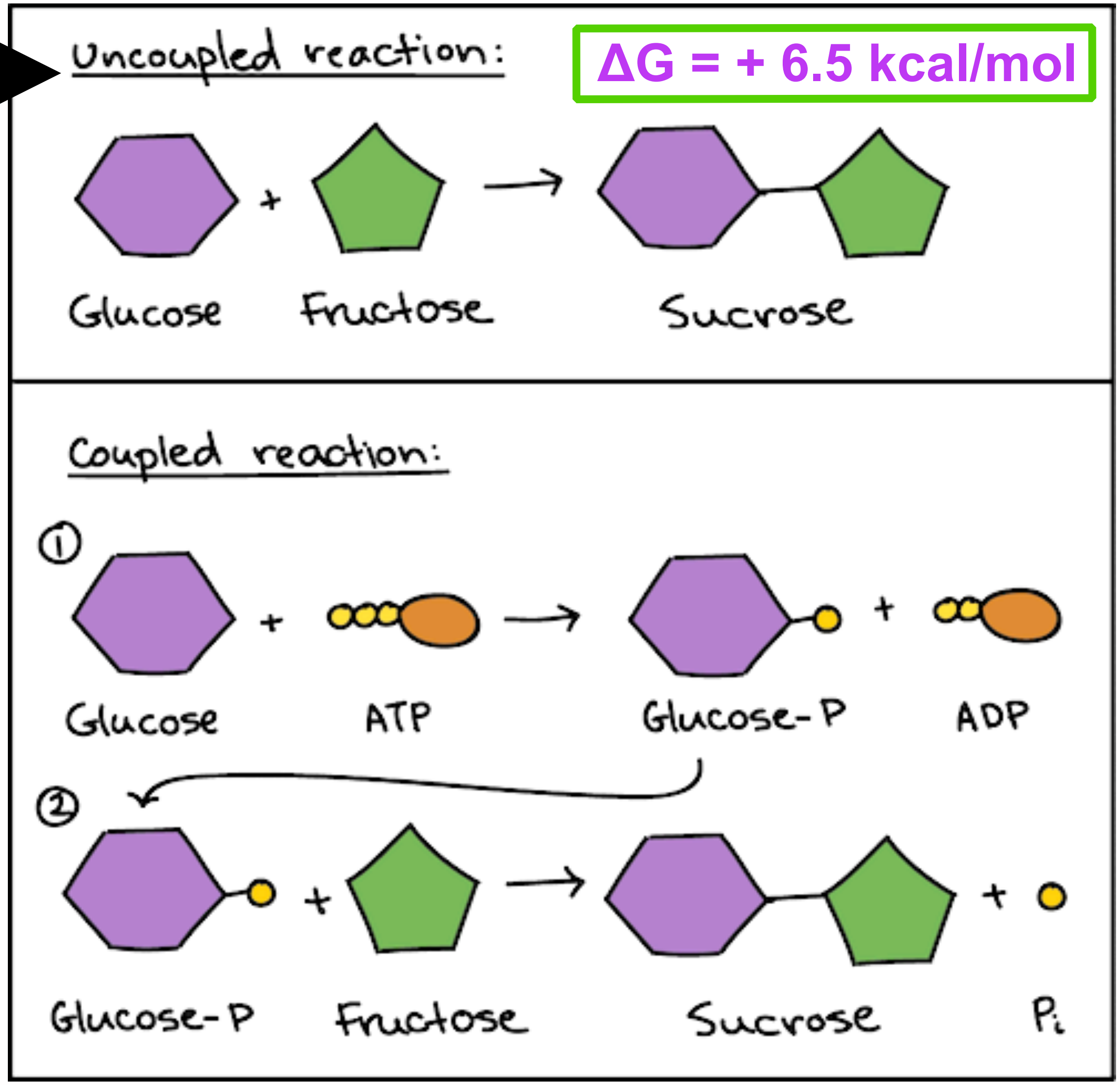
- When a phosphate group from ATP is covalently attached to another protein (when a protein gets phosphorylated), the protein changes shape.
- When the phosphorylated protein is later de-phosphorylated, it changed back to its original shape.
  - This process helps carriers actively transport solutes against their concentration gradients.



(a) Transport work: ATP phosphorylates transport proteins

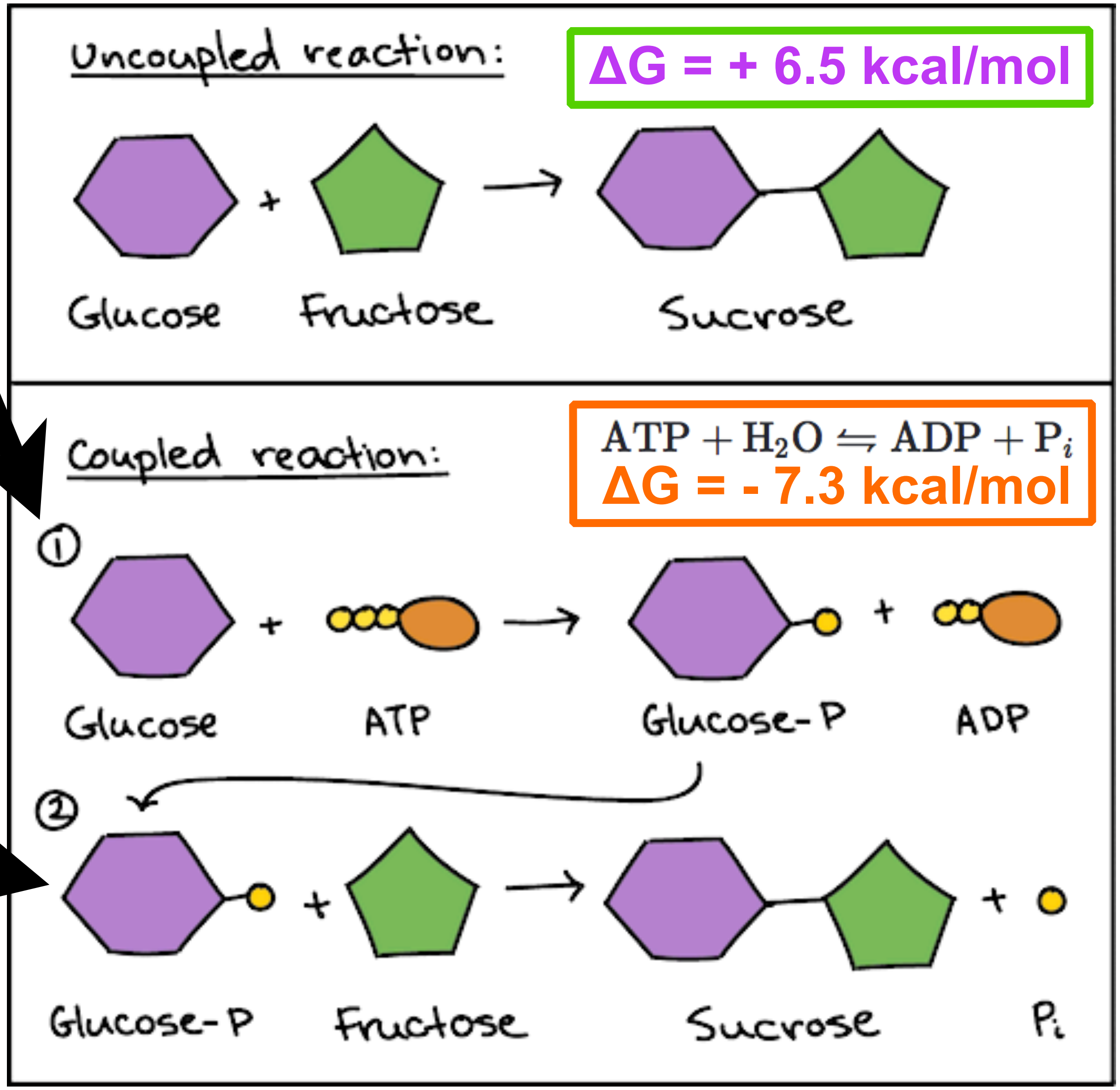
Doing cellular chemical work involves non-spontaneous processes that need energy to proceed

- In an **endergonic chemical reaction**, the product(s) will contain more Gibbs Free energy than the reactants.
  - A source of energy is needed to supply this needed energy, even when the presence of an enzyme lowers the overall activation energy of the reaction.



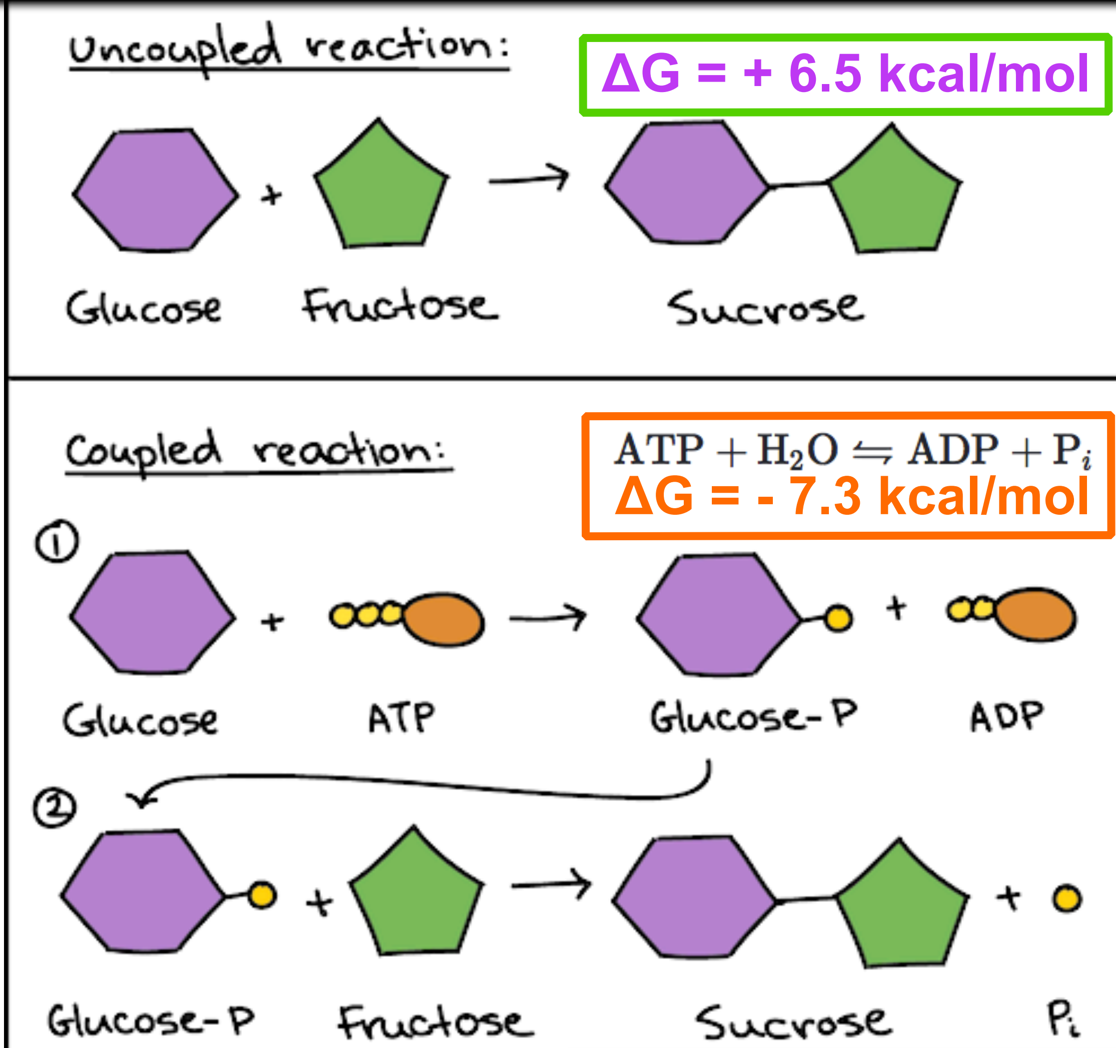
Doing cellular chemical work involves non-spontaneous processes that need energy to proceed

- A **phosphate group from ATP can be transferred onto a reactant**, covalently bonding to the reactants, **destabilizing it so that it will favor reacting.**
  - When, the phosphate is removed from the phosphorylated intermediate, the energy released helps atoms in the reactants rearrange.



Doing cellular chemical work involves non-spontaneous processes that need energy to proceed

- In this way, the exergonic reaction of ATP hydrolysis is used to drive the endergonic reaction to take place between the lower-energy reactant(s) in order for them to form the higher-energy product(s).
  - The overall ΔG went from being +ΔG in the uncoupled reaction to being -ΔG in the coupled reaction.



ΔG = + 6.5 kcal/mol

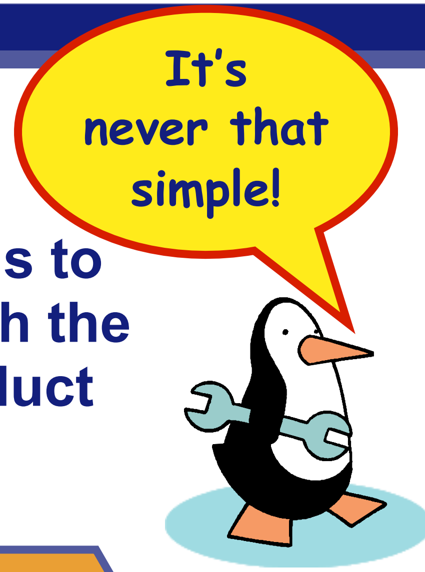
$$ATP + H_2O \leftrightharpoons ADP + P_i$$

ΔG = - 7.3 kcal/mol

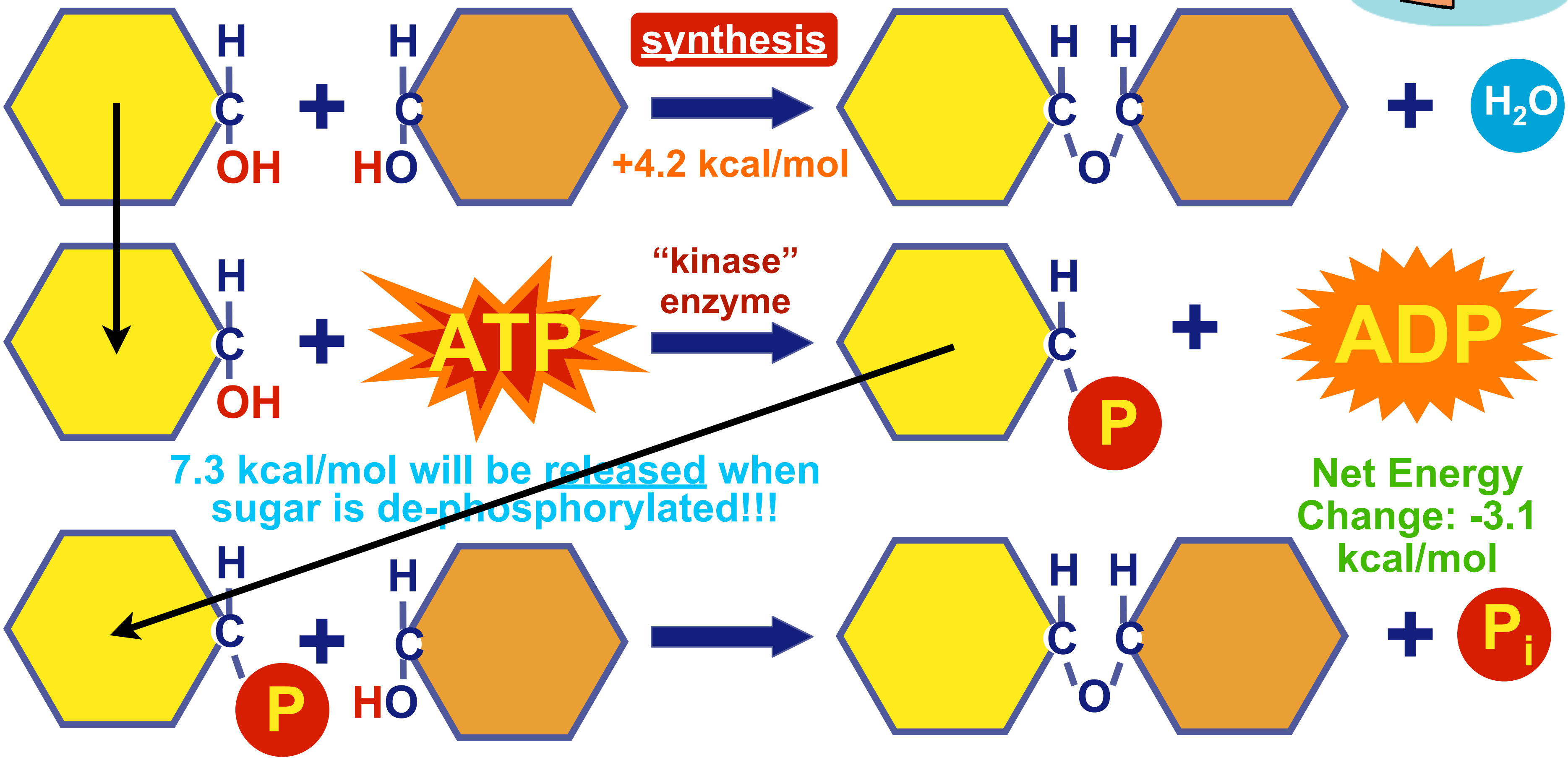
$$glucose + fructose + ATP \leftrightharpoons sucrose + ADP + P_i$$

ΔG = - 0.8 kcal/mol

Ex. of Phosphorylation…



- **When building polymers from monomers one needs to destabilize the reactants first and provide them with the energy needed to rearrange their atoms into a product**
  - **Solution: PHOSPHORYLATE!**



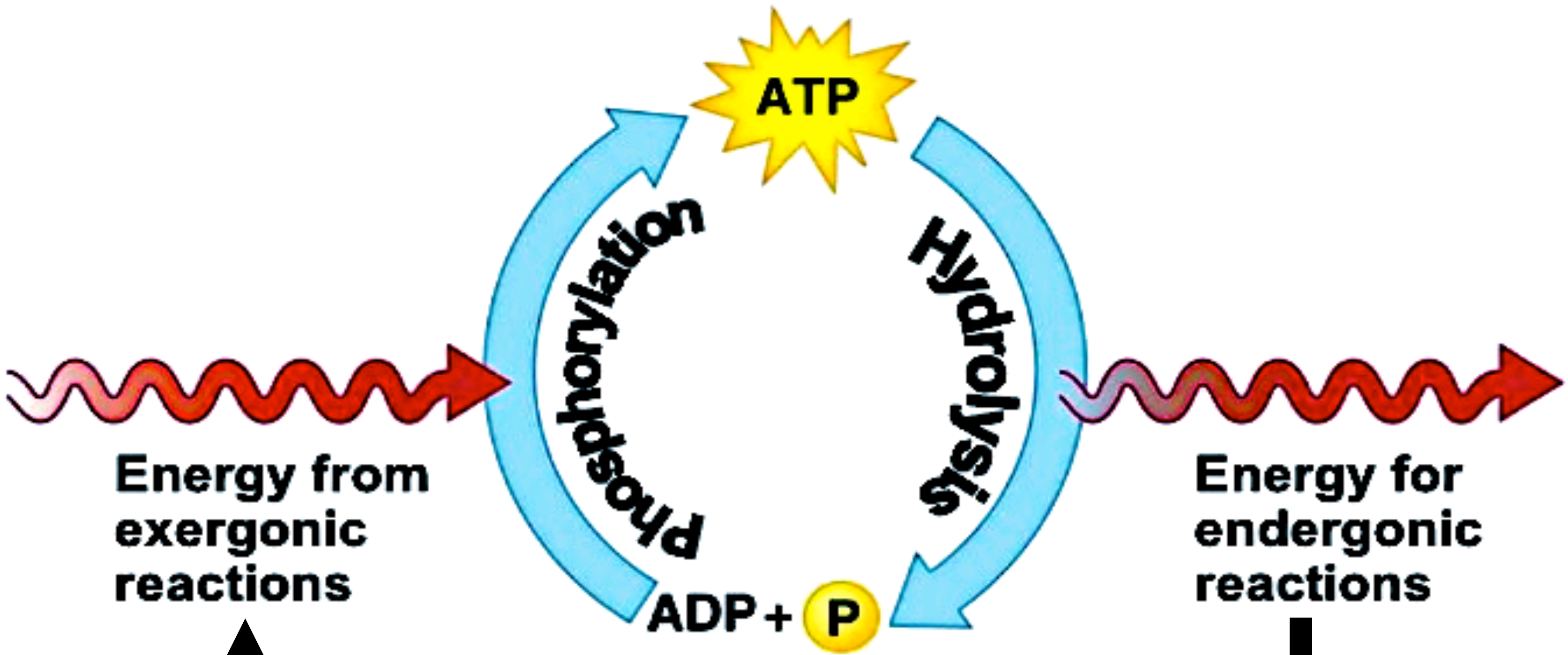
ATP is continually hydrolyzed and then synthesized anew inside cells.

- **ATPs take their chemical energy to the various locations in the cell where energy is needed for doing WORK.**
  - **In an exergonic reaction, ATP is hydrolyzed in order to release energy, resulting in ADP + phosphate.**

$$ATP + H_2O \leftrightharpoons ADP + P_i + energy$$

- **ADP + P will be converted back into ATP via more exergonic cellular respiration (coupled to endergonic ADP phosphorylation "ATP Synthesis)**

An ATP Cycle Exists in All Cells



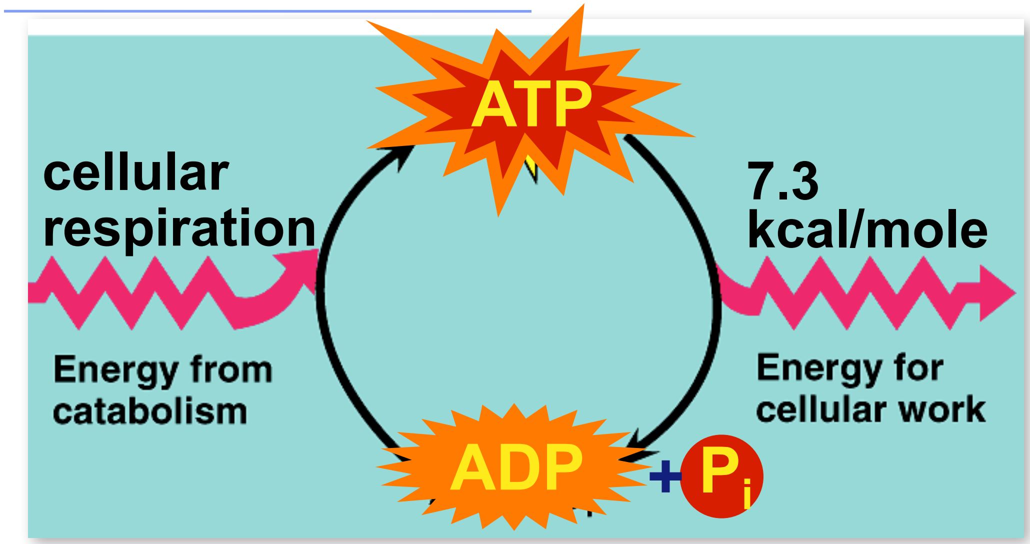
Energy obtained from Cellular Respiration

Energy from ATP used for doing WORK

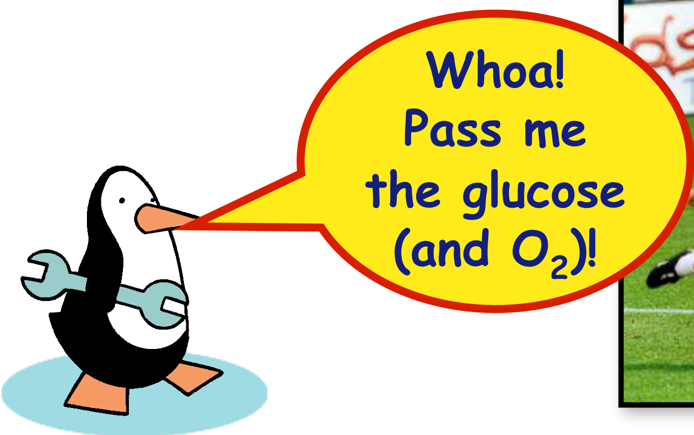
Can't store ATP longterm

- good energy donor, but not good for energy storage
  - ✓ too reactive
  - ✓ only short term energy storage
    - carbohydrates & fats are stable long term energy storage

ATP / ADP+P_i Cycle



A working muscle recycles over 10 million ATPs per second



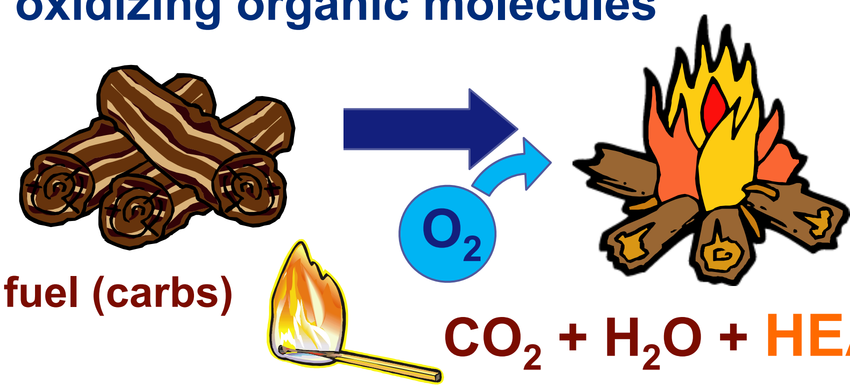
Harvesting the stored energy of high-energy organic molecules

- The net chemical equation for <u>aerobic cellular respiration</u> and <u>combustion</u> may look similar, yet the processes are <u>not</u> the same.

$$C_6H_{12}O_6 + 6O_2 \longrightarrow 6CO_2 + 6H_2O$$

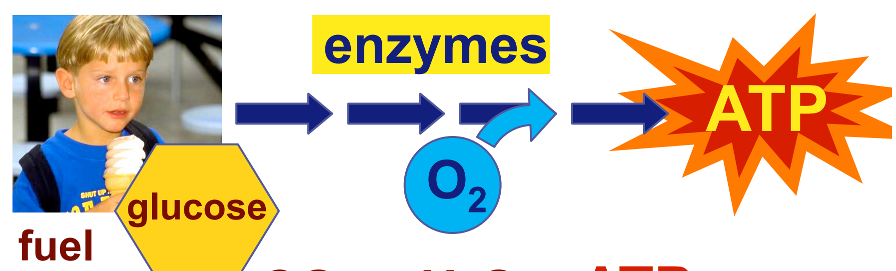
  - Both are exergonic processes that release energy from the bonds of high-energy organic molecules but...

<u>COMBUSTION</u> = releasing a lot of heat energy in <u>one step</u> by oxidizing organic molecules



Energy of Activation

<u>RESPIRATION</u> = releasing energy in <u>many small steps</u> by oxidizing organic molecules in order to store that energy on ATP (with some energy also lost as heat)

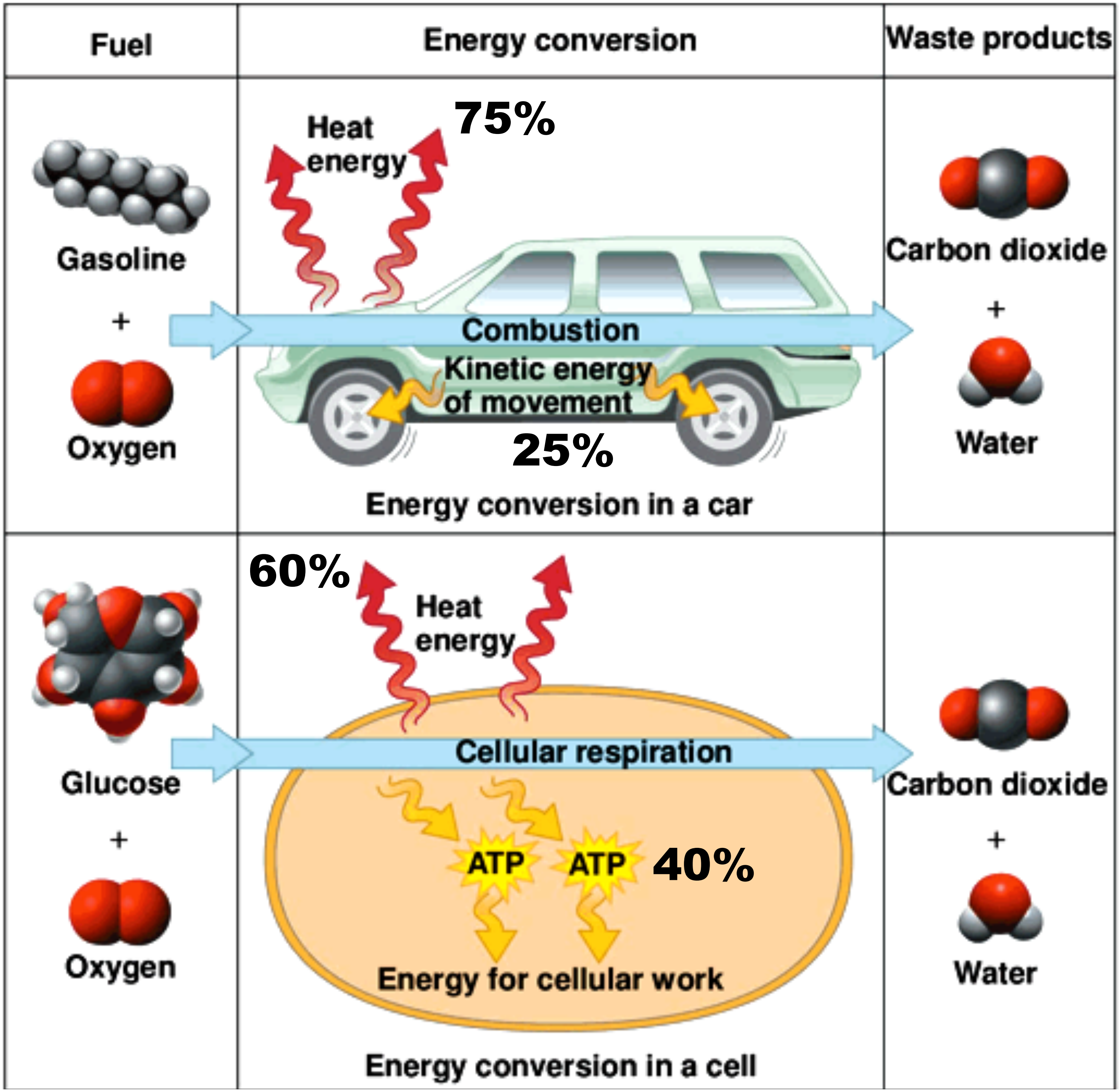


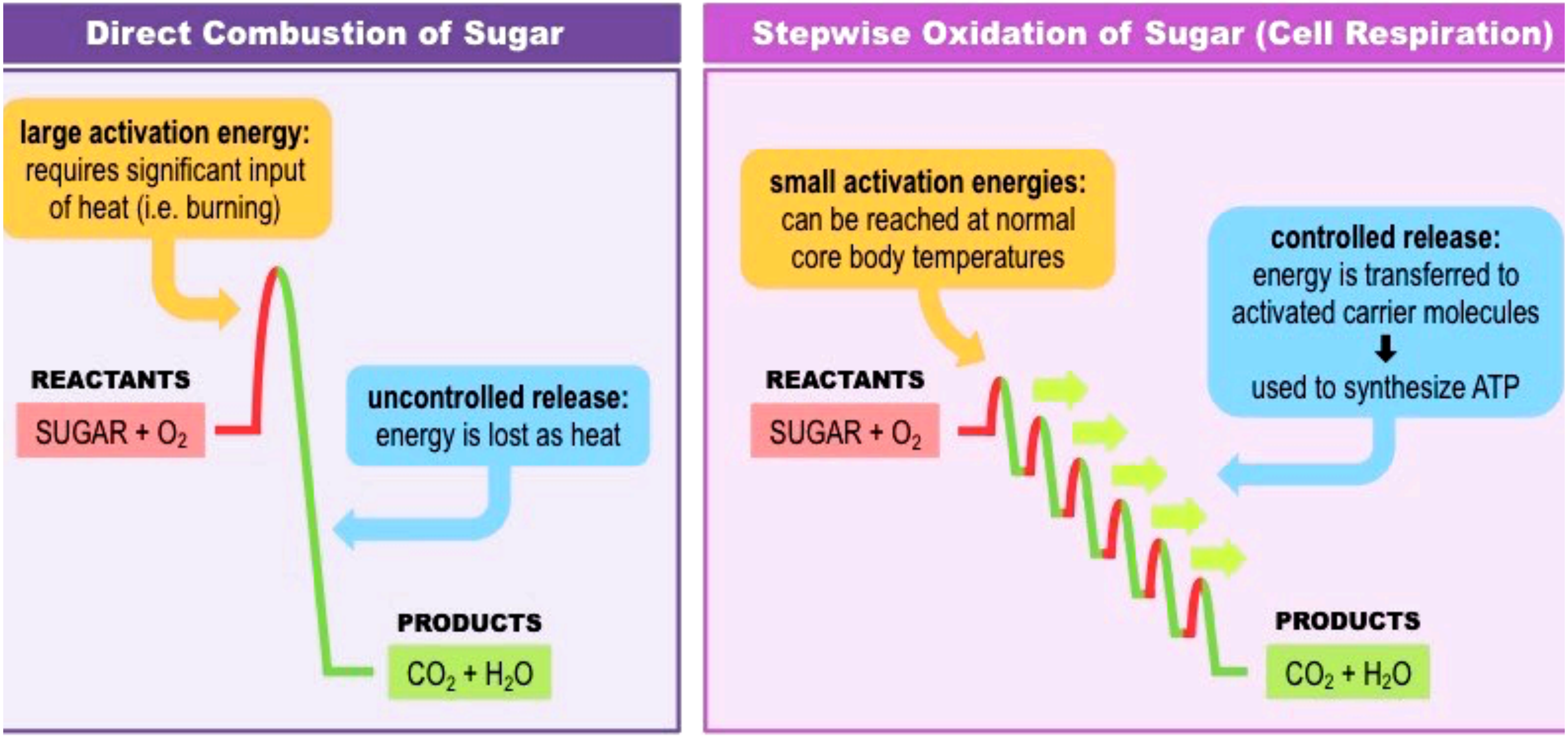
fuel (carbs)

$CO_2 + H_2O$ + ATP (+ heat)

Harvesting the stored energy of high-energy organic molecules

- In combustion, all the bonds of the reactants O_2 and $C_6H_{12}O_6$ are broken and the atoms are rearranged immediately into CO_2 and H_2O
  - A lot of chemical energy stored in the high energy C-H and C-C bonds of glucose is released at once
    - This energy is lost as thermal energy, heat, (and light) to the environment
- When organic molecules are broken down by cell respiration, the bonds of the reactant $C_6H_{12}O_6$ are broken one at a time over multiple chemical reactions that eventually lead (with the help of O_2) to the formation of CO_2 and H_2O
  - The chemical energy stored in the high energy carbon-carbon and carbon-hydrogen bonds of glucose is released in small sequential amounts
    - Though some energy is lost as thermal energy (heat) to the environment, some of that energy can be stored on ATP


Fuel
Energy conversion
Waste products
Gasoline
+
Oxygen
Heat energy
75%
Combustion
Kinetic energy of movement
25%
Energy conversion in a car
Carbon dioxide
+
Water
Glucose
+
Oxygen
60%
Heat energy
Cellular respiration
ATP
ATP
40%
Energy for cellular work
Energy conversion in a cell
Carbon dioxide
+
Water

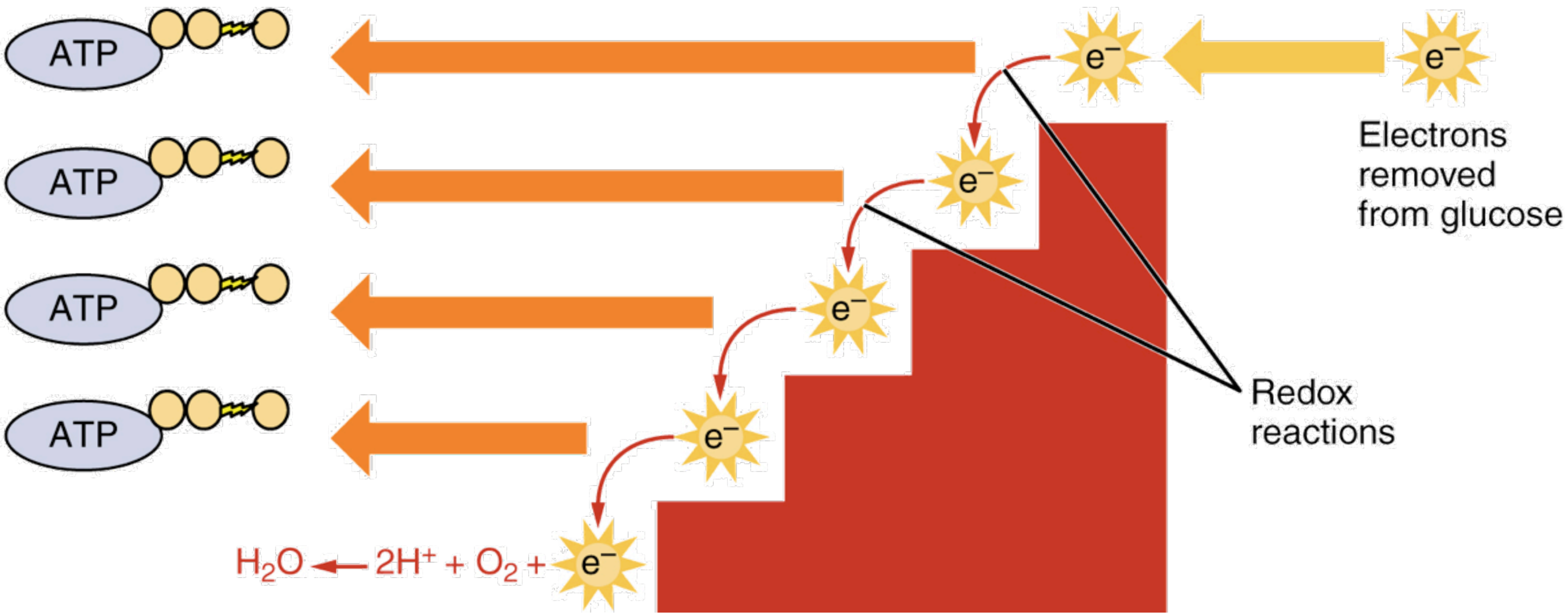


Cell respiration is the **controlled** breakdown of organic molecules over many steps

(energy released can be captured via ***redox reactions*** *and used to generate ATP)*

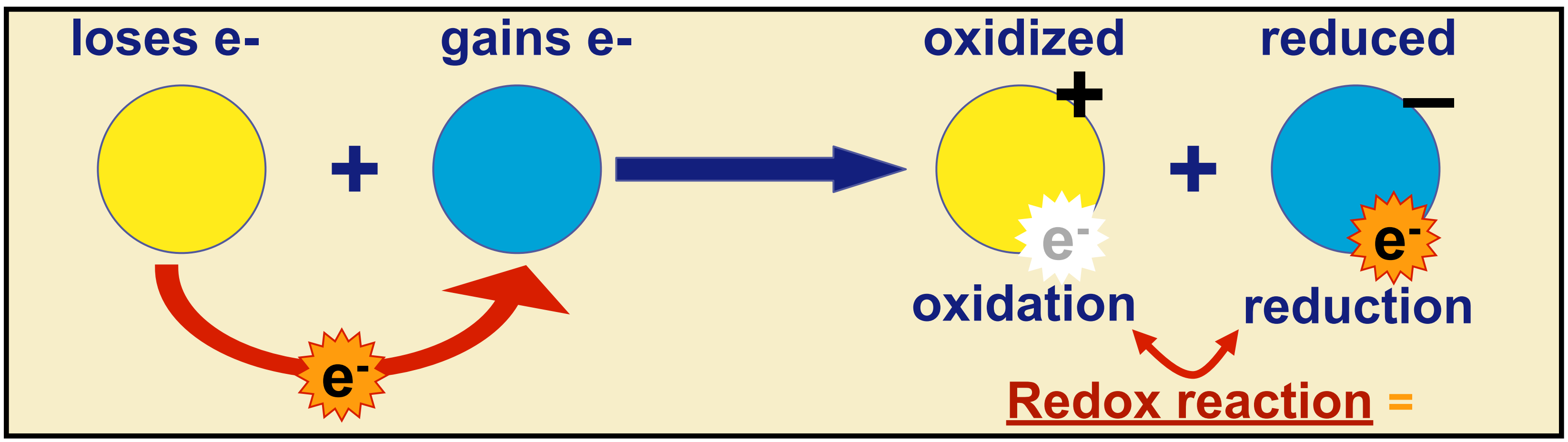
The Importance of High-Energy Electrons

- Certain electrons in C-C & C-H bonds of organic molecules have a lot of potential energy due to their position in atoms
  - In respiration, bonds are broken & high-energy electrons are moved from a high-energy organic molecule to another
    - As electrons move, they "carry energy" with them
      - That potential energy of these high-energy electrons is then released slowly and (40%) stored on ATP



Harvesting the stored energy of high-energy organic molecules

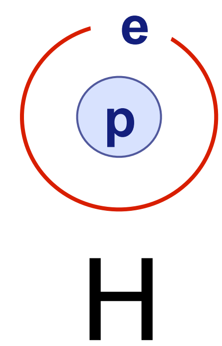
- In Cellular Respiration, chemical energy is transferred by means of redox reactions
  - Redox reactions involved the reduction of one chemical species and the oxidation of another (redox = reduction / oxidation)
- Most redox reactions typically involve the transfer of electrons, hydrogen or oxygen
  - Reduction is the gain of electrons *(but can also result from the gain of hydrogen or the loss of oxygen)*
  - Oxidation is the loss of electrons *(but can also result from the loss of hydrogen or the gain of oxygen)*

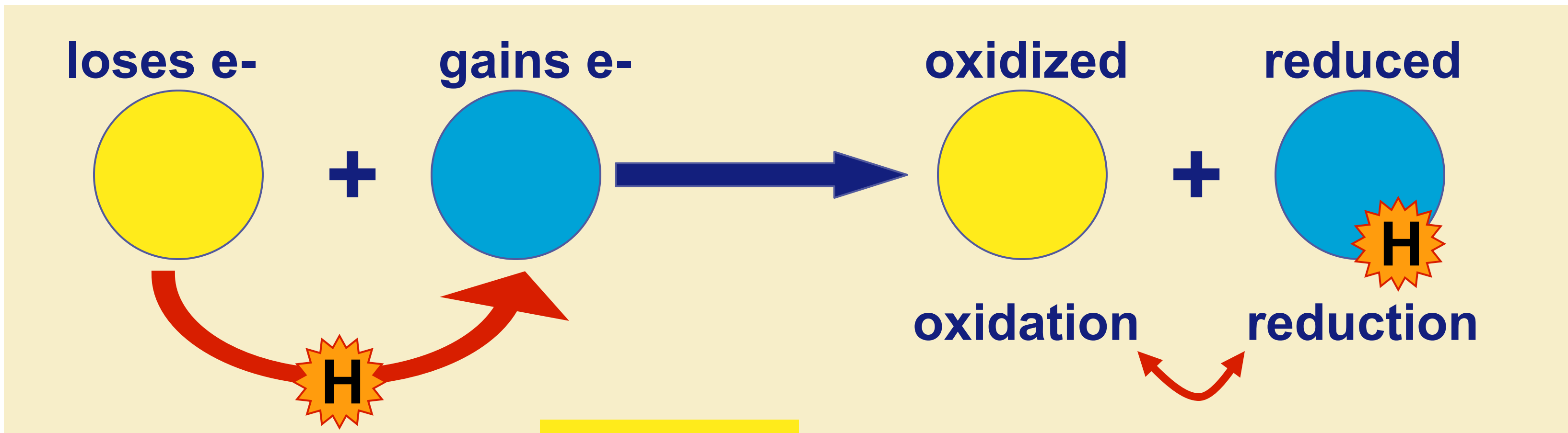


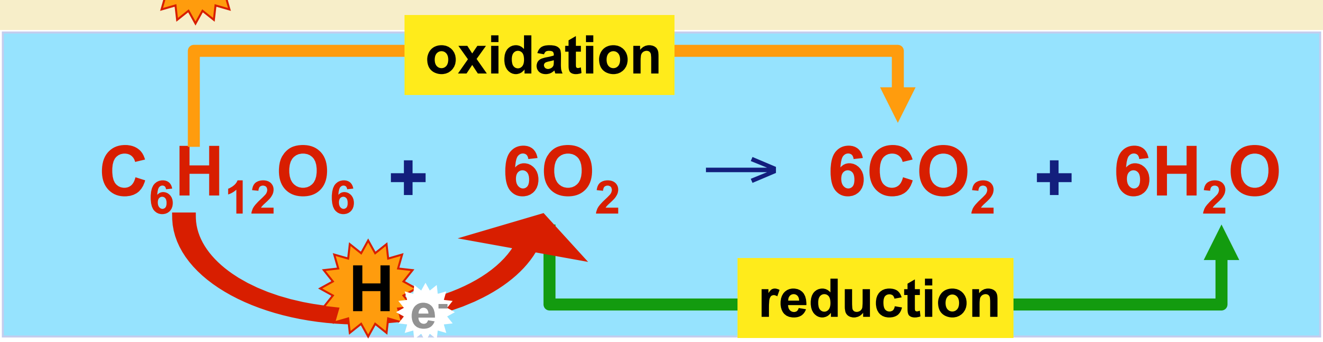
Chemical reaction that transfer e-'s

How do we move electrons in biology?

- **Moving electrons in living systems**
  - electrons mostly do not move alone in cells
    - electrons move as part of <u>H atom</u>
      - <u>move H = move electrons</u>
  - Oxidation = loss of e- from a substance
  - Reduction = gain of e- by a substance







Coupling oxidation & reduction

- **Purpose of REDOX reactions in respiration:**
  - Release the potential energy stored in covalent bonds as the cell breaks down high-energy organic molecules
    - break C-C bonds
    - strip off electrons from C-H bonds by removing H atoms
      - $C_6H_{12}O_6 \rightarrow 6CO_2$ = glucose gets oxidized
    - electrons attracted to more electronegative atoms
      - in biology, the most electronegative atom is?
      - $6O_2 \rightarrow 6H_2O$ = oxygen gets reduced

O_2

  - Cells couple REDOX reactions & then use the released energy to synthesize ATP

oxidation

$$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O$$

reduction

Released energy used to synthesize ATP

Oxidation vs Reduction

- **Oxidation**
  - adding O (high electronegativity of O pulls electron density away from atoms its bonded to like C resulting on the C becoming partially oxidized)
  - removing H
  - loss of electrons
  - releases energy
  - **Exergonic**
    - The electron donor= reducing agent

- **Reduction**
  - removing (replacing) O (replacing a very electronegativity O bonded to a C with a medium electronegativity H or new C, means the original C gets back some electron density now electrons will be shared more equally in the bond)
  - adding H
  - gain of electrons
  - stores energy
  - **Endergonic**
    - The electron acceptor = oxidizing agent

oxidation

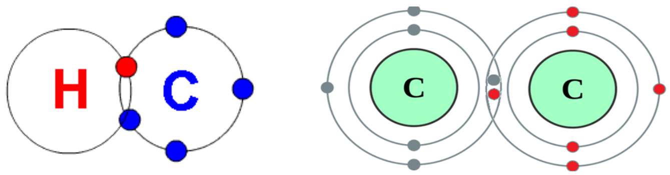
$$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O$$

reduction

Released energy used to synthesize **ATP**

Chemical Energy = Potential Energy

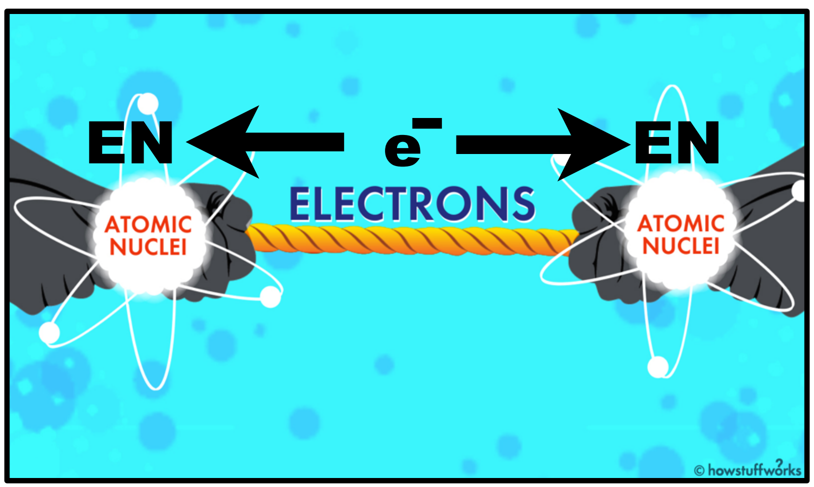
- The Potential Energy found in high-energy chemical bonds is due to the position of the shared valence electrons in the covalent bond of the two atoms involved.
  - C-C bonds and C-H bonds are rich in chemical energy

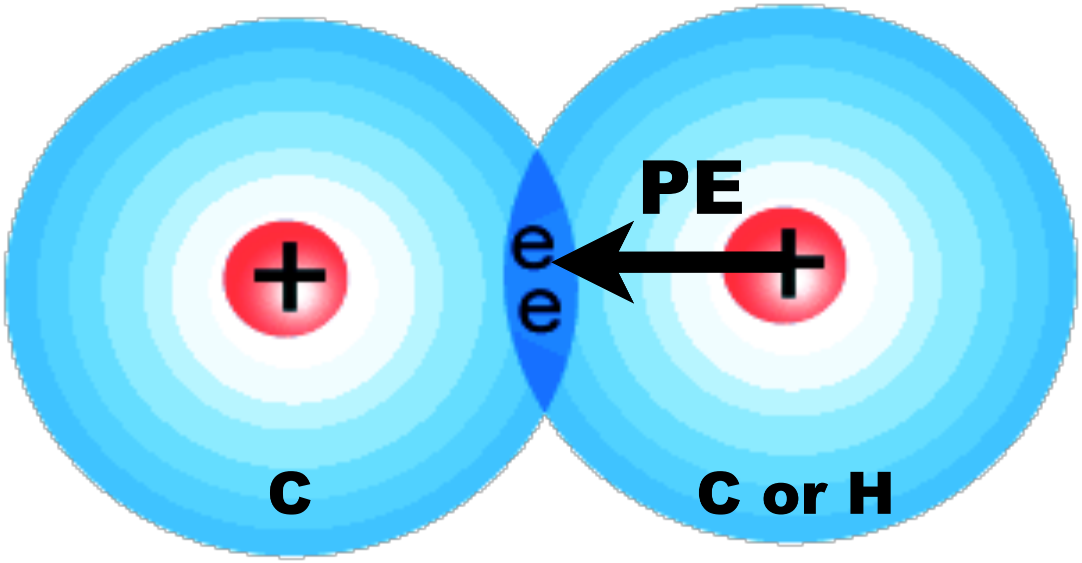


    - Both C and H atoms are similar in electronegativity and so tug on shared electrons with similar strength, the electrons not "falling" much closer to one nucleus on average over the other.
      - Because of the attraction of electrons to the C/H nuclei and the distance of the electrons from the C/H nuclei in C-C and C-H bonds, the electrons have a certain amount of Potential Energy due to their position within the atom.

Electrons in C-C & C-H bonds are considered high in Potential Energy

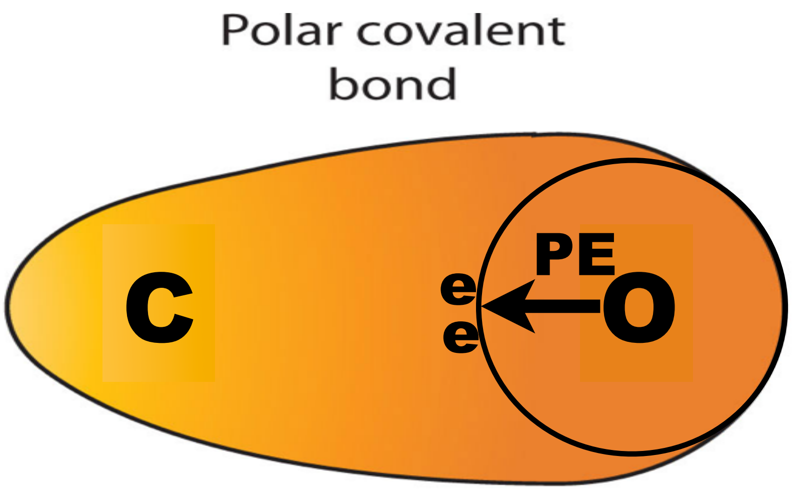
- Molecules with high-energy electrons [thus high energy bonds] are considered energy-rich molecules
  - Carbohydrates & fats are rich in high-energy electrons since they are rich in C-C and C-H bonds (despite some of the bonds being low energy C-O bonds)
    - Electrons in their many C-C and C-H bonds have a lot of potential energy (PE) due to their position.

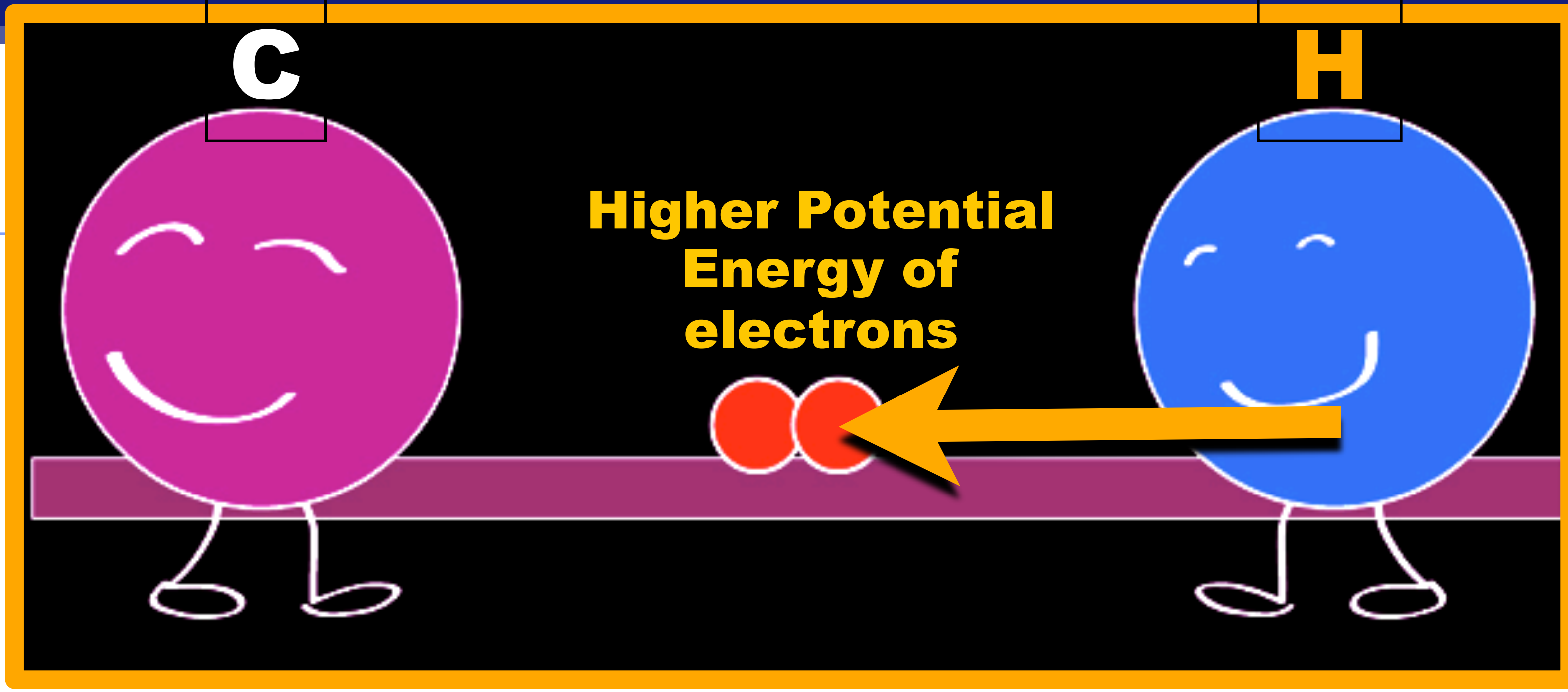


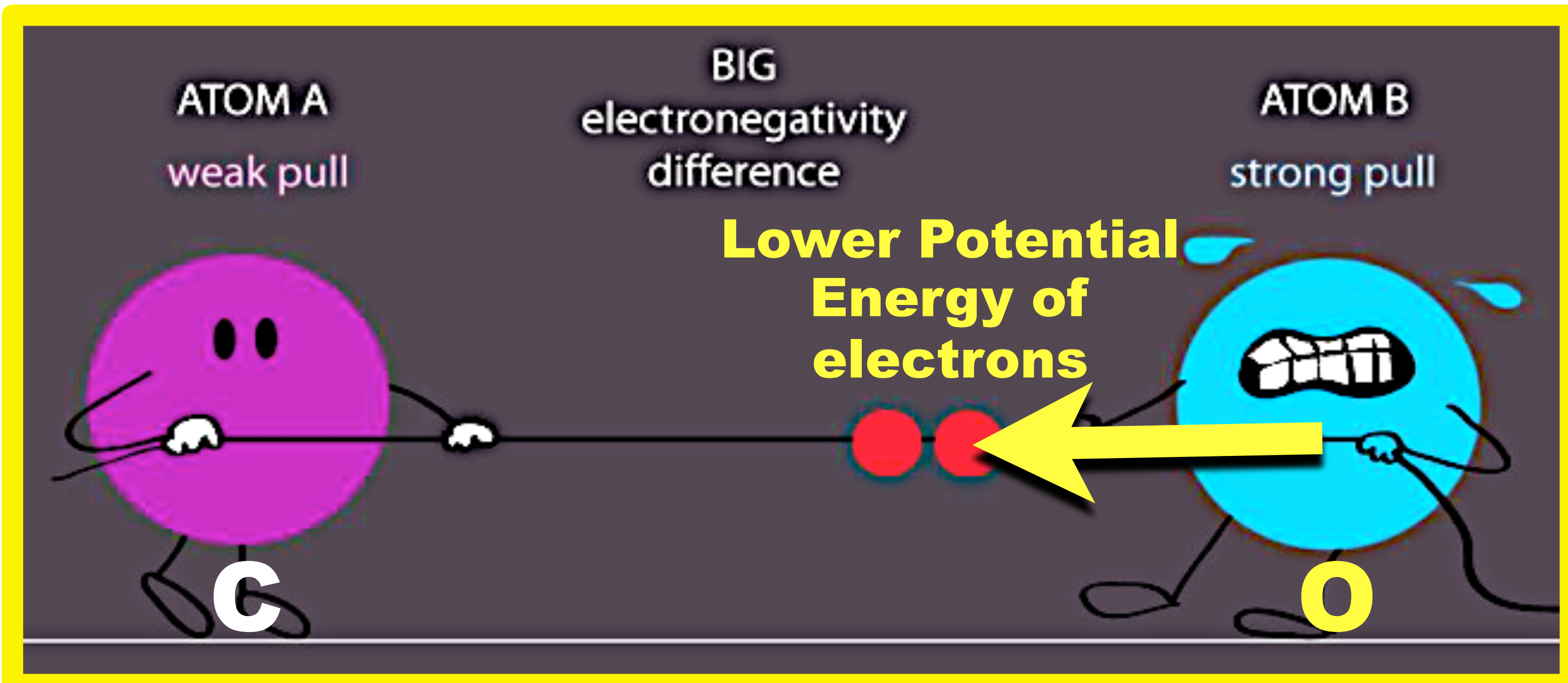


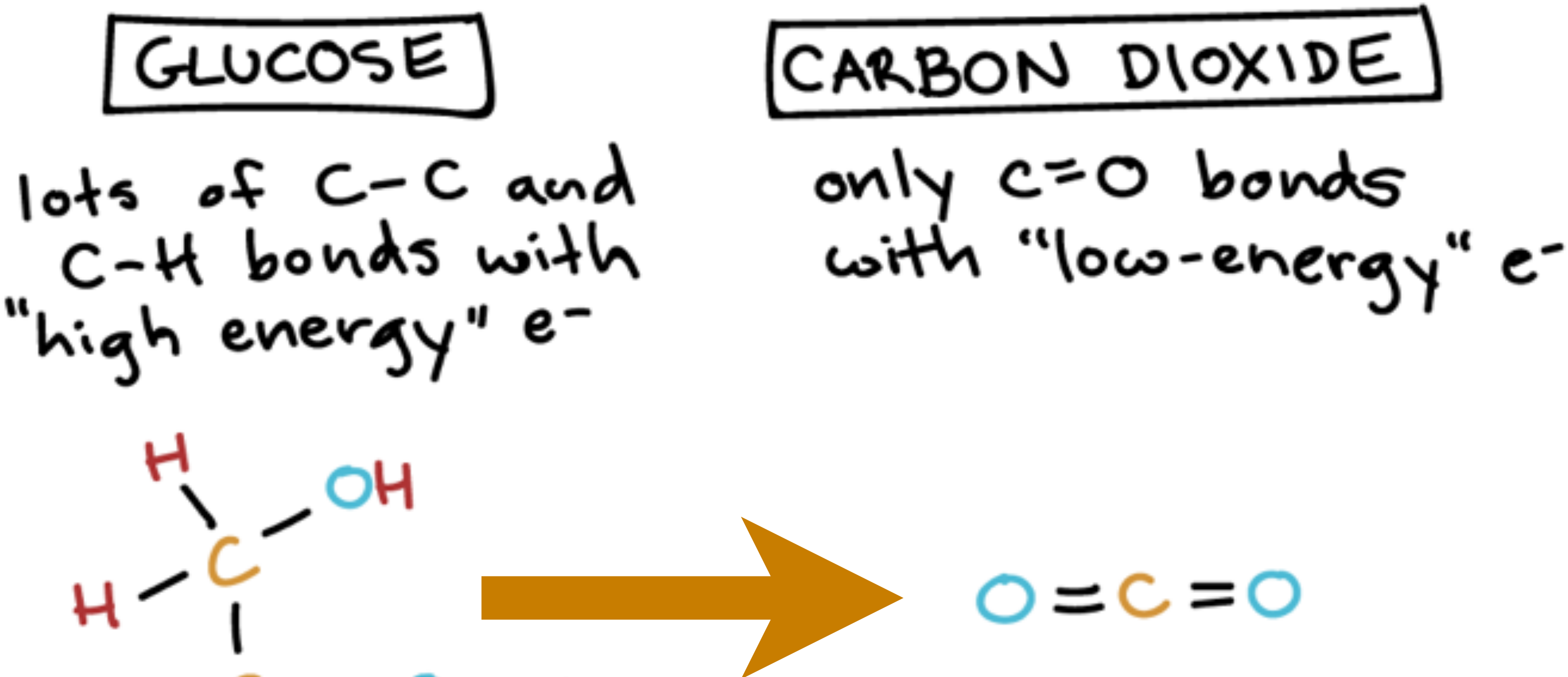
High-Energy Electrons vs. Low-Energy Electrons

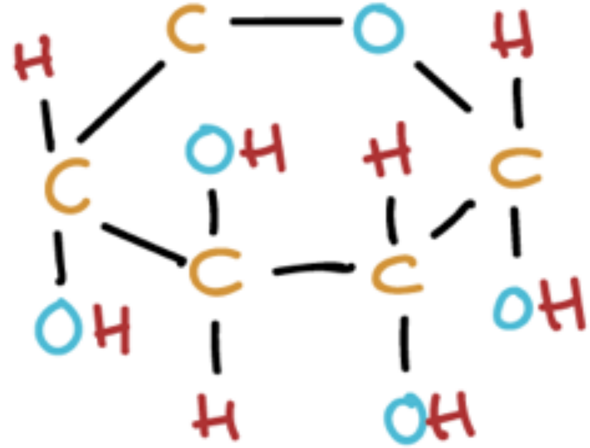
- O is much more electronegative than C
  - O pulls on the shared valence electrons within a covalent bond with C with greater force of attraction
    - If the carbon in a C-C or a Hydrogen in a C-H non-polar covalent bond is replaced with an O to make a C-O polar covalent bond, the shared valence e^- in the new C-O bond sits, on average, far from the C nucleus, and much more closely to the O's nucleus.
      - the shared e^-' now has less potential energy than it had before, because its distance to the O nucleus is smaller than before when it was involved in a C - C or C - H bond and its distance to the C or H nucleus was larger.




C
H
Higher Potential
Energy of
electrons


ATOM A
weak pull
BIG
electronegativity
difference
ATOM B
strong pull
Lower Potential
Energy of
electrons
C
O

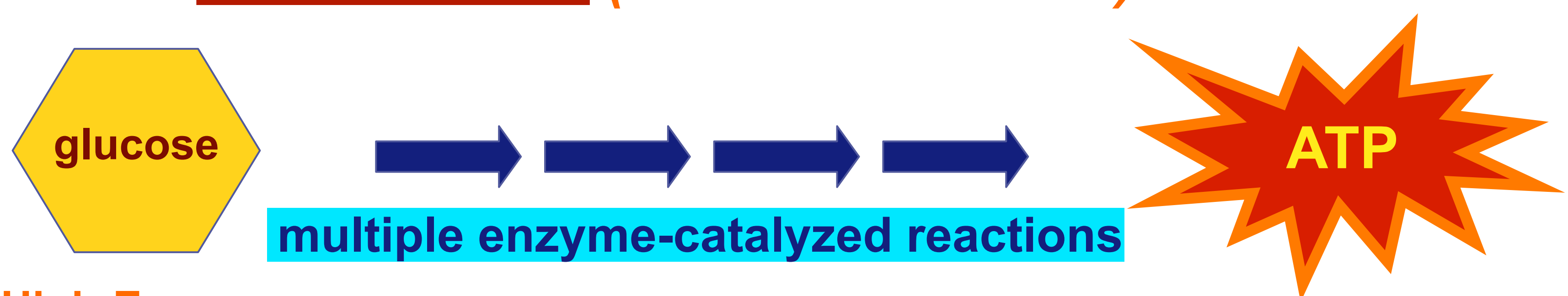




During [Aerobic Cellular Respiration](), $C_6H_{12}O_6$ get's oxidized through sequential chemical reactions ("broken down") into molecules of CO_2

Electrons can change from being High in PE to Low in PE based depending on the atoms they are associated with.

- The electrons that are involved in a bond between a C-O instead of a C-C or C-H have lost Potential Energy.
  - They have gone from being HIGH ENERGY ELECTRONS to being LOW ENERGY ELECTRONS.
    - In Cellular Respiration, high energy electrons are collected and allowed to lose potential energy in a controlled manner, the lost potential energy being stored on ATP *(some lost as heat)*



High-Energy Organic Molecules

CO_2 + H_2O + ATP (+ heat)

Aerobic Cellular respiration: Big Picture

- Involves the oxidation and catalysis of glucose ($C_6H_{12}O_6$) and other organic monomers (making CO_2, a waste product) in order to collect high-energy electrons.
  - Carbohydrates and fats, with many C-C & C-H bonds are large reservoirs of electrons with high potential energy
- The potential energy stored in the high-energy electrons is extracted and is used to synthesize ATP
  - The high-energy electrons become low-energy electrons
    - These now low-energy electrons then reduce O_2 which becomes H_2O (a waste product)

oxidation

$$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O$$

reduction

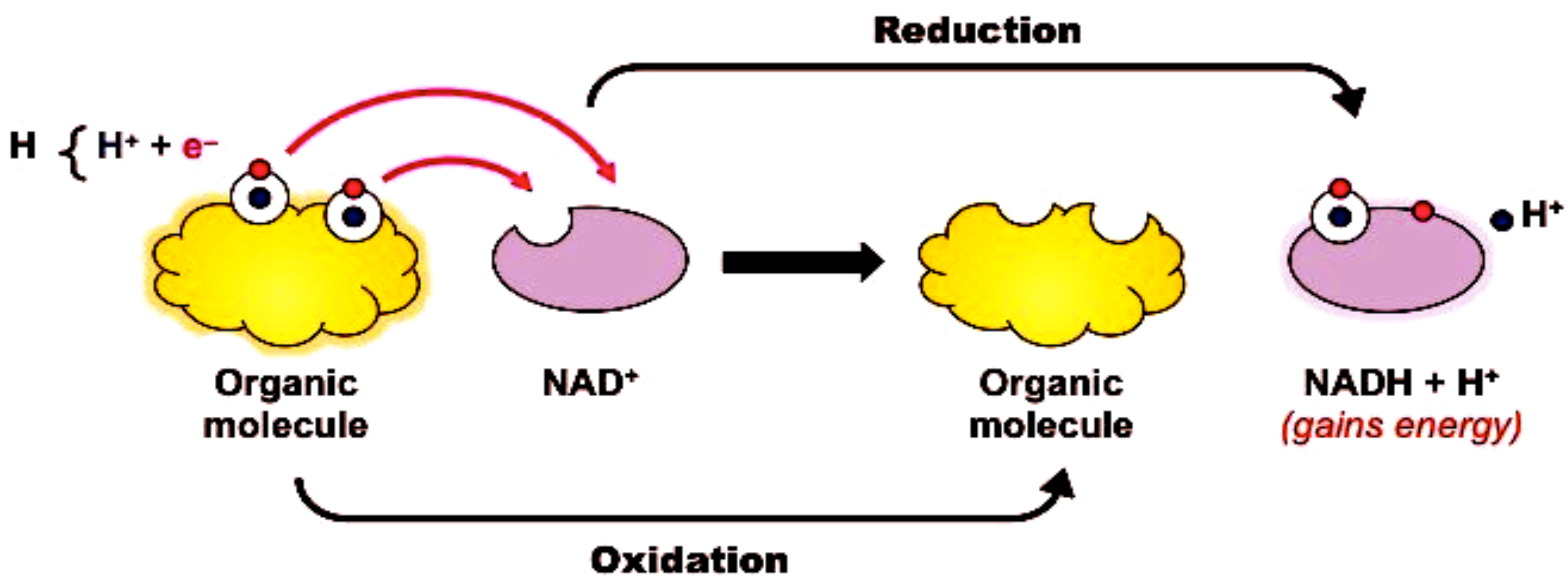
Potential Energy extracted from high-energy electrons used to synthesize ATP

Harvesting Electrons with the help of NAD+/FAD

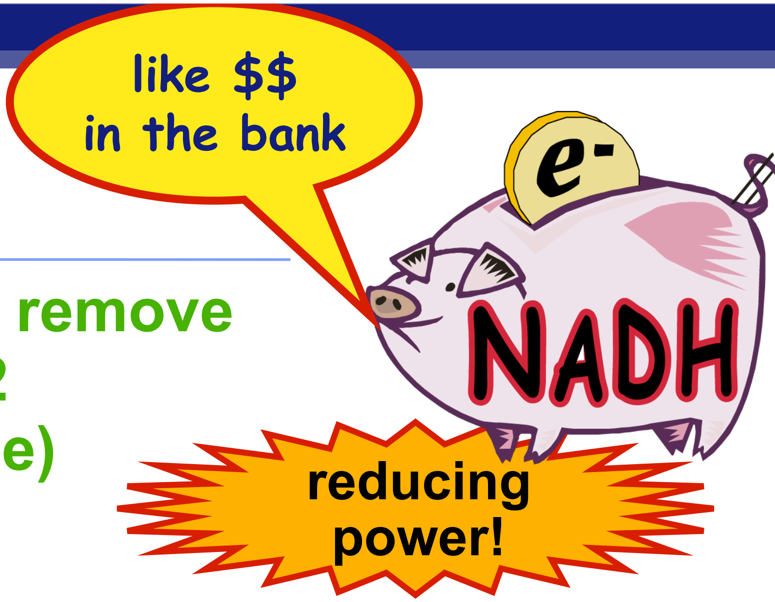
- Electrons are not transferred directly to oxygen in one explosive step during respiration.
- Hydrogen atoms (and their high-energy electrons) are transferred to electron carriers (oxidizing agents also knowns as coenzymes).
  - Electron carriers move collect high-energy electrons by shuttling H atoms (and their electrons) around the cell
    - Electrons transferred to these electron carriers lose very little potential energy!!!
      - When a carrier gains electrons or H atoms, it gets reduced and is holding onto stored potential energy.

Harvesting Electrons with the help of NAD+/FAD

- Two electron carriers (coenzymes) are used in cells
  - $NAD^+ \rightarrow$ NADH (reduced) + H^+
    - One proton and 2 e-'s are transferred to NAD+
    - Second proton released into solution
  - FAD $\rightarrow$ $FADH_2$ (reduced)
    - two protons and 2 e-'s are transferred to FAD

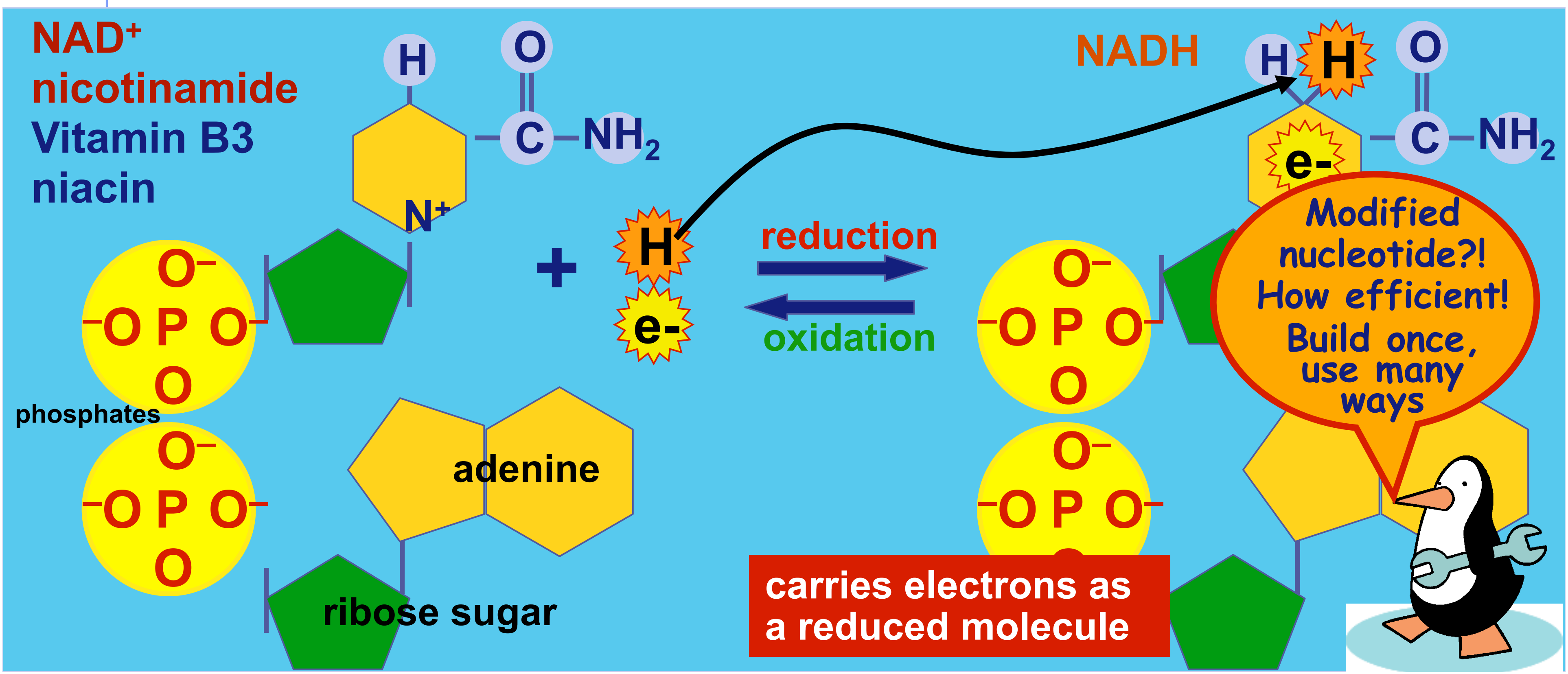


NAD^+ reduction

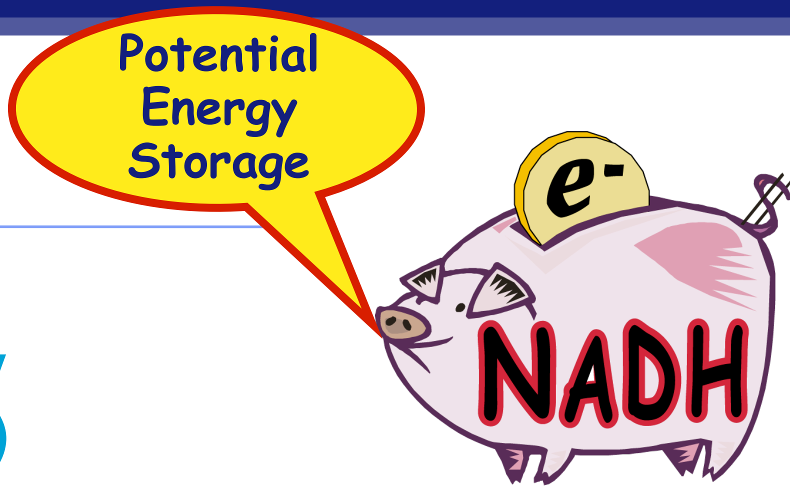


Enzymes called *dehydrogenases* remove pairs of hydrogen atoms (2 e- & 2 protons) from substrates (glucose)

$NAD^+ \rightarrow$ NADH (reduced)

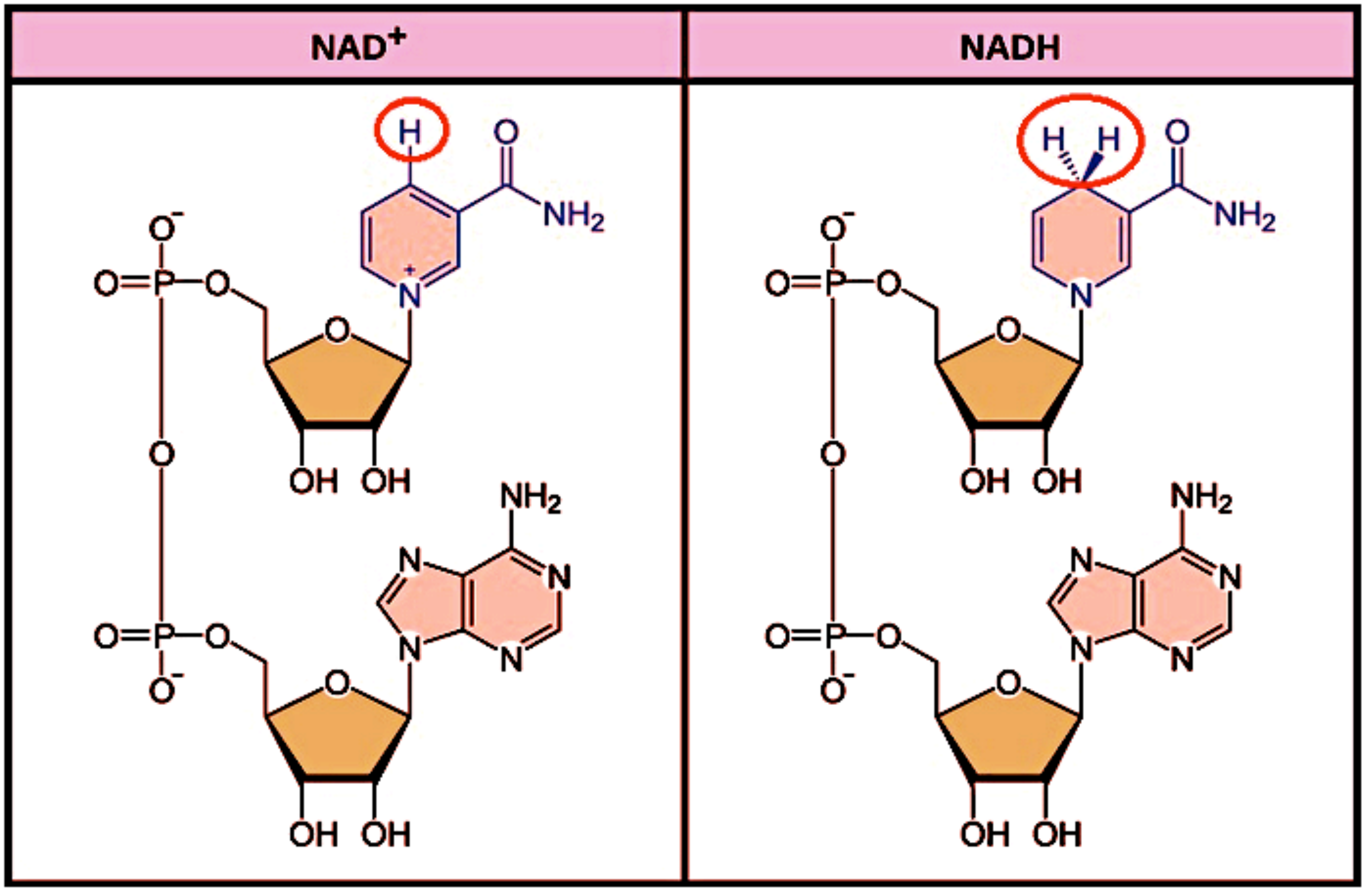


NAD+ reduction

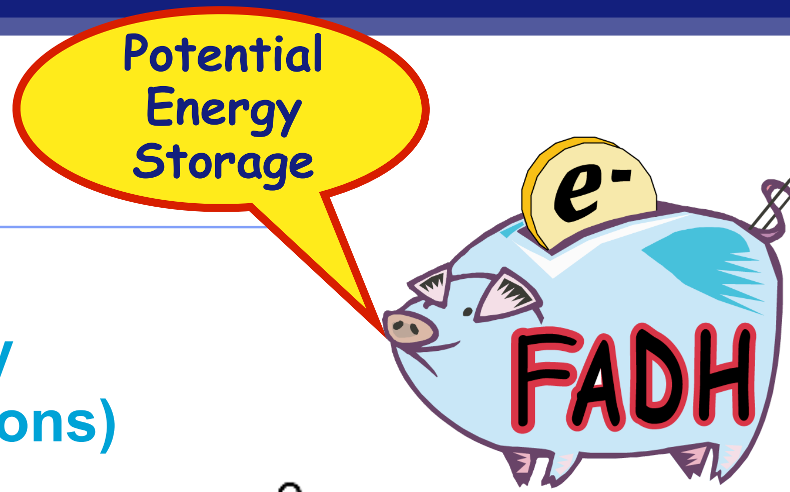


$NAD^+ \rightarrow$ NADH (reduced)

Carries two high energy electrons (and a proton)

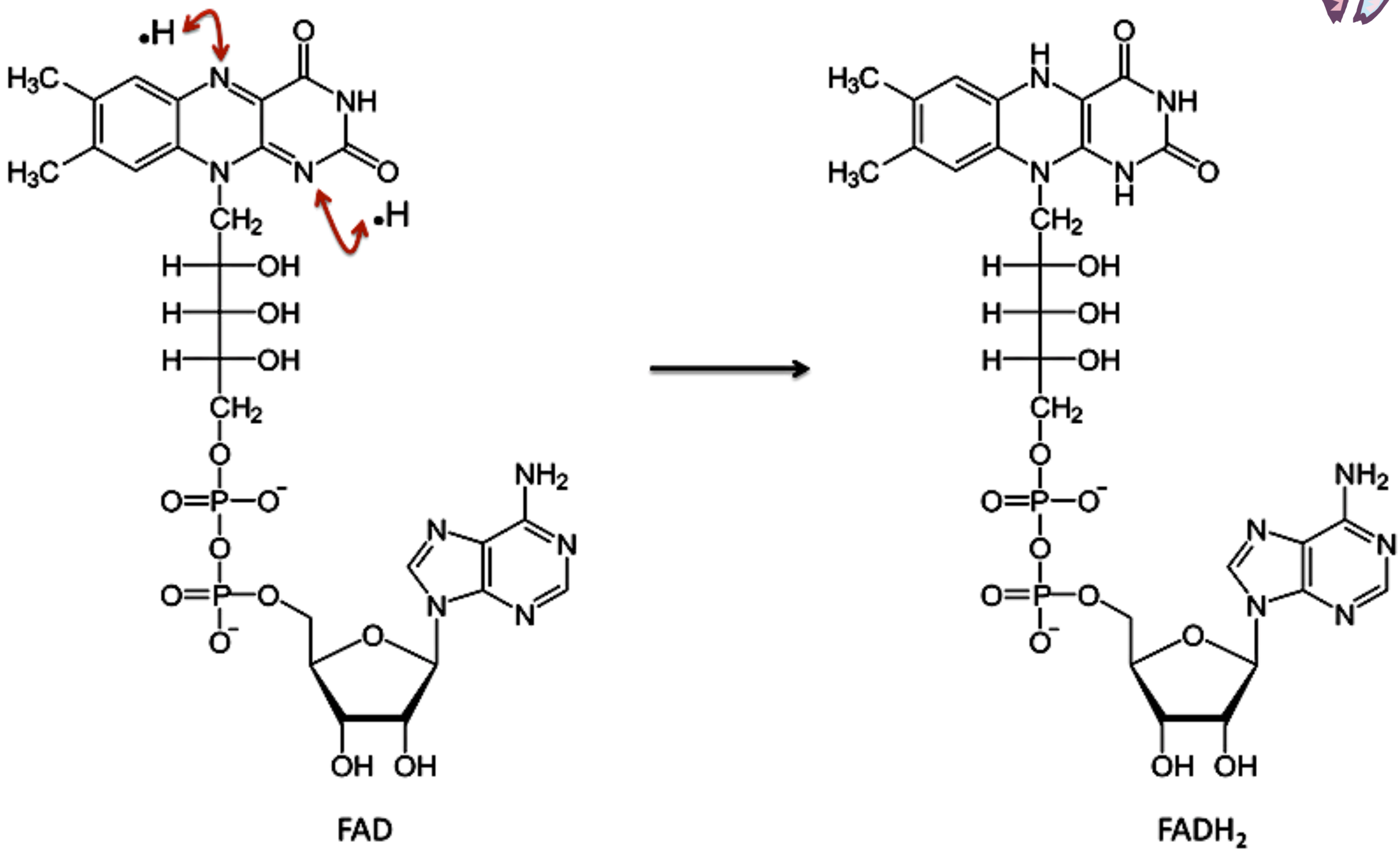


FAD reduction



FAD → FADH$_2$ (reduced)

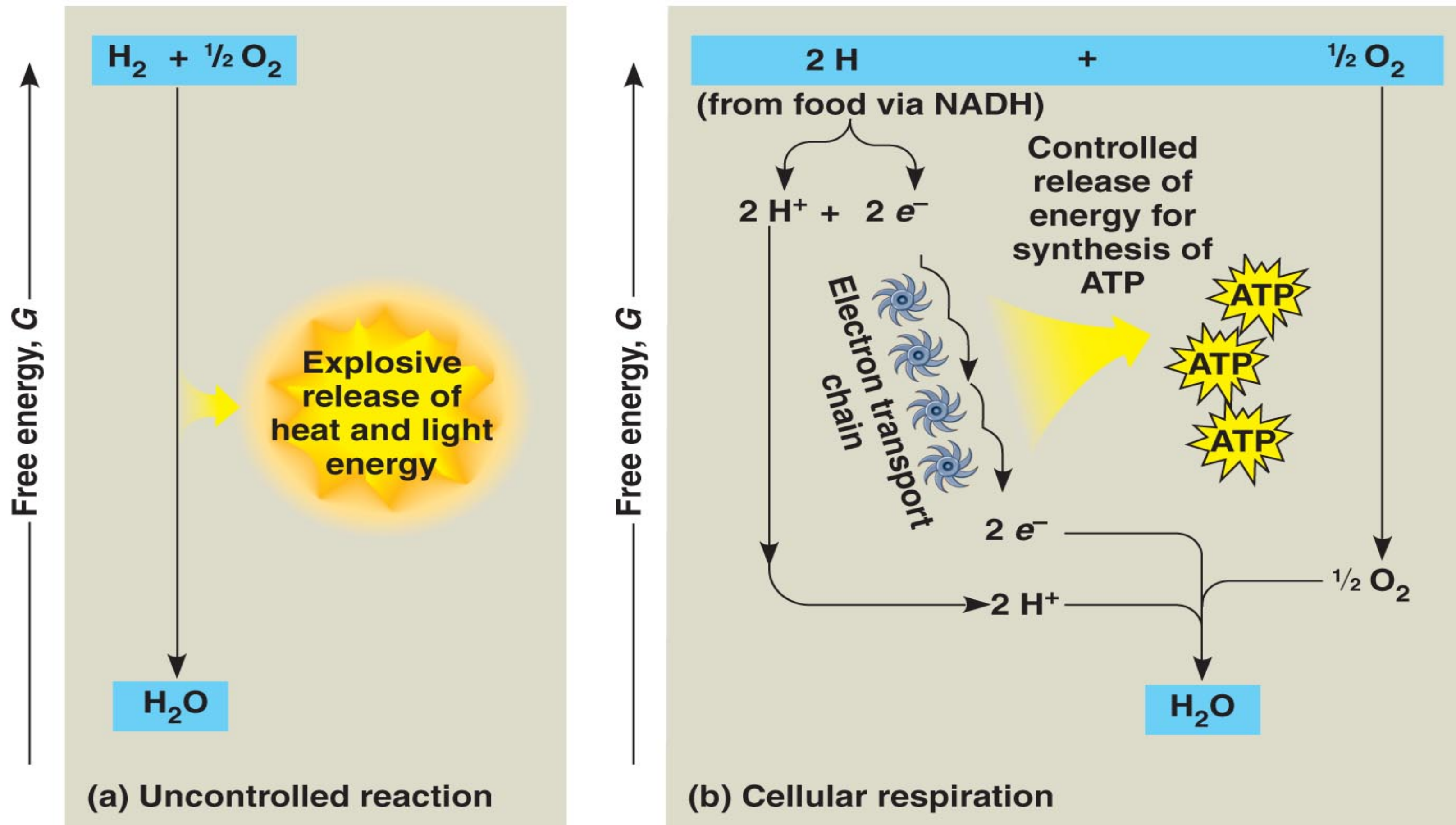
Carries two high energy electrons (and two protons)



Electron Transport Chain in Aerobic Respirators

Electron carriers transfer electrons in organisms that can engage in aerobic respiration to electron transport chain where they are slowly passed down from molecule to molecule, through a series of redox reactions, loosing a little energy with each pass till they reach oxygen at the bottom of the chain and make H2O

- **The energy releases is used to make ATP from ADP and P**



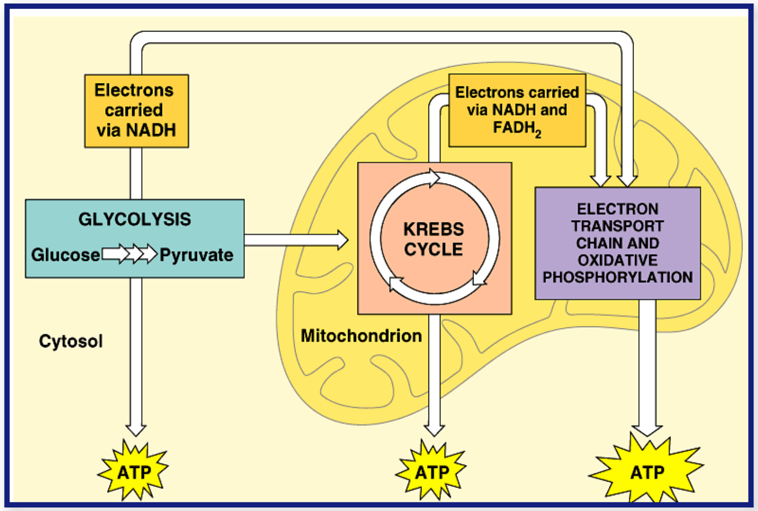
Overview: Cellular Respiration

Anaerobic respiration and Fermentation

- Respiration (extracting E from high-energy e-) and building ATP without O_2
- Fermentation takes place in cytosol only in both prokaryotes or eukaryotes; Anaerobic respiration occurs in the cytosol AND plasma membrane in prokaryotes or mitochondria in eukaryotes

Aerobic respiration

- Respiration using O_2
- Takes place in cytosol AND plasma membrane in prokaryotes or mitochondria in eukaryotes



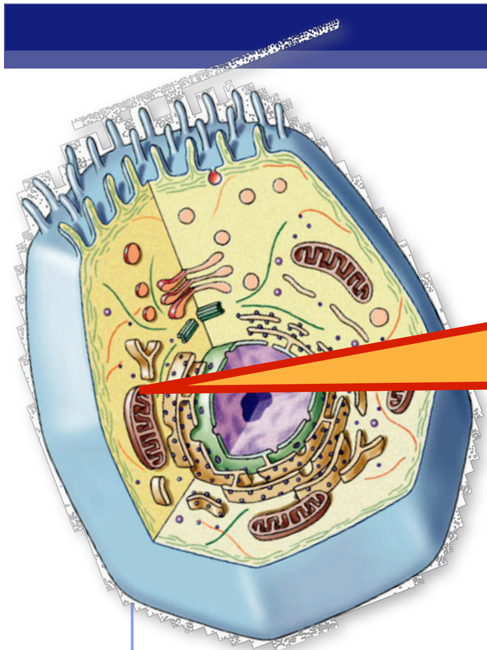
- 3 (more like 4) metabolic stages
  1. Glycolysis
  * (Pyruvate oxidation to Acetyl CoA)
  2. Krebs (Citric Acid) cycle
  3. Electron transport chain & ATP Synthase

What Should You Follow in Every Step of This Biocehmical Process?

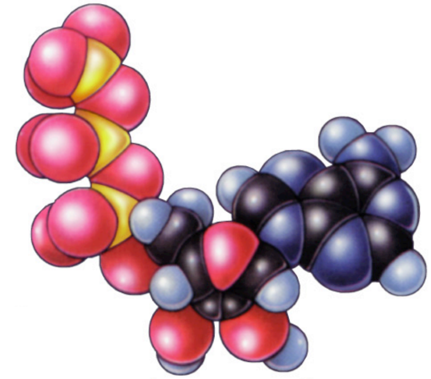
1. Follow the number and location of carbon atoms!!!

2. Follow the location, movement, and use of ENERGY!!!

3. Follow the location and use of oxygen atoms from molecular oxygen O_2!!!

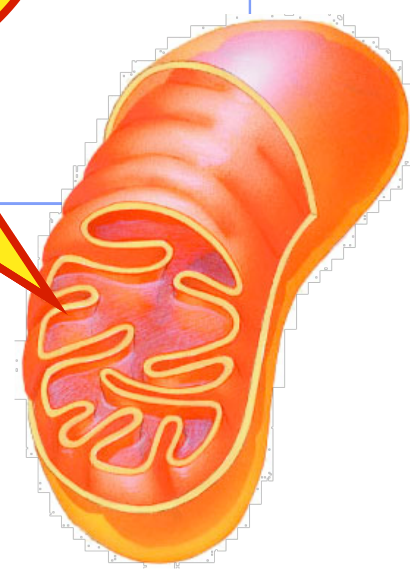


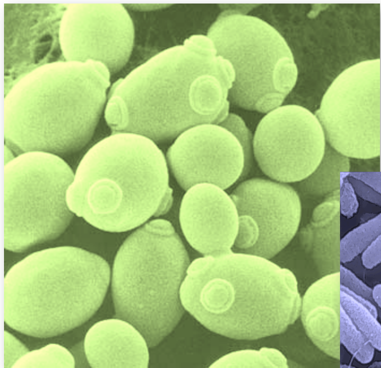
What's the point of respiration?

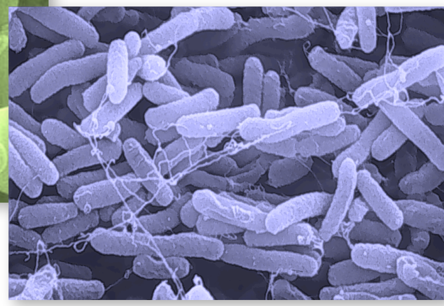


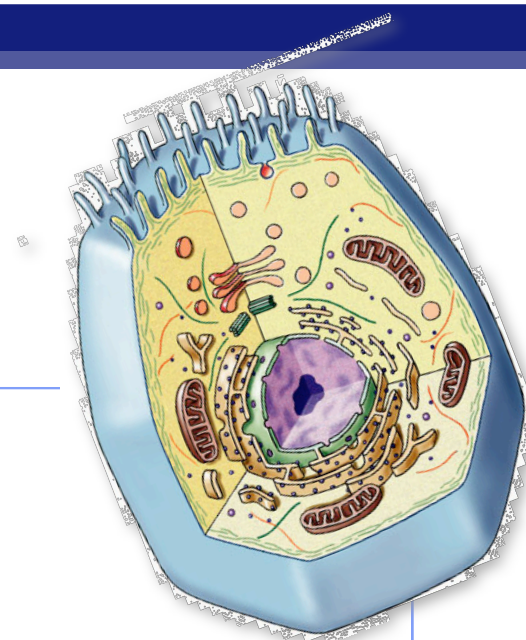
The point is to make ATP!

ATP









Cellular Respiration

Stage 1:

Glycolysis

Glycolysis

Breaking down GLUCOSE

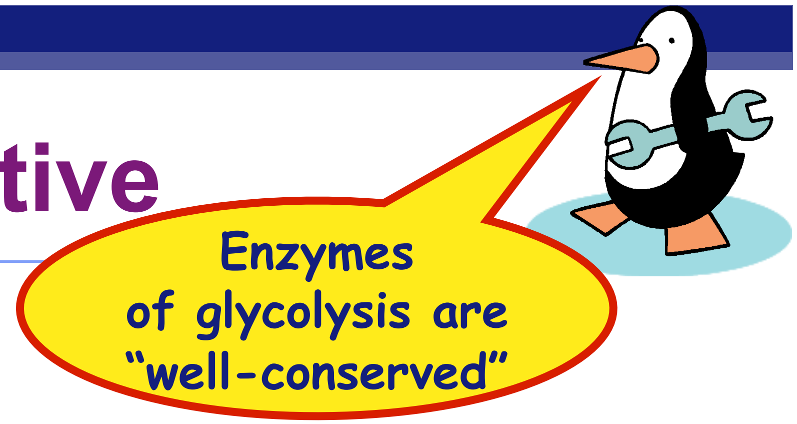
- "glyco – lysis" (splitting sugar)

glucose → → → → → pyruvate

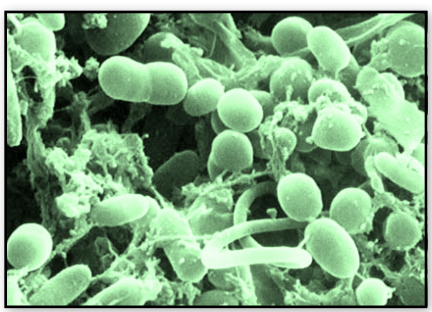
6C 2x 3C

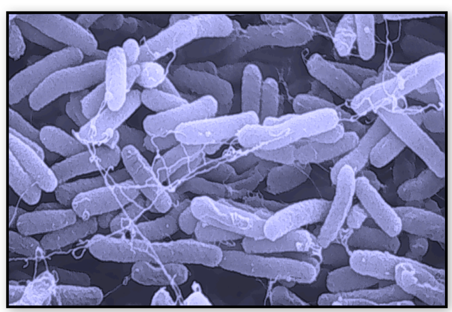
- ancient pathway which harvests energy
  - where energy transfer first evolved
  - transfer energy from organic molecules to ATP
  - still is starting point for ALL cellular respiration
- but it's inefficient
  - generate only 2 ATP for every 1 glucose
- occurs in cytosol

Evolutionary perspective



- Prokaryotes
  - first cells had no organelles
    - energy processing started, therefore, in the cytoplasm
- Anaerobic atmosphere
  - life on Earth first evolved **without free oxygen** (O_2) in atmosphere
  - energy had to be captured from organic molecules in absence of O_2
- **Prokaryotes** that evolved glycolysis are ancestors of all modern life
  - **ALL** organisms still utilize glycolysis

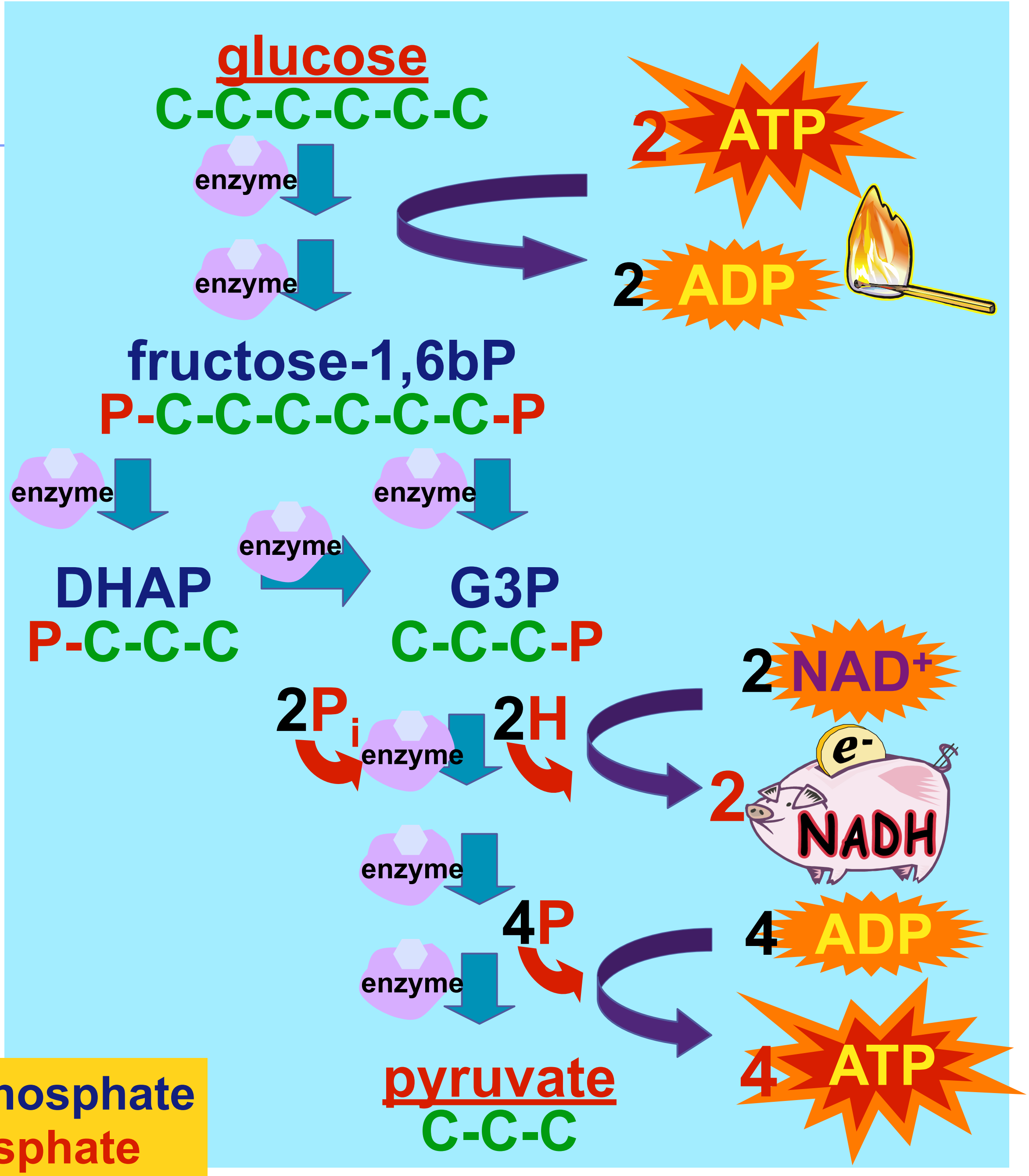




Glycolysis Overview

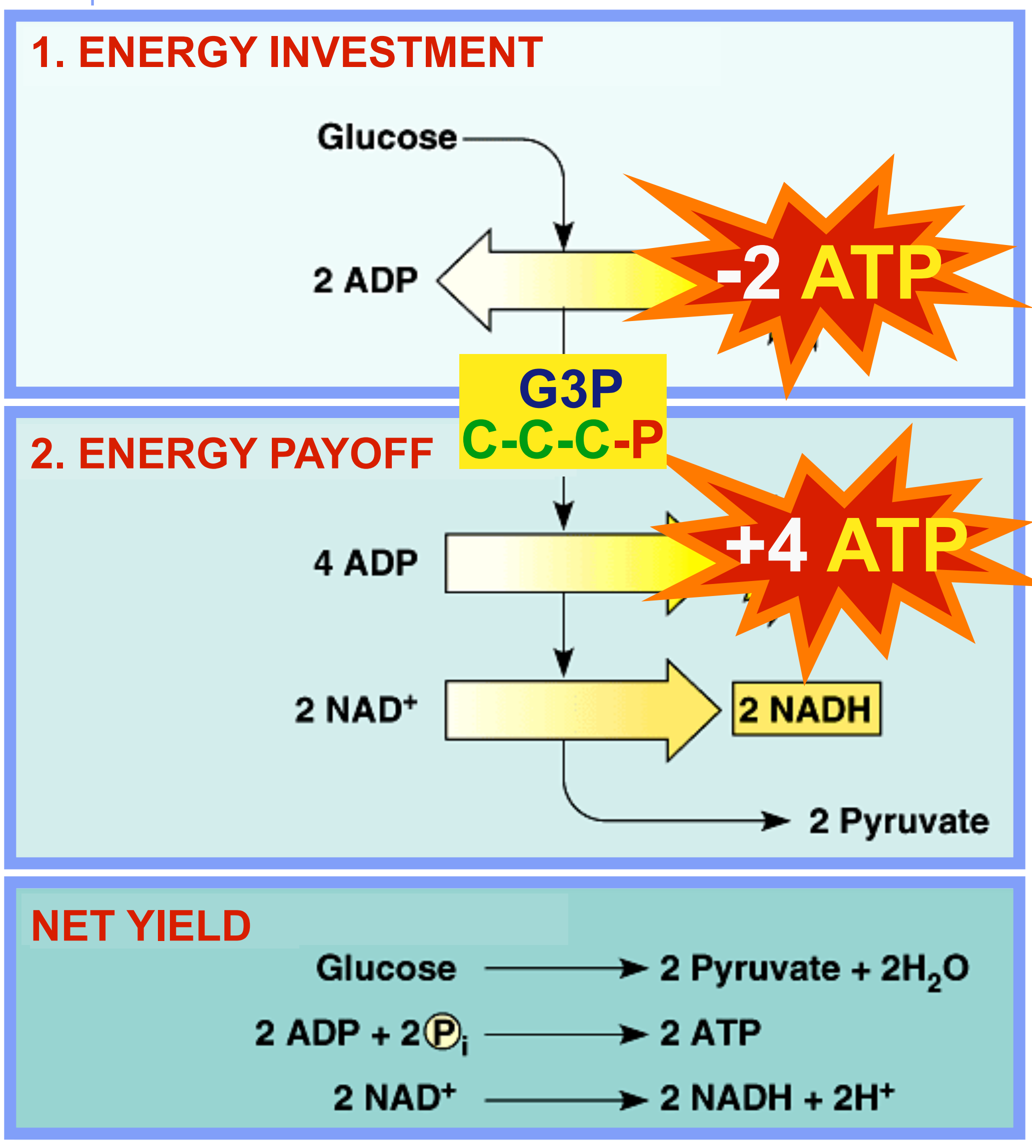
10 reactions:

- convert glucose (6C) to 2 pyruvate (3C)
- produces: 4 ATP & 2 NADH & 2 H^+
- consumes: 2 ATP
- net yield: 2 ATP & 2 NADH & 2 H^+



DHAP = dihydroxyacetone phosphate
G3P = glyceraldehyde-3-phosphate

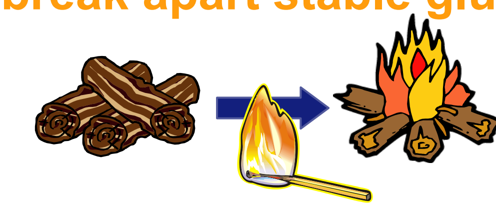
Glycolysis is divided into 2 phases



endergonic

invest some ATP

(to overcome activation energy and break apart stable glucose



exergonic

harvest a little ATP & a little NADH

net yield

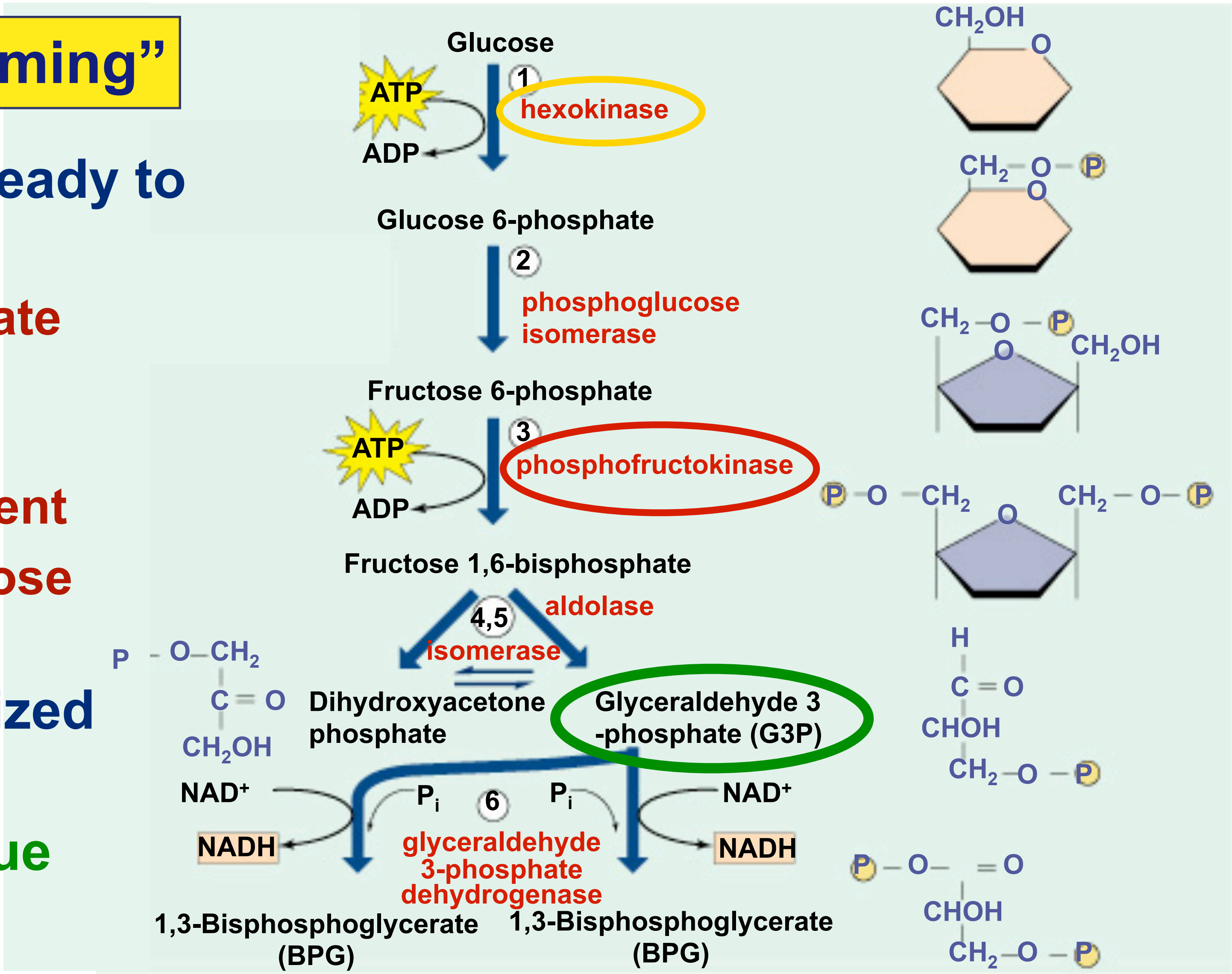
✓2 ATP

✓2 NADH

1st half of glycolysis (5 reactions)

Glucose "priming"

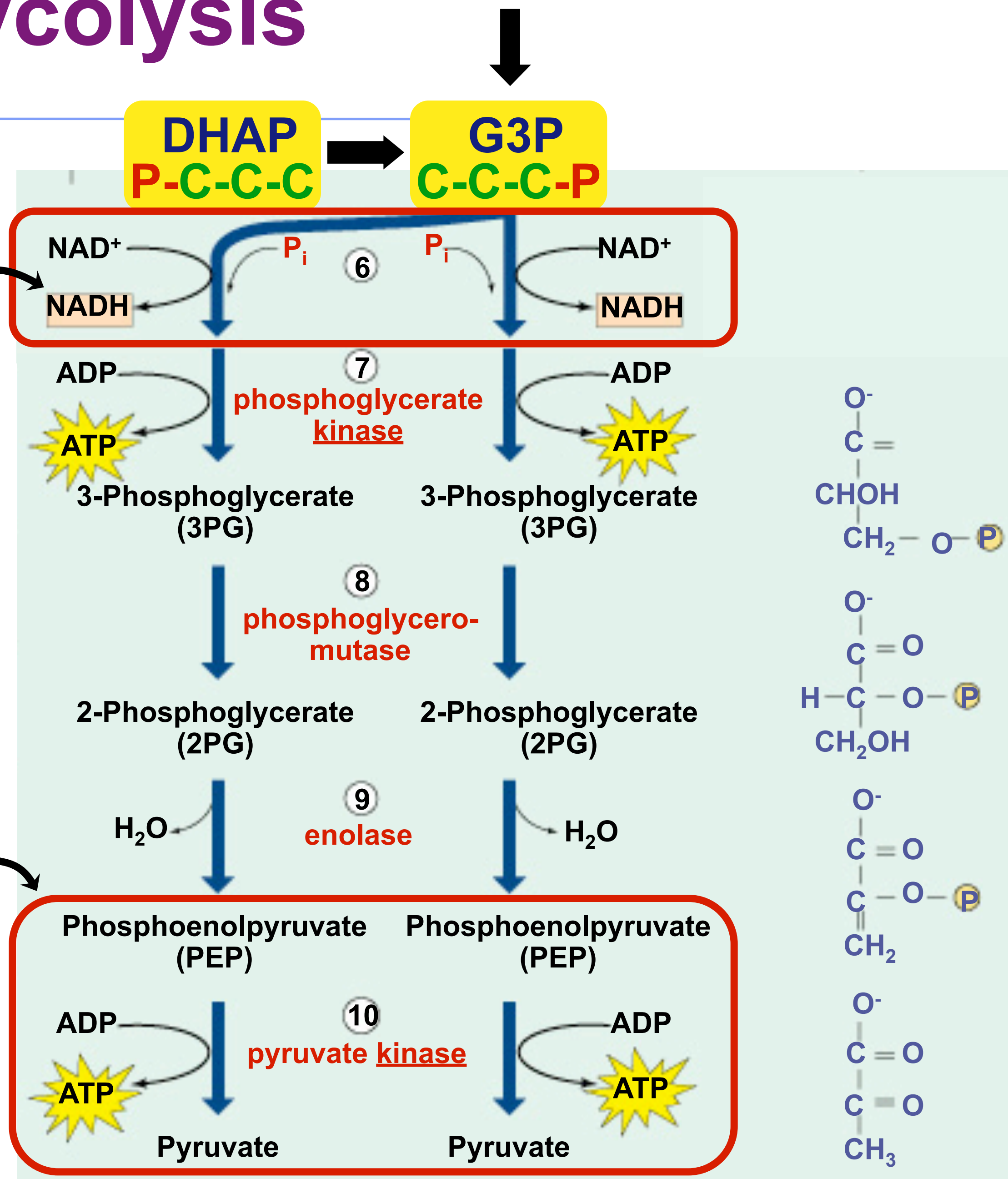
- get glucose ready to split
  - phosphorylate glucose
  - molecular rearrangement
  - Makes glucose unstable
- split destabilized glucose
- 2 G3P continue glycolysis

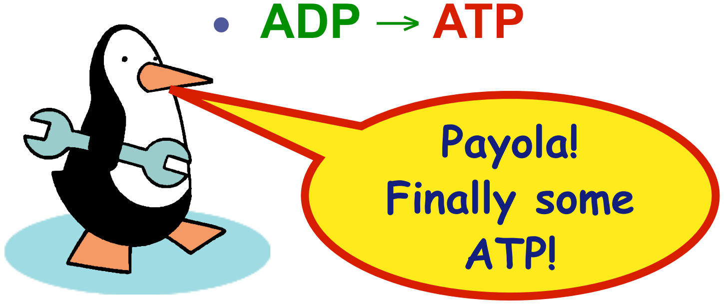


2nd half of glycolysis
(5 reactions)

Energy Harvest

- NADH production
  - G3P donates H + e-
  - oxidizes the sugar
  - reduces NAD^+
    - $NAD^+ \rightarrow NADH$
- ATP production
  - G3P → → → pyruvate
    - PEP sugar donates P for "substrate level phosphorylation"
    - ADP → ATP

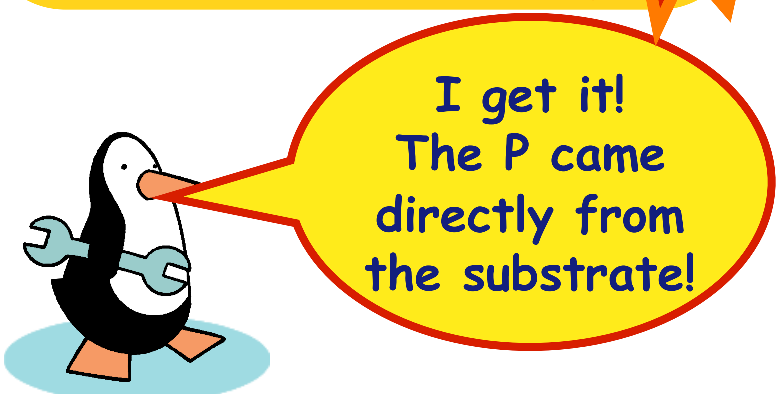


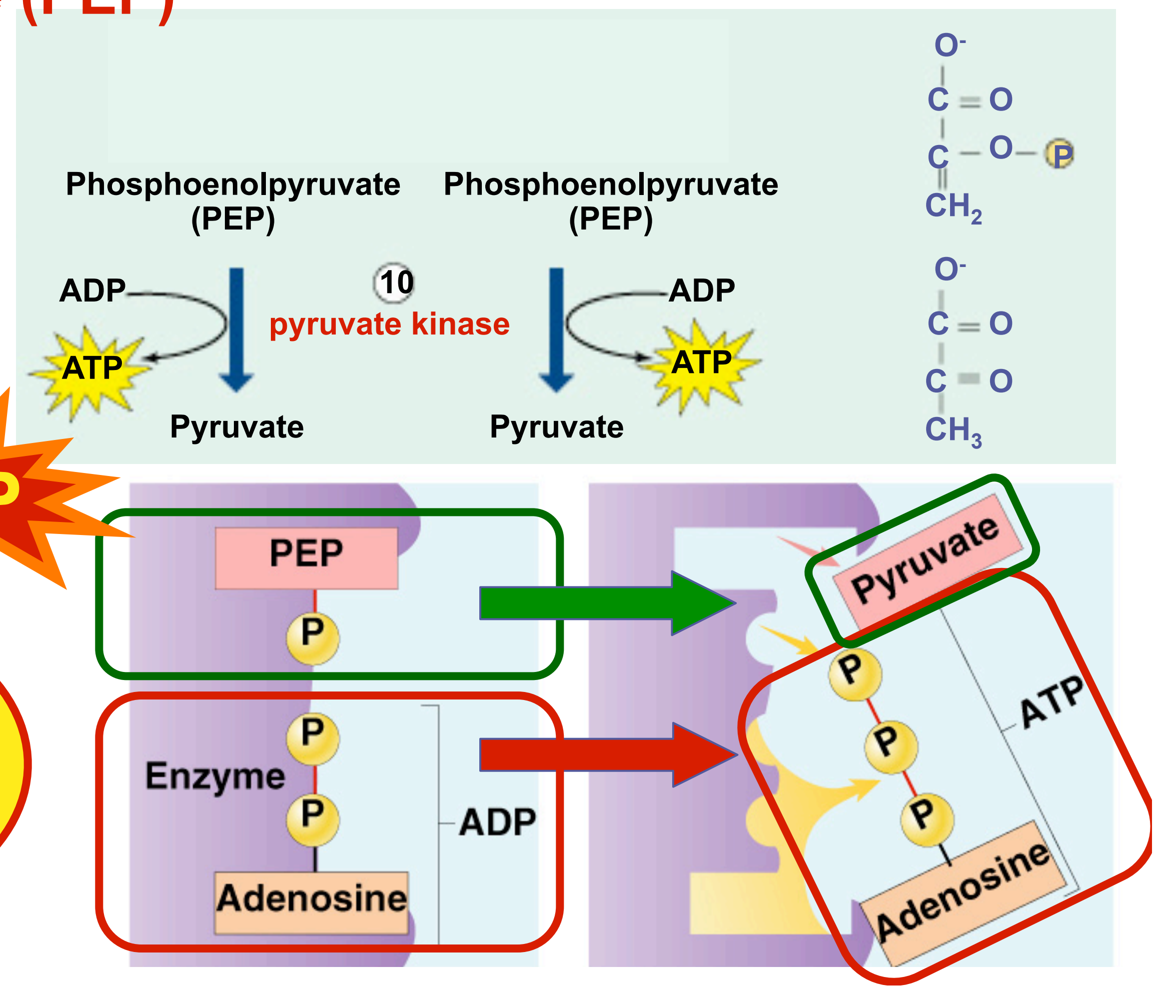


Substrate-level Phosphorylation

- In the last steps of glycolysis, where did the P come from to make ATP? *[This phosphate is NOT inorganic!]*
  - the sugar substrate (PEP)

P group transferred from PEP to ADP
- ✓ kinase enzyme used
- ✓ ADP → ATP

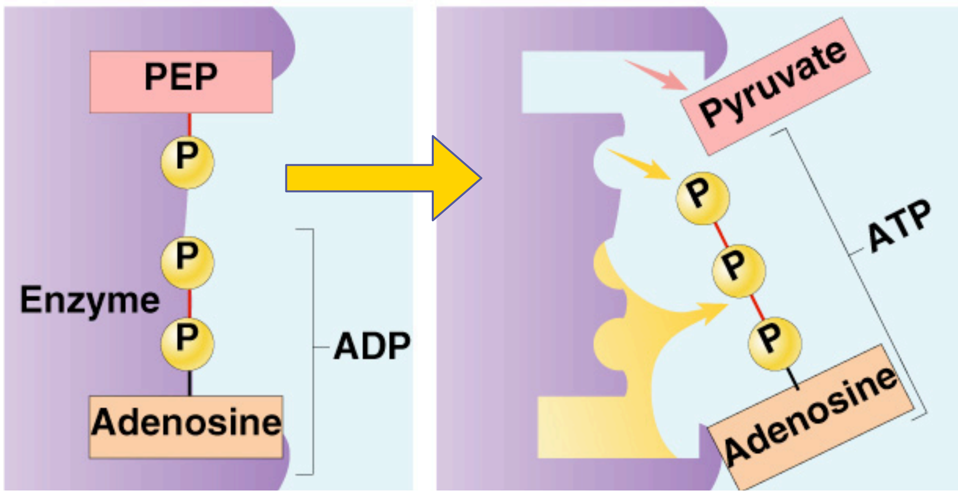




Substrate-level Phosphorylation

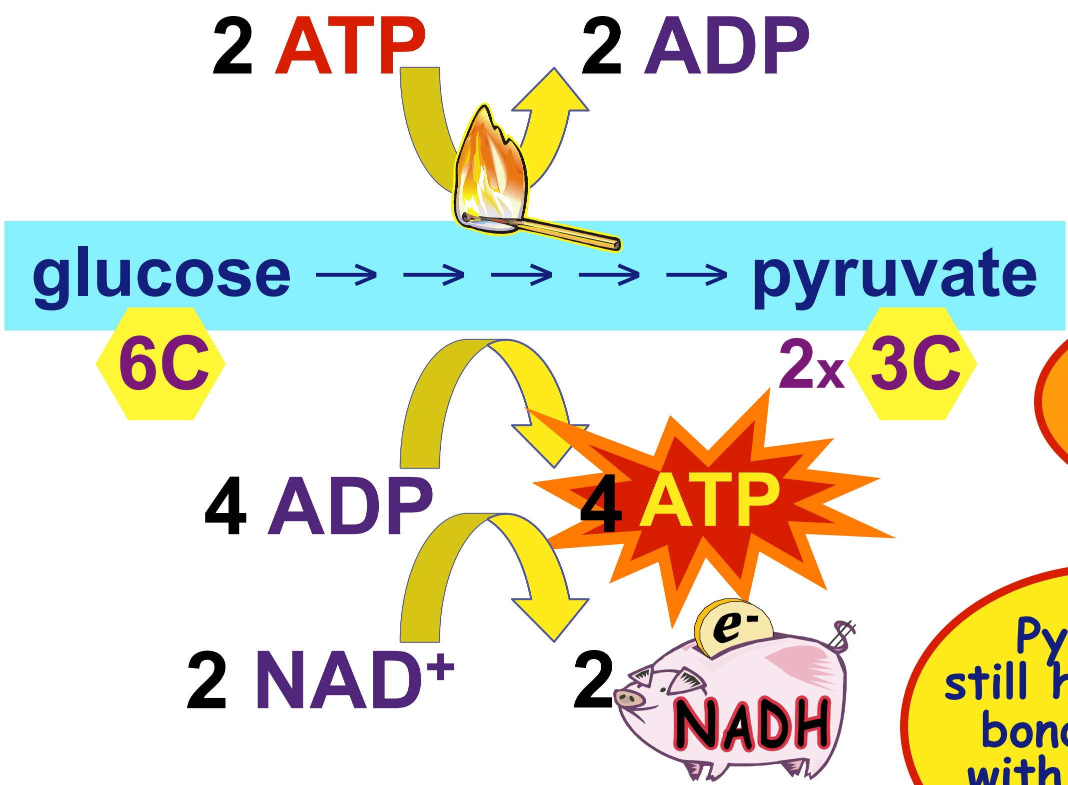
- Accounts for only 10% of ATP made in eukaryotic organisms undergoing cellular respiration

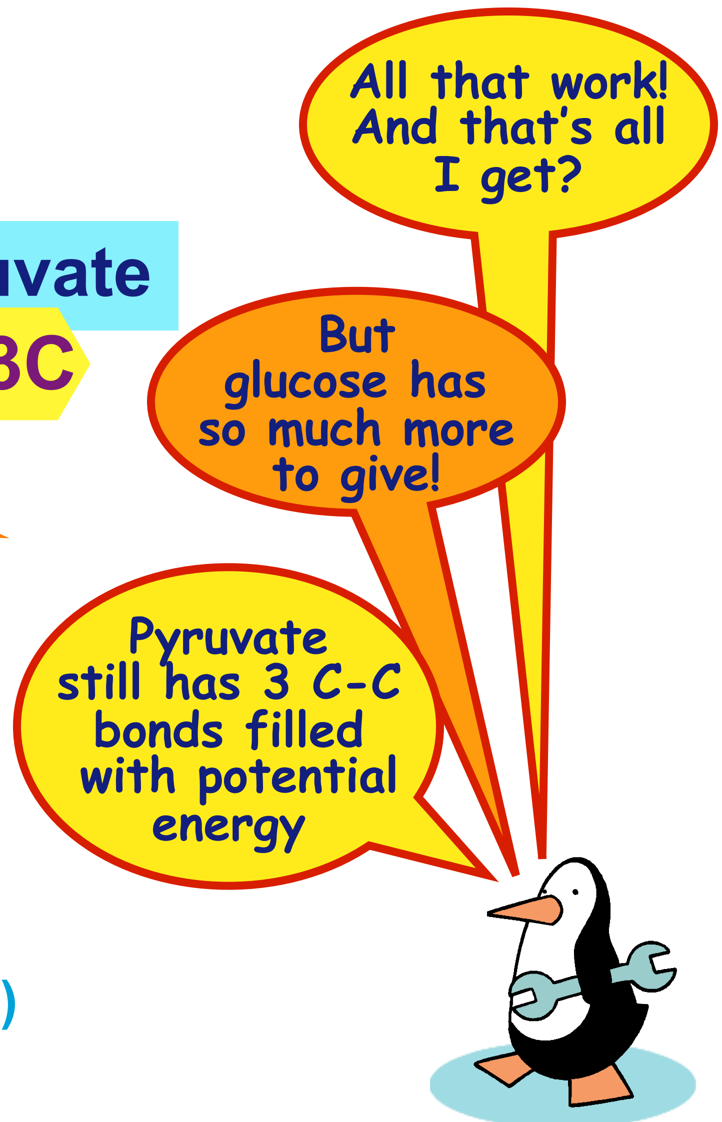
- ATP synthesis involving the transfer of a phosphate group from a substrate molecule by an enzyme to ADP



  - Different from Oxidative phosphorylation as we will see soon where a free inorganic phosphate is added to ADP.

Energy accounting of glycolysis





- Net gain = 2 ATP + 2 NADH
  - some energy investment (- 2 ATP)
  - small energy return (+ 4 ATP + 2 NADH)
- 1 6C sugar → 2 3C sugars

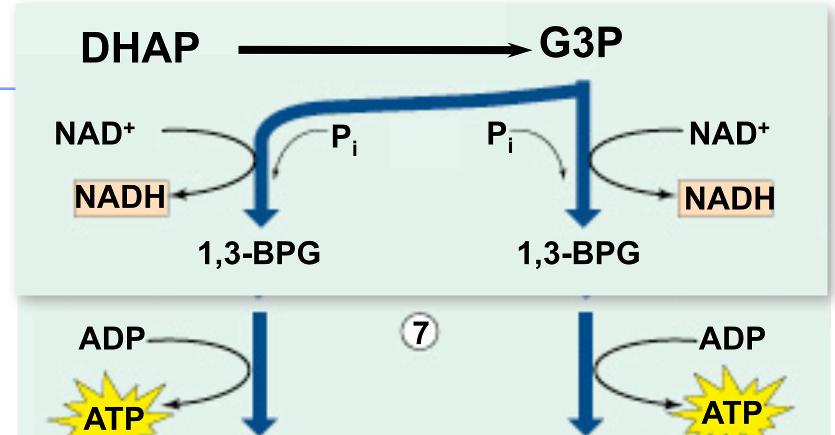
Is that all there is?

- Not a lot of energy is extracted from each glucose during glycolysis alone…
  - for 1 billon years+ this is how life on Earth survived
    - no O_2 = slow population growth, slow reproduction
      - Glycolysis doesn't require O_2 so these first organisms were anaerobic respirators.
    - only harvest 3.5% of energy stored in glucose
      - products of anaerobic respiration contained more carbons to strip off (more energy to harvest) but new enzymes [so new chemistry] had to first evolve to allow further energy extraction

glucose → → → → pyruvate

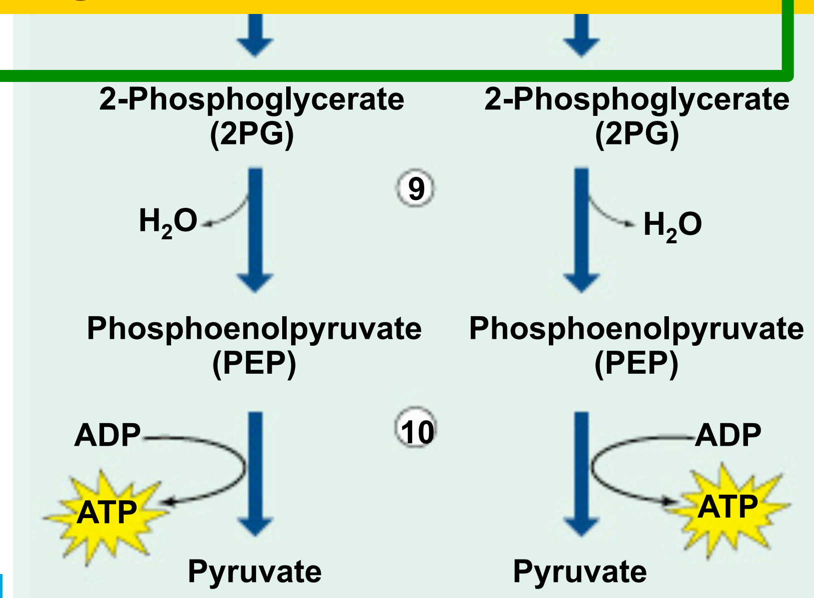
6C   2x 3C

But can't stop with glycolysis alone!



Glycolysis:

glucose + 2ADP + 2P_i + 2 NAD^+ → 2 pyruvate + 2ATP + 2NADH



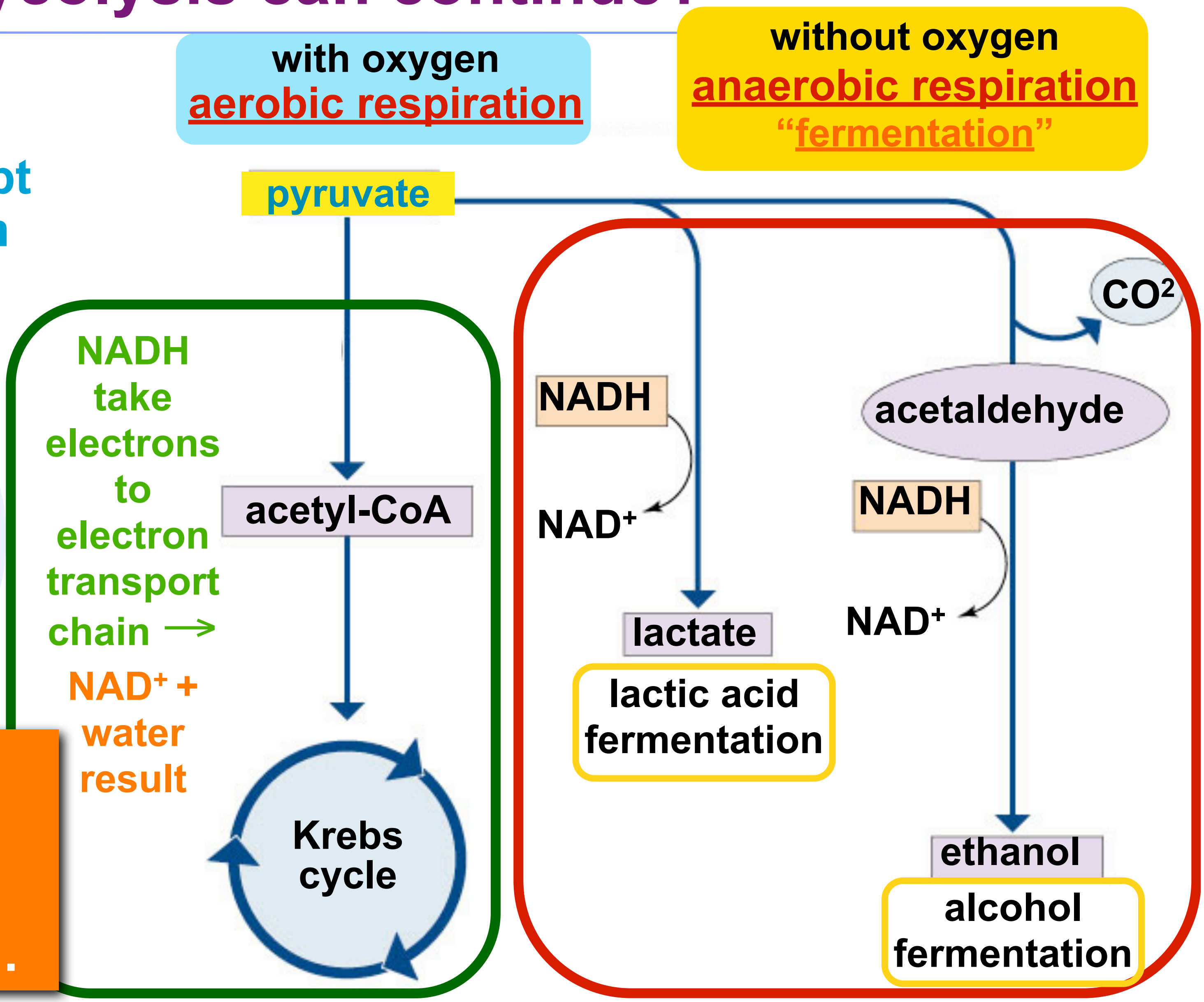
Going to run out of NAD^+

- without regenerating NAD^+, energy production & glycolysis would stop!!!!!
- another molecule must accept H + e^- from NADH
  - NAD^+ is freed up for another round

How is NADH recycled to NAD^+ (oxidized) so more glycolysis can continue?

Another molecule must accept H & e- from NADH

To recycle NADH:



Which path you use depends on who you are…

Fermentation (anaerobic) - Pyruvate serves directly or indirectly as the electron acceptor to oxidize NADH back to NAD^+

- **Bacteria, Yeast**

  pyruvate → ethanol + CO_2

  3C → 2C + 1C

  NADH → NAD^+

  - beer, wine, bread (CO$_2$ is what makes bread rise)

- **Animals, some Fungi**

  pyruvate → lactic acid (lactate)

  3C → 3C

  NADH → NAD^+

  - cheese, anaerobic exercise (When not enough O_2 in muscle cells, lactic acid then builds up in muscle cells that switch from aerobic to anaerobic respiration)

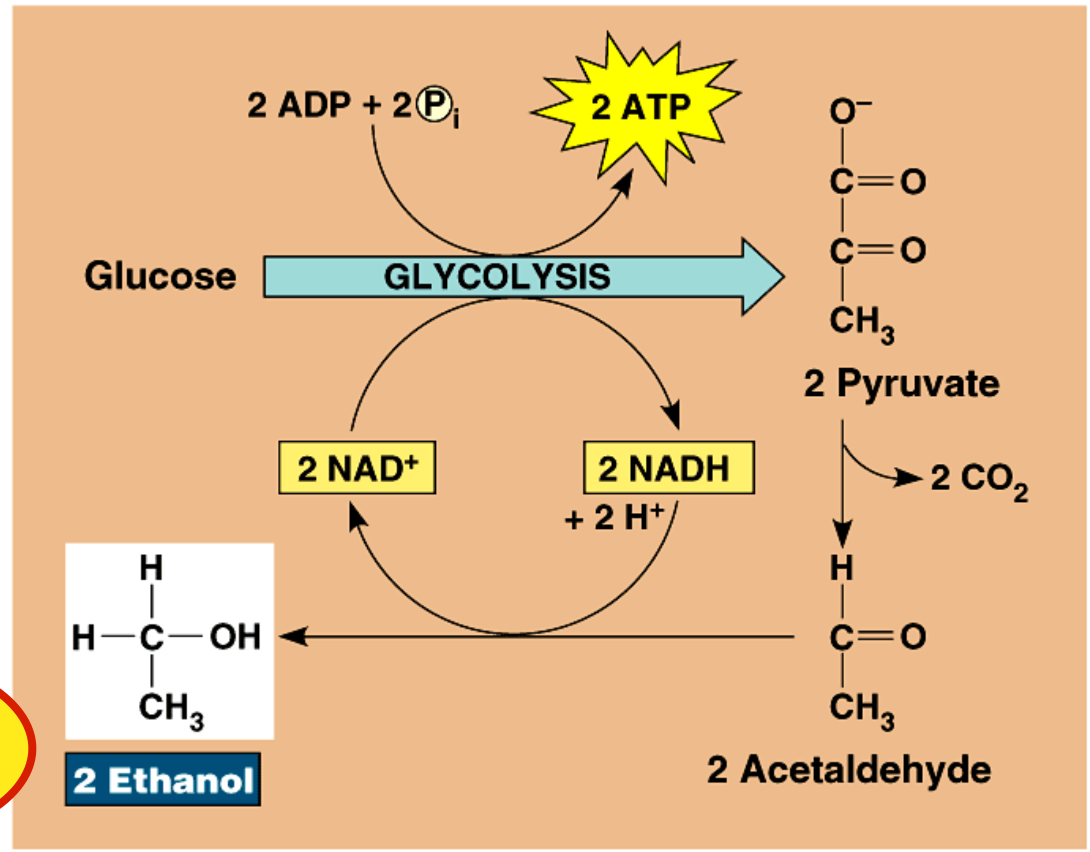
Alcohol Fermentation

bacteria
yeast

pyruvate → ethanol + CO_2

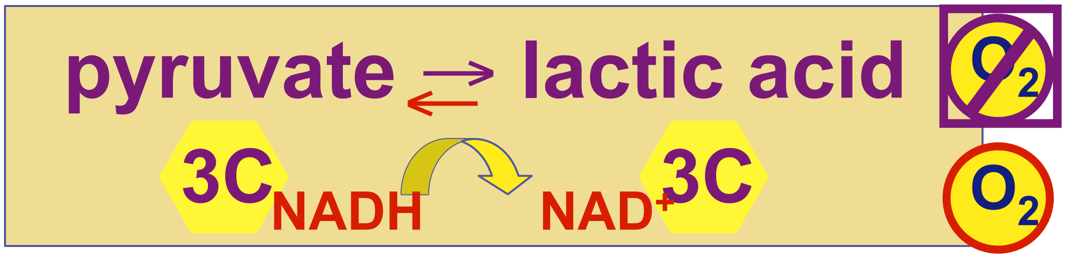
3C NADH → NAD$^+$ 2C 1C

- **Dead end process**
  - at ~12% ethanol kills yeast
  - can't reverse the reaction
    - If the waste products cannot be removed from the environment, the yeast thus dies.

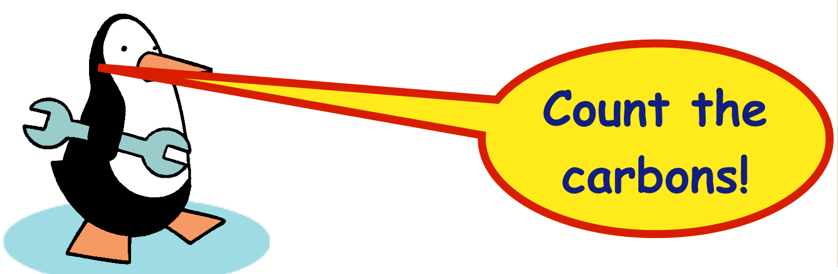


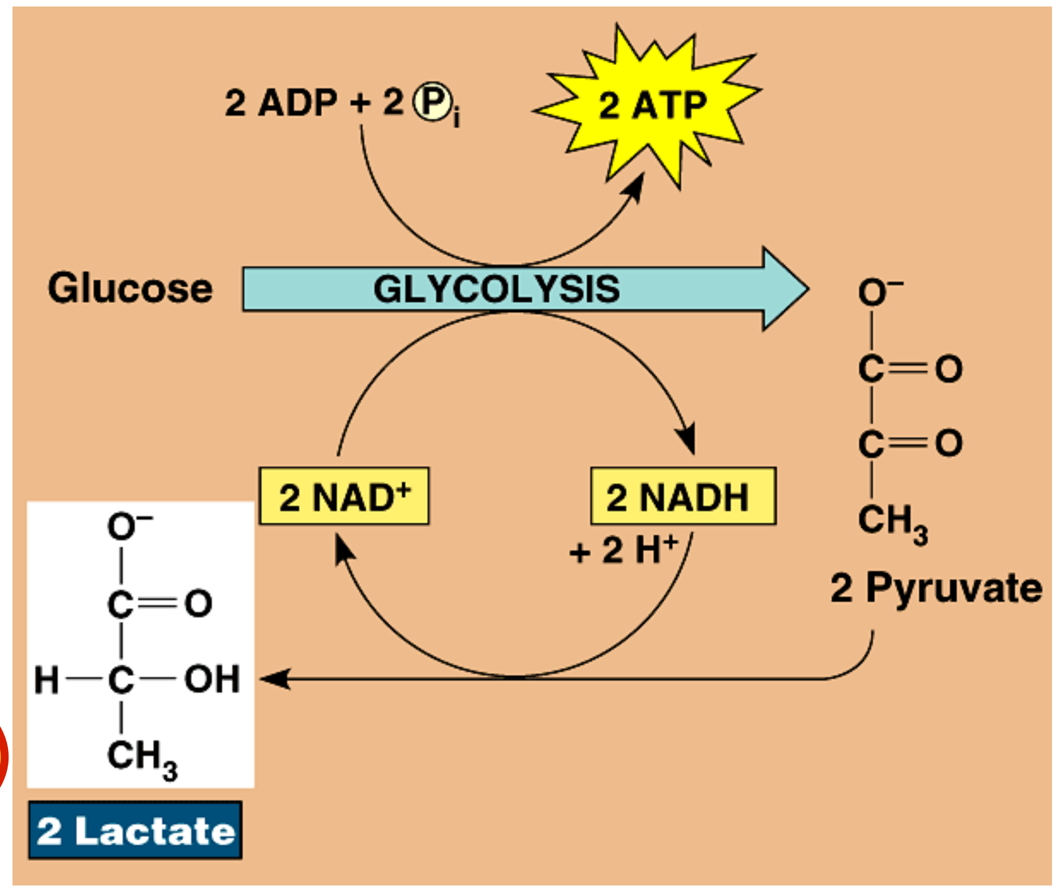
Lactic Acid Fermentation

animals
some fungi



- In our bodies, the production of lactic acid can be undone.
  - once O_2 is available again, lactate [released into the blood stream] is converted back to pyruvate by the liver





<u>Pyruvate is a branching point</u> - What happens next depends on whether O_2 is present and which genes you have to engage in one of two pathways.

Pyruvate

No O_2 | O_2

Pyruvate stays in the cytoplasm in order to complete **Fermentation** [a form of anaerobic respiration]

Pyruvate moves into the Mitochondria in eukaryotes *[stays in cytoplasm in prokaryotes]* to participate in the **Citric Acid/ Krebs cycle** [aerobic respiration]