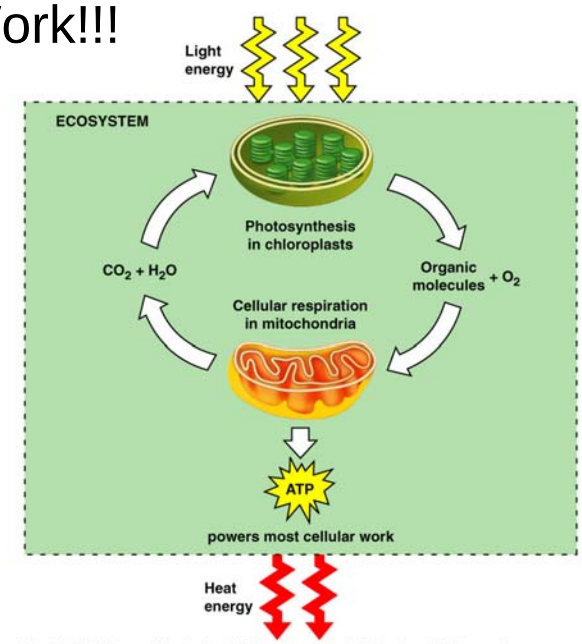
Chapter 9
Harvesting Chemical Energy: Cellular Respiration

Life is Work!!!



Catabolic pathways and ATP production

- Catabolic pathways release energy by breaking down large molecules into smaller ones
- The energy is potential energy in the form of the chemical bonds which hold these large molecules together
- This energy is used phosphorylate ADP to make ATP (and it also generates some heat)

Two basic catabolic paths:

- Cellular respiration
  - A.K.A – aerobic respiration
  - Requires oxygen
  - Occurs in mitochondria of most eukaryotic cells
- Fermentation
  - Occurs without oxygen
  - Less efficient than aerobic cellular respiration
    - Makes fewer ATPs

Recall that the process to phosphorylate ADP (add a phosphate) to make ATP requires energy

- This energy comes from the catabolism of organic fuels
  - Glucose
  - Lipids
  - Proteins
  - Etc…
- The key to understanding how this energy is transferred is related to the understanding of oxidation-reduction reactions
  - ***Redox reactions***

Redox reactions

- Involve the transfer of electrons
- The loss of electrons
  - Called oxidation
- The gain of electrons
  - Called reduction

Is similar to ionic bonds, but do not confuse the two!!!!

- As these electrons are transferred from one substance to another, energy is transferred as well.
- Recall that electrons have energy!!!!
- Think of these electrons as moving packets of energy as they *oxidize* substances they leave and *reduce* substances which gain them.
  - – Oxidized substances lose energy
  - – Reduced substances gain energy

Aerobic cellular respiration

- ***Know this reaction***:

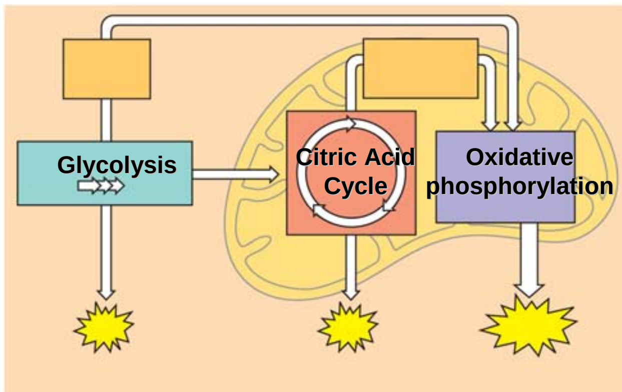
Becomes oxidized – loses electrons

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

Becomes reduced – gains electrons

There are three stages to aerobic cellular respiration

1. Glycolysis
2. Citric Acid Cycle
3. Oxidative phosphorylation: e- transport and chemiosmosis

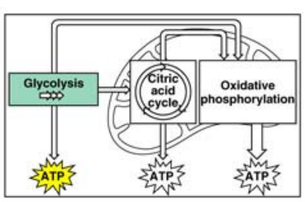


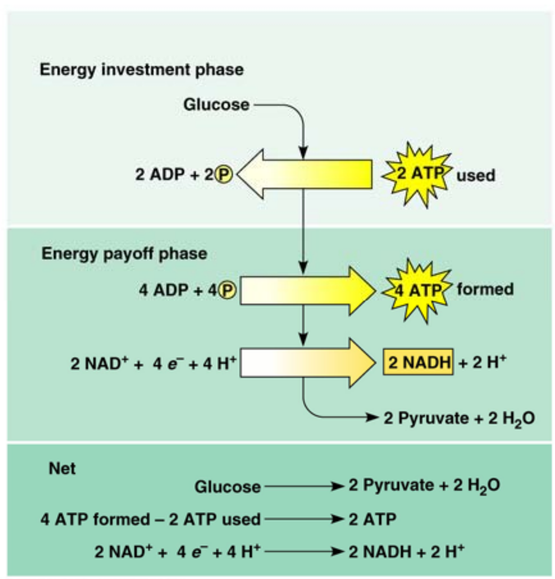
1. Glycolysis

- “splitting sugar”
- Glucose – $C_6H_{12}O_6$
  - How many carbons??
  - HINT: These reactions are much simpler if you keep track of the carbons!!!
    - Remember – glucose is going to be catabolized and oxidized- the carbons will be split apart!!!!
    - Keep track of them!!!!!
- Occurs in the cytoplasm

Two phases of glycolysis

- Energy investment phase-
  - Requires 2 ATPs
  - Glucose is split and the and oxidized
- Energy payoff phase
  - Produces 4 ATPs
  - Produces 2 NADH from NAD+
    - Nicotanimide adenine dinucleotide
    - NADH is reduced form – gained electrons with H atom
    - NADH in this reduced form is an energy carrier!!!!
  - Produces 2 molecules of pyruvate – three carbon acid





So…in summary

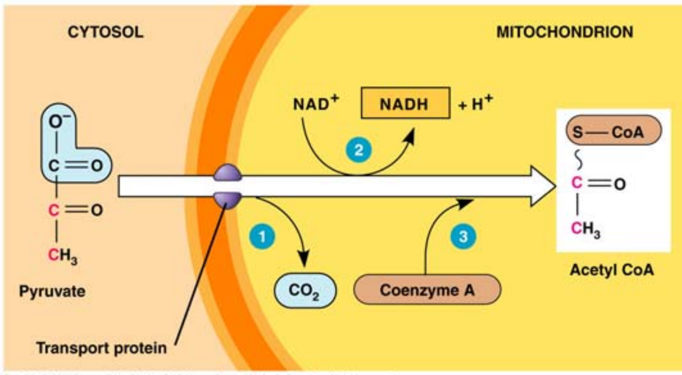
- One molecule of glucose proceeds through glycolysis and we get:
  - A net of 2 ATPs (but recall we made 4 ATPs)
  - 2 NADH – reduced NAD+ (energy carriers)
  - 2 Pyruvate (3 C *each* – still six carbons right??)

  - Glycolysis does not require oxygen!
  - Occurs in the cytoplasm of the cell!

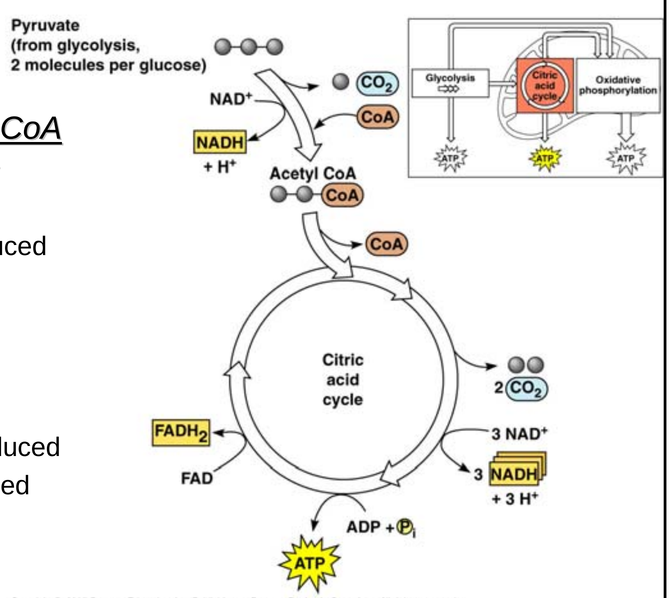
2. Citric Acid Cycle

- Also known as the Krebs Cycle
  - Hans Krebs – scientist who mapped pathway in 1930s
- After glycolysis, we still have a lot of energy remaining in what was our glucose molecule.
  - *Where is it??*
    - Pyruvate (2) (3 C each)
    - NADH (2)
- If there is oxygen present, pyruvate enters the mitochondrion

- Pyruvate (3 C each) from glycolysis enters the mitochondrion
  - If oxygen is present
- Using Coenzyme A, each pyruvate is converted into a molecule of Acetyl CoA (2 C)
  - What happened to the other carbon from each molecule of pyruvate?
    - CO_2 released
  - NAD+ is reduced to form NADH



- ***For each Acetyl CoA*** which enters the citric acid cycle:
  - 2 CO_2 are produced
    - Catabolism of glucose now complete
  - 3 NADH are produced
  - 1 $FADH_2$ is produced
  - 1 ATP is produced



Biology – Kevin Dees

So, let's review what has happened up to this point

- Glycolysis – 1 glucose molecule
  - Net gain of 2 ATP
    - Total produced – 4 ATP
  - 2 NADH
  - 2 Pyruvate
- Citric Acid Cycle
  - Each pyruvate converted into Acetyl CoA
    - CO_2 produced
    - NADH produced
  - Each Acetyl CoA "spins the citric acid wheel"
    - 2 CO_2 produced
    - 3 NADH produced
    - 1 $FADH_2$ produced
    - 1 ATP produced
  - Glucose is catabolized

- Net production from catabolism of 1 glucose:
  - 4 ATP
  - 10 NADH
  - 2 $FADH_2$
  - 6 CO_2 produced

WHERE is all of the energy????

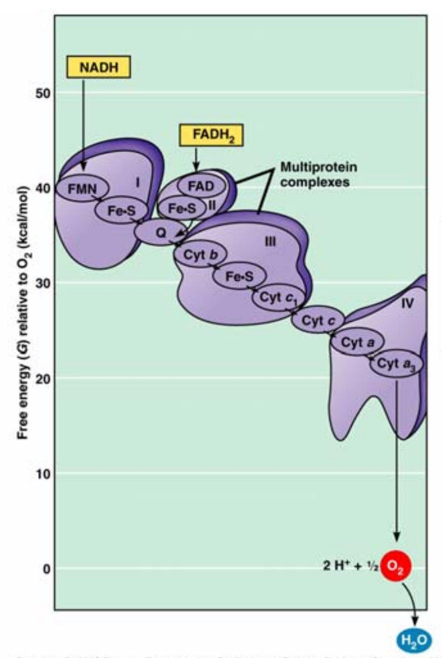
Most of the energy is tied up in the energy carrier molecules

- NADH and $FADH_2$
- These energy carrier molecules are routed to the cristae of the mitochondria
- The cristae membrane is the site of **oxidative phosphorylation**
  - Two steps to oxidative phosphorylation
    - Electron transport
    - Chemiosmosis

Complexes of proteins are located on the cristae – recall it was highly folded right??

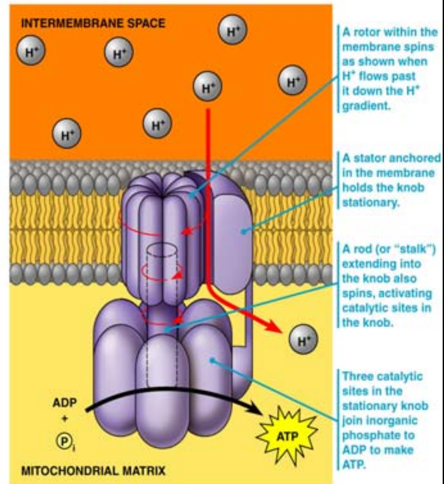
- **electron transport chain**
- The NADH and $FADH_2$ are oxidized once again as they lose their electrons
- These electrons "fall" down an energy gradient on the electron transport chain
- This forces H+ (protons) into the intermembrane space

- Electrons fall down the energy gradient on the electron transport chain
- Oxidizing and reducing along the way
- Final electron acceptor:
  - OXYGEN
  - Makes water molecule



Chemiosmosis

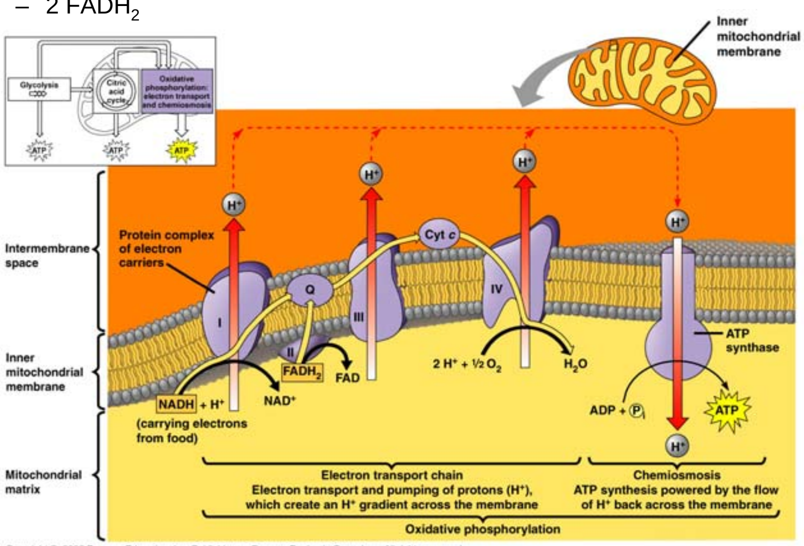
- Recall that H+ were forced into the intermembrane space; high concentration of H+
- ATP synthase proteins are also located on the cristae
- These H+ form an energy gradient along the membrane and ass they pass through ATP synthase the energy released is used to phosphorylate ADP to make **ATP**



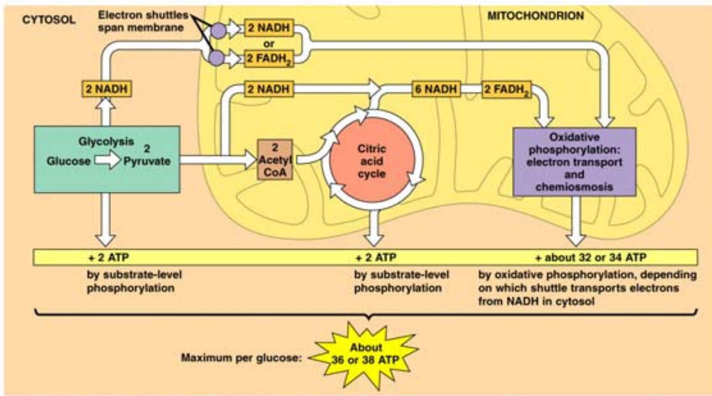
Oxidative phosphorylation – a review

- 10 NADH
- 2 $FADH_2$

Net production of 32 -34 ATP

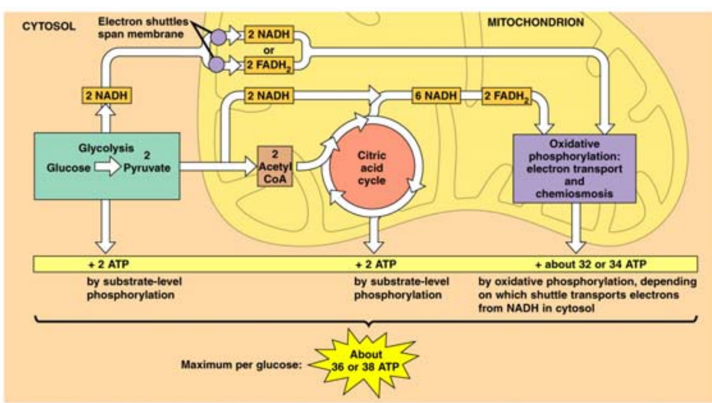


A review of cellular respiration



- For each glucose which enters the process, a net yield of 36 to 38 ATP occurs

Why is oxygen required??



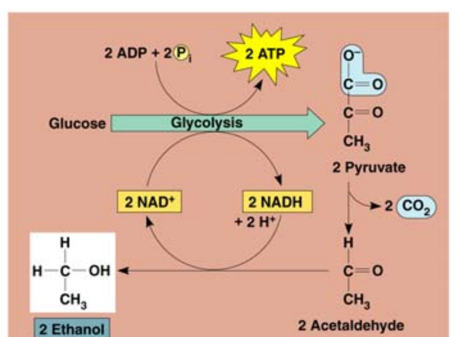
- *Final electron acceptor* (final reduced substance)

What if oxygen is not present??

- Fermentation can occur
- ATP production is limited to glycolysis
  - Net gain of 2 ATP per glucose
  - Pyruvate must be converted – not stable

Alcohol fermentation

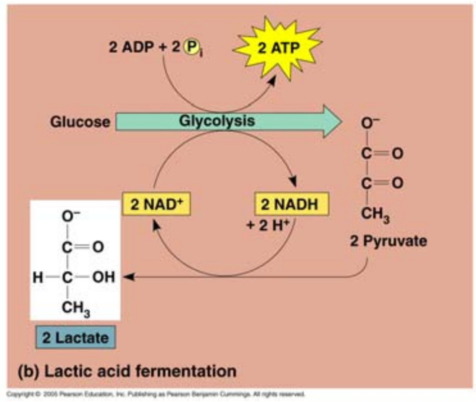
- Many bacteria and yeasts under anaerobic conditions
  - Pyruvate is converted into ethanol
  - Important in brewing, winemaking and baking



(a) Alcohol fermentation

Lactic acid fermentation

- Human muscle cells
  - Occurs during strenuous exercise when sugar catabolism for ATP production outpaces muscle's supply of oxygen in blood
  - Achy muscles!!!



Simple sugars like glucose a not the only catabolized molecules

Each different organic macromolecule can enter the pathway at different steps