Chapter 7

Introduction:

- Living cells constantly use energy for activities such as movement, protein synthesis, active transport and cell division — most of this energy to power these processes comes from ATP

- Cell constantly replace ATP - it does this by:
  - breaking down organic food molecules
  - releasing energy that is used to join ADP and phosphate to form ATP

- breakdown of food to release energy occurs by 2 kinds of processes:

1. respiration
2. fermentation

small, controlled steps @ releasing a little of the food molecules energy

exchange of oxygen and CO_2 between cells and atmosphere

taking in O and giving off CO_2 and H_2O

I. Cellular Respiration: the stepwise oxidation of food molecules using an inorganic substance as the final acceptor of electrons

that's why its called aerobic (i.e. aerobic exercise, like)

(occurs in mitochondria) (occurs in every cell) (described by Krebs cycle) (occurs when O is available)

in humans is 1st choice for metabolism of nutrients and production of ATP

1. * **aerobic**: uses molecular oxygen (O_2) as the final electron receptor — end products are the low-energy molecules CO_2 & H_2O

same equation described combustion reaction

$$\text{organic molecules} + O_2 \rightarrow CO_2 + H_2O + \text{energy}$$

(occurs in cytoplasm) 2. **anaerobic** (little or no CO_2 available)

metabolism w/o O used as back up system when not enough O available

- some kinds of bacteria carry out anaerobic respiration which * uses other inorganic substances (i.e. NO_3^- (nitrate) or SO_4^- (sulfate)) instead of O_2, as a final electron acceptor

metabolic pathways of anaerobic resp. are entered only to keep cells alive — w/o a.r. producing molecules that accept e^-, all respiratory cycles come to grinding halt. When that happens ATP not produced - no ATP cell di

* are nonprotein organic molecules which function in association w/ enzyme

II. Coenzymes i act as shuttle molecules, carrying substances from one enzyme reaction to another

- also carry energy i passing the substance they carry to the second reaction releases a lot of free energy, which drives the reaction
- * most coenzymes in biological reactions are made from vitamins
- last for a long time and can be used again and again and as a results are required in very small amts

III. Aerobic respiration has 3 steps:

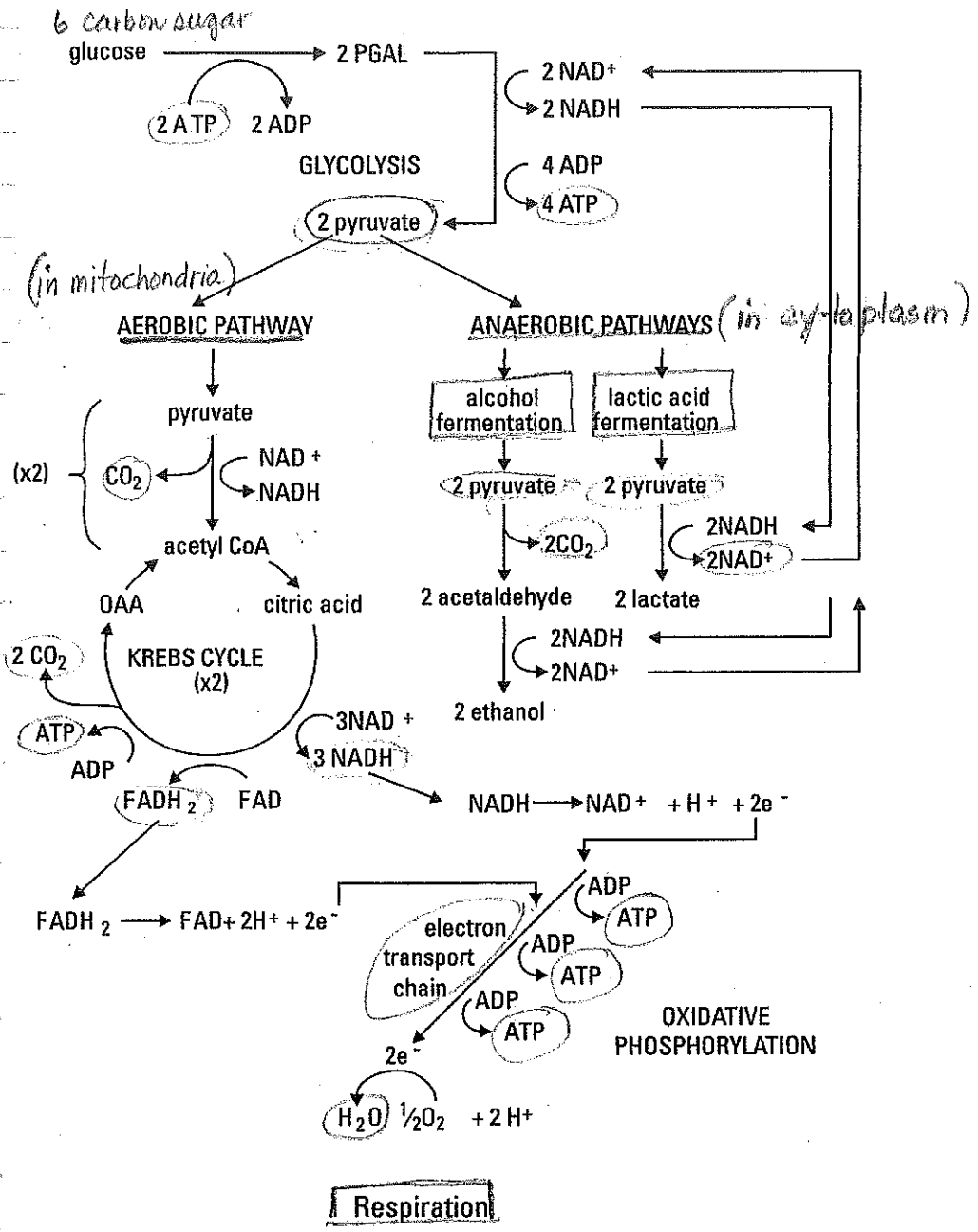
1. glycolysis: process that breaks down glucose and converts it to pyruvate

2. Krebs cycle (citric acid cycle): takes pyruvate and puts it through conversions that result in the production of the coenzymes NADH and $FADH_2$, as well as a molecule of ATP and some CO_2

3. oxidative phosphorylation: process that takes NADH and $FADH_2$ and passes them through an electron transport chain until ATP is produced.

So @ end of entire process of respiration (after all 3 steps have been completed) the result is 38 molecules of ATP for you to expend any way you wish. The more you use, the more you make, though, so don't be stingy w/ your energy!

(refer to next pg.)



Chemical equation for cellular respiration

$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O +$ Energy (38 ATP)

($C_6H_{12}O_6$: 1 molecule of glucose; $6O_2$: 6 molecules of oxygen; $6CO_2$: 6 molecules of carbon dioxide; $6H_2O$: 6 molecules of water)

takes place in cytoplasm

1. Glycolytic pathway (glycolysis)

(6 C sugar)

primary metabolic function: This pathway turns 1 molecule of glucose into

glucose degraded to:
- * a. 2 molecules of pyruvic acid

formed from metabolism of glucose:
- * b. 2 molecules of NADH
- * c. 2 molecules of ATP (donate phosphate to the 6 carbon sugar)

There is a total of 10 chemical reactions in this pathway. Important to note that some reactions in this pathway are reversible. (That means a plant can make glucose by running through this same pathway backwards.)

(refer to next page) ←

2. Krebs Cycle (citric acid cycle)

This pathway is a major biological pathway because it occurs in plants/animals. It is part of aerobic respiration.

→ once pyruvic acid produced it crosses mitochondria of plant and starts Krebs cycle

preparatory step for citric cycle

* a. @ beginning of aerobic respiration, the pyruvic acid created from glucose in the glycolytic pathway has a molecule of NAD^+ (e^- carrier) added to it to get things going.

↓

* b. This reaction causes the release of CO_2 and hi-energy molecule NADH and the product - acetyl coenzyme A (acetyl CoA)

↓

carbohydrate molecule that starts Krebs cycle in motion

* i.e. pyruvate is converted to acetyl CoA molecule and CO_2, NADH is formed

THE STEPS OF GLYCOLYSIS occurs in cytoplasm of cell

The steps of glycolysis are an example of the changes that occur in a metabolic pathway. Examine the molecular diagrams for each step in Figure 7–A as you read the text description. The numbers on the arrows correspond with those in the text. The enzyme that catalyzes each step is named next to the arrow.

1. The first step of glycolysis actually uses up an ATP: a phosphate group from ATP is attached to the sixth carbon atom of glucose, forming glucose 6-phosphate. This reaction activates glucose by transferring some energy to it. In addition, the negatively charged phosphate group traps the glucose molecule inside the cell. It also provides a recognition site that binds to the enzyme for the next reaction. Other carbohydrates, such as glycogen, sucrose, and galactose, can be converted into glucose 6-phosphate and enter glycolysis at this point.

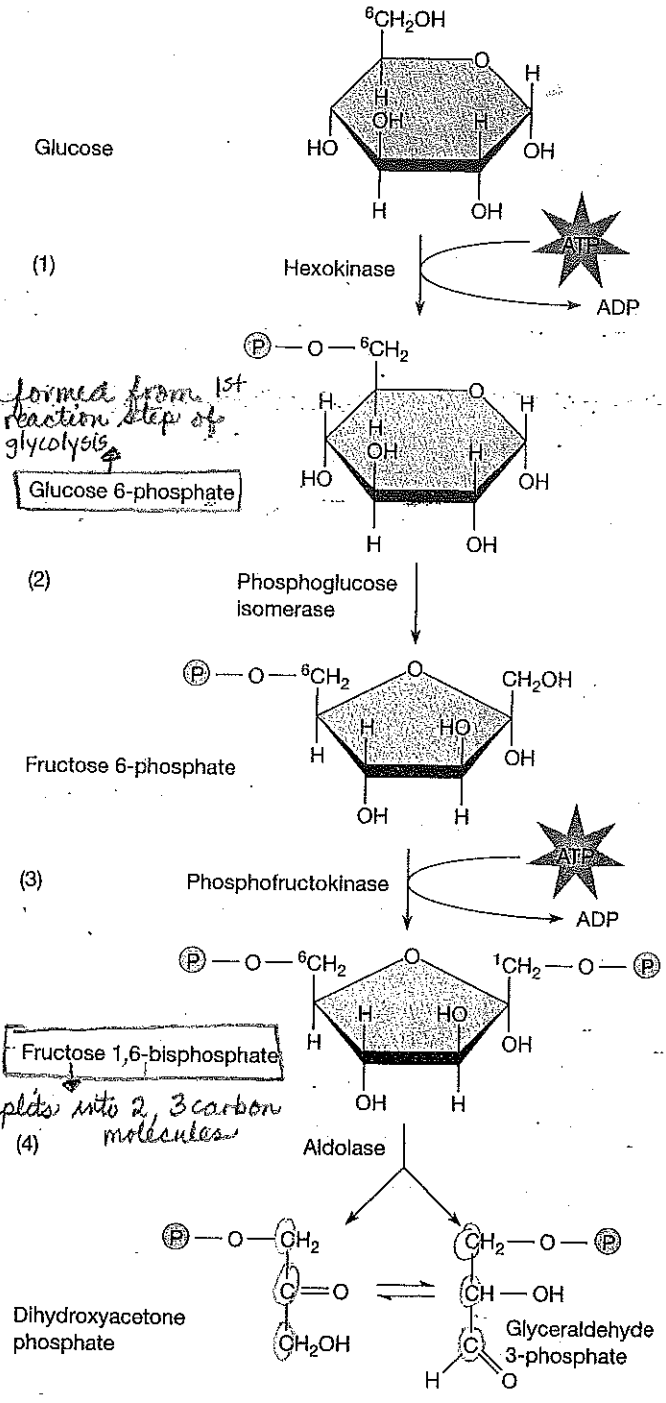
2. Glucose 6-phosphate is rearranged, forming another six-carbon sugar, fructose 6-phosphate. Notice that this leaves the molecule's first carbon poking out from the sugar's ring structure.

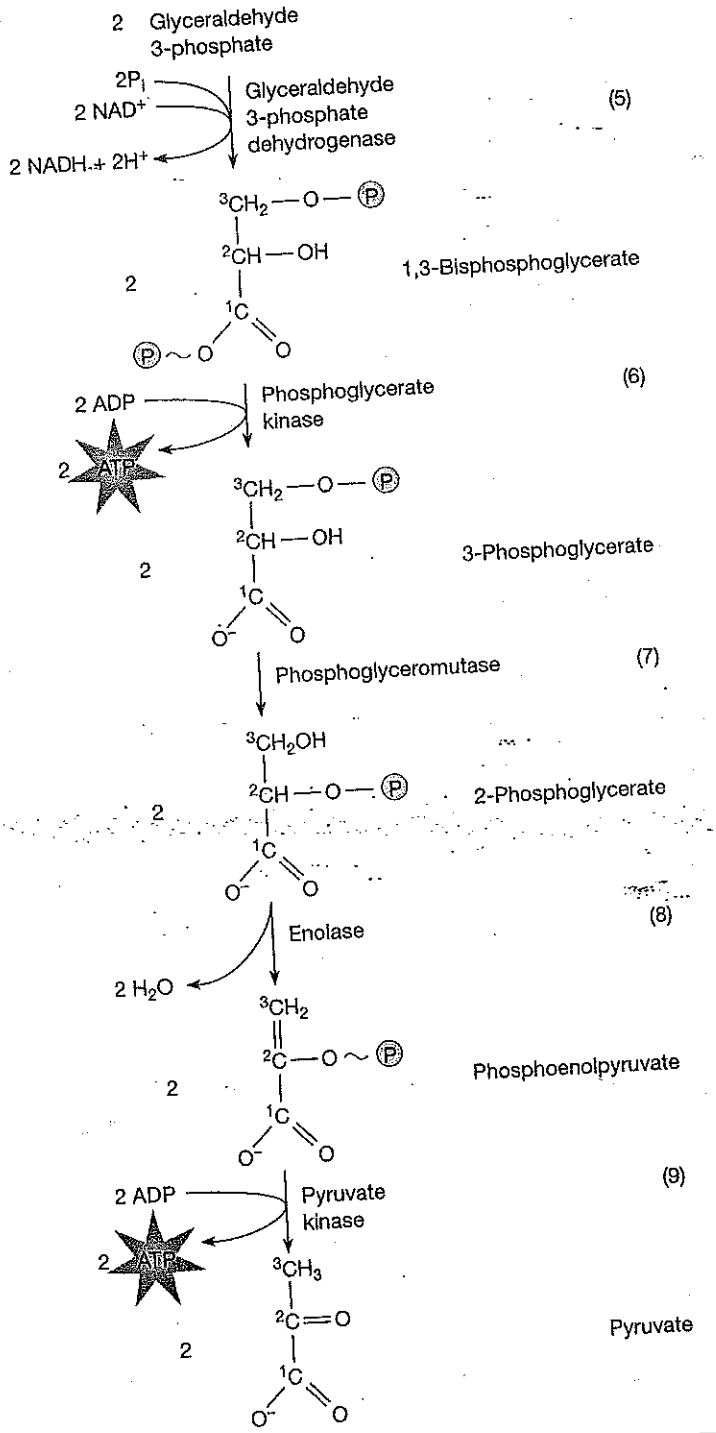
3. A second ATP is invested, donating another phosphate group, which is attached to the newly exposed carbon atom. This produces fructose 1,6-bisphosphate.

4. Fructose 1,6-bisphosphate is split into two three-carbon molecules, each with a phosphate group at one end. One of these molecules, dihydroxyacetone phosphate, is converted into the same form as the other, glyceraldehyde 3-phosphate, which is the substrate of the next enzyme.

Up to this point, the reaction sequence has invested energy, in the form of two ATP. Beginning with the next step, the cell begins to extract its energy profit.

FIGURE 7–A The reactions of glycolysis.





5. Two glyceraldehyde 3-phosphate molecules are oxidized and phosphorylated. The oxidation provides energy for the phosphorylation. This reaction requires two inorganic phosphate groups (P_i) from the cytosol and two molecules of coenzyme NAD^+. A phosphate group is added to each molecule of glyceraldehyde 3-phosphate, and two hydrogen atoms are removed, one from glyceraldehyde 3-phosphate and one from P_i. These two hydrogens reduce NAD^+ to NADH + H^+. The product of this reaction is 1,3-bisphosphoglycerate. This is called a high-energy phosphate compound because breaking the bond, written as a squiggle (~), is a highly exergonic reaction that yields enough energy to transfer the phosphate group to ADP, forming ATP.
6. In the next step, these newly added phosphate groups are transferred from the high-energy phosphate compound to ADP, a substrate-level phosphorylation (Section 6–F). Note that steps #5 and #6 of glycolysis are responsible for the net gain of ATP during glycolysis. These steps provide a pathway for adding an unattached phosphate group to ADP.
7. The remaining phosphate group of each phosphoglycerate molecule is transferred to the molecule's center carbon.
8. A molecule of water is removed from each 2-phosphoglycerate molecule, forming phosphoenolpyruvate. This is another high-energy phosphate compound: removing its phosphate group (at the ~ bond) is another highly exergonic reaction.
9. The remaining phosphate group is transferred from phosphoenolpyruvate to ADP (another substrate-level phosphorylation), leaving the three-carbon compound pyruvate. This reaction repays the ATP energy used in steps #1 and #3.

KREBS CYCLE (citric acid cycle)

* citric acid is formed by combination of an acetyl molecule w/ 4 C molecule.

acetyl (C_2) attaches to (C_4) forming citric acid (C_6) → goes through reactions where it loses 2 C atoms as CO_2 → remaining C_4 molecule accepts another acetyl group → this cycle forms some ATP, H^+ atoms plucked off & picked up by coenzymes NAD^+/FAD which form $NADH$/$FADH_2$

- addition of H_2O and acetyl CoA, oxaloacetic acid is converted to citric acid
- loss of H_2O, citric acid changes to cis-aconitic acid
- H_2O taken in, cis-aconitic acid becomes iso-citric acid and CO_2 / NADH is given off.
- NAD^+ joins in, convert iso-citric to α-ketoglutarate reaction gives off CO_2 / NADH
- α-ketoglutarate converts to succinyl-coenzyme A when NAD^+ and coenzyme A are added. CO_2 / NADH given off
- Succinyl CoA joined by guanosine diphosphate (GDP) and inorganic phosphate molecule (P) to form succinic acid. Coenzyme A and guanosine triphosphate (GTP) given off.
- succinic acid is converted to fumaric acid when oxidized FAD is added.
  ↳ remember this is an e^- carrier and a nonprotein coenzyme

REMEMBER: When a substance is reduced, it gains e^-'s — when a substance is oxidized it loses e^-

Combines w/ 2 H atoms ← FAD is reduced to $FADH_2$ in this reaction

- then more H_2O is added to fumaric acid (fumarate) and converts it to malic acid. NAD^+ joins cycle again converting malic acid to oxaloacetic acid. NADH given o

In this cycle (citric acid)

* a lot of H^+ atoms are removed from reactants

So, @ end of 1 pass through Krebs cycle, you have the following amts. of energy-rich molecules:

3 molecules of NADH
1 molecule of $FADH_2$
1 molecule of ATP

oxidative phosphorylation (coenzymes, $NADH$, $FADH_2$ are converted to ATP because ATP is much more efficient form of energy.)

As $NADH$, $FADH_2$ pass through the respiratory chain, transporting e^-'s, they themselves lose energy. The energy lost is used to add phosphorous to ADP to create ATP. And creating ATP is the ultimate goal of breaking down fuel to generate energy.

For (1) NADH molecule that's produced in the Krebs cycle 3 molecules of ATP can be generated. For (1) molecule of $FADH_2$ that is produced in the Krebs cycle, 2 molecules of ATP are made.

But remember that 2 molecules of NADH are produced when pyruvate is converted to acetyl CoA just before the Krebs cycle begins. Those NADH molecules are equivalent to 3 molecules of ATP.

And 2 molecules of NADH are produced in the glycolytic pathway. Those NADH molecules are equivalent to 2 molecules of ATP.

Respiratory chain (electron transport chain)

- $NADH$, $FADH_2$ are the e^- carriers are produced when their oxidized partners (NAD^+, FAD) become reduced. So $NADH$, $FADH_2$ are compounds that have gained e^-, and therefore energy.

- In the respiratory chain, oxidation and reduction occur over and over. The purpose → to pass e^-

EX: Reduced e^- carrier $NADH$ enters respiratory chain and adopts an oxidized state. That means it is available to become oxidized and lose an e^-.

And that is precisely what happens, and $NADH$ becomes NAD^+. The NAD^+ immediately adopts a reduced state, meaning it is able to pick up an e^- and become reduced. Because it "picks up" an e^- it's called an e^- carrier. The picked-up e^- is passed to the 2nd e^- carrier and the process is repeated until the finial e^- carrier is reached. At the end of the respiratory chain, oxygen is the final e^- receptor and becomes reduced to H_2O

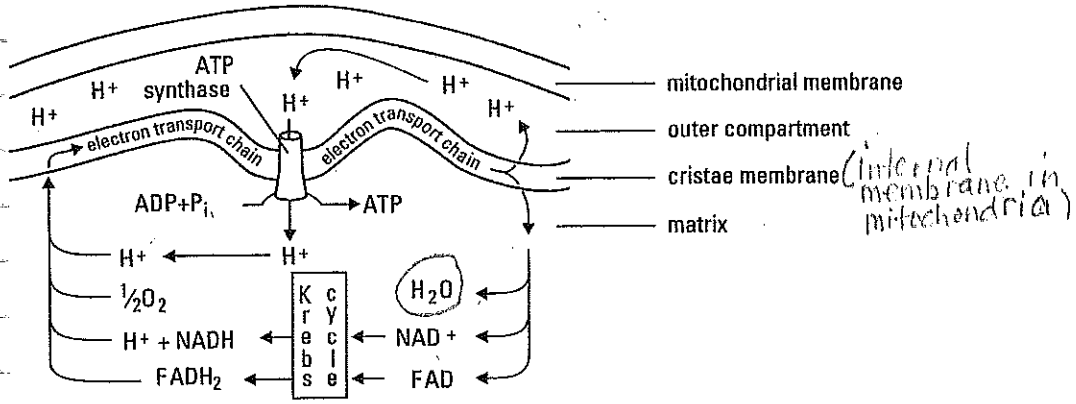
In the normal functioning of the e^- transport system:

- H^+ ions are transported to one side of a membrane and a H gradient is formed
- H^+ ions, e^-'s and oxygen atoms combine to form water
- Carrier molecules which make up this system are found in w/in the inner membrane of the mitochondria.
- protein carriers of this system are called cytochromes

Chemiosmotic theory

Remember - during oxidative phosphorylation is the coenzymes NADH, $FADH_2$ are passed from e⁻ carrier to e⁻ carrier through an e⁻ transport chain. Think of a bucket brigade here that works by one firefighter dumping a bucket full of water into the next firefighter's bucket. The buckets are the e⁻ "carriers", and the water inside bucket represents coenzymes.

@ end of e⁻ transport chain, the coenzymes have given up energy so phosphate molecules could be added to ADP to create ATP. The chemiosmotic theory describes this process.



Starts w/ Krebs cycle occurring in matrix of mitochondria. During Krebs cycle, NADH, $FADH_2$ & Hydrogen ions (H^+) are being produced and are then shuttled through the e⁻ transport chain, along w/ oxygen.

H_2O is formed during the chemiosmotic synthesis of ATP

The Krebs cycle is an aerobic process; that's why the oxygen is necessary for it to take place.

When NADH and $FADH_2$ are moving through the electron transport chain, the H^+ ions are pumped out of matrix, across the cristae, and into the outer compartment. The H^+ ions gather in the outer compartment of the mitochondria – that is, outside the cristae – which creates a proton gradient and an e^- gradient. (A gradient is a stash of potential energy.) So, the protons, which are the H^+ ions, are held in the outer compartment until they are needed. Likewise, the energy from the electron transport chain builds up until it is needed.

There are proteins in the cristae that allow the H^+ ions to flow back into the matrix. The H^+ flow through the cristae via tiny openings called channels, so the proteins are called channel proteins. In reality, they are ATP synthases. A synthase is an enzyme that initiates the production (synthesis) of a substance – in this case, ATP.

As the H^+ ions move back and forth through the channels, they create energy. This energy is enough to "kick-start" the production of ATP.

Once the ATP is made, it is quickly consumed by cells so the entire process can continue.

(H^+ ion in $FADH_2$ act as "glue" to add phosphate to ADP to produce ATP)

* 3. Fermentation : the breakdown of food molecules in which the final H^+ electron receptor is (pyruvate)
  - organic rather than inorganic molecules.

• less ATP produced

a. alcohol fermentation : (plants)

Sometimes humans really appreciate when plants can no longer go through glycolysis. Then, instead of breaking down sugars by the normal glycolytic pathway, the plant materials ferments. The alcohol that they produce during fermentation is the source of alcohol in beer (fermenting barley) and wine (fermenting grapes).

Here's what happens. The pyruvate molecule that normally is converted to acetyl CoA @ the start of the Krebs cycle during aerobic respiration instead produce acetaldehyde and CO_2 (bubbles in champagne and beer). The acetaldehyde uses NADH to produce ethanol (alcohol). NADH is used because this process is happening under anaerobic conditions. W/o oxygen, the respiratory chain cannot function, and NAD^+ can't be produced.

In the process of alcoholic fermentation, NAD^+ is released when the ethanol is produced, and the NAD^+ can be used to allow glycolysis

to continue. Unfortunately, if alcoholic fermentation continues long enough (that is if oxygen does not become available), the alcohol that is produced kills the plant, and glycolysis has no need to continue.

b. lactic acid fermentation: (animals)

In animals, if oxygen is not available, lactic acid fermentation occurs to allow glycolysis to continue. To generate some NAD^+ to put through the glycolytic pathway, pyruvate (from beginning of the cycle) is converted to lactic acid when NADH is added to the reaction. The lactic acid is stored in muscle tissues until oxygen becomes available. (Lactic acid also causes the pain you feel usually 2 days after lifting weights, stomach crunches, or otherwise fatiguing a muscle group.) Once oxygen is available, lactic acid is broken down to release energy, although it provides less energy than aerobic respiration produces.

Because the lactic acid is stored up until oxygen is available, the animal is kind of behind the eight ball, so to speak, when it can get oxygen. Therefore, lactic acid fermentation is said to create oxygen debt because once oxygen is available, it must 1st be used to break down lactic acid before it can be used in aerobic respiration.

- most cells use glucose to make ATP
- But remember organic molecules contain stored energy, so any of these molecules may break down to release the energy needed to produce ATP
- carbohydrates are processed via glycolysis
- Fats / proteins are metabolized in many ways and eventually reach either glycolysis or citric acid cycle.
- Fats have a higher H to O ratio than carbohydrates or proteins and as such provide more than 2x as much energy per gram.