Cellular Respiration and Fermentation

I. Overview

A. Remember that photosynthesis makes glucose (and other carbohydrates) from the energy of the sun. Organisms that do not perform photosynthesis consume other organisms to get the glucose (and other materials) for the energy they need.

1. **Cells cannot use glucose directly for energy – they need ATP.**
2. **Cellular respiration and fermentation are the chemical pathways used to get ATP from glucose.**

B. The overall process of cellular respiration uses oxygen to release energy from glucose. Fermentation does not use oxygen and is referred to as anaerobic.

II. Cellular Respiration

A. Cellular respiration is the process that releases energy from food in the presence of oxygen.

1. **The overall reaction of cellular respiration is:**

$$\underset{\text{oxygen}}{6O_2} + \underset{\text{glucose}}{C_6H_{12}O_6} \longrightarrow \underset{\text{carbon dioxide}}{6CO_2} + \underset{\text{water}}{6H_2O}$$

2. **Does it look familiar? It should. It is photosynthesis in reverse!**
3. **Photosynthesis (which makes glucose) removes carbon dioxide from the atmosphere, and cellular respiration puts it back. Photosynthesis releases oxygen into the atmosphere, and cellular respiration uses that oxygen to release energy from food.**
4. **So how did the atmosphere gain any oxygen to begin with? Wouldn't the plants be removing the same**

amount of oxygen from the atmosphere as they put into it? Think about what must be true about the rates of these reactions.

B. Cellular respiration happens in 3 steps: glycolysis, Krebs cycle, and electron transport.

1. **Glycolysis: "sugar breaking"**
    a. **Glycolysis happens in the cytoplasm and does NOT require oxygen to happen. It happens incredibly fast and that can be a huge advantage when energy needs suddenly increase for the cell.**
    b. **During glycolysis, 1 molecule of glucose (6 carbons) is transformed into 2 molecules of pyruvic acid (3 carbons each).**
    c. **As the bonds are broken and rearranged, energy is released.**
    d. **Some ATP has to be used to get the reaction started, but more ATP is generated at the end. So the result is a NET gain of 2 ATP from each glucose molecule.**
    e. **In addition to ATP, another energy storing molecule is made in glycolysis – NADH. We will need the NADH for the next step.**
2. **Krebs Cycle**
    a. **The Krebs cycle happens in the mitochondria.**
    b. **During the Krebs cycle, pyruvic acid is broken down into carbon dioxide in a series of reactions that release energy.**
    c. **Also called the citric acid cycle since citric acid is created in the first reaction.**

d. **Over the course of the Krebs cycle, many carbon molecules are broken and rearranged, again releasing energy that is used to make electron carriers (energy rich compounds) like ATP, NADH, and a new one, $FADH_2$.**
e. **The Krebs cycle gains an ATP for each pyruvic acid molecule, and since there are 2 pyruvic acid molecules from each molecule of glucose that went through glycolysis, that means there is a net gain of 2 ATP.**
f. **Carbon dioxide is made during the Krebs cycle, and since it is not useful to the cell, it is released. This is what you exhale.**
g. **The other electron carriers are going to be used to power the last step, electron transport.**

3. **Electron Transport**
    a. **This step happens in the mitochondria.**
    b. **Electron transport requires oxygen and the products of glycolysis and the Krebs cycle – namely the electron carriers NADH and $FADH_2$.**
    c. **Electron transport uses the high energy electrons in NADH and $FADH_2$ to create ATP.**
        - **The electron transport chain is made of proteins in the inner membrane of the mitochondrion.**
        - **As they move from protein to protein, the energy from the electrons is used to actively transport H^+ ions into the space between the mitochondrion's two membranes, creating a gradient.**

- **Hydrogen ions then move back across the membrane through ATP synthase, an enzyme the makes ATP (just like in the light dependent reactions of photosynthesis).**

d. **At the end of the electron transport chain an enzyme that combines the "spent" electrons with hydrogen ions and oxygen to form water.**
e. **This solves the problem of getting rid of the "low energy" electrons, and is also why oxygen is essential for the process.**
f. **How much ATP is made from electron transport? 32 molecules!**
g. **What about prokaryotes? Can they perform aerobic respiration without any mitochondria?**
   - **Yes. The reactions of the Krebs cycle can happen in the cytosol and the electron transport chain in prokaryotes is embedded in the cell membrane instead of the mitochondrial membrane.**

C. The Totals

1. **Cellular respiration generates roughly 36 molecules of ATP for every glucose molecule. (Some textbooks say 38.)**
2. **That's only about 36% of the total energy in glucose.**
3. **The other 64% is released mostly as heat – which is why your body feels warmer after strenuous exercise and why your temperature can remain steady at 37° C day and night.**

III. Fermentation

A. When oxygen is not available, glycolysis is followed by a pathway that makes it possible for glycolysis to keep going without having oxygen – this is fermentation.

B. Fermentation: process by which cells release energy from glucose in the absence of oxygen.

1. There are 2 different kinds of fermentation – alcoholic fermentation and lactic acid fermentation.
2. For either type, glycolysis is the first step – so you have a net gain of 2 ATP molecules, and that is all the ATP you are going to get. You also have pyruvic acid.

   a. In alcoholic fermentation, the second step looks like this:

$$\text{pyruvic acid} + \text{NADH} \longrightarrow \text{ethanol} + CO_2 + NAD^+$$

   b. The regeneration of NAD^+ allows glycolysis to keep going.

   c. Alcoholic fermentation is used to make beer, wine, and to raise bread.

   d. Most organisms cannot perform alcoholic fermentation, but yeasts (and a few other microorganisms) can and they do when they run out of oxygen. That is why yeast is needed in the recipe.

   e. In lactic acid fermentation, the second step looks like this:

$$\text{pyruvic acid} + \text{NADH} \longrightarrow \text{lactic acid} + NAD^+$$

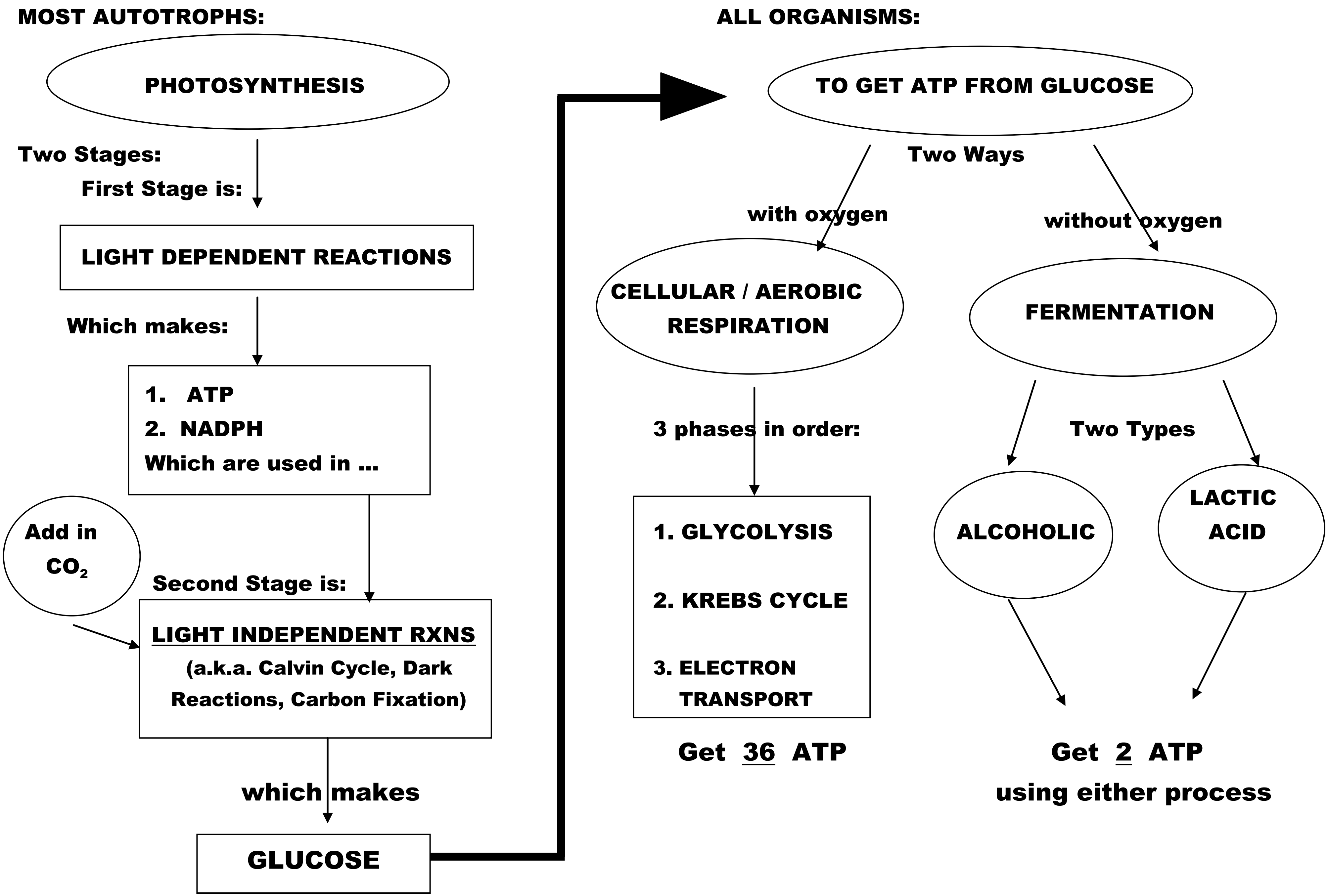
   f. Note that you don't have any carbon dioxide from this equation.

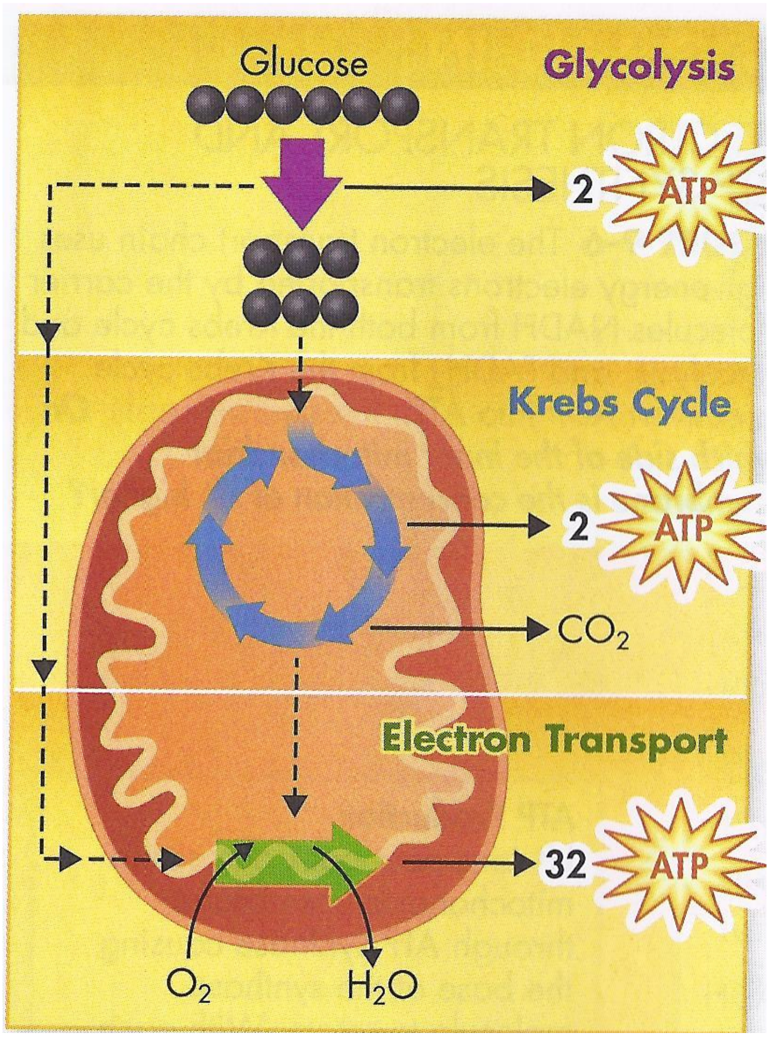
g. **Most organisms use lactic acid fermentation when they run out of oxygen or require lots of ATP for short bursts of activity – our muscle cells are particularly good at using it for that purpose.**
h. **Certain bacteria that use lactic acid fermentation are used in industry in the making of cheese, yogurt, buttermilk, sour cream, pickles, sauerkraut are just a few. The lactic acid gives the familiar sour taste.**

C. **The Totals**

1. **Either pathway of fermentation results in just 2 ATP molecules from each molecule of glucose.**
2. **In comparison, we got 36 ATP from aerobic respiration. That means that aerobic respiration is 18x more efficient than fermentation.**

Connecting Photosynthesis and Energy Production





Notice the three stages of cellular respiration (aerobic respiration) in the diagram at left. The completed process results in 36 ATP molecules from each molecule of glucose.

The two types of fermentation (alcoholic and lactic acid) are illustrated below. Note that each yields 2 ATP molecules from each glucose molecule.