UNIT 1: METABOLIC PROCESSES

A. Cellular Respiration: *An Overview*

- since the beginning of life organisms have evolved mechanisms to harness environmental energy and convert it into usable forms to power any and all endergonic processes of life
- for example, **photoautotrophs**, meaning "light-using self-feeders", transform light energy into chemical potential energy in glucose – this makes them the only self-sufficient organisms on earth
- everything else is a **heterotroph**, meaning "other-eaters" – they rely on **autotrophs** for energy
- most of life is heterotrophic (animals, fungi, most protists, and bacteria)
- almost all that heterotrophs eat was once alive
- there are a group of organisms, called **chemoautotrophs**, meaning "chemical self-feeders", that take in inorganic materials, such as iron and sulfur-containing matter, and convert them into usable energy – much like a car battery extracts energy from sulfuric acid
- these are usually found in extreme environments like volcanoes, sulfur springs, and salt flats
- with the exception of chemoautotrophs, all organisms use glucose as their "fuel" to make usable energy
- the process involves a series of enzyme-controlled redox rxs that rip apart a glucose molecule and rearrange its constituents into more stable configuration molecules
- since the products of this process are more chemically stable, i.e. they contain less chemical potential, the reaction is exergonic – free energy is released
- this free energy goes into making ATP molecules
- basically electrons are transferred from glucose to oxygen – therefore oxygen is reduced to water, and glucose is oxidized to carbon dioxide
- the over all summary of the reaction is: $C_6H_{12}O_6$ (aq) + $6O_2$ (g) $\rightarrow$ $6CO_2$ (g) + $6H_2O$ (l) + heat energy + 36 ATP molecules
- the average human consumes more than their weight in ATP molecules in one day!!
- the process that yields 36 ATP molecules from one glucose molecule is called **aerobic cellular respiration**
- "aerobic" means that oxygen is used in the process
- the actual process takes about 20 steps, where the product of one step becomes the reactant of another with the help of specific catalysts for each step

First Half of the Combustion Process

$$C_6H_{12}O_6\ (aq) + 6O_2\ (g) \rightarrow 6CO_2\ (g) + 6H_2O\ (l)$$

- the burning of any organic substance, which in this case is glucose, results in the pulling of hydrogen apart from a carbon atom by a strong oxidizing agent, which in this case is oxygen

- this is because as each hydrogen is pulled away from a carbon and combines with oxygen, it carries electrons with it and transfers them to the oxygen

- the transferred electrons that were beside the carbon atoms (and were almost equally shared by both the hydrogen and the carbon in the glucose molecule) are now with the oxygen atoms and are not equally shared, since oxygen has a stronger pull on them then hydrogen does

- this means that the electrons end up closer to the oxygen's nucleus, which in turn results in them possessing less potential energy – electrons that are closer to any nucleus possess less energy than if they were further away from a nucleus

- however, since the electrons went from being equally shared between the carbon and hydrogen in the organic molecule, to being unequally shared between the oxygen and hydrogen in the water molecule, they increased in randomness or entropy

- therefore, the oxidation process, which caused the transferred electrons to decrease in potential, yet increase in entropy, resulted in a decrease of free energy and an overall exergonic condition

Second Half of the Combustion Process

$$C_6H_{12}O_6\,(aq) + 6O_2\,(g) \rightarrow 6CO_2\,(g) + 6H_2O\,(l)$$

- six oxygen atoms from the oxygen gas molecule, plus the six oxygen atoms from the glucose molecule, combine with the carbon atom to make six CO_2 (g) molecules

- this process is also an oxidation process since once the C=O bonds form in the CO_2, the oxygen draws the electrons closer to it, making them possess less potential energy, while at the same time they go from being equally shared to being unequally shared, which now means they have more randomness or entropy

- due to both halves; the transfer of hydrogens, thus electrons, from the glucose to the oxygen, and the attachment of the oxygens to the carbon, valence electrons go from a high potential to a low potential, and from a low entropy to a high entropy

- the result is a decrease in free energy (i.e. a release of energy)

- Figure 2, p. 92 shows the free energy diagram of glucose being burned in a test tube – carbon dioxide and water are formed as well as a substantial amount of light and heat energy

- living cells, however, trap some of the free energy released in this process (about 34% of it) by moving the positions of electrons in certain molecules to higher free energy states, such as into an ATP molecule, which in turn becomes a readily available source of free energy to power endergonic processes throughout the cell

- it is important to note that the mere presence of oxygen alone does not automatically result in the oxidation of hydrocarbons – every time an oxygen atom collides with a hydrocarbon molecule (like glucose or any other organic molecule) it doesn't automatically have the power to strip away electrons from it

- otherwise combustion would always be spontaneous – since organic molecules are continuously in contact with air (21% oxygen)

- the activation energy necessary to push the reaction to completion is what controls the oxidation of organic molecules (i.e. respiration)

- for example, in order for paper to burn, a spark or flame is necessary
- in living systems, the "spark" is provided by catalytic enzymes
- specific enzymes catalyze every step in the aerobic respiration process – see Figure 2, p. 92
- it is interesting to note that oxygen is not always used in cellular respiration as the "electron grabber" – some microorganisms use NO_2, SO_4, CO_2, and even Fe^{3+} as final electron acceptors
- these organisms are called **obligate anaerobes**, which include *Clostridium tetani* (tetanus), *Clostridium botulinum* (a form of food poisoning), and *Clostridium perfringes* (gas gangrene) – seen in Figure 3a, p. 92
- obligate anaerobes only live in areas with no oxygen
- most organisms are **obligate aerobes**, such as most animals, plants, protists, fungi, and bacteria
- these organisms require oxygen to survive since they use this gas as their final electron acceptor in the respiration process
- organisms that can withstand both aerobic and anaerobic conditions are called **facultative anaerobes** – most of which are bacteria, including *Escherichia coli* (dysentery), *Vibrio cholerae* (cholera), and *Salmonella enteritidus* (common food poisoning) – these are seen in Figure 3b, p. 92

Homework: p. 93, 1-4.

B. Cellular Respiration: *A Detailed View*

- the overall equation is $C_6H_{12}O_6\ (aq) + 6\ O_2\ (g) \rightarrow 6\ CO_2\ (g) + 6\ H_2O\ (l)$
- as a result of this process, 36 ATP molecules are made
- essentially, entire process meets three major goals:

1. breaks the bonds between the six carbon atoms of glucose, resulting in six carbon dioxide molecules
2. moves hydrogen atom electrons from glucose to oxygen, forming six water molecules
3. traps as much of the free energy released in the process as possible in the form of ATP

- the entire process takes place in four stages and in three different places within the cell:

NAME OF STAGE	***DESCRIPTION***	***LOCATION***
Glycolysis	• a 10-step process that begins with glucose and ends with pyruvate (pyruvic acid)	cytoplasm

Pyruvate Oxidation a.k.a Oxidative Decarboxylation	• a one-step process that begins with pyruvate and ends with acetyl CoA	mitochondrial matrix
Kreb's Cycle a.k.a Tricarboxylic Acid Cycle, a.k.a. TCA cycle, a.k.a. Citric Acid Cycle	• an eight-step cyclical process that begins with acetyl CoA combining with oxaloacetate to form citric acid • the citrate cycles through and ends up as oxaloacetate again, since it loses two carbons along the way	mitochondrial matrix
Electron Transport Chain and Chemiosmosis a.k.a. Electron Transport System a.k.a Oxidative Phosphorylation	• a multi-step redox process that transfers high energy electrons along a chain of proteins, while establishing a chemiosmotic gradient • the gradient is used to activate an enzyme (ATPase) which helps make ATP	inner mitochondrial membrane

- Figure 1, p. 94 shows the four stages of respiration, making reference to the location of each stage
- you should think of respiration as a play, where each stage is like an act, and the steps or reactions in each stage are like scenes of the play
- basically, the ultimate goal of respiration is to extract energy from nutrient molecules (preferably glucose) and store it in a form that the cell "recognizes" as free energy – the "baton" of energy is passed from glucose to ATP
- the goal of capturing as much of the available free energy as possible in the form of ATP is accomplished through two distinctly different energy-transfer mechanisms called:

1. **Substrate-Level Phosphorylation**

   - ATP is formed directly in an enzyme-catalyzed reaction
   - a phosphate-containing compound (phosphoenolpyruvate – PEP) transfers a phosphate group directly to ADP, forming ATP (see Figure 2, p. 95)
   - for every glucose molecule processed, six ATP are made this way – 4 in glycolysis, and 2 in Kreb's Cycle
   - Figure 3, p. 95 illustrates where this takes place

2. **Oxidative Phosphorylation**

- ATP is formed indirectly
- it involves a series of redox reactions – a passing down of electron "batons", where the oxidizing agent becomes the reducing agent for the next oxidizer in the chain
- oxygen is the final electron acceptor
- this mechanism is more efficient at producing ATP per glucose molecule
- basically, coenzyme compounds, one of them called **nicotinamide adenine dinucleotide (NAD^+)**, and the other called **flavin adenine dinucleotide (FAD)**, remove two hydrogen atoms, therefore two protons and two electrons, from a portion of the original glucose molecule
- they work a little differently – for NAD^+, both electrons, and only one of the protons, attach to the NAD^+ to produce NADH + H^+ -- the other proton just dissolves in the surrounding solution as H^+ (aq)
- whereas in FAD, both protons and both electrons bind directly onto the FAD to produce $FADH_2$
- of course, both reductions (of NAD^+ or of FAD) do not take place unless a **dehydrogenase enzyme** is present to catalyze the reaction
- the oxidized form and the reduced form of NAD^+ are both seen in Figure 5, p. 96
- the reduction of NAD^+ takes place at three separate points during the entire respiratory process:
  1. once during one of the steps of the glycolysis stage
  2. once during the pyruvate oxidation stage
  3. three times during the Kreb's Cycle
- Figure 6, p. 96 shows the 5 different places where the NAD^+ is reduced to NADPH + H^+ (usually written as NADPH)
- the reduction of FAD takes place at only spot during the entire respiratory process – in the Kreb's Cycle (see Figure 7, p. 96)
- the reaction that produce both NADH and $FADH_2$ are considered to be "energy-harvesting" processes because these intermediate energy carriers will eventually transfer most of their free energy to ATP molecules during the electron transport and chemiosmosis stage of respiration

THE "ACTS"

ACT I. *Glycolysis*

- the word means "sugar splitting"
- basically, 1 six carbon glucose molecule is "put through the ringer" – it is added to, rearranged, modified, split apart, and broken up until it ends up being two 3-carbon molecules of pyruvate (see Figure 9, p. 97)
- glycolysis occurs in the cytoplasm (see Figure 8, p. 97)
- the ten "scenes", or reactions, of glycolysis are outlined in Figure 11, p. 97

- the major events of each scene are as follows:

  - ACT I, scene 1: - glucose enters the cell via protein channels and is immediately phosphorylated to make G6P

    - an ATP molecule is invested to “prime” the glucose and prevent it from escaping the cell
  - ACT I, scene 2: - the glucose 6-phosphate is rearranged into fructose 6-phosphate via enzyme involvement
  - ACT I, scene 3: - another ATP is used up to phosphorylate, thus stabilize, the fructose 6-phosphate -- a very unstable structure that would spontaneously revert back to the more stable glucose 6-phosphate form, which ensures that the whole respiratory process moves forward – this scene is the “engine” of respiration
  - ACT I, scene 4/5: - fructose 1,6-bisphosphate is split into dihydroxyacetone phosphate (DHAP) and glyceraldehydes 3-phosphate (G3P), and then an enzyme called isomerase converts the DHAP into another G3P molecule, resulting in 2 G3P molecules by the end of the scenes 4 and 5

  - from here on in, each G3P molecule then undergoes the exact process from then on – like identical twin characters in a movie that experience the exact same events (see Figure 17, p. 103)