STUDY GUIDE - *Ch. 9.4 - During oxidative phosphorylation, chemiosmosis couples electron transport to ATP synthase* **NAME:** _____

- **PHYSICALLY PRINT OUT this PDF and HANDWRITE (with a black or blue pen) your answers directly on this PDF.** *Typed or digitally-written work is **not** accepted. Do **not** answer questions on separate paper.*
- **Importantly, study guides are NOT GROUP PROJECTS!!!** *You, and you alone, are to answer the questions as you **read** your assigned textbook. You are **not** to share answers with other students. You are **not** to copy any answers from any other source, including the internet.*
- **Get in the habit of writing LEGIBLY, neatly, and in a medium-sized font.** *AP essay readers and I will skip grading anything that cannot be easily read so start perfecting your handwriting, and don't write so large you can't add all the relevant details and key elaborations in the space provided.*
- **SCAN physical documents in color and with good resolution. Then, upload your final work as PDFs to Archie.** *Avoid uploading dark, shaded, washed-out, sideways, or upside-down scans of homework. Keep completed physical study guides organized in your biology binder to use as future study and review tools.*
- **READ FOR UNDERSTANDING and not merely to complete an assignment.** ***First**, read a section quickly to get an overview of the topic covered. Then, read it a **second** time slowly, paraphrasing each paragraph **out loud** and analyzing every figure. Finally, read it a **third** time as you answer the study guide questions if assigned and start building your memory. Try to write answers out in your own words, when possible, and try to purposefully and accurately use all new terminology introduced.*

So far, you have learned that glucose is completely oxidized through multiple biochemical steps, potential energy being released from certain high-energy covalent bonds, like C-H bonds, the energy being used to **drive the immediate endergonic construction of ATP molecules**, high-energy electrons also being collected on specific electron carriers.

The stages of Aerobic (O_2-requiring) Cellular Respiration you should now be very familiar with include:

1. **Glycolysis**: In the first stage of Cellular Respiration, a six-carbon high-energy organic molecule, **glucose**, is oxidized and broken down into **2 three-carbon pyruvate molecules** (sometimes referred to as pyruvic acids).
   - In the process, **2 net ATPs form** and **2 NAD^+ electron carriers are reduced into 2 NADH**, each carrier carrying two high-energy electrons.
     - In prokaryotes, these electrons will be **delivered by NADH to the Electron Transport Chain in the plasma membrane.**
     - In eukaryotes, these **electrons will be transported from the NADH outside the mitochondria to an NAD^+ inside the mitochondria**, resulting in the reduction of two NADH with high-energy electrons inside the mitochondria, these **NADHs delivering the high-energy electrons to the Electron Transport Chain located in the Inner Mitochondrial Membrane.**

2. Next, each of the two pyruvate molecules is oxidized further in a shorter biochemical pathway called **Pyruvate Oxidation**. In this process, **1 carbon is lost from the three-carbon pyruvate as an CO_2** molecule (a non-polar waste product that diffuses down its concentration gradient out of the cell), and the **remaining two-carbon Acetyl is joined with a Coenzyme A molecule, forming a molecule of Acetyl Coenzyme A** (Acetyl CoA)
   - Pyruvate Oxidation occurs in the **cytoplasm in prokaryotes.**
   - Pyruvate is transported into the **mitochondrial matrix in eukaryotes,** where Pyruvate Oxidation then occurs.
     - In the process of Pyruvate Oxidation, **1 NAD^+ electron carriers, for each pyruvate, is reduced to NADH**, carrying two high-energy electrons.
       - Since there were two pyruvate that formed in Glycolysis, **2 reduced NADH electron carriers form by the end of 2 Pyruvate Oxidations.**
       - Since there were two pyruvate that formed in Glycolysis from one glucose molecule, **2 Acetyl CoA's are left at the end of 2 Pyruvate Oxidations.**

3. The **two-carbon Acetyl portion of each Acetyl CoA** will then become the precursor for the biochemical pathway known as the **Citric Acid Cycle** (also known as the **Krebs Cycle**).
   - The Citric Acid/Krebs Cycle takes place in the **cytoplasm in prokaryotes**
   - The Citric Acid/Krebs Cycle takes place in the **mitochondrial matrix in prokaryotes**

- The first chemical reaction of this biochemical pathway involves the **two-carbon Acetyl** joining the four-carbon Oxaloacetate, forming Citric Acid, which itself will get **oxidized** further through the rearranging of atoms and removal of high energy electrons that occurs as part of this biochemical cycle, **the four-carbon Oxaloacetate reforming at the conclusion of the Citric Acid (Krebs) Cycle.**

  - Per Citric Acid (Krebs) Cycle, **2 CO_2 waste molecules form**.
  - Per Citric Acid (Krebs) Cycle, four pairs of **high-energy electrons are extracted** from intermediates and **stored on 1 FAD electron carrier, which gets reduced into 1 $FADH_2$, and on 3 NAD^+ electron carriers which get reduced into 3 NADH.**
  - Per Citric Acid (Krebs) Cycle, the potential energy released from the exergonic chemistry drives the formation of one GTP molecule (GDP + Pi -> GTP), the GTP being used to then phosphorylate an ADP into **1 ATP.**

    - Since there were two two-carbon Acetyl groups that entered the CAC/Krebs Cycle **per original glucose**, **4 CO_2, 2 $FADH_2$, 6 additional NADH, and 2 ATP form in the CAC/Krebs Cycle.**

Now, let's read about how the Electron Transport Chain, along with ATP Synthase, will be used to make many more ATPs using the energy located in all the high energy electrons stored on all the reduced electron carriers (NADHs and $FADH_2$s).

1. a. Glucose has been fully oxidized by the end of the Citric Acid Cycle, 6 carbons entering Glycolysis as $C_6H_{12}O_6$ (glucose) and 6 CO_2 waste molecules forming by the end of the Citric Acid/Krebs Cycle. However, **how many ATPs have formed by doing Glycolysis, Pyruvate Oxidation, and the Citric Acid/Krebs Cycle**? *(A rather low number!)*

   b. Where is all the **remaining potential energy that was once a part of glucose now located**?

2. a. Describe the composition/structure of the **Electron Transport Chain** (ETC)? *Be sure to also explain the prosthetic groups associated with the ETC components.*

   b. Where are the **Electron Transport Chains located in prokaryotes**?

   c. Where are the **Electron Transport Chains located in eukaryotes**?

3. a. Read this entire "The Pathway of Electron Transport" part of Ch.9 Section 4. Then turn to Figure 9.12, reading its legend and analyzing all part of the figure closely. What are two **electron carrier molecules that feed *(high-energy)* electrons into the electron transport system**?

   1. _____ & 2. _____

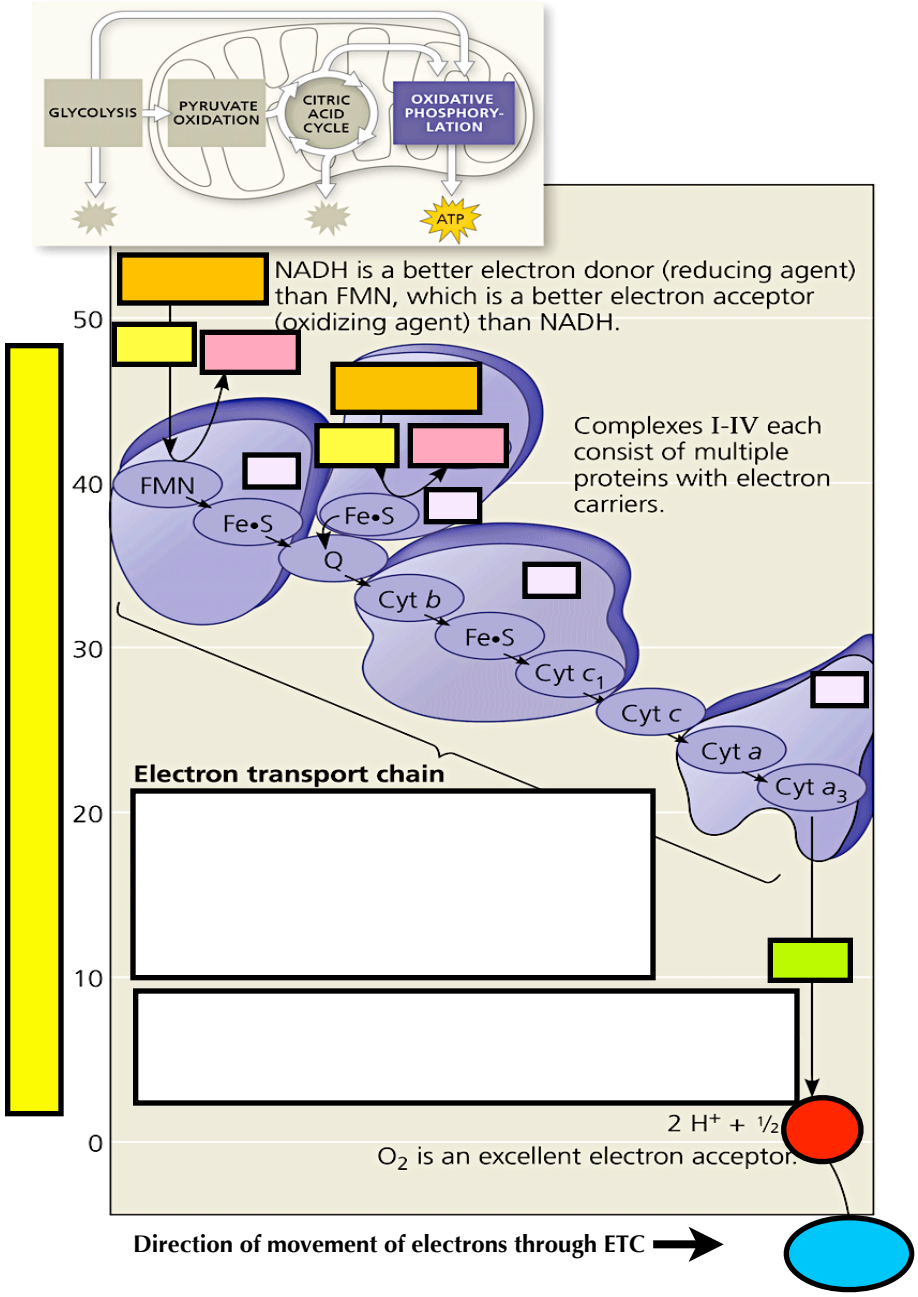
   b. What is the **purpose (benefit) of passing high-energy electrons through the ETC**? *Focus on what happens to the free energy (the available potential energy stored in the electrons) as they move through the ETC.*

c. Explain **how electrons physically move** through the ETC.

4. a. Based on your reading, **why is oxygen the ultimate electron acceptor** at the end of the Electron Transport Chain?

b. **Oxygen atoms** from O_2 molecules **(non-polar molecules that diffuse down their concentration gradient into the cell and mitochondria)** gain electrons *(which started off as **high-energy** electrons when they first entered the ETC, but leave the ETC now as **low-energy** electrons)* and combine with two hydrogen ions to **form what compound at the end of the Electron Transport Chain**?

c. To review what happens in the **Electron Transport Chain**, label and study the figure below.



d. Onto which complex in the ETC do the electrons of **NADH** get placed? (To which complex does **NADH donate electrons**?)

e. Onto which complex in the ETC do the electrons of **$FADH_2$** get placed? (To which complex does **$FADH_2$ donate electrons**?)

f. What is **Q**?

g. What is **Cytochrome C**?

Notice that the **Electron Transport Chain does not make ATP itself!** It is only **used to "extract" the energy from high-energy electrons collected during the oxidation of glucose** as shown in the illustration in #4.c.!!! **After moving through the entire ETC, a high-energy electron is considered a low-energy electron.**

5. Explain **why is it an adaptation for the inner membrane of mitochondria to be highly folded**? Remember, when you are asked to explain why an **adaptation** is an **adaptation**, you need to explain **how** having that structure/behavior/physiology allows an organize to **better survive and reproduce**!

6. a. Near every Electron Transport Chain, you'll find ATP Synthases. Where is the protein **ATP Synthase** (an enzyme and proton channel) **located in prokaryotes**?

b. Where is the protein **ATP Synthase** (an enzyme and proton channel) **located in eukaryotes**?

c. What does **ATP Synthase do** that is so important to a cell?

d. **Making ATP is an endergonic process: it necessitates a net input of energy** (unlike cellular respiration which is exergonic and releases energy). The product, ATP, has ***more*** potential energy stored in it than the ADP and phosphate had that made it. Where is the **energy stored that ATP Synthase uses** to drive this endergonic reaction (where is the potential energy stored right before ATP Synthase transfers it onto ATP)? *(Note that it would be counterproductive for ATP Synthase to use up ATP as a source of energy just to make more ATP)*

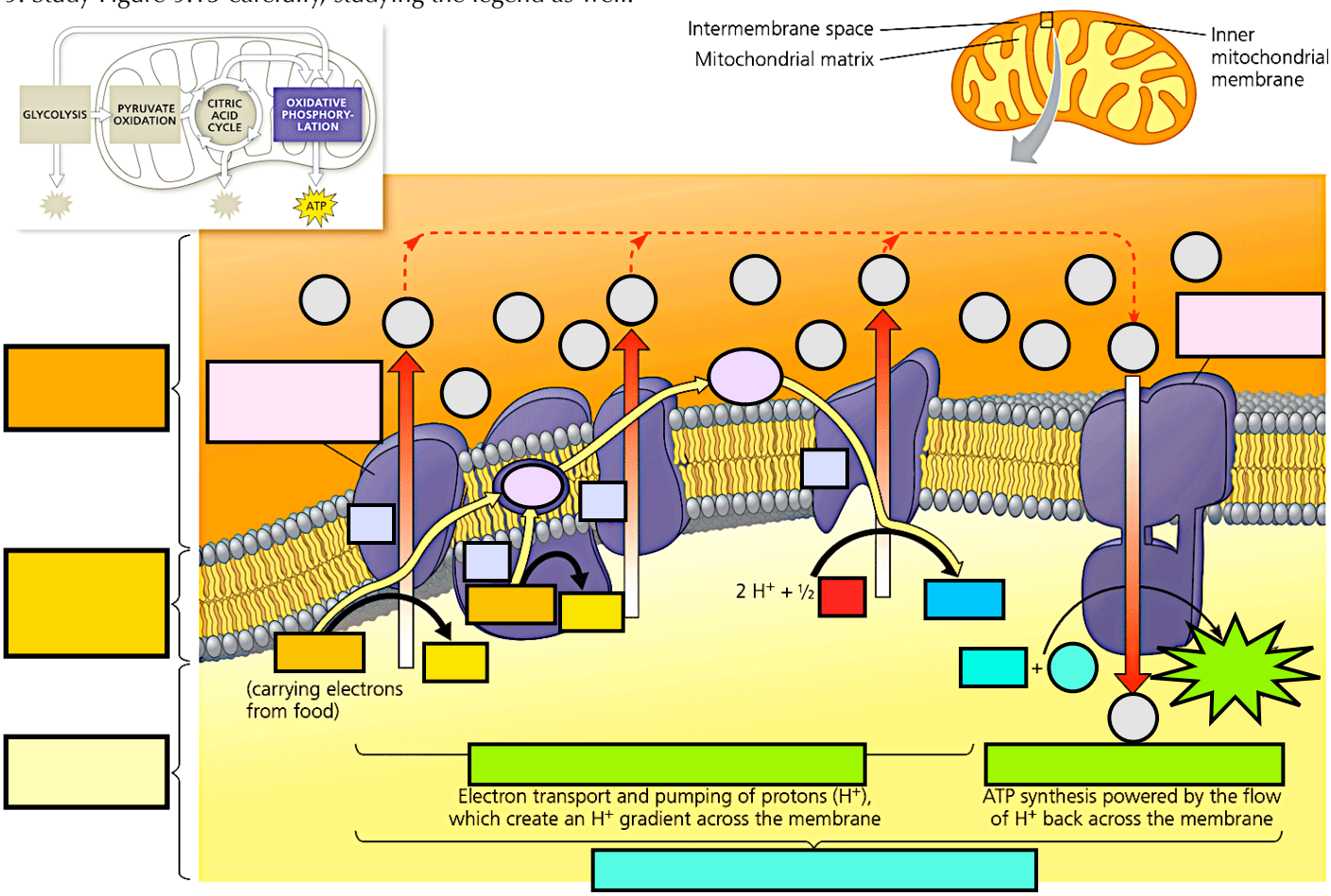
7. Explain the term **chemiosmosis**.

8. a. Review Figure 9.13. When ATP Synthase is constructing ATP, and, therefore, protons (H^+ ions) are flowing down their concentration gradient through ATP Synthase, **where in the mitochondria would you find the high concentration of protons**?

b. What **structure helps build the proton (H^+) concentration gradient** across the inner mitochondrial membrane?

c. Why can we **describe the Electron Transport Chain as an energy converted**?

9. Study Figure 9.13 carefully, studying the legend as well.



10. a. Based on the illustration in #9, **which of the four complexes** in the Electron Transport Chain **use the potential energy released from the electrons as they travel through the ETC to pump protons (H^+) from the large volume of the Mitochondrial Matrix into the smaller volume of the Intermembrane Space** in eukaryotes *(remember, in prokaryotes the ETC is located in the plasma membrane, these same complexes pumping H^+ actively from the cytoplasm to the region just outside the plasma membrane)*?

b. What do we call the resulting **protons (H^+) gradient** that forms across the inner mitochondrial membrane in eukaryotes (or across the plasma membrane in prokaryotes) when the Electron Transport Chain is operating?

c. Let's see if you understand the process by which a cell extracts the energy from high-energy electrons collected on electron carriers (NADH and $FADH_2$) and uses it in Aerobic Respiration to build extra ATPs (in addition to the 4 ATPs built by oxidizing glucose in Glycolysis & the Citric Acid/Krebs Cycle). Explain again **how a proton gradient is built and how the building of a proton gradient allows the cell to build ATP** *by phosphorylating ADP with an inorganic Phosphate* (with the help of the enzyme ATP Synthase). To explain, make a numbered **list** of the **step-by-step** events that occur in order to *move* the **potential energy** **from the high-energy electrons** removed from the intermediates that form as glucose is oxidized in Glycolysis, Pyrvuate Oxidation, and the Citric Acid/Krebs Cycle *onto* eventually **ATP molecules**.

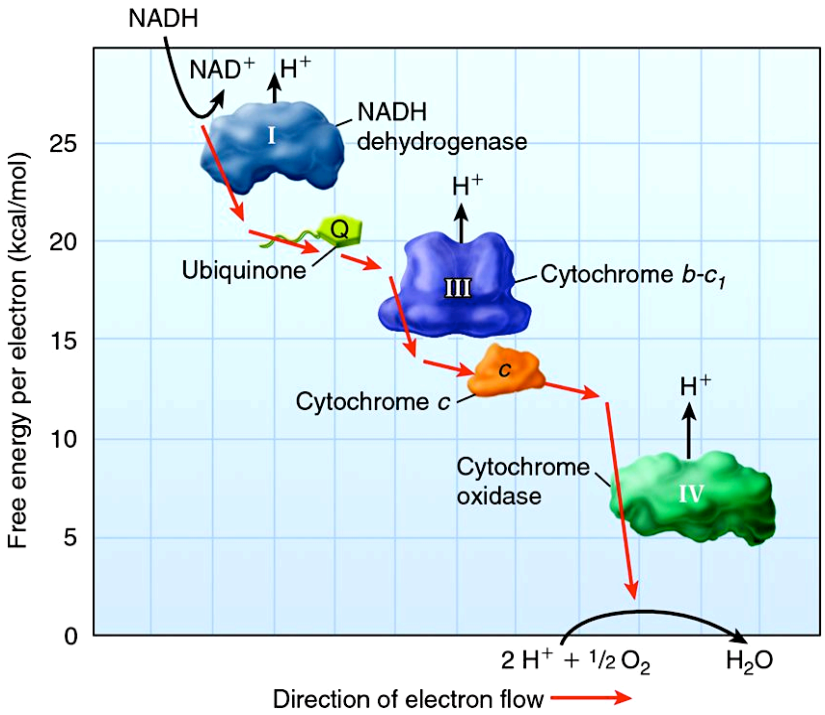
11. **Review Figure 9.15**. During Glycolysis and the Citric Acid Cycle, ATPs were made by taking a phosphate off of a carbon-based molecule and transferring the phosphates to ADP. This way of making ATP is called **substrate-level phosphorylation**, since the phosphate is attached to the *organic* substrate that enters the kinase enzyme that will phosphorylate the substrate ADP into ATP.

    a. **Per Glucose, a total of _____ (number of) ATPs are made by substrate-level phosphorylation.**

    As you can see in Figure 9.14, **oxidative phosphorylation** occurs with the help of the Electron Transport Chain and ATP Synthase. During oxidative phosphorylation, the cell uses the energy that is released when protons are allowed to diffuse down their proton gradient (which was built by the activity of the Electron Transport Chain) to attach an *inorganic* phosphate to an ADP, both of which enter the ATP Synthase's active site as substrates.

    b. **Per Glucose, a total of _____ additional (number of) ATPs are made by oxidative phosphorylation.**

    Study the figure below, making sure to analyze the information displayed on the x and y axes. **Oxidative phosphorylation involves two components: the electron transport chain activity and ATP synthesis**. After analyzing the figure below, the electrons, as they pass from one complex to the next in the electron transport chain, they are **lower** in **FREE ENERGY** than they were when they were on the preceding member (complex) of the chain. When the electrons are passed onto an O atom (the most electronegative atom compared to any atom in the complexes of the ETC), the oxygen taking the electrons off of the ETC and combining with protons to form water, the free energy of the electrons is the lowest it can be. **The energy from the electrons has been lost and is now stored in the proton gradient the ETC helped create** *(except for some energy that is lost as heat)*



12. a. *Think:* What is Complex IV were rendered nonfunctional. Could chemiosmosis help produce any ATP?

b. *Think:* How would the rate of ATP synthesis differ (from before when the Complex IV was operational)? Why?

(Check your answer to 12.a. & b. by going to the Ch.9 ***Figure Questions*** *for* ***Figure 9.14*** *in Appendix A of your textbook)*

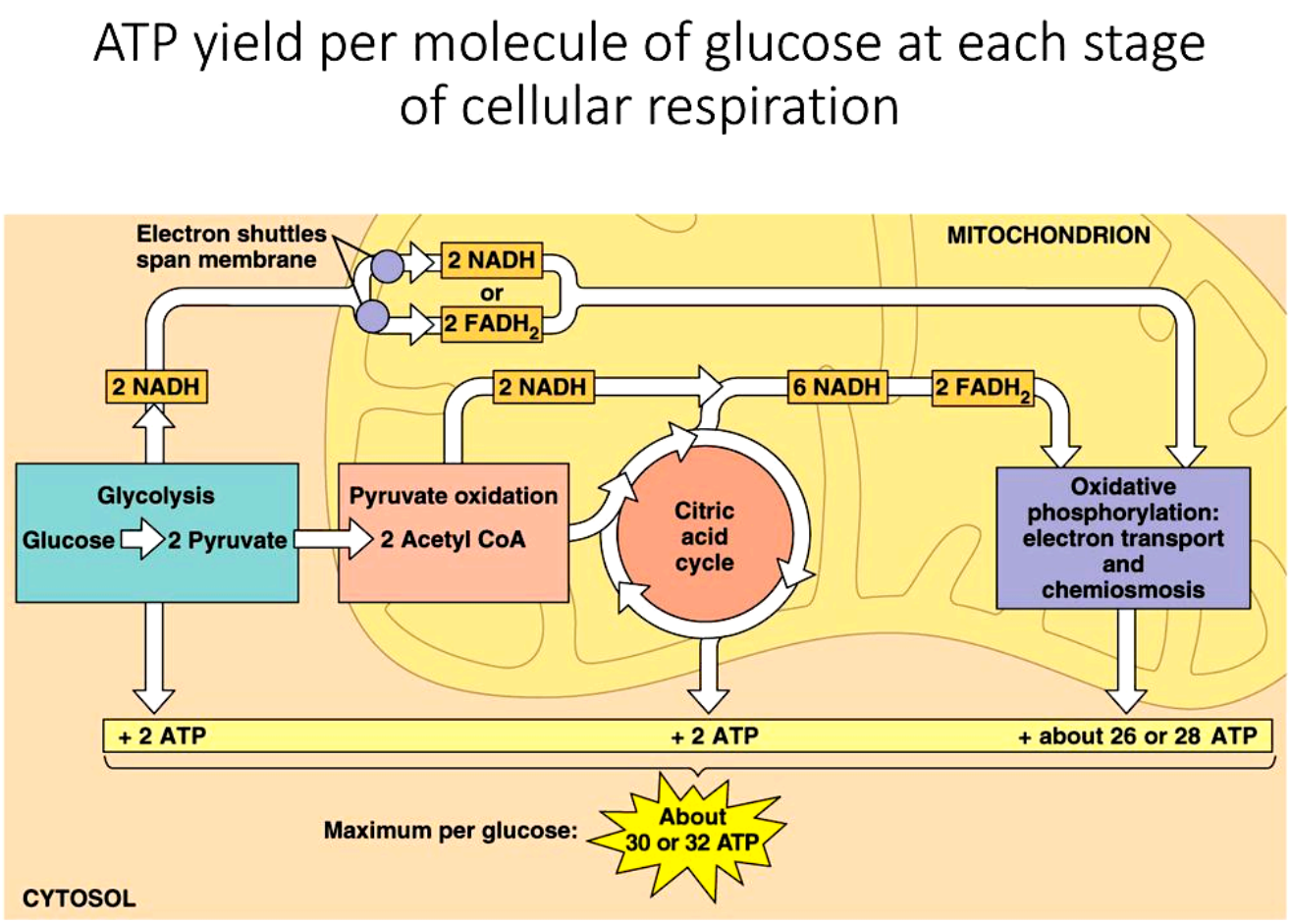
13. a. *Think:* What effect would the **absence of O_2** have on the process shown in Figure 9.14?

(Check your answer by going to the ***Ch.9.4 Concept Check Question #1*** *answer in Appendix A)*

b. *Think:* What would happen - in the absence of O_2 - if you decrease the pH of the intermembrane space of the mitochondrion? **Explain**.

(Check your answer by going to the ***Ch.9.4 Concept Check Question #2*** *answer in Appendix A)*

14. Study Figure 9.15 (below) well, which highlights the **production of ATP during Aerobic Cellular Respiration**.



15. As you read, cellular respiration has an efficiency of about 34%. What happened to the other 66% of the energy that did not get stored on the 30 to 32 ATPs produced? *(This is true for every cell in any kind of organism from plants to fungi and protists, from bacteria to animals)*

16. a. What type of transport protein is an **uncoupling protein**?

    b. Where (in which membrane) is this **uncoupling protein found** in eukaryotic cells?

    c. What is the **benefit of having these uncoupling proteins** to use when needed?