

Chapter 9: How do cells harvest energy?

- 1. Differentiate between aerobic respiration, anaerobic respiration, and fermentation.**
- 2. Write the overall chemical equation for aerobic respiration and note what gets oxidized and what gets reduced.**
- 3. List and describe the 4 general types of reactions in aerobic respiration.**
- 4. Fill out aerobic respiration chart (class activity).**
- 5. Describe the use of proteins as an energy source. Include discussion of relative energy provision, pathway entry point(s), and key terms (amino acid, deamination).**
- 6. Describe the use of triacylglycerol lipids as an energy source. Include discussion of relative energy provision, pathway entry point(s), and key terms (glycerol, fatty acid, G3P, β oxidation).**
- 7. Differentiate between anaerobic respiration, alcohol fermentation, and lactic acid fermentation. Include comparisons to aerobic respiration in terms of process and energy yield; where these processes are found in nature; key terms and products (NAD^+ regeneration, ethanol, CO_2 , lactic acid); and human uses of these processes.**

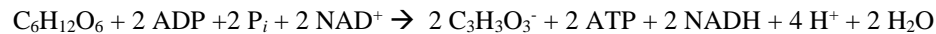
BIOL 1020 – CHAPTER 9 LECTURE NOTES

Chapter 9: How do cells harvest energy?

- I. Three terms describe the ways in which cells generate ATP
 - A. **aerobic respiration** – a generally efficient process that requires O₂; most, but not all, organisms can use a form of this process at least some of the time; also called **cellular respiration** (How is this different from breathing, and how is it related to breathing?)
 - B. **anaerobic respiration** – processes similar to aerobic respiration but that do not use O₂; used mainly by bacteria that live in anaerobic (O₂-deficient) environments
 - C. **fermentation** – generally inefficient processes used mainly when other pathways cannot be used or when ATP is needed quickly; fermentation processes do not use O₂
- II. **Aerobic respiration**: a redox process
 - A. aerobic respiration, the most efficient form of cellular respiration, is used by most organisms
 - B. nutrients (typically glucose) are catabolized to water and carbon dioxide, and energy is stored in ATP
$$\text{C}_6\text{H}_{12}\text{O}_6 + 6 \text{O}_2 + 6 \text{H}_2\text{O} \rightarrow 6 \text{CO}_2 + 12 \text{H}_2\text{O} + \text{energy (stored in 36-38 ATP molecules)}$$
 1. this is a redox process – glucose is oxidized to carbon dioxide, and oxygen is reduced to water
 2. above equation is overall; aerobic respiration is actually a series of reactions
 3. water is shown on both sides above because it is consumed in some reactions and generated in others
 4. the overall process is the same as what you would get from burning glucose (but the energy would all be lost as heat)
 - C. aerobic respiration is a complex series of enzyme-catalyzed reactions that can be grouped into four types of reactions:
 1. **substrate-level phosphorylation** – coupled reactions that directly phosphorylate ADP or GDP
 2. **dehydrogenation reactions** – redox reactions that transfer hydrogen to NAD⁺ or FAD
 3. **decarboxylation reactions** – carboxyl groups are removed; CO₂ is released
 4. **preparation reactions** – molecules are rearranged to prepare for other reactions
 5. of the above, only substrate-level phosphorylation and dehydrogenation provide energy for cells
- III. Aerobic respiration is conventionally divided into four stages
 - A. **glycolysis**
 1. occurs in the cytosol (both in prokaryotes and eukaryotes)
 2. overall, **glucose is converted to 2 pyruvate** molecules (a 3-carbon molecule)
 3. released energy is stored in a **net yield of 2 ATP and 2 NADH** molecules
 4. occurs under both aerobic and anaerobic conditions (no O₂ required)

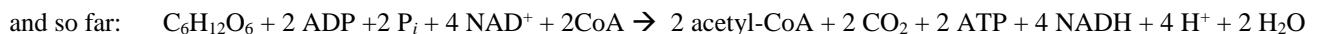
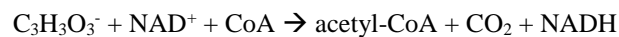
BIOL 1020 – CHAPTER 9 LECTURE NOTES

- actually a series of ten reactions, each catalyzed by a different enzyme; broken into two phases (energy investment and energy payoff)
- first phase** requires **energy investment**
 - phosphorylation, using two ATP, charges the sugar with two phosphates
 - 2 molecules of **glyceraldehyde 3-phosphate (G3P)** are formed
- second phase**, the **energy payoff phase**, yields private and energy captured in ATP and NADH
 - each G3P is converted to **pyruvate**, $C_3H_3O_3^-$ (net of 2 pyruvates)
 - aside: -ate and -ic acid forms are essentially equivalent in cells; for example, pyruvate and pyruvic acid
 - produces 4 ATP (net of 2 ATP)
 - produces 2 NADH + H^+
- overall:



B. formation of acetyl coenzyme A (acetyl-CoA) from pyruvate (AKA **pyruvate oxidation**)

- pyruvate is sent to the mitochondria in eukaryotes (stays in cytosol of prokaryotes)
- set of three enzymes catalyze the reactions, grouped together in the **pyruvate dehydrogenase complex**
- oxidative decarboxylation**: a carboxyl group is removed from pyruvate (CO_2 is produced)
- remaining 2-carbon fragment is oxidized (loses 2 electrons); NADH is produced
- remaining 2-carbon fragment, an acetyl group, is joined to **coenzyme A** (from B-vitamin pantothenic acid) to form **acetyl-CoA**
- overall:

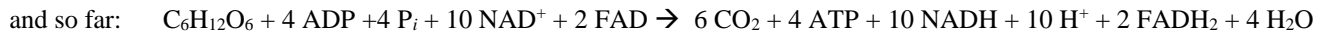
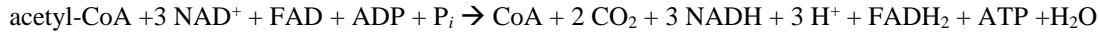


C. citric acid cycle

- AKA tricarboxylic acid cycle, TCA cycle, Krebs cycle
- still in mitochondria of eukaryotes
- series of 8 enzyme-catalyzed steps, and one side reaction where $GTP + ADP \rightarrow GDP + ATP$
- entry: acetyl-CoA + oxaloacetate \rightarrow citrate + CoA
- rest of cycle: citrate + $H_2O \rightarrow 2 CO_2$ + oxaloacetate + energy
 - note there is no net gain or loss of oxaloacetate in the cycle
 - energy is stored in three NADH and one $FADH_2$ for each cycle, plus one ATP

BIOL 1020 – CHAPTER 9 LECTURE NOTES

6. overall:



7. note that at this point glucose has been completely catabolized, yet only 4 ATP have been formed; the rest of the energy is stored in NADH and FADH₂

D. oxidative phosphorylation: the electron transport chain and chemiosmosis

- occurs in mitochondria of eukaryotes, and on membrane surface in prokaryotes
- electrons from NADH and FADH₂ are transferred to a chain of membrane-bound electron acceptors, and eventually passed to oxygen
 - acceptors include flavin mononucleotide (FMN), ubiquinone, iron-sulfur proteins, cytochromes
 - in the end, electrons wind up on molecular oxygen, and water is formed
 $(\text{NADH or FADH}_2) + \frac{1}{2} \text{O}_2 \rightarrow \text{H}_2\text{O} + (\text{NAD}^+ \text{ or FAD}) + \text{energy}$
 - lack of oxygen or compounds like cyanide stop the transport chain, and energy cannot be obtained from NADH and FADH₂ – this usually starves cells, killing them
- hydrogen ions (protons) are pumped across the inner mitochondrial membrane, creating a concentration gradient with high proton concentration in the intermembrane space
 - energy for the pumping comes from energy lost as electrons are transferred
 - gradient allows opportunity for energy capture
- chemiosmosis produces ATP
 - protons are charged and do not readily cross a cell membrane
 - special protein channel, **ATP synthase** (also called ATP synthetase) allows proton transport with the gradient
 - energy is captured and used to make ATP
- energy from oxidation of NADH yields ~3 ATP (only ~2 if the electrons from the NADH from glycolysis wind up on FADH₂ after being shuttled across the mitochondrial membrane)
- energy from oxidation of FADH₂ yields ~2 ATP

BIOL 1020 – CHAPTER 9 LECTURE NOTES

IV. Aerobic respiration theoretically yields 36 or 38 ATP molecules from one glucose molecule

Glycolysis	2 ATP
Citric Acid Cycle	2 ATP
FADH ₂ oxidation (2 x 2)	4 ATP
NADH oxidation (8 x 3, 2 x 2 or 3)	28-30 ATP
TOTAL	36-38 ATP

The actual yield is typically about 30 ATP per glucose. Why only ~30? Chemiosmosis doesn't actually give round figures, and some of the energy from the proton gradient is used for other things too, like bringing pyruvate into the mitochondrion. The overall efficiency of aerobic respiration is typically about 32%; the rest of the energy from combustion of glucose is released as heat (compare this to a car's internal combustion engine, typically about 20-25% efficiency).

V. Non-glucose energy sources

- A. other substances can be oxidized to produce ATP in living systems
- B. along with carbohydrates, proteins and lipids (fats) are generally major energy sources in foods; nucleic acids are not present in high amounts in foods and thus aren't as important in providing cells with energy
- C. proteins are broken into amino acids, which can be broken down further
 1. amino group is removed (deamination)
 2. amino group may eventually be converted to urea and excreted
 3. remaining carbon chain enters aerobic respiration at various points, depending on chain length
 4. provide roughly the same amount of energy per unit weight as does glucose
- D. lipids (focus on triacylglycerols)
 1. lipids are more reduced than glucose (note less oxygen in lipids), thus more energetic
 2. glycerol is converted to glyceraldehyde-3-phosphate (**G3P**), entering glycolysis
 3. fatty acids are oxidized and split into acetyl groups that are combined with CoA to make acetyl-CoA (this process is called **β oxidation**)
 4. typically provides over twice as much energy per unit weight as glucose
 5. as an example, oxidation of a 6-carbon fatty acid yields up to 44 ATP

VI. Regulation of aerobic respiration

- A. ATP/ADP balance regulates much of oxidative phosphorylation
 1. ATP synthesis continues until ADP stores are largely depleted
 2. rapid use of ATP leads to excess ADP, and thus speeds up aerobic respiration
- B. **phosphofructokinase**, the enzyme for one of the earliest steps in glycolysis, is highly regulated
 1. ATP, though a substrate, also serves as an allosteric inhibitor

BIOL 1020 – CHAPTER 9 LECTURE NOTES

2. citrate is also an allosteric inhibitor
3. AMP serves as an allosteric activator

VII. Anaerobic respiration

- A. bacteria that live in environments where O_2 is not abundant perform anaerobic respiration
- B. still uses an electron transport chain
- C. some other compound such as NO_3^- , SO_4^{2-} or CO_2 serves as the ultimate electron acceptor
- D. not as efficient as aerobic respiration (exact efficiency varies depending on the process and the species)

VIII. Fermentation

- A. involves no electron transport chain
- B. inefficient; net is 2 ATP per glucose molecule (only glycolysis works)
- C. if glycolysis only, then NAD^+ must be regenerated, thus fermentation, where NADH reduces an organic molecule
 1. **alcohol fermentation** produces ethanol, CO_2 , and NAD^+
 - pyruvate is converted to ethanol and CO_2 to regenerate NAD^+
 - ethanol is a potentially toxic waste product, and is removed from cells
 - yeast (and many bacteria) perform alcoholic fermentation in low oxygen environments
 - used in making alcoholic beverages, baking
 2. **lactic acid fermentation** produces lactate and NAD^+
 - pyruvate is reduced to lactate to regenerate NAD^+
 - performed by some bacteria and fungi, and by animals (when muscles need energy fast)
 - used in making cheese, yogurt, sauerkraut

BIOL 1020 – CHAPTER 9 LECTURE NOTES

PROCESS	Where?	(carbon) compounds in	(carbon) compounds out	Net ATP made	Net NADH made	Net FADH₂ made	Other notable items
glycolysis							
acetyl-CoA formation							
citric acid cycle							
oxidative phosphorylation							
TOTAL							