Introduction – Chapter 6

In eukaryotes, cellular respiration
- harvests energy from food,
- yields large amounts of ATP, and
- Uses ATP to drive cellular work.

A similar process takes place in many prokaryotic organisms.

6.1 Photosynthesis and cellular respiration provide energy for life

- Mostly energy ultimately comes from the sun and producers perform photosynthesis.
- In cellular respiration
  - glucose is broken down to CO₂ and H₂O and
  - makes ATP.
- Takes place in the mitochondria of eukaryotic cells.

6.3 Cellular respiration banks energy in ATP molecules

- Cellular respiration - exergonic process that transfers energy from the bonds in glucose to form ATP.
- Cellular respiration
  - produces about 32-36 ATP molecules from 1 glucose molecule and
  - gets about 34% of the energy stored in glucose.
- Other foods (organic molecules) can also be used as a source of energy.

\[
\text{Glucose} + 6 \text{O}_2 \rightarrow 6 \text{CO}_2 + 6 \text{H}_2\text{O} + \text{ATP}
\]
6.4 CONNECTION: The human body uses energy from ATP for all its activities

- Average adult human ~ 2,200 kcal of energy per day.
  - ~75% of these calories are used to maintain a healthy body.
  - The remaining 25% is used to power physical activities.
- A kilocalorie (kcal) is
  - amount of heat required to raise the temperature of 1 (kg) of water by 1°C,
  - the same as a food Calorie, and
  - used to measure the nutritional values on food labels.

6.5 Cells tap energy from electrons “falling” from organic fuels to oxygen

- When the carbon-hydrogen bonds of glucose are broken, electrons are transferred to oxygen.
  - Oxygen attracts electrons.
  - Loses energy when it “falls” to oxygen.
- The energy is dissipated as heat and light and is not available to living organisms.

6.5 Cells tap energy from electrons “falling” from organic fuels to oxygen

- Cellular respiration is the controlled breakdown of organic molecules.
- Energy is
  - gradually released in small amounts,
  - captured by a biological system, and
  - stored in ATP.
6.5 Cells tap energy from electrons “falling” from organic fuels to oxygen

- Enzymes are necessary to oxidize glucose and other foods.
- NAD⁺
  - is an important enzyme in oxidizing glucose,
  - accepts electrons, and
  - becomes reduced to NADH.

6.6 Overview: Cellular respiration occurs in three main stages (draw this together)

- Cellular respiration consists of a sequence of steps that can be divided into three stages.
  - Stage 1 – Glycolysis
  - Stage 2 – Pyruvate oxidation and citric acid cycle
  - Stage 3 – Oxidative phosphorylation

- Stage 1: Glycolysis
  - occurs in the cytoplasm,
  - begins cellular respiration, and
  - breaks down glucose into two molecules of a three-carbon compound called pyruvate.
6.6 Overview: Cellular respiration occurs in three main stages (draw this together)

- **Stage 2: The citric acid cycle**
  - takes place in mitochondria,
  - oxidizes pyruvate to a two-carbon compound, and
  - supplies the third stage with electrons.

- **Stage 3: Oxidative phosphorylation**
  - involves electrons carried by NADH and FADH₂,
  - shuttles these electrons to the electron transport chain embedded in the inner mitochondrial membrane,
  - involves chemiosmosis, and
  - generates ATP through oxidative phosphorylation associated with **chemiosmosis**.

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6.7 Glycolysis harvests chemical energy by oxidizing glucose to pyruvate (DO NOT COPY)

- In **glycolysis**,
  - a single molecule of glucose is enzymatically cut in half through a series of steps,
  - two molecules of pyruvate are produced,
  - two molecules of NAD⁺ are reduced to two molecules of NADH, and
  - a net of two molecules of ATP is produced.
6.7 Glycolysis harvests chemical energy by oxidizing glucose to pyruvate (DO NOT COPY)

- ATP is formed in glycolysis by substrate-level phosphorylation during which
  - an enzyme transfers a phosphate group from a substrate molecule to ADP and
  - ATP is formed.
- The compounds that form between the initial reactant, glucose, and the final product, pyruvate, are called intermediates.

The steps of glycolysis can be grouped into two main phases.
- In steps 1–4, the energy investment phase,
  - energy is consumed as two ATP molecules are used to energize a glucose molecule,
  - which is then split into two small sugars that are now primed to release energy.
- In steps 5–9, the energy payoff,
  - two NADH molecules are produced for each initial glucose molecule and
  - ATP molecules are generated.
6.8 Pyruvate is oxidized prior to the citric acid cycle (DO NOT COPY)

- The pyruvate formed in glycolysis is transported from the cytoplasm into a mitochondrion where
  - the citric acid cycle and
  - oxidative phosphorylation will occur.

- Two molecules of pyruvate are produced for each molecule of glucose that enters glycolysis.
- Pyruvate does not enter the citric acid cycle, but undergoes some chemical grooming in which
  - a carboxyl group is removed and given off as CO₂,
  - the two-carbon compound remaining is oxidized while a molecule of NAD⁺ is reduced to NADH,
  - coenzyme A joins with the two-carbon group to form acetyl coenzyme A, abbreviated as acetyl CoA, and
  - acetyl CoA enters the citric acid cycle.

6.9 The citric acid cycle completes the oxidation of organic molecules, generating many NADH and FADH₂ molecules (DO NOT COPY)

- The citric acid cycle
  - is also called the Krebs cycle (after the German-British researcher Hans Krebs, who worked out much of this pathway in the 1930s),
  - completes the oxidation of organic molecules, and
  - generates many NADH and FADH₂ molecules.
6.9 The citric acid cycle completes the oxidation of organic molecules, generating many NADH and FADH\(_2\) molecules (DO NOT COPY)

- During the citric acid cycle
  - the two-carbon group of acetyl CoA is added to a four-carbon compound, forming citrate,
  - citrate is degraded back to the four-carbon compound,
  - two CO\(_2\) are released, and
  - 1 ATP, 3 NADH, and 1 FADH\(_2\) are produced.

Remember that the citric acid cycle processes two molecules of acetyl CoA for each initial glucose.

Thus, after two turns of the citric acid cycle, the overall yield per glucose molecule is

- 2 ATP,
- 6 NADH, and
- 2 FADH\(_2\).
6.10 Most ATP production occurs by oxidative phosphorylation (DO NOT COPY)

- Oxidative phosphorylation
  - involves electron transport and chemiosmosis and
  - requires an adequate supply of oxygen.

- Electrons from NADH and FADH₂ travel down the electron transport chain to O₂.
- Oxygen picks up H⁺ to form water.
- Energy released by these redox reactions is used to pump H⁺ from the mitochondrial matrix into the intermembrane space.
- In chemiosmosis, the H⁺ diffuses back across the inner membrane through ATP synthase complexes, driving the synthesis of ATP.

6.11 CONNECTION: Interrupting cellular respiration can have both harmful and beneficial effects

- Cellular poisons block the process of oxidative phosphorylation. These poisons
  1. block the electron transport chain (for example, rotenone, cyanide, and carbon monoxide),
  2. inhibit ATP synthase (for example, the antibiotic oligomycin), or
  3. make the membrane leaky to hydrogen ions (called uncouplers, examples include dinitrophenol).
6.11 CONNECTION: Interrupting cellular respiration can have both harmful and beneficial effects (DO NOT COPY)

- Brown fat is
  - a special type of tissue associated with the generation of heat and
  - more abundant in hibernating mammals and newborn infants.
- In brown fat,
  - the cells are packed full of mitochondria,
  - the inner mitochondrial membrane contains an uncoupling protein, which allows $H^+$ to flow back down its concentration gradient without generating ATP, and
  - ongoing oxidation of stored fats generates additional heat.

6.12 Review: Each molecule of glucose yields many molecules of ATP (DO NOT COPY)

- Recall that the energy payoff of cellular respiration involves
  1. glycolysis,
  2. alteration of pyruvate,
  3. the citric acid cycle, and
  4. oxidative phosphorylation.
6.13 Fermentation enables cells to produce ATP without oxygen

- Fermentation - harvests energy without oxygen.
  - Uses glycolysis,
  - produces two ATP molecules per glucose, and
  - reduces NAD⁺ to NADH.
- The trick of fermentation is to provide an anaerobic path for recycling NADH back to NAD⁺.

Your muscle cells and certain bacteria can oxidize NADH through lactic acid fermentation, in which
  - NADH is oxidized to NAD⁺ and
  - pyruvate is reduced to lactate.

The dairy industry uses lactic acid fermentation by bacteria to make cheese and yogurt.

Other types of microbial fermentation turn
  - soybeans into soy sauce and
  - cabbage into sauerkraut.
6.13 Fermentation enables cells to produce ATP without oxygen

- The baking and winemaking industries have used **alcohol fermentation** for thousands of years.
- In this process yeasts (single-celled fungi)
  - oxidize NADH back to NAD⁺ and
  - convert pyruvate to CO₂ and ethanol.

### Obligate anaerobes
- are poisoned by oxygen, requiring anaerobic conditions, and
- live in stagnant ponds and deep soils.

### Facultative anaerobes
- include yeasts and many bacteria, and
- can make ATP by fermentation or oxidative phosphorylation.
6.14 EVOLUTION CONNECTION: Glycolysis evolved early in the history of life on Earth

- Glycolysis is the universal energy-harvesting process of life.
  - life long before oxygen was present,
  - when only prokaryotes inhabited the Earth,
  - about 3.5 billion years ago.
- The ancient history of glycolysis is supported by its
  - occurrence in all the domains of life and
  - location within the cell, using pathways that do not involve any membrane-bounded organelles.

6.15 Cells use many kinds of organic molecules as fuel for cellular respiration

- ATP is generated using
  - carbohydrates,
  - fats, and
  - proteins.
- Fats - excellent cellular fuel because they
  - Have many hydrogen atoms and thus many energy-rich electrons and
  - yield more than twice as much ATP per gram than a gram of carbohydrate or protein.
6.16 Food molecules provide raw materials for biosynthesis

- Cells use intermediates from cellular respiration for the biosynthesis of other organic molecules.