

Chapter 9

Overview: Life Is Work

- Living cells require energy from outside sources
- Some animals, such as the chimpanzee, obtain energy by eating plants, and some animals feed on other organisms that eat plants
- Energy flows into an ecosystem as sunlight and leaves as heat
- Photosynthesis generates O₂ and organic molecules, which are used in cellular respiration
- Cells use chemical energy stored in organic molecules to regenerate ATP, which powers work

Concept 9.1: Catabolic pathways yield energy by oxidizing organic fuels

- Several processes are central to cellular respiration and related pathways

Catabolic Pathways and Production of ATP

- The breakdown of organic molecules is exergonic
- **Fermentation** is a partial degradation of sugars that occurs without O₂
- **Aerobic respiration** consumes organic molecules and O₂ and yields ATP
- Anaerobic respiration is similar to aerobic respiration but consumes compounds other than O₂
- **Cellular respiration** includes both aerobic and anaerobic respiration but is often used to refer to aerobic respiration
- Although carbohydrates, fats, and proteins are all consumed as fuel, it is helpful to trace cellular respiration with the sugar glucose
$$\text{C}_6\text{H}_{12}\text{O}_6 + 6 \text{O}_2 \rightarrow 6 \text{CO}_2 + 6 \text{H}_2\text{O} + \text{Energy (ATP + heat)}$$

Redox Reactions: Oxidation and Reduction

- The transfer of electrons during chemical reactions releases energy stored in organic molecules
- This released energy is ultimately used to synthesize ATP

The Principle of Redox

- Chemical reactions that transfer electrons between reactants are called oxidation-reduction reactions, or **redox reactions**
- In **oxidation**, a substance loses electrons, or is oxidized
- In **reduction**, a substance gains electrons, or is reduced (the amount of positive charge is reduced)
- The electron donor is called the **reducing agent**
- The electron receptor is called the **oxidizing agent**
- Some redox reactions do not transfer electrons but change the electron sharing in covalent bonds
- An example is the reaction between methane and O₂

Oxidation of Organic Fuel Molecules During Cellular Respiration

- During cellular respiration, the fuel (such as glucose) is oxidized, and O₂ is reduced

Stepwise Energy Harvest via NAD⁺ and the Electron Transport Chain

- In cellular respiration, glucose and other organic molecules are broken down in a series of steps
- Electrons from organic compounds are usually first transferred to **NAD⁺**, a

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- coenzyme
- As an electron acceptor, NAD^+ functions as an oxidizing agent during cellular respiration
- Each NADH (the reduced form of NAD^+) represents stored energy that is tapped to synthesize ATP
- NADH passes the electrons to the **electron transport chain**
- Unlike an uncontrolled reaction, the electron transport chain passes electrons in a series of steps instead of one explosive reaction
- O_2 pulls electrons down the chain in an energy-yielding tumble
- The energy yielded is used to regenerate ATP

The Stages of Cellular Respiration: A Preview

- Harvesting of energy from glucose has three stages
 - **Glycolysis** (breaks down glucose into two molecules of pyruvate)
 - The **citric acid cycle** (completes the breakdown of glucose)
 - **Oxidative phosphorylation** (accounts for most of the ATP synthesis)
- The process that generates most of the ATP is called oxidative phosphorylation because it is powered by redox reactions
- Oxidative phosphorylation accounts for almost 90% of the ATP generated by cellular respiration
- A smaller amount of ATP is formed in glycolysis and the citric acid cycle by **substrate-level phosphorylation**
- For each molecule of glucose degraded to CO_2 and water by respiration, the cell makes up to 32 molecules of ATP

Concept 9.2: Glycolysis harvests chemical energy by oxidizing glucose to pyruvate

- Glycolysis (“splitting of sugar”) breaks down glucose into two molecules of pyruvate
- Glycolysis occurs in the cytoplasm and has two major phases
 - Energy investment phase
 - Energy payoff phase
- Glycolysis occurs whether or not O_2 is present

Concept 9.3: After pyruvate is oxidized, the citric acid cycle completes the energy-yielding oxidation of organic molecules

- In the presence of O_2 , pyruvate enters the mitochondrion (in eukaryotic cells) where the oxidation of glucose is completed

Oxidation of Pyruvate to Acetyl CoA

- Before the citric acid cycle can begin, pyruvate must be converted to acetyl Coenzyme A (**acetyl CoA**), which links glycolysis to the citric acid cycle
- This step is carried out by a multienzyme complex that catalyses three reactions

The Citric Acid Cycle

- The citric acid cycle, also called the Krebs cycle, completes the break down of pyruvate to CO_2

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- The cycle oxidizes organic fuel derived from pyruvate, generating 1 ATP, 3 NADH, and 1 FADH₂ per turn
- The citric acid cycle has eight steps, each catalyzed by a specific enzyme
- The acetyl group of acetyl CoA joins the cycle by combining with oxaloacetate, forming citrate
- The next seven steps decompose the citrate back to oxaloacetate, making the process a cycle
- The NADH and FADH₂ produced by the cycle relay electrons extracted from food to the electron transport chain

Concept 9.4: During oxidative phosphorylation, chemiosmosis couples electron transport to ATP synthesis

- Following glycolysis and the citric acid cycle, NADH and FADH₂ account for most of the energy extracted from food
- These two electron carriers donate electrons to the electron transport chain, which powers ATP synthesis via oxidative phosphorylation

The Pathway of Electron Transport

- The electron transport chain is in the inner membrane (cristae) of the mitochondrion
- Most of the chain's components are proteins, which exist in multiprotein complexes
- The carriers alternate reduced and oxidized states as they accept and donate electrons
- Electrons drop in free energy as they go down the chain and are finally passed to O₂, forming H₂O
- Electrons are transferred from NADH or FADH₂ to the electron transport chain
- Electrons are passed through a number of proteins including **cytochromes** (each with an iron atom) to O₂
- The electron transport chain generates no ATP directly
- It breaks the large free-energy drop from food to O₂ into smaller steps that release energy in manageable amounts

Chemiosmosis: The Energy-Coupling Mechanism

- Electron transfer in the electron transport chain causes proteins to pump H⁺ from the mitochondrial matrix to the intermembrane space
- H⁺ then moves back across the membrane, passing through the proton, **ATP synthase**
- ATP synthase uses the exergonic flow of H⁺ to drive phosphorylation of ATP
- This is an example of **chemiosmosis**, the use of energy in a H⁺ gradient to drive cellular work
- The energy stored in a H⁺ gradient across a membrane couples the redox reactions of the electron transport chain to ATP synthesis
- The H⁺ gradient is referred to as a **proton-motive force**, emphasizing its capacity to do work

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An Accounting of ATP Production by Cellular Respiration

- During cellular respiration, most energy flows in this sequence:
glucose → NADH → electron transport chain → proton-motive force → ATP
- About 34% of the energy in a glucose molecule is transferred to ATP during cellular respiration, making about 32 ATP
- There are several reasons why the number of ATP is not known exactly

Concept 9.5: Fermentation and anaerobic respiration enable cells to produce ATP without the use of oxygen

- Most cellular respiration requires O₂ to produce ATP
- Without O₂, the electron transport chain will cease to operate
- In that case, glycolysis couples with fermentation or anaerobic respiration to produce ATP

- Anaerobic respiration uses an electron transport chain with a final electron acceptor other than O₂, for example sulfate
- Fermentation uses substrate-level phosphorylation instead of an electron transport chain to generate ATP

Types of Fermentation

- Fermentation consists of glycolysis plus reactions that regenerate NAD⁺, which can be reused by glycolysis
- Two common types are **alcohol fermentation** and **lactic acid fermentation**

- In alcohol fermentation, pyruvate is converted to ethanol in two steps, with the first releasing CO₂
- Alcohol fermentation by yeast is used in brewing, winemaking, and baking
- In lactic acid fermentation, pyruvate is reduced to NADH, forming lactate as an end product, with no release of CO₂
- Lactic acid fermentation by some fungi and bacteria is used to make cheese and yogurt
- Human muscle cells use lactic acid fermentation to generate ATP when O₂ is scarce

Comparing Fermentation with Anaerobic and Aerobic Respiration

- All use glycolysis (net ATP = 2) to oxidize glucose and harvest chemical energy of food
- In all three, NAD⁺ is the oxidizing agent that accepts electrons during glycolysis
- The processes have different final electron acceptors: an organic molecule (such as pyruvate or acetaldehyde) in fermentation and O₂ in cellular respiration
- Cellular respiration produces 32 ATP per glucose molecule; fermentation produces 2 ATP per glucose molecule
- **Obligate anaerobes** carry out fermentation or anaerobic respiration and cannot survive in the presence of O₂
- Yeast and many bacteria are **facultative anaerobes**, meaning that they can survive using either fermentation or cellular respiration
- In a facultative anaerobe, pyruvate is a fork in the metabolic road that leads to two

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alternative catabolic routes

The Evolutionary Significance of Glycolysis

- Ancient prokaryotes are thought to have used glycolysis long before there was oxygen in the atmosphere
- Very little O₂ was available in the atmosphere until about 2.7 billion years ago, so early prokaryotes likely used only glycolysis to generate ATP
- Glycolysis is a very ancient process

Concept 9.6: Glycolysis and the citric acid cycle connect to many other metabolic pathways

- Glycolysis and the citric acid cycle are major intersections to various catabolic and anabolic pathways

The Versatility of Catabolism

- Catabolic pathways funnel electrons from many kinds of organic molecules into cellular respiration
- Glycolysis accepts a wide range of carbohydrates
- Proteins must be digested to amino acids; amino groups can feed glycolysis or the citric acid cycle
- Fats are digested to glycerol (used in glycolysis) and fatty acids (used in generating acetyl CoA)
- Fatty acids are broken down by **beta oxidation** and yield acetyl CoA
- An oxidized gram of fat produces more than twice as much ATP as an oxidized gram of carbohydrate

Biosynthesis (Anabolic Pathways)

- The body uses small molecules to build other substances
- These small molecules may come directly from food, from glycolysis, or from the citric acid cycle

Regulation of Cellular Respiration via Feedback Mechanisms

- Feedback inhibition is the most common mechanism for control
- If ATP concentration begins to drop, respiration speeds up; when there is plenty of ATP, respiration slows down
- Control of catabolism is based mainly on regulating the activity of enzymes at strategic points in the catabolic pathway