

I. Cellular Respiration

A. Overview: Life is Work

1. Living cells require energy from outside sources
2. Some animals, such as the giant panda, obtain energy by eating plants, and some animals feed on other organisms that eat plants.
3. Energy flows into an ecosystem as sunlight and leaves as heat
4. Photosynthesis generates O_2 and organic molecules, which are used in cellular respiration
5. Cells use chemical energy stored in organic molecules to regenerate ATP, which powers work

B. Catabolic pathways yield energy by oxidizing organic fuels

1. Several processes are central to cellular respiration and related pathways

C. Catabolic Pathways and the Production of ATP

1. The breakdown of organic molecules is exergonic
2. **Fermentation** is a partial digestion of sugars that occurs without O_2
3. **Aerobic respiration** consumes organic molecules and O_2 and yields ATP
4. *Anaerobic* respiration is similar to aerobic respiration but consumes compounds other than O_2
5. **Cellular respiration** includes both aerobic and anaerobic respiration but is often used to refer to aerobic respiration
6. Although carbohydrates, fats and proteins are all consumed as fuel, it is helpful to trace cellular respiration with the sugar glucose:
 - a) $C_6H_{12}O_6 \rightarrow 6O_2 \rightarrow 6CO_2 + 6H_2O + \text{Energy (ATP + heat)}$

D. Redox Reactions: Oxidation & Reduction

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

E. The principles of redox

1. Chemical reactions that transfers electrons between reactants are called oxidation-reductions reactions, or **redox reactions**
2. In **oxidation**, a substance loses electrons, or is oxidized
3. In **reduction**, a substance gains electrons, or is reduces (the amount of positive charge is reduced)
4. $Na + Cl \rightarrow Na^+ + Cl^-$
 - a) The Na becomes oxidized (loses an electron)
 - b) and the Cl becomes reduced (gains an electron)
5. The electron donor is called the **reducing agent**
6. The electron receptor is called the **oxidizing agent**
7. Some redox reactions do not transfer electrons but change the electron sharing in covalent bonds
8. An example is the reactions between methane and O_2

F. Oxidation of Organic Fuel Molecules During Cellular Respiration

1. During cellular respiration, the fuel (such as glucose) is oxidized, and O_2 is reduced:

G. Stepwise Energy Harvest via NAD^+ and the Electron Transport Chain

1. In cellular respiration, glucose and other organic molecules are broken down in a series of steps
2. Electrons from organic compounds are usually first transferred to NAD^+ , a coenzyme
3. As an electron acceptor, NAD^+ functions as an oxidizing agent during cellular respiration
4. Each NADH (the reduction form of NAD^+) represents stored energy that is trapped to synthesize ATP
5. NADH passes the electrons to the **electron transport chain**
6. Unlike an uncontrolled reaction, the electron transport chain passes electron in a series of steps instead of one explosive reaction
7. O_2 pulls electrons down the change in an energy-yielding tumble
8. The energy yielded is used to regenerate ATP

H. The Stages of Cellular Respiration: A Preview

1. Cellular respiration has three stages:
 - a) **Glycolysis** (breaks down glucose into molecules of pyruvate 2ATP)
 - b) The **citric acid cycle** (completes the breakdown of glucose) 2 ATP
 - c) **Oxidative phosphorylation** (accounts for most of the ATP synthesis) 24ATP
2. The process that generates most of the ATP is called oxidative phosphorylation because it is powered by redox reactions

3. Oxidative phosphorylation accounts for almost 90% of the ATP generated by cellular respiration
 4. A smaller amount of the ATP is formed in glycolysis and the citric acid cycle by substrate-level phosphorylation
- I. **Concept 9.2: Glycolysis harvests chemical energy by oxidizing glucose to pyruvate**
1. Glycolysis ("splitting of sugar") breaks down glucose into two molecules of pyruvate
 2. Glycolysis occurs in the cytoplasm and has two major phases:
 - a) Energy investment phase
 - b) Energy payoff phase
- J. **Concept 9.3: The citric acid cycle completes the energy-yielding oxidation of organic molecules**
1. In the presence of O_2 , pyruvate enters the mitochondrion
 2. Before the citric acid cycle can begin, pyruvate must be converted to **acetyl CoA**, which links the cycle to glycolysis.
 3. The citric acid cycle, also called the Krebs cycle, takes place within the mitochondria matrix
 4. The cycle oxidizes organic fuel derived from pyruvate, generating 1 ATP, 3 NADH, and 1 $FADH_2$ per turn
 5. The citric acid cycle has eight steps, each catalyzed by a specific enzyme
 6. The acetyl group of acetyl CoA joins the cycle by combining with oxaloacetate, forming citrate
 7. The next seven steps decompose the citrate back to oxaloacetate, making the process a cycle
 8. The NADH and $FADH_2$ produced by the cycle relay electrons extracted from food to the electron transport chain
- K. **Concept 9.4: During oxidative phosphorylation, chemiosmosis couples electron transport to ATP synthesis**
1. Following glycolysis and the citric acid cycle, NADH and $FADH_2$ account for most of the energy extracted from food
 2. These two electron carriers donate electrons to the electron transport chain, which powers ATP synthesis via oxidative phosphorylation
- L. **The Pathway of Electron Transport**
1. The electron transport chain is in the cristae of the mitochondrion
 2. Most of the chain's components are proteins, which exist in multi-protein complexes
 3. The carriers alternate reduced and oxidized states as they accept and donate electrons
 4. Electrons drop in free energy as they go down the chain and are finally passes to O_2 , forming H_2O
 5. Electrons are transferred from NADH or $FADH_2$ to the electron transport chain
 6. Electrons are passed through a number of proteins including **cytochromes** (each with an iron atom) to O_2
 7. The electron transport chain generates no ATP
 8. The chain's function is to break the large free-energy drop from food to O_2 into smaller steps that release energy in manageable amounts
- M. **Chemiosmosis: The Energy-Coupling Mechanism**
1. Electron transfer in the electron transport chain causes proteins to pump H^+ from the mitochondrial matrix to the intermembrane space
 2. H^+ then moves back across the membrane, passing through channels in ATP synthase
 3. ATP synthase uses the exergonic flow of H^+ to drive phosphorylation of ATP
 4. This is an example of chemiosmosis, the use of energy in a H^+ gradient to drive cellular work
 5. The energy stored in a H^+ gradient across a membrane couples the redox reactions of the electron transport chain to ATP syntheses
 6. The H^+ gradient is referred to as proton-motive force, emphasizing its capacity to do work
- N. **An Accounting of ATP Production by Cellular Respiration**
1. During cellular respiration, most energy flows in this sequence:
 - a) Glucose \rightarrow NADH \rightarrow electron transport chain \rightarrow proton-motive force \rightarrow ATP
 2. About 40% of the energy in a glucose molecule is transferred to ATP during cellular respiration, making about 38 ATP
- O. **Concentration 9.5: Fermentation and anaerobic respiration enable cells to produce ATP without the use of oxygen**
1. Most cellular respiration requires O_2 to produce ATP

2. Glycolysis can produce ATP with or without O₂ (in aerobic or anaerobic conditions)
3. In the absence of O₂, glycolysis couples with fermentation or anaerobic respiration to produce ATP
4. Anaerobic respiration uses an electron transport chain with an electron acceptor other than O₂, for example, sulfate
5. Fermentation uses phosphorylation instead of an electron transport chain to generate ATP

P. Types of Fermentation

1. Fermentation consists of glycolysis plus reactions that regenerate NAD⁺, which can be reused by glycolysis
2. Two common types are alcohol fermentation and lactic acid fermentation
3. In **alcohol fermentation**, pyruvate is converted to ethanol in two steps, with the first releasing CO₂
4. Alcohol fermentation by yeast is used in brewing, winemaking, and baking
5. In **lactic acid fermentation**, pyruvate is reduced to NADH, forming lactate as an end product, with no release of CO₂
6. Lactic acid fermentation by some fungi and bacteria is used to make cheese and yogurt
7. Human muscle cells use lactic acid fermentation to generate ATP when O₂ is scarce

Q. Fermentation and Aerobic Respiration Compared

1. Both processes use glycolysis to oxidize glucose and other organic fuels to pyruvate
2. The processes have different final electron acceptors: an organic molecule (such as pyruvate or acetaldehyde) in fermentation and O₂ in cellular respiration
3. Cellular respiration produces 38 ATP per glucose molecule; fermentation produces 2 ATP per glucose molecule
4. **Obligate anaerobes** carry out fermentation or anaerobic respiration and cannot survive in the presence of O₂
5. Yeast and many bacteria are **facultative anaerobes**, meaning that they can survive using either fermentation or cellular respiration
6. In a facultative anaerobe, pyruvate is a fork in the metabolic road that leads to two alternative catabolic routes.

R. The Evolutionary significance of Glycolysis

1. Glycolysis occurs in nearly all organisms
2. Glycolysis probably evolved in ancient prokaryotes before there was oxygen in the atmosphere

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

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

T. The Versatility of Catabolism

1. Catabolic pathways funnel electrons from many kinds of organic molecules into cellular respiration
2. Glycolysis accepts a wide range of carbohydrates
3. Proteins must digest to amino acids; amino groups can feed glycolysis or the citric acid cycle