Introduction: How Is a Marathoner Different from a Sprinter?

- Individuals inherit various percentages of the two main types of muscle fibers, slow and fast
  - The difference between the two is the process each uses to make ATP
  - Slow fibers make it aerobically using oxygen
  - Fast fibers work anaerobically without oxygen
Introduction: *How Is a Marathoner Different from a Sprinter?*

- The percentage of slow and fast muscle fibers determines the difference between track athletes
  - Those with a large percentage of slow fibers make the best long-distance runners
  - Those with more fast fibers are good sprinters

- All of our cells harvest chemical energy (ATP) from our food
INTRODUCTION TO CELLULAR RESPIRATION
6.1 Photosynthesis and cellular respiration provide energy for life

- Energy is necessary for life processes
  - These include growth, transport, manufacture, movement, reproduction, and others
  - Energy that supports life on Earth is captured from sun rays reaching Earth through plant, algae, protist, and bacterial photosynthesis
6.1 Photosynthesis and cellular respiration provide energy for life

- Energy in sunlight is used in photosynthesis to make glucose from CO$_2$ and H$_2$O with release of O$_2$

- Other organisms use the O$_2$ and energy in sugar and release CO$_2$ and H$_2$O

- Together, these two processes are responsible for the majority of life on Earth
Sunlight energy → Photosynthesis in chloroplasts → Cellular respiration in mitochondria → ATP (for cellular work) → Heat energy
6.2 Breathing supplies oxygen to our cells for use in cellular respiration and removes carbon dioxide

- Breathing and cellular respiration are closely related
  - Breathing is necessary for exchange of CO$_2$ produced during cellular respiration for atmospheric O$_2$
  - Cellular respiration uses O$_2$ to help harvest energy from glucose and produces CO$_2$ in the process
Muscle cells carrying out Cellular Respiration

Glucose + O₂

CO₂ + H₂O + ATP
6.3 Cellular respiration banks energy in ATP molecules

- Cellular respiration is an exergonic process that transfers energy from the bonds in glucose to ATP
  - Cellular respiration produces 38 ATP molecules from each glucose molecule
  - Other foods (organic molecules) can be used as a source of energy as well
Glucose + 6 Oxygen → 6 Carbon dioxide + 6 Water + ATPs

C₆H₁₂O₆ + 6O₂ → 6CO₂ + 6H₂O + ATPs
6.4 CONNECTION: The human body uses energy from ATP for all its activities

- The average adult human needs about 2,200 kcal of energy per day

  - A kilocalorie (kcal) is the quantity of heat required to raise the temperature of 1 kilogram (kg) of water by 1°C

  - This energy is used for body maintenance and for voluntary activities
<table>
<thead>
<tr>
<th>Activity</th>
<th>Kcal Consumed per Hour by a 67.5-kg (150-lb) Person*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Running (7 min/mi)</td>
<td>979</td>
</tr>
<tr>
<td>Dancing (fast)</td>
<td>510</td>
</tr>
<tr>
<td>Bicycling (10 mph)</td>
<td>490</td>
</tr>
<tr>
<td>Swimming (2 mph)</td>
<td>408</td>
</tr>
<tr>
<td>Walking (3 mph)</td>
<td>245</td>
</tr>
<tr>
<td>Dancing (slow)</td>
<td>204</td>
</tr>
<tr>
<td>Sitting (writing)</td>
<td>28</td>
</tr>
</tbody>
</table>

*Not including kcal needed for body maintenance
6.5 Cells tap energy from electrons “falling” from organic fuels to oxygen

- The energy necessary for life is contained in the arrangement of electrons in chemical bonds in organic molecules

- An important question is how do cells extract this energy?
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 has a strong tendency to attract electrons
6.5 Cells tap energy from electrons “falling” from organic fuels to oxygen

- Energy can be released from glucose by simply burning it
- 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

- On the other hand, cellular respiration is the controlled breakdown of organic molecules
  - Energy is released in small amounts that can be captured by a biological system and stored in ATP
6.5 Cells tap energy from electrons “falling” from organic fuels to oxygen

- A cellular respiration equation is helpful to show the changes in hydrogen atom distribution
  - Glucose loses its hydrogen atoms and is ultimately converted to CO₂
  - At the same time, O₂ gains hydrogen atoms and is converted to H₂O
    - Loss of electrons is called **oxidation**
    - Gain of electrons is called **reduction**
Glucose: $\text{C}_6\text{H}_{12}\text{O}_6$ + 6 $\text{O}_2$ → 6 $\text{CO}_2$ + 6 $\text{H}_2\text{O}$ + Energy (ATP)

Loss of hydrogen atoms (oxidation)

Gain of hydrogen atoms (reduction)
6.5 Cells tap energy from electrons “falling” from organic fuels to oxygen

- Enzymes are necessary to oxidize glucose and other foods
  - The enzyme that removes hydrogen from an organic molecule is called dehydrogenase
  - Dehydrogenase requires a coenzyme called NAD$^+$ (nicotinamide adenine dinucleotide) to shuttle electrons
    - NAD$^+$ can become reduced when it accepts electrons and oxidized when it gives them up
Oxidation

Dehydrogenase

Reduction

NAD$^+$ + 2 H $\rightarrow$ NADH + H$^+$

(carries 2 electrons)
6.5 Cells tap energy from electrons “falling” from organic fuels to oxygen

- The transfer of electrons to NAD\(^+\) results in the formation of NADH, the reduced form of NAD\(^+\)
  
  - In this situation, NAD\(^+\) is called an electron acceptor, but it eventually becomes oxidized (loses an electron) and is then called an electron donor
6.5 Cells tap energy from electrons “falling” from organic fuels to oxygen

- There are other electron “carrier” molecules that function like NAD$^+$
  - They form a staircase where the electrons pass from one to the next down the staircase
  - These electron carriers collectively are called the **electron transport chain**, and as electrons are transported down the chain, ATP is generated
ATP

NAD

NADH

H

H

2e

2e

Controlled release of energy for synthesis of ATP

Electron transport chain

NAD

H

O

H2O

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STAGES OF CELLULAR RESPIRATION AND FERMENTATION
6.6 Overview: Cellular respiration occurs in three main stages

- **Stage 1: Glycolysis**
  - Glycolysis begins respiration by breaking glucose, a six-carbon molecule, into two molecules of a three-carbon compound called pyruvate
  - This stage occurs in the cytoplasm
Stage 2: The citric acid cycle

- The citric acid cycle breaks down pyruvate into carbon dioxide and supplies the third stage with electrons
- This stage occurs in the mitochondria
6.6 Overview: Cellular respiration occurs in three main stages

- Stage 3: Oxidative phosphorylation
  - During this stage, electrons are shuttled through the electron transport chain
  - As a result, ATP is generated through oxidative phosphorylation associated with chemiosmosis
  - This stage occurs in the inner mitochondrion membrane
6.6 Overview: Cellular respiration occurs in three main stages

- During the transport of electrons, a concentration gradient of $\text{H}^+$ ions is formed across the inner membrane into the intermembrane space
  - The potential energy of this concentration gradient is used to make ATP by a process called chemiosmosis
  - The concentration gradient drives $\text{H}^+$ through ATP synthases and enzymes found in the membrane, and ATP is produced
Mitochondrion

High-energy electrons carried by NADH

NADH

Cytoplasm

ATP

Substrate-level phosphorylation

CO₂

Glucose → Pyruvate

GLYCOLYSIS

Mitochondrion

NADH and FADH₂

Inner mitochondrial membrane

ATP

Oxidative phosphorylation

Cytoplasm

ATP

Substrate-level phosphorylation

CO₂

OXIDATIVE PHOSPHORYLATION (Electron Transport and Chemiosmosis)

Cytoplasm → Inner mitochondrial membrane → Mitochondrion

NADH + FADH₂ → ATP

Glycolysis

Pyruvate → Oxidative phosphorylation

Glucose
6.7 Glycolysis harvests chemical energy by oxidizing glucose to pyruvate

- In glycolysis, a single molecule of glucose is enzymatically cut in half through a series of steps to produce two molecules of pyruvate
  - In the process, two molecules of NAD$^+$ are reduced to two molecules of NADH
  - At the same time, two molecules of ATP are produced by substrate-level phosphorylation
6.7 Glycolysis harvests chemical energy by oxidizing glucose to pyruvate

- In **substrate-level phosphorylation**, an enzyme transfers a phosphate group from a substrate molecule to ADP, forming ATP
  - This ATP can be used immediately, but NADH must be transported through the electron transport chain to generate additional ATP
Glucose $\rightarrow$ 2 ADP + 2 P + 2 NAD$^+$ + 2 ATP + 2 H$^+$ → 2 Pyruvate
ADP
ATP
Substrate
Enzyme
Product
Enzyme
P
P
P

Substrate → Product

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Steps 1–3 A fuel molecule is energized, using ATP.

1. ATP → ADP
2. Glucose → Glucose-6-phosphate
3. Fructose-6-phosphate

Step 4 A six-carbon intermediate splits into two three-carbon intermediates.

4. Fructose-1,6-bisphosphate

Step 5 A redox reaction generates NADH.

5. NADH + H⁺ → NAD⁺ + H⁺

Steps 6–9 ATP and pyruvate are produced.

6. ATP → ADP
7. 3-Phosphoglycerate
8. 2-Phosphoglycerate
9. Phosphoenolpyruvate (PEP)

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Steps 1–3 A fuel molecule is energized, using ATP.

1. Glucose → Glucose-6-phosphate
2. ATP → Fructose-6-phosphate
3. ADP → Fructose-1,6-bisphosphate

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Steps 1–3 A fuel molecule is energized, using ATP.

Step 4 A six-carbon intermediate splits into two three-carbon intermediates.
Step 5 A redox reaction generates NADH.
Step 5 A redox reaction generates NADH.

Steps 6–9 ATP and pyruvate are produced.
6.8 Pyruvate is chemically groomed for the citric acid cycle

- The pyruvate formed in glycolysis is transported to the mitochondria, where it is prepared for entry into the citric acid cycle
  - The first step is removal of a carboxyl group that forms \( \text{CO}_2 \)
  - The second is oxidization of the two-carbon compound remaining
  - Finally, coenzyme A binds to the two-carbon fragment forming acetyl coenzyme A
Pyruvate → Coenzyme A → Acetyl coenzyme A

1. Pyruvate → CO₂
2. NAD⁺ → NADH + H⁺
3. Coenzyme A
6.9 The citric acid cycle completes the oxidation of organic molecules, generating many NADH and FADH$_{2}$ molecules

- With the help of CoA, the acetyl (two-carbon) compound enters the citric acid cycle
  - At this point, the acetyl group associates with a four-carbon molecule forming a six-carbon molecule
  - The six-carbon molecule then passes through a series of redox reactions that regenerate the four-carbon molecule (thus the “cycle” designation)
Acetyl CoA

CoA

CoA

FADH₂

FAD

FAD

NAD⁺

NADH

NAD⁺

3 H⁺

2 CO₂

CITRIC ACID CYCLE

ATP

ADP + P

CoA

CoA

CoA

CoA

CoA
Acetyl CoA stokes the furnace.
Acetyl CoA enters the cycle.

Steps 2–3:
NADH, ATP, and CO₂ are generated during redox reactions.
CITRIC ACID CYCLE

Step 1
Acetyl CoA stokes the furnace.

Steps 2 – 3
NADH, ATP, and CO₂ are generated during redox reactions.

Steps 4 – 5
Redox reactions generate FADH₂ and NADH.
6.10 Most ATP production occurs by oxidative phosphorylation

- Oxidative phosphorylation involves electron transport and chemiosmosis and requires an adequate supply of oxygen
  - NADH and FADH$_2$ and the inner membrane of the mitochondria are also involved
  - A H$^+$ ion gradient formed from all of the redox reactions of glycolysis and the citric acid cycle provide energy for the synthesis of ATP
间质空间
内膜
线粒体基质
蛋白质复合体的电子载体
电子流
NADH
FADH₂
FAD
NAD⁺
O₂
1/2
H₂O
ADP + P
H⁺
ATP
ATP合成酶
氧化磷酸化
电子传递链
Chemiosmosis
线粒体内膜
通过质子泵的质子转移
外膜
外膜空间

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6.11 CONNECTION: Certain poisons interrupt critical events in cellular respiration

- There are three different categories of cellular poisons that affect cellular respiration
  - The first category blocks the electron transport chain (for example, rotenone, cyanide, and carbon monoxide)
  - The second inhibits ATP synthase (for example, oligomycin)
  - Finally, the third makes the membrane leaky to hydrogen ions (for example, dinitrophenol)
\[
\text{ATP} + O_2 \rightarrow \text{H}_2\text{O} + 2\text{H}^+ + \text{NAD}^+ + \text{NADH} + \text{FADH}_2 + \text{FAD}
\]

**Chemiosmosis**

**Electron Transport Chain**

- **Rotenone** inhibits the electron transport chain at the site where NADH enters.
- **Cyanide, carbon monoxide** bind to cytochrome c, preventing electron transfer.
- **Oligomycin** blocks ATP synthase, preventing ATP formation.
- **DNP** accelerates proton translocation, bypassing the electron transport chain.

**ATP Synthase**

- **ADP + P** are converted to ATP.
- \( \frac{1}{2} \text{O}_2 + 2\text{H}^+ \rightarrow \text{H}_2\text{O} \)
6.12 Review: Each molecule of glucose yields many molecules of ATP

- Recall that the energy payoff of cellular respiration involves (1) glycolysis, (2) alteration of pyruvate, (3) the citric acid cycle, and (4) oxidative phosphorylation

- The total yield of ATP molecules per glucose molecule has a theoretical maximum of about 38

- This is about 40% of a glucose molecule potential energy

- Additionally, water and CO₂ are produced
Cytoplasm

Electron shuttle across membrane

Mitochondrion

Maximum per glucose:

About 38 ATP
6.13 Fermentation enables cells to produce ATP without oxygen

- Fermentation is an anaerobic (without oxygen) energy-generating process
  - It takes advantage of glycolysis, producing two ATP molecules and reducing NAD\(^+\) to NADH
  - The trick is to oxidize the NADH without passing its electrons through the electron transport chain to oxygen
6.13 Fermentation enables cells to produce ATP without oxygen

- Your muscle cells and certain bacteria can oxidize NADH through **lactic acid fermentation**
  - NADH is oxidized to NAD$^+$ when pyruvate is reduced to lactate
  - In a sense, pyruvate is serving as an “electron sink,” a place to dispose of the electrons generated by oxidation reactions in glycolysis
Glucose

GLYCOLYSIS

2 ADP + 2 P → 2 ATP

2 ATP → 2 NADH

2 NADH → 2 Lactate

Lactic acid fermentation
6.13 Fermentation enables cells to produce ATP without oxygen

The baking and winemaking industry have used **alcohol fermentation** for thousands of years

- Yeasts are single-celled fungi that not only can use respiration for energy but can ferment under anaerobic conditions
- They convert pyruvate to CO$_2$ and ethanol while oxidizing NADH back to NAD$^+$
Glucose $\rightarrow$ 2 ADP + 2 P $\rightarrow$ 2 ATP

2 ATP $\rightarrow$ 2 NAD$^+$

2 Pyruvate $\rightarrow$ 2 NADH

2 NADH $\rightarrow$ 2 NAD$^+$

2 CO$_2$ released

2 Ethanol

Alcohol fermentation
6.14 EVOLUTION CONNECTION: Glycolysis evolved early in the history of life on Earth

- Glycolysis is the universal energy-harvesting process of living organisms
  - So, all cells can use glycolysis for the energy necessary for viability
  - The fact that glycolysis has such a widespread distribution is good evidence for evolution
INTERCONNECTIONS BETWEEN MOLECULAR BREAKDOWN AND SYNTHESIS
6.15 Cells use many kinds of organic molecules as fuel for cellular respiration

- Although glucose is considered to be the primary source of sugar for respiration and fermentation, there are actually three sources of molecules for generation of ATP
  - Carbohydrates (disaccharides)
  - Proteins (after conversion to amino acids)
  - Fats
Food, such as peanuts

- Proteins
- Fats
- Carbohydrates

- Glucose
- OXIDATIVE PHOSPHORYLATION (Electron Transport and Chemiosmosis)

- CITRIC ACID CYCLE
- Acetyl CoA

- Glycerol
- Fatty acids
- Amino acids

- Sugars

- Glycolysis
  - Glucose → G3P → Pyruvate

- ATP

- Amino groups
6.16 Food molecules provide raw materials for biosynthesis

- Many metabolic pathways are involved in biosynthesis of biological molecules
  - To survive, cells must be able to biosynthesize molecules that are not present in its foods
  - Often the cell will convert the intermediate compounds of glycolysis and the citric acid cycle to molecules not found in food
Cells, tissues, organisms

Proteins

Amino acids

Glycerol

Sugars

Fats

Carbohydrates

Cells, tissues, organisms

ATP needed to drive biosynthesis

CITRIC ACID CYCLE

Acetyl CoA

GLUCOSE SYNTHESIS

Pyruvate → G3P → Glucose

Amino acids

Fatty acids

G3P

ATP
Cytoplasm

Glycolysis

Glucose → Pyruvate

NADH

Mitochondrion

NADH and FADH$_2$

Oxidative phosphorylation (Electron Transport and Chemiosmosis)

Citric acid cycle

CO$_2$

ATP

CO$_2$

ATP

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Cellular respiration

- Generates ATP
- Has three stages
- Oxidizes glucose and organic fuels
- Uses

(a) produces some
(b) produces many
(c) uses H^+ for energy for cellular work
(d) uses to pull electrons down
(e) uses to produce H^+ gradient
(f) uses to oxidize C_6H_{12}O_6

Chemiosmosis

- H^+ diffuse through ATP synthase
- Produces ATP

Energy for cellular work

H^+ gradient
The diagrams illustrate changes in color intensity over time.

- **Diagram a**: Color intensity increases with time, represented by three lines with slopes of 0.1, 0.2, and 0.3.

- **Diagram b**: Color intensity decreases with time, represented by three lines with slopes of 0.1, 0.2, and 0.3.

- **Diagram c**: Color intensity decreases with time, represented by three lines with slopes of 0.1, 0.2, and 0.3.

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You should now be able to

1. Explain how photosynthesis and cellular respiration are necessary to provide energy that is required to sustain your life

2. Explain why breathing is necessary to support cellular respiration

3. Describe how cellular respiration produces energy that can be stored in ATP

4. Explain why ATP is required for human activities
You should now be able to

5. Describe the process of energy production from movement of electrons

6. List and describe the three main stages of cellular respiration

7. Describe the major steps of glycolysis and explain why glycolysis is considered to be a metabolic pathway

8. Explain how pyruvate is altered to enter the citric acid cycle and why coenzymes are important to the process
You should now be able to

9. Describe the citric acid cycle as a metabolic pathway designed for generating additional energy from glucose

10. Discuss the importance of oxidative phosphorylation in producing ATP

11. Describe useful applications of poisons that interrupt critical steps in cellular respiration

12. Review the steps in oxidation of a glucose molecule aerobically
You should now be able to

13. Compare respiration and fermentation

14. Provide evidence that glycolysis evolved early in the history of life on Earth

15. Provide criteria that a molecule must possess to be considered a fuel for cellular respiration

16. Discuss the mechanisms that cells use to biosynthesize cell components from food