# Chapter 7: How Cells Harvest Energy

## Essential Knowledge

| | | |
|---|---|---|
| **1.B.1** | Organisms share many conserved core processes and features that evolved and are widely distributed among organisms today. **(7.1)** | **Big Idea 1** |
| **1.D.2** | Scientific evidence from many different disciplines supports models of the origin of life. **(7.10)** | **Big Idea 1** |
| **2.A.1** | All living systems require constant input of free energy. **(7.1, 7.2, 7.4)** | **Big Idea 2** |
| **2.A.2** | Organisms capture and store free energy for use in biological processes. **(7.2, 7.3, 7.4, 7.5, 7.8, 7.9)** | **Big Idea 2** |
| **4.A.2** | The structure and function of subcellular components, and their interactions, provide essential cellular processes. **(7.5)** | **Big Idea 4** |
| **4.B.1** | Interactions between molecules affect their structure and function. **(7.7)** | **Big Idea 4** |

## Chapter Overview

Cells harvest energy through cellular respiration. Cellular respiration is a universal process, in which chemical bonds of organic molecules, such as glucose, are broken down through a series of redox reactions into carbon dioxide, water, and ATP. Cellular respiration can be aerobic or anaerobic, and can be described through a series of metabolic reactions.

## 7.1 Overview of Respiration

### Recall It

The role of respiration is to provide energy to the cell. Cellular respiration occurs aerobically (with oxygen) and anaerobically (without oxygen). Electron carriers play a critical role in cellular respiration, carrying energy throughout the system. The electron transport chain in the mitochondria of eukaryotic cells is used to move electrons in order to capture energy efficiently. The ultimate goal of cellular respiration is synthesis of ATP. ATP is then used to power most of the cell's activities. Cells can make ATP through two different mechanisms: (1) Substrate-level phosphorylation, in which phosphate is directly transferred to ADP, and (2) oxidative phosphorylation which generates ATP via the enzyme ATP synthase.

**Essential Knowledge covered**

*1.B.1: Organisms share many conserved core processes and features that evolved and are widely distributed among organisms today.*
*2.A.1: All living systems require constant input of free energy.*
*2.A.2: Organisms capture and store free energy for use in biological processes.*

### Review It

Write the chemical equation for cellular respiration. Identify which molecules are oxidized and which are reduced.

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## 7.1 Overview of Respiration continued

List three types of electron carriers and how they transport electrons.

Name two charged particles $NAD^+$ can carry.

### Use It

Why does respiration occur in steps and not all at once?

How does ATP synthase catalyze the following reaction?

$ADP + P_i \rightarrow ATP$

## 7.2 Glycolysis: Splitting Glucose

### Recall It

Glycolysis is the stage in cellular respiration where glucose is converted into two pyruvate molecules, producing two molecules of ATP and NADH in the process. Glycolysis occurs in a series of reactions. The first five reactions require ATP to convert a molecule of glucose into two molecules of glyceraldehyde 3-phosphate (G3P). The second set of reactions covert G3P into pyruvate through the oxidation of G3P, reducing $NAD^+$ to NADH. In the presence of oxygen, $NAD^+$ is regenerated in the electron transport chain. A fermentation reaction is required in the absence of oxygen to regenerate $NAD^+$ through the reduction of pyruvate. Pyruvate is used in aerobic respiration to produce acetyl groups, which are needed to produce ATP in the Krebs cycle.

**Essential Knowledge covered**

*2.A.1: All living systems require constant input of free energy.*
*2.A.2: Organisms capture and store free energy for use in biological processes.*

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## Review It

Determine the number of molecules produced during the process of glycolysis:

ATP

Pyruvate

NADH

Circle the reaction that occurs in the absence of oxygen.

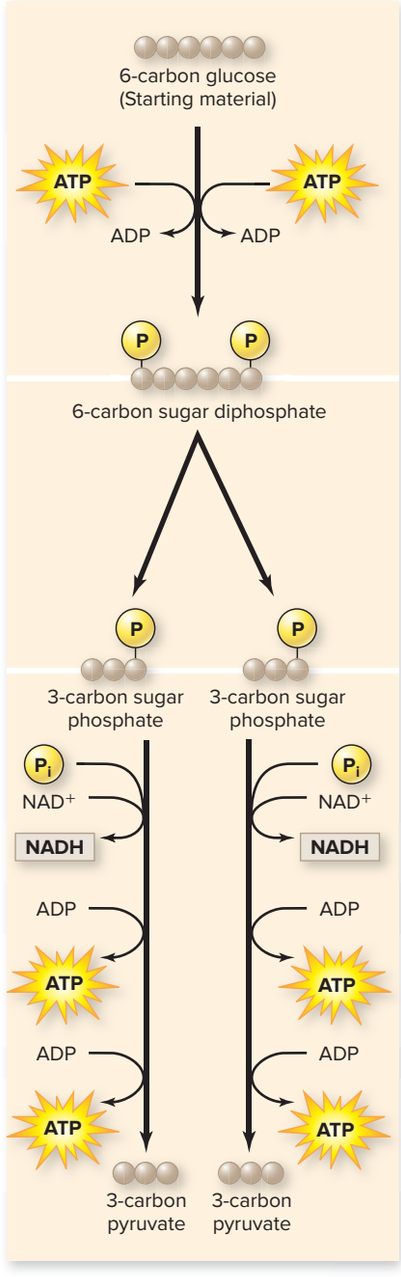
Aerobic respiration Fermentation

Describe the location of where glycolysis occurs in the cell.

## Use It

Substrate-level ATP synthesis occurs in the later steps of glycolysis. Draw a picture of how an enzyme might transfer phosphate to ADP to form ATP. Be sure to label the enzyme and molecules.

Glycolysis occurs in a series of reactions, as shown on the right. Take a look now at the series of different reactions. Consider the inputs and outputs of the different reactions. Which reaction do you think evolved first based on your knowledge of biochemical pathways?




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## 7.3 The Oxidation of Pyruvate to Produce Acetyl-CoA

### Recall It

The pyruvate produced by glycolysis can be further oxidized in the presence of oxygen. Pyruvate is oxidized in the mitochondria, where it yields one molecule of $CO_2$, one NADH, and one acetyl-CoA. Acetyl-CoA feeds acetyl groups into the Krebs cycle.

**Essential Knowledge covered**

*2.A.2: Organisms capture and store free energy for use in biological processes.*

### Review It

Fill in the blanks to complete the oxidation of pyruvate.

Pyruvate + _____ + CoA → _____ + NADH + ____ + $H^+$

Define multienzyme complex.

### Use It

How does the oxidation of pyruvate link glycolysis and the Krebs cycle?

## 7.4 The Krebs Cycle

### Recall It

The Krebs cycle extracts electrons and synthesizes one ATP in a series of nine reactions. The first reaction is an irreversible condensation that produces citrate; it is inhibited when ATP is plentiful. The second and third steps reposition the hydroxyl group on the citrate to allow for subsequent reactions. The fourth and fifth steps are oxidations, both of which reduce $NAD^+$ to NADH. The sixth reaction is a substrate-level phosphorylation producing GTP, and from that ATP. The seventh reaction is another oxidation that reduces FAD to $FADH_2$. Reactions eight and nine regenerate oxaloacetate, including one final oxidation that reduces $NAD^+$ to NADH. While only one ATP is generated during one cycle, most of the energy is retained in form of the electrons in NADH and $FADH_2$. This energy is used to generate a proton gradient to drive ATP synthesis.

**Essential Knowledge covered**

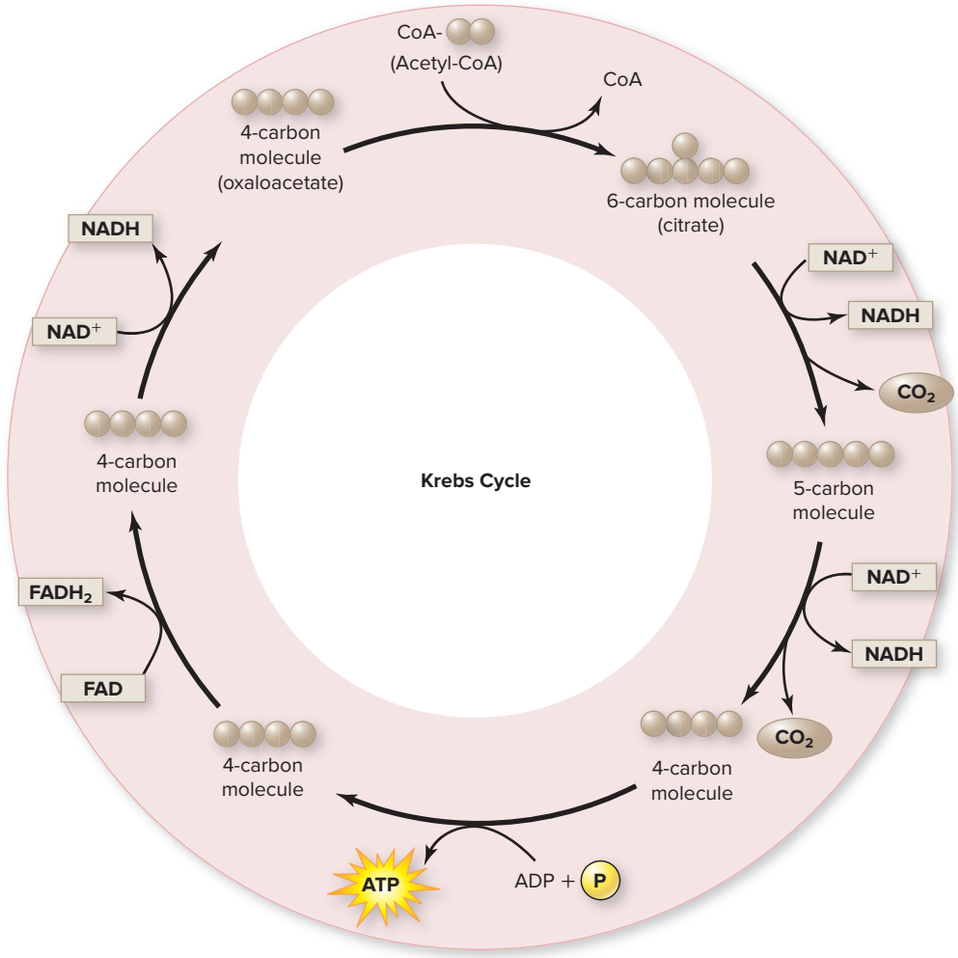
*2.A.1: All living systems require constant input of free energy.*
*2.A.2: Organisms capture and store free energy for use in biological processes.*

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## Review It

Identify the parts in the diagram of the Krebs Cycle with the following symbols:

| | |
|---|---|
| An enzyme | ● |
| ATP synthesis | ♥ |
| $CO_2$ | ▼ |
| Electron carriers | ■ |




## Use It

Through cellular respiration, glucose is broken down and turned into energy. Identify the energy produced in the Krebs cycle.

Underline any FALSE statements regarding the Krebs cycle.

A. Carbon dioxide is consumed during the Krebs Cycle.

B. The sixth reaction of the Krebs Cycle is optional.

C. There are many enzymes that make the Krebs Cycle possible.

D. The Krebs cycle reactions take place in the mitochondrial matrix.

How and where is ATP formed during the Krebs Cycle?

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## 7.5 The Electron Transport Chain and Chemiosmosis

### Recall It

The electron transport chain (ETC) is a series of membrane-associated proteins. Electrons carried by NADH and $FADH_2$ from the Krebs Cycle are transferred along these proteins toward the terminal electron receptor, oxygen. The energy released from the electron transfer allows for protons to be pumped into the intermembrane space. This creates an electrochemical gradient. Here, the process known as chemiosmosis occurs; protons move back across the membrane, down their concentration gradient, powering the enzyme ATP synthase to phosphorylate ADP into ATP.

**Essential Knowledge covered**

*2.A.2: Organisms capture and store free energy for use in biological processes.*
*4.A.2: The structure and function of subcellular components, and their interactions, provide essential cellular processes.*

### Review It

Name the following enzymes found in the electron transport chain.

| Enzyme | Description |
|---|---|
| | Produces ATP from ADP and $P_i$ |
| | Oxidizes NADH to $NAD^+$ |

Identify if the following happens on the side of the mitochondrial matrix **(MM)**, the inner mitochondrial membrane **(IM)**, or the intermembrane space **(IS)**:

ATP synthase creates ATP.

Protons form a high concentration gradient.

$FADH_2$ contributes an electron to the electron transport chain.

NADH contributes an electron to the electron transport chain.

Water is formed.

### Use It

There are many electron carries in the electron transport chain. What is the terminal acceptor in aerobic systems?

Can ATP synthase work without a proton gradient? Why or why not?

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## 7.6 Energy Yield of Aerobic Respiration

### Recall It

The theoretical yield of ATP harvested from glucose by aerobic respiration is 32 molecules of ATP. This number is reduced to 30 in eukaryotes due to the cost of NADH transport into the mitochondria.

### Review It

The formation of 30 to 32 ATP molecules are theoretically possible when glucose is broken down completely. How many ATP are produced during glycolysis?

If a bacterial completely broke down 3 molecules of glucose, what would be the prokaryote's the theoretical yield of ATP?

If a human cell broke these three glucose molecules, would it produce more or less ATP than the bacterial cell?

## 7.7 Regulation of Aerobic Respiration

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### Recall It

Glucose catabolism is controlled by the concentration of ATP molecules. When levels of ATP are high, key reactions of cellular respiration are inhibited. In this way, ATP is an allosteric inhibitor. When ATP levels are low, ADP activates enzymes in the pathway to being producing more ATP.

**Essential Knowledge covered**

*4.B.1: Interactions between molecules affect their structure and function.*

### Review It

List the two key points along the biochemical pathway of cellular respiration where the reaction can be inhibited

## 7.7 Regulation of Aerobic Respiration continued

### Use It

How are levels of ATP in the biochemical pathway for in glucose metabolism an example of feedback inhibition?

## 7.8 Oxidation Without $O_2$

### Recall It

Some organisms live in areas that lack oxygen. These organisms can still respire anaerobically, using inorganic molecules as final electron acceptors in place of oxygen in the electron transport chain. Other organisms use fermentation which uses organic compounds as electron acceptors. Fermentation is the regeneration of $NAD^+$ by oxidation of NADH and reduction of an organic molecule. Unlike in animals where pyruvate is reduced directly to lactate and stored in the muscles, in yeast pyruvate is decarboxylated, then reduced to ethanol.

**Essential Knowledge covered**

*2.A.2: Organisms capture and store free energy for use in biological processes.*

### Review It

Provide the final electron acceptor in respiration for following organisms:

| Organism | Electron acceptor |
|---|---|
| Yeast | |
| Methanogens | |
| Sulfur bacteria | |

Name two types of fermentation that eukaryotic cells are capable of performing.

### Use It

Lactic acid fermentation and ethanol fermentation both reduce a metabolite of glucose, oxidizing NADH back to $NAD^+$. How are the end products of these two reactions similar and how are they different?

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## 7.9 Catabolism of Proteins and Fats

### Recall It

Proteins and fats are important sources of energy. The catabolism of proteins breaks down amino acids and then removes amino groups. The catabolism of fatty acids occurs through conversion of fatty acids into acetyl groups through successive oxidations. These acetyl groups are then fed into the Krebs cycle to be oxidized and generate NADH for electron transport and ATP production.

**Essential Knowledge covered**

*2.A.2: Organisms capture and store free energy for use in biological processes.*

### Review It

Name two processes which receive energy from protein catabolism.

List two key intermediates which connect the oxidation of food molecules to metabolism.

### Use It

Describe the macromolecules you could metabolize from eating a slice of pizza with peppers, onions, and sausage.

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## 7.10 Evolution of Metabolism

### Recall It

The stages of metabolism evolved over time. The most primitive life forms probably obtained carbon containing molecules that were abiotically produced, then began storing this energy in the bonds of ATP. Glycolysis most likely followed shortly after. The third major event in the evolution of metabolism was anoxygenic photosynthesis, followed by oxygen-forming photosynthesis. This paved the way for nitrogen fixation and aerobic respiration.

**Essential Knowledge covered**

*1.D.2: Scientific evidence from many different disciplines support models of the origin of life.*

## Review It

Place the following evolutionary events of metabolism in chronological order **(1–6)**:

Anoxygenic photosynthesis

Storage of energy in ATP

Nitrogen fixation

Oxygen-forming photosynthesis

Glycolysis

Aerobic respiration

## Use It

Provide two pieces of evidence that support the idea that aerobic respiration evolved after photosynthesis during evolution of metabolism.

# 7 Chapter Review

## Summarize It

1. How does glycolysis support the concept of common ancestry for all organisms?

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2. Earth's atmosphere is now 20.9% oxygen. Did Earth's atmosphere always contain this much oxygen? What data is available to us to answer this question?

3. A sample of bacteria was taken from a sulfur-containing hot spring and spread on a petri dish rich with glucose to grow in the lab. The bacteria died. Why was this bacteria unable to survive?

4. A scientist was studying an organism that had inadequate ATP output during metabolism and isolated the issue to the electron transport chain. What question might the scientist pose to determine where in the electron transport chain was defective?

5. Cyanide is a poisonous substance because it can bind to cytochrome, one of the membrane proteins found in the electron transport chain. Why would this be dangerous?

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