

Cellular Energy



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إعداد: Basim Alrahman Abd

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Complex Inheritance and Human Heredity Revision Paper Solution

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CHAPTER 7

CELLULAR ENERGY



CHAPTER SUMMARY

by Abd Alrahman Basim

SECTION 1:
HOW ORGANISMS OBTAIN ENERGY

SECTION 2:
PHOTOSYNTHESIS

SECTION 3:
CELLULAR RESPIRATION



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HOW ORGANISMS OBTAIN ENERGY

Transformation of Energy

Many chemical reactions and processes in your cells are ongoing, even when you might not think that you are using any energy.

- Macromolecules are assembled and broken down,
- substances are transported across cell membranes,
- and genetic instructions are transmitted.

All of these cellular activities require **energy**—the ability to do work.

Laws of Thermodynamics

Thermodynamics is the study of the flow and transformation of energy in the universe.

- The **first law of thermodynamics** is the **law of conservation of energy**, which states that energy can be converted from one form to another, but it cannot be created nor destroyed.

For example, the stored energy in food is converted to chemical energy when you eat and to mechanical energy when you run or kick a ball.

- The **second law of thermodynamics** states that energy cannot be converted without the loss of usable energy. The energy that is “lost” is generally converted to thermal energy.

Entropy is the measure of disorder, or unusable energy, in a system. Therefore, the second law of thermodynamics can also be stated as “**entropy increases**”.

One example of the second law of thermodynamics is evident in food chains. Recall that in a food chain, the amount of usable energy that is available to the next trophic level decreases.

Autotrophs and Heterotrophs

Directly or indirectly, nearly all the energy for life comes from the **Sun**. Some organisms **make** their own food, while others must **obtain** it from other organisms.

HOW ORGANISMS OBTAIN ENERGY

- **Autotrophs:** are organisms that make their own food.

Some autotrophs, called **chemoautotrophs**, use **inorganic** substances such as **hydrogen sulfide** as a source of energy.

Other autotrophs **convert** light energy from the Sun into chemical energy. **Autotrophs that convert energy from the Sun are called photoautotrophs.**

- **Heterotrophs** are organisms that need to ingest food to obtain energy.

Metabolism

All of the chemical reactions in a cell are referred to as the cell's **metabolism**.

A series of chemical reactions in which the product of one reaction is the substrate for the next reaction is called a **metabolic pathway**.

Metabolic pathways include **two** broad types:

- **Catabolic Pathways**

Release energy by breaking down larger molecules into smaller molecules.

- **Anabolic Pathways**

Use the energy released by catabolic pathways to build larger molecules from smaller molecules.

The relationship of anabolic and catabolic pathways results in the continual **flow** of energy within an organism. Energy continually flows between the metabolic reactions of organisms in an ecosystem.

Photosynthesis is the anabolic pathway in which light energy from the Sun is converted to chemical energy for use by the cell. In this reaction, **autotrophs** use:

- light energy,
- carbon dioxide,
- and water

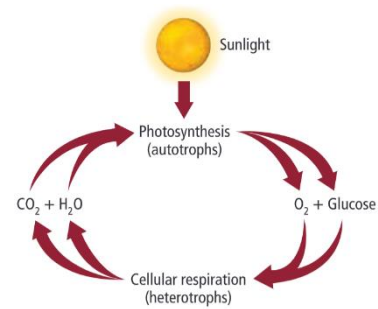
to form **glucose** and **oxygen**.

The energy stored in the **glucose** produced by photosynthesis can be transferred to other organisms when the molecules are consumed as food.

HOW ORGANISMS OBTAIN ENERGY

Cellular respiration is the catabolic pathway in which organic molecules are broken down to release energy for use by a cell. In cellular respiration, **oxygen** is used to break down organic molecules, resulting in the production of **carbon dioxide** and **water**.

Notice the **cyclical nature** of these processes in this figure, where the products of one reaction are the reactants for the other reaction.



ATP: The Unit of Cellular Energy

Energy exists in many forms, including:

- light energy,
- mechanical energy,
- thermal energy,
- and chemical energy.

In living organisms, **chemical energy** is stored in biological molecules and can be converted to other forms of energy when needed.

For example, the chemical energy in biological molecules is converted to mechanical energy when muscles contract.

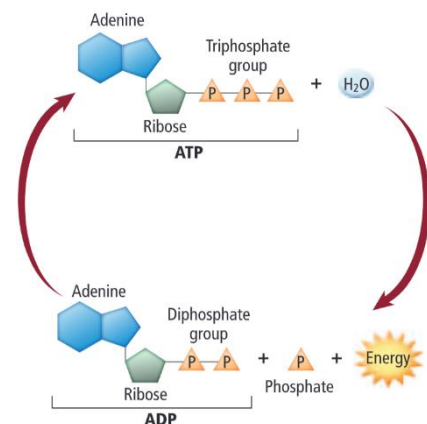
Adenosine triphosphate (ATP) is the most important biological molecule that provides chemical energy.

ATP Structure

ATP is a multipurpose storehouse of **chemical energy** that can be used by cells in a variety of reactions. Although other carrier molecules transport energy within cells, ATP is the **most** abundant energy-carrier molecule in cells and is found in all types of organisms.

As shown in the figure, ATP is a nucleotide made of:

- an **adenine base**,
- a **ribose sugar**,
- and **three phosphate groups**.



HOW ORGANISMS OBTAIN ENERGY

ATP Function

ATP releases energy when the bond between the **second** and **third** phosphate groups is **broken**, forming a molecule called **adenosine diphosphate (ADP)** and a free phosphate group, as shown in the figure above.

Energy is stored in the **phosphate bond** formed when ADP receives a phosphate group and becomes ATP. As shown in the figure above, ATP and ADP can be interchanged by the addition or removal of a phosphate group.

Sometimes **ADP** becomes **adenosine monophosphate (AMP)** by losing an additional phosphate group. There is less energy released in this reaction, so most of the energy reactions in the cell involve ATP and ADP.



PHOTOSYNTHESIS

Overview of Photosynthesis

Photosynthesis is a process in which light energy is converted into chemical energy. Most autotrophs, including plants, make organic compounds, such as sugars, by photosynthesis.

The overall chemical equation for photosynthesis is shown below.

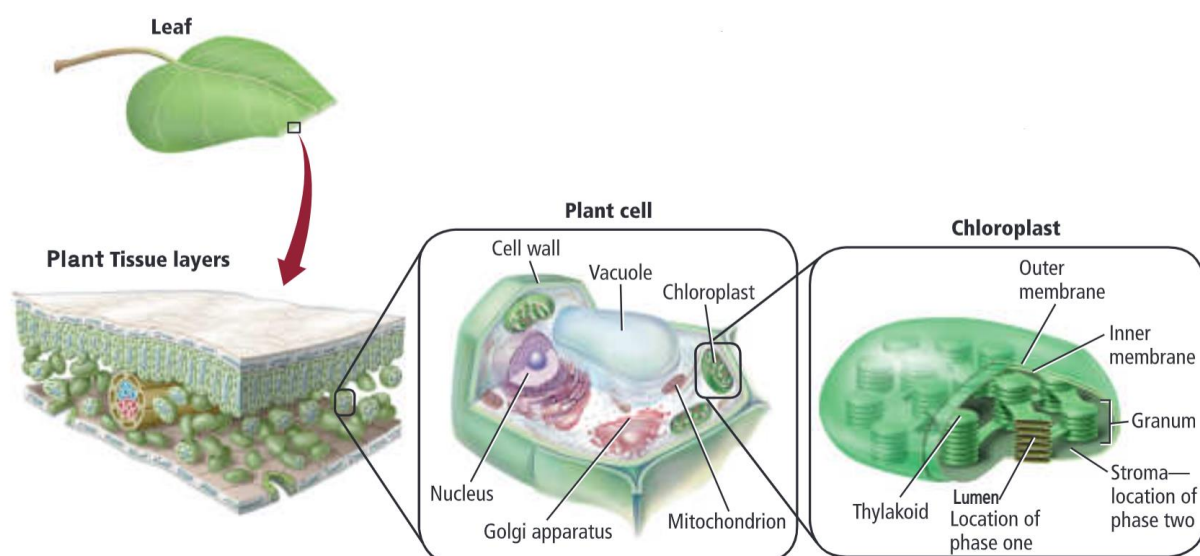


Photosynthesis occurs in **two** phases:

1. In phase **one**, the **light-dependent reactions**, light energy is **absorbed** and then **converted** into chemical energy in the form of **ATP** and **NADPH**.
2. In phase **two**, the **light-independent reactions**, the ATP and NADPH that were formed in phase one are used to make **glucose**.

Once glucose is produced, it can be joined to other simple sugars to form larger molecules. These larger molecules are **complex carbohydrates**, such as **starch**.

Recall that carbohydrates are composed of **repeating** units of small organic molecules. The end products of photosynthesis also can be used to make other organic molecules, such as **proteins**, **lipids**, and **nucleic acids**.



PHOTOSYNTHESIS

Phase One: Light Reactions

The absorption of light is the **first** step in photosynthesis. Plants have special organelles to capture light energy. Once the energy is captured, two energy storage molecules, **NADPH** and **ATP**, are produced to be used in the light-independent reactions.

Chloroplasts

Chloroplasts are large organelles that capture light energy in photosynthetic organisms. In plants, chloroplasts are found mainly in the cells of leaves.

Chloroplasts are **disk-shaped** organelles that contain two main compartments essential to photosynthesis:

- The **first** compartment is called the thylakoid. **Thylakoids** are flattened, saclike membranes that are arranged in stacks. These stacks are called **grana** (*singular, granum*).

Light-dependent reactions take place within the thylakoids.

- The **second** important compartment is called the **stroma**, the fluid-filled space that is outside the grana. This is the location of the light-independent reactions in phase two of photosynthesis.

Pigments

Light-absorbing colored molecules called **pigments** are found in the thylakoid membranes of chloroplasts. Different pigments absorb specific wavelengths of light.

The major light-absorbing pigments in plants are **chlorophylls**. There are several types of chlorophylls, but the most common two are **chlorophyll a** and **chlorophyll b**.

The structure of chlorophyll can differ from one molecule to another, enabling distinct chlorophyll molecules to absorb light at unique areas of the visible spectrum.

In general, chlorophylls absorb most strongly in the **violet-blue** region of the visible light spectrum and reflect light in the green region of the spectrum. This is why plant parts that contain chlorophyll appear green to the human eye.

In addition to chlorophylls, most **photosynthetic** organisms contain **accessory pigments** that allow plants to trap additional light energy from other areas of the visible spectrum.

PHOTOSYNTHESIS

One such group of accessory pigments is the **carotenoids**. Carotenoids, such as β -carotene (*beta-carotene*), absorb light mainly in the **blue** and **green** regions of the spectrum, while reflecting most light in the **yellow**, **orange**, and **red** regions. Carotenoids produce the colors of **carrots** and **sweet potatoes**.

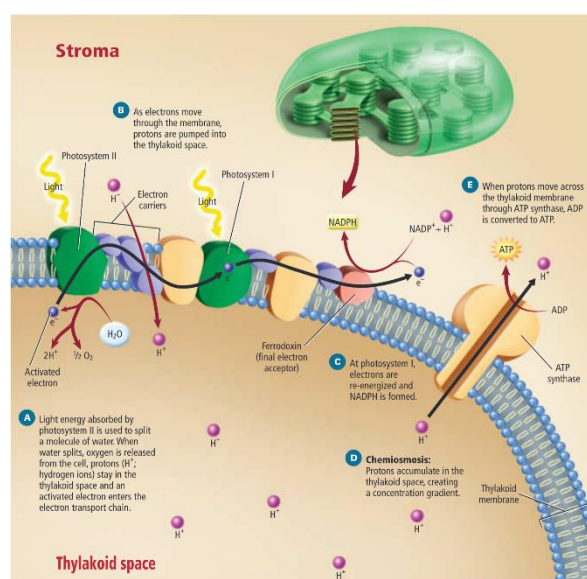
Chlorophylls are more **abundant** than other pigments in leaves, and thus **hide** the colors of the other pigments. However, autumn in certain parts of the United States can bring out shades of yellow, red, and orange as the leaves turn colors.

As trees prepare to **lose** their leaves before winter, the chlorophyll molecules **break down**, revealing the colors of the other pigments.

Electron Transport

The structure of the thylakoid membrane is the key to efficient energy transfer during electron transport. Thylakoid membranes have a **large surface area**, which provides the space needed to hold large numbers of electron-transporting molecules and **two** types of protein complexes called **photosystems**. **Photosystem I** and **photosystem II** contain light-absorbing pigments and proteins that play important roles in the light reactions. Follow along in the figure as you continue to read about electron transport.

- **First**, the light energy **excites** electrons in photosystem II. The light energy also causes a water molecule to **split**, releasing an **electron** into the electron transport system, a **hydrogen ion (H^+)**—also called a *proton*—into the thylakoid space, and **oxygen (O_2)** as a waste product. This breakdown of water is essential for photosynthesis to occur.
- **Second**, the excited electrons move from photosystem II to an electron-acceptor molecule in the thylakoid membrane.
- **Third**, the electron-acceptor molecule transfers the electrons along a series of electron-carriers to photosystem I.
- **Fourth**, in the presence of light, photosystem I transfers the electrons to a protein called **ferredoxin**. The electrons lost by photosystem I are replaced by electrons shuttled from photosystem II.
- **Finally**, ferredoxin transfers the electrons to the electron carrier **$NADP^+$** , forming the energy-storage molecule **$NADPH$** .



PHOTOSYNTHESIS

Chemiosmosis

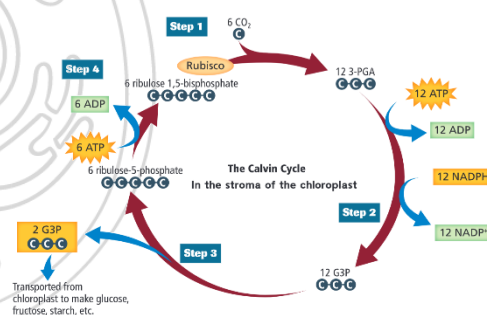
ATP is produced in conjunction with electron transport by the process of **chemiosmosis**—the mechanism by which ATP is produced as a result of the flow of electrons down a concentration gradient. The breakdown of water is **essential** not only for providing the electrons that initiate the electron transport chain, but also for providing the **protons (H^+)** necessary to drive ATP synthesis during chemiosmosis.

The H^+ released during electron transport accumulate in the interior of the thylakoid. As a result of a **high** concentration of H^+ in the **thylakoid** interior and a **low** concentration of H^+ in the **stroma**, H^+ protons **diffuse** down their concentration gradient out of the thylakoid interior into the stroma through ion channels spanning the membrane, as shown in the figure above. These channels are **enzymes** called **ATP synthases**. As H^+ moves through ATP synthases, ATP is formed in the stroma.

Phase Two: The Calvin Cycle

Although NADPH and ATP provide cells with large amounts of energy, these molecules are **not** stable enough to store chemical energy for **long** periods of time.

Thus, there is a **second** phase of photosynthesis called the **Calvin cycle**, in which energy is stored in organic molecules such as glucose. The reactions of the Calvin cycle are also referred to as the **light-independent reactions**. Follow along in the figure as you learn the steps of the Calvin cycle.



1. In the **first** step of the Calvin cycle, called **carbon fixation**, **six** carbon dioxide (CO_2) molecules combine with **six** 5-carbon compounds to form **twelve** 3-carbon molecules called **3-phosphoglycerate (3-PGA)**.
The joining of carbon dioxide with other organic molecules is called **carbon fixation**.
2. In the **second** step, the chemical energy stored in **ATP** and **NADPH** is **transferred** to the **3-PGA molecules** to form high-energy molecules called **glyceraldehyde 3-phosphates (G3P)**.
ATP supplies the phosphate groups for forming G3P molecules, while NADPH supplies hydrogen ions and electrons.
3. In the **third** step, two G3P molecules leave the cycle to be used for the production of glucose and other organic compounds.
4. In the **final** step of the Calvin cycle, an enzyme called **rubisco** converts the remaining **ten G3P molecules** into 5-carbon molecules called **ribulose 1, 5-bisphosphates (RuBP)**. These molecules combine with new carbon dioxide molecules to continue the cycle.

PHOTOSYNTHESIS

Because rubisco converts **inorganic** carbon dioxide molecules into **organic** molecules that can be used by the cell, it is considered one of the **most** important biological enzymes.

Plants use the sugars formed during the Calvin cycle both as a source of energy and as building blocks for complex carbohydrates, including cellulose, which provides structural support for plants.

Alternative Pathways

Environments in which the amount of water or carbon dioxide available is insufficient can decrease the ability of a photosynthetic organism to convert light energy into chemical energy. Many plants in extreme climates have alternative photosynthesis pathways to maximize energy conversion.

C₄ Plants

The **C₄ pathway** occurs in plants such as **sugarcane** and **corn**. These plants are called C₄ plants because they fix carbon dioxide into **four-carbon** compounds instead of **three-carbon** molecules during the Calvin cycle.

C₄ plants also have significant structural modifications in the arrangement of cells in the leaves. In general, C₄ plants keep their **stomata** (*plant cell pores*) **closed** during hot days, while the four carbon compounds are transferred to special cells where CO₂ enters the Calvin cycle. This allows for sufficient carbon dioxide uptake, while simultaneously minimizing water loss.

CAM Plants

The **crassulacean acid metabolism** (*CAM photosynthesis*) pathway occurs in **water-conserving** plants that live in **deserts**, **salt marshes**, and other environments where access to water is **limited**.

CAM plants, such as **cacti**, **orchids**, and **pineapple**, allow carbon dioxide to enter the leaves **only** at **night**, when the atmosphere is cooler and more humid. At night, these plants fix carbon dioxide into organic compounds.

During the day, carbon dioxide is released from these compounds and enters the Calvin cycle. This pathway also allows for sufficient carbon dioxide uptake while minimizing water loss.

CELLULAR RESPIRATION

Overview of Cellular Respiration

Living organisms obtain energy by breaking down organic molecules during **cellular respiration**.

The function of cellular respiration is to harvest **electrons** from **carbon** compounds, such as glucose, and use that energy to make **ATP**. ATP is used to provide energy for cells to do work.

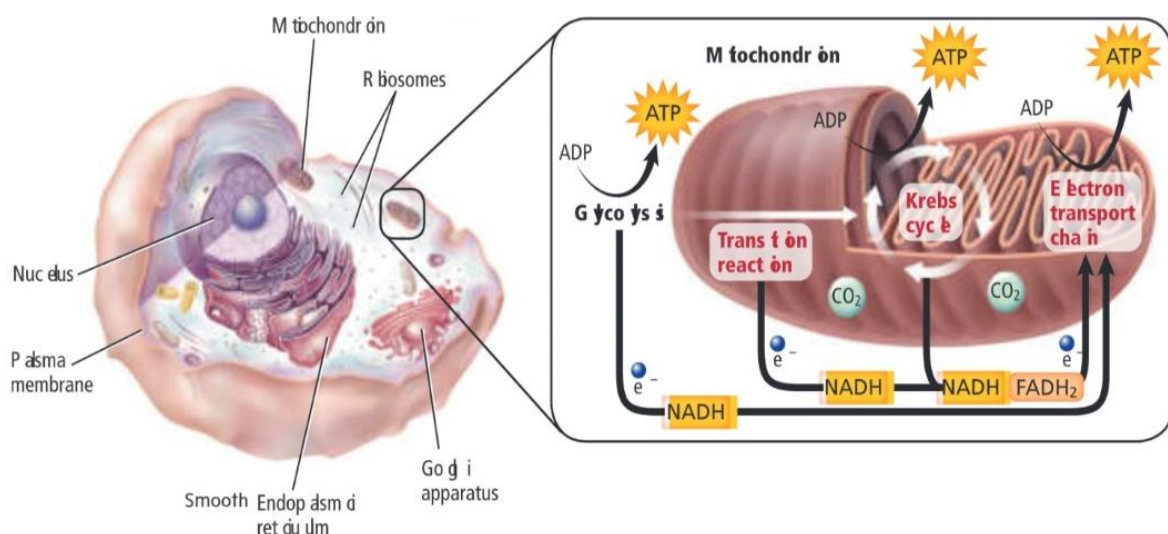
Notice that the equation for cellular respiration is the opposite of the equation for photosynthesis.



Cellular respiration occurs in **two** main parts:

1. The **first** stage, **glycolysis**, is an anaerobic process. **Anaerobic processes do not require oxygen.**
2. **Aerobic respiration** includes the Krebs cycle and electron transport and is an aerobic process. **Aerobic processes require oxygen.**

Cellular respiration with aerobic respiration is summarized in the figure below.

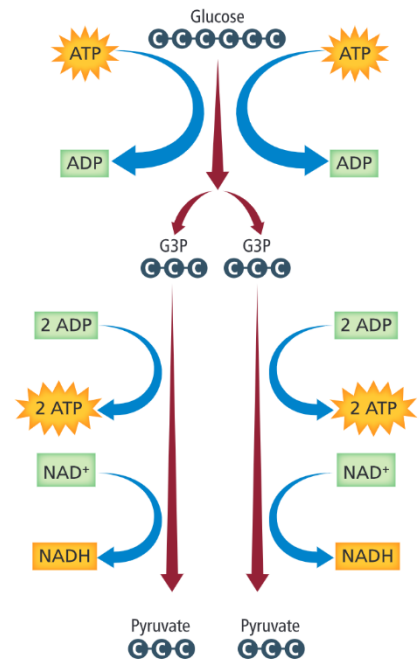


CELLULAR RESPIRATION

Glycolysis

Glucose is broken down in the cytoplasm through the process of **glycolysis**. **Two** molecules of **ATP** and **two** molecules of **NADH** are formed for each molecule of glucose that is broken down. Follow along with the figure as you read about the steps of glycolysis.

- **First**, two phosphate groups, derived from two molecules of ATP, are joined to glucose. Notice that some energy, two ATP, is required to start the reactions that will produce energy for the cell.
- **Then**, the 6-carbon molecule is broken down into two 3-carbon compounds.
- **Next**, two phosphates are added, and electrons and hydrogen ions (H^+) combine with two NAD^+ molecules to form two NADH molecules. NAD^+ is similar to NADP, an electron carrier used during photosynthesis.
- **Last**, the two 3-carbon compounds are converted into two molecules of **pyruvate**. At the same time, four molecules of ATP are produced.



Krebs Cycle

Glycolysis has a net result of **two** ATP and **two** pyruvate molecules. Most of the energy from the glucose is still contained in the pyruvate. In the presence of oxygen, pyruvate is transported into the **mitochondrial matrix**, where it is eventually converted to **carbon dioxide**.

The series of reactions in which pyruvate is broken down into carbon dioxide is called the **Krebs cycle**, or the **tricarboxylic acid (TCA) cycle**. This cycle also is referred to as the **citric acid cycle**.

Steps of the Krebs cycle

Prior to the Krebs cycle, pyruvate first reacts with **coenzyme A (CoA)** to form a 2-carbon intermediate called **acetyl CoA**. At the same time, carbon dioxide is released and NAD^+ is converted to **NADH**. Acetyl CoA then moves to the mitochondrial matrix.

CELLULAR RESPIRATION

The reaction results in:

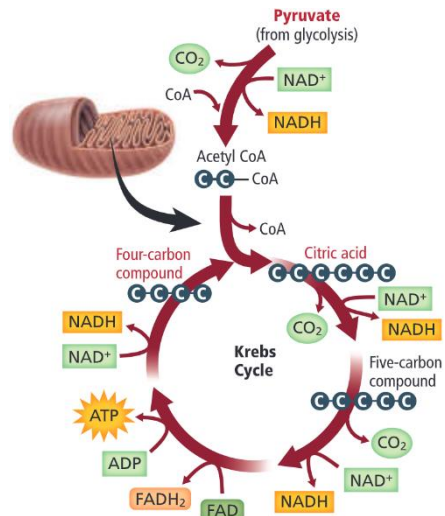
- the production of two carbon dioxide molecules
- and two NADH molecules.

Follow along in the figure as you continue reading about the steps of the Krebs cycle.

1. The Krebs cycle begins with **acetyl CoA** combining with a **4-carbon compound** to form a **6-carbon compound** known as **citric acid**.
2. Citric acid is then broken down in the next series of steps, releasing:
 - **two** molecules of **carbon dioxide**
 - and generating **one ATP**,
 - **three NADH**,
 - and **one FADH₂**.

FAD is another electron carrier similar to **NAD⁺** and **NADP⁺**.

3. Finally, acetyl CoA and citric acid are generated and the cycle continues.



Recall that **two** molecules of **pyruvate** are formed during glycolysis, resulting in two “turns” of the Krebs cycle for each glucose molecule. The net yield from the Krebs cycle is:

- six carbon dioxide molecules,
- two ATP,
- eight NADH,
- and two FADH₂.

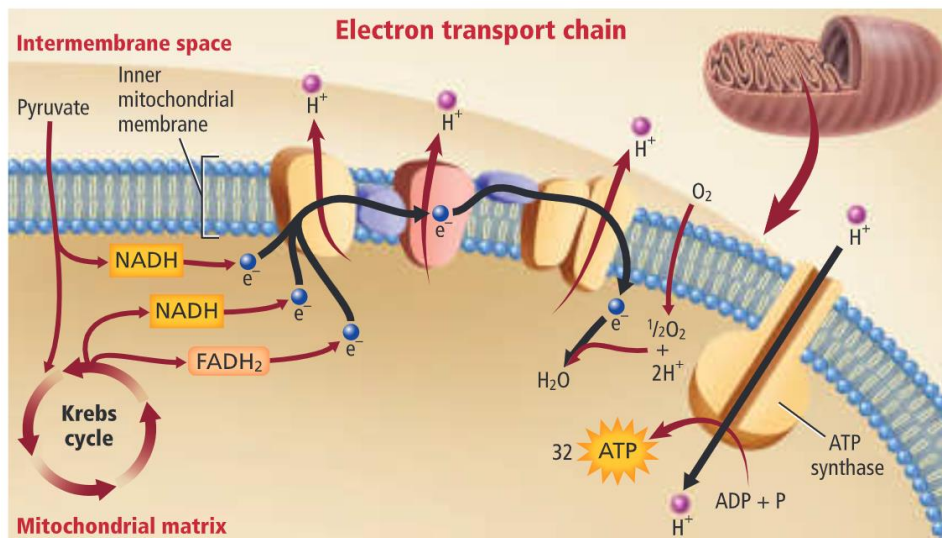
Ten NADH and two FADH₂ move on to play a significant role in the next stage of aerobic respiration.

Electron Transport

In aerobic respiration, electron transport is the **final** step in the break-down of glucose. It also is the point at which most of the ATP is produced.

High-energy electrons and hydrogen ions from **NADH** and **FADH₂** produced in the Krebs cycle are used to convert **ADP** to **ATP**.

CELLULAR RESPIRATION



As shown in the figure, electrons move along the **mitochondrial membrane** from one protein to another. As **NADH** and **FADH₂** release electrons, the energy carriers are converted to **NAD⁺** and **FAD**, and **H⁺** ions are released into the mitochondrial matrix.

The **H⁺** ions are pumped into the mitochondrial matrix across the inner mitochondrial membrane. **H⁺** ions then **diffuse** down their concentration gradient back across the membrane and into the matrix through **ATP synthase** molecules in chemiosmosis.

Electron transport and **chemiosmosis** in cellular respiration are similar to these processes in photosynthesis. **Oxygen** is the **final** electron acceptor in the electron transport system in cellular respiration.

Protons and **electrons** are transferred to oxygen to form **water**. Overall, electron transport produces **32 ATP**. Each **NADH** molecule produces **three ATP** and each group of **three FADH₂** produces **two ATP**.

In **eukaryotic cells**, one molecule of glucose yields **36 ATP** under ideal conditions. pyruvate is transported to the mitochondria.

Some **prokaryotes** also undergo aerobic respiration. Because prokaryotes do **not** have mitochondria, there are differences in the process.

The main difference involves the use of the **prokaryotic cellular membrane** as the location of electron transport. In prokaryotes, this movement is unnecessary, saving the prokaryotic cell **two ATP**, and increasing the **net total of ATP produced** to **38 ATP**.

CELLULAR RESPIRATION

Anaerobic Respiration

Some cells can function for a short time when oxygen levels are low. Some prokaryotes are **anaerobic organisms**—they grow and reproduce without oxygen.

In some cases, these cells continue to produce ATP through glycolysis. However, there are problems with solely relying on glycolysis for energy. Glycolysis provides only two net ATP for each molecule of glucose, and a cell has a limited amount of NAD^+ .

Glycolysis will stop when all the NAD^+ is used up if there is not a process to replenish NAD^+ .

The anaerobic pathway that follows glycolysis is anaerobic respiration, or fermentation. **Fermentation occurs in the cytoplasm and regenerates the cell's supply of NAD^+ while producing a small amount of ATP.** The two main types of fermentation are:

- **Lactic Acid Fermentation**

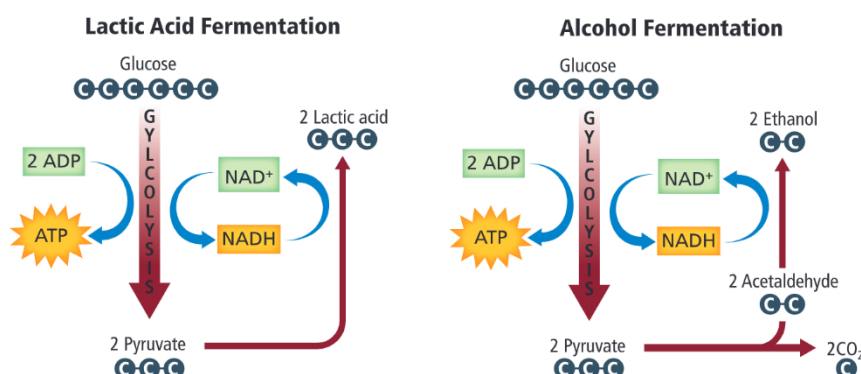
In lactic acid fermentation, enzymes convert the **pyruvate** made during glycolysis to **lactic acid**, as shown in the figure below. This involves the transfer of high-energy electrons and protons from **NADH**.

Skeletal muscles produce lactic acid when the body cannot supply enough oxygen, causing cramps, that occur during periods of strenuous exercise.

When lactic acid builds up in muscle cells, muscles become fatigued and might feel sore. Lactic acid also is produced by several microorganisms that often are used to produce many foods, including cheese, yogurt, and sour cream.

- **Alcohol Fermentation**

Alcohol fermentation occurs in **yeast** and **some bacteria**. The figure below shows the chemical reaction that occurs during alcohol fermentation when **pyruvate** is converted to **ethyl alcohol** and **carbon dioxide**. Similar to lactic acid fermentation, **NADH** donates electrons during this reaction and **NAD^+** is regenerated.



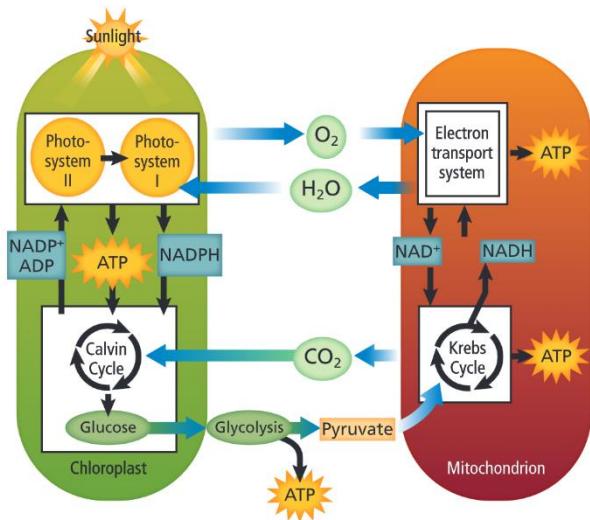
CELLULAR RESPIRATION

Photosynthesis and Cellular Respiration

Photosynthesis and cellular respiration are metabolic pathways that produce and break down simple carbohydrates. The figure below shows how these two processes are related.

Recall that the **products** of photosynthesis are **oxygen** and **glucose**, the reactants needed for cellular respiration.

The **products** of cellular respiration, which are **carbon dioxide** and **water**, are the reactants for photosynthesis.



CHAPTER 7

CELLULAR ENERGY

CHAPTER SUMMARY

Resources

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