Chapter 5

Cellular Respiration

5.1 Lesson 5.1: Powering the Cell: Cellular Respiration and Glycolysis

Lesson Objectives

- Clarify the relationship between breathing and cellular respiration.
- Trace the flow of energy from food molecules through ATP to its use in cellular work.
- Compare cellular respiration to burning.
- Analyze the chemical equation for cellular respiration.
- Briefly describe the role of mitochondria in producing ATP.
- Compare cellular respiration to photosynthesis.
- Show how carbon and oxygen atoms cycle through producers, consumers, and the environment.
- Recognize that glycolysis is the first and most universal of three stages in cellular respiration.
- Explain why biologists consider glycolysis to be one of the oldest energy production pathways.
- Describe how some of the energy in glucose is transferred to ATP in the cytoplasm, without oxygen.

Introduction

You know that humans deprived of oxygen for more than a few minutes will quickly become unconscious and die. Breathing, also known as respiration, is essential for human life, because the body cannot store oxygen for later use as it does food. The mammalian respiratory system, shown in **Figure** 5.1 features a diaphragm, trachea, and a thin membrane whose

surface area is equivalent to the size of a handball court - all for efficient oxygen intake. Other forms of life employ different types of respiratory organs: fish and aquatic amphibians and insects flaunt gills, spiders and scorpions develop "book lungs," and terrestrial insects use an elaborate network of tubes called tracheae, which open via spiracles, as shown in **Figure** 5.2 and **Figure** 5.3. A constant supply of oxygen gas is clearly important to life. However, do you know why you need oxygen?

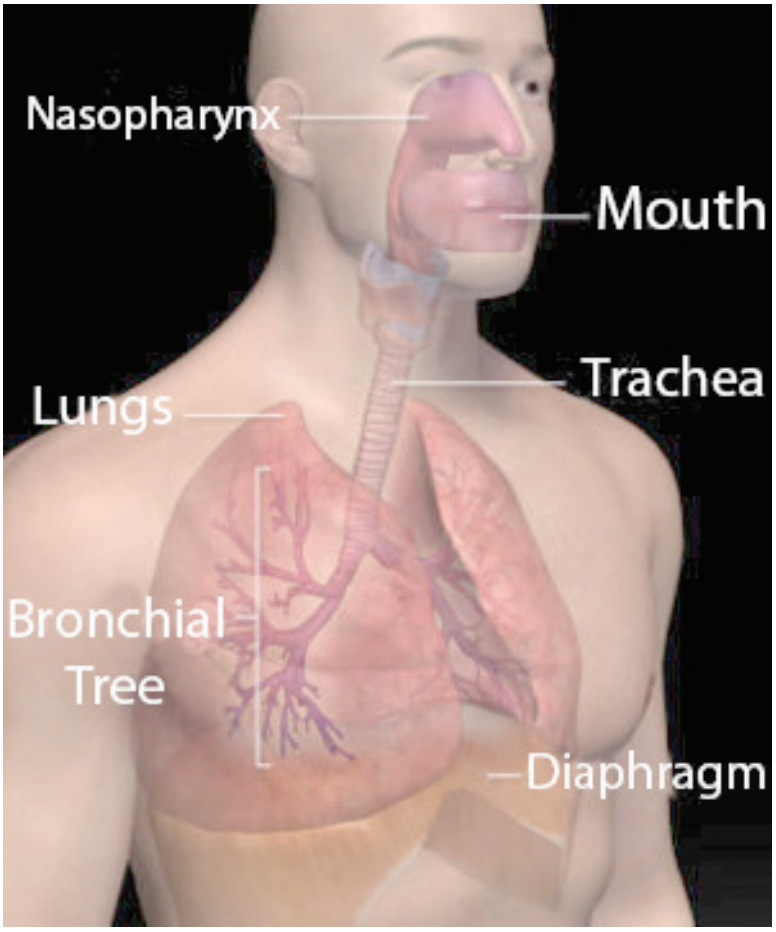


Figure 5.1: The human respiratory system is only part of the story of respiration. Diaphragm, lungs, and trachea take air deep into the body and provide oxygen gas to the bloodstream. The fate of that oxygen is the story of cellular respiration. (2)

Many people would answer that oxygen is needed to make carbon dioxide, the gas exhaled or released by each of the respiratory systems listed above. However, CO_2 is waste product. Surely, there is more to the story than just gas exchange with the environment! To begin to appreciate the role of oxygen inside your body, think about when your breathing rate increases: climbing a steep slope, running a race, or skating a shift in a hockey game. Respiration rate correlates with energy use, and that correlation reflects the link between oxygen and energy metabolism. For this reason, the chemical reactions inside your cells that

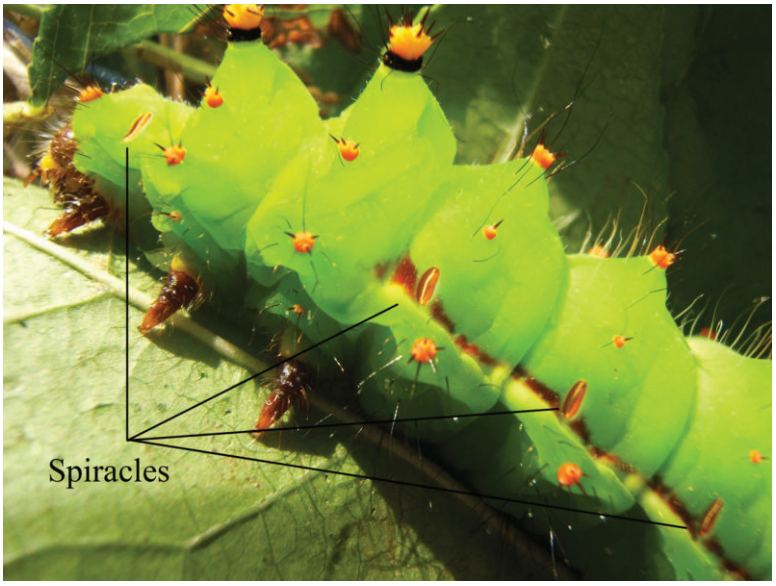


Figure 5.2: Spiracles in this Indian Luna Moth (*Actias selene*) caterpillar connect to a system of internal tubes (tracheae) which carry oxygen throughout the animal's body. (20)

Figure 5.3: Gills in this alpine newt larva, *Triturus alpestris*, bring blood close to an extensive surface area so that the newt can absorb dissolved oxygen gas from its watery habitat. (15)

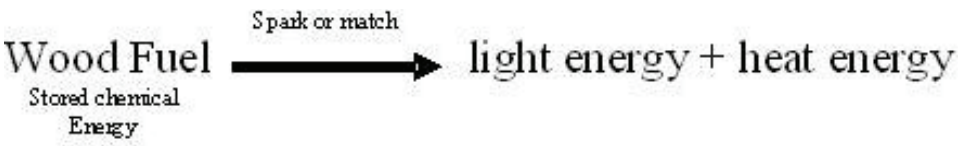
consume oxygen to produce usable energy are known as **cellular respiration**. This chapter will introduce you to the overall process of cellular respiration, and then focus on the first stage, which by itself does not require oxygen.

An Overview of Cellular Respiration

Another way to think about the role of oxygen in your body - and a good starting point for understanding the whole process of cellular respiration - is to recall the last time you sat by a campfire (see below figure) and noticed that it was "dying." Often people will blow on a campfire to keep it from "dying out." How does blowing help? What happens in a campfire?

Figure 5.4: Analyzing what happens when wood burns in a campfire is a good way to begin to understand cellular respiration. (16)

You know that a fire produces light and heat energy. However, it cannot "create" energy (remember that energy cannot be created or destroyed). Fire merely transforms the energy stored in its fuel – chemical energy – into light and heat. Another way to describe this energy transformation is to say that burning releases the energy stored in fuel. As energy is transformed, so are the compounds that make up the fuel. In other words, burning is a chemical reaction. We could write our understanding of this energy-releasing chemical reaction up to this point as:



Now return to what happens when you blow on a fire. The fire was "dying out," so you blew on it to get it going again. Was it movement or something in the air that promoted the chemical reaction? If you have ever "smothered" a fire, you know that a fire needs something in the air to keep burning. That something turns out to be oxygen. Oxygen gas is a reactant in the burning process. At this point, our equation is:

$$O_2 + \underset{\text{Stored chemical Energy}}{\text{Wood Fuel}} \xrightarrow{\text{Spark or match}} \text{light energy} + \text{heat energy}$$

To complete this equation, we need to know what happens to matter, to the atoms of oxygen, and to the atoms of the fuel during the burning. If you collect the gas rising above a piece of burning wood in an inverted test tube, you will notice condensation - droplets appearing on the sides of the tube. Cobalt chloride paper will change from blue to pink, confirming that these droplets are water. If you add bromothymol blue (BTB) to a second tube of collected gases, the blue solution will change to green or yellow (**Figure** 5.5), indicating the presence of carbon dioxide. Thus, carbon dioxide and water are products of burning wood.

Figure 5.5: Bromothymol blue (BTB) changes from blue to green to yellow as carbon dioxide is added. Thus, it is a good indicator for this product of burning or cellular respiration. (18)

$$O_2 + \underset{\text{Stored chemical Energy}}{\text{Wood Fuel}} \xrightarrow{\text{Spark or match}} CO_2 + H_2O + \text{light energy} + \text{heat energy}$$

Now we know what happened to those oxygen atoms during the chemical reaction, but we need to be sure to identify the sources of the carbon atoms in the CO_2 and of the hydrogen atoms in the water. If you guessed that these atoms make up the wood fuel – and nearly all fuels we burn, from coal to propane to candle wax to gasoline (hydrocarbons!), you have solved the equation completely. Overall, burning is the combining of oxygen with hydrogen and carbon atoms in a fuel (combustion or oxidation) to release the stored chemical energy as heat and light. Products of combustion are CO_2 (oxidized carbon) and H_2O (oxidized hydrogen). Or in symbols,

$$O_2 + \underset{\text{Stored chemical Energy}}{C_x\text{-}H_y} \xrightarrow{\text{Spark or match}} CO_2 + H_2O + \text{light energy} + \text{heat energy}$$

Return to the fate of the oxygen gas you breathe in and absorb. Recall that we related breathing rate and oxygen intake to energy use. Burning consumes oxygen as it releases stored chemical energy, transforming it into light and heat. Cellular respiration is actually a slow burn. Your cells absorb the oxygen carried by your blood from your lungs, and use the O_2 to release stored chemical energy so that you can use it.

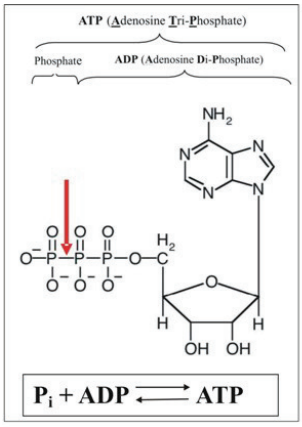
However, releasing energy within cells does not produce light or intense heat. Cells run on chemical energy – specifically, the small amount temporarily stored in adenine triphosphate (ATP) molecules. Cellular respiration transfers chemical energy from a "deliverable" fuel molecule – **glucose** – to many "usable" molecules of **ATP**. Like oxygen, glucose is delivered by your blood to your cells. If ATP were delivered to cells, more than 60,221,417,930,000,000,000,000,000 of these large molecules (which contain relatively small amounts of energy) would clog your capillaries each day. Pumping them across cell membranes would "cost" a great deal of energy. A molecule of glucose contains a larger amount of chemical energy in a smaller package. Therefore, glucose is much more convenient for bloodstream delivery, but too "powerful" to work within the cell. The process of cellular respiration uses oxygen to help transfer the chemical energy from glucose to ATP, which can be used to do work in the cell. This chemical equation expresses what we have worked out:

$$O_2 + \underset{\text{stored chemical energy, deliverable}}{C_6H_{12}O_6} \longrightarrow \underset{\text{stored chemical energy, usable}}{ATP}$$

As with burning, we must trace what happens to atoms during cellular respiration. You can readily see that when the carbon atoms in glucose are combined with oxygen, they again form carbon dioxide. And when the hydrogen atoms in glucose are oxidized, they form water, as in burning. You can detect these products of cellular respiration in your breath on a cold day (as water condensation) and in the lab (BTB turns yellow when you blow into it through a straw). The equation:

$$O_2 + \underbrace{C_6H_{12}O_6}_{\text{stored chemical energy, deliverable}} \longrightarrow \underbrace{ATP}_{\text{stored chemical energy, usable}} + CO_2 + H_2O$$

This accounts for the energy transfer and the carbon, hydrogen, and oxygen atoms, but it does not show the "raw materials" or reactants which build ATP. Recall that the energy temporarily stored in ATP is released for use when the bond between the second and third phosphates is broken. The resulting ADP can be recycled within the cell by recombining it with inorganic phosphate (P_i).



Now you should be able to see that the source of energy for re-attaching the phosphate is the chemical energy in glucose! Materials cycle and recycle, but energy gets used up and must be replaced. That is the key to understanding cellular respiration: it is a "recharging of the batteries" - ATP molecules – which power cellular work. How many ATP can be made by harnessing the energy in a single glucose molecule? Although this number varies under certain conditions, most cells can capture enough energy from one molecule of glucose to build 38 molecules of ATP. Our equation becomes:

$$O_2 + \underbrace{C_6H_{12}O_6}_{\text{stored chemical energy, deliverable}} + 38ADP + 38P_i \longrightarrow \underbrace{38\ ATP}_{\text{stored chemical energy, usable}} + CO_2 + H_2O$$

This equation for cellular respiration is not quite complete, however, because we can easily mix air and glucose sugar (even adding ADP and P_i) and nothing will happen. For the campfire, we indicated above the arrow that a necessary condition was a spark or match to start the reaction. A spark or match would damage or destroy living tissue. What necessary condition initiates the slow burn that is cellular respiration? Recall that enzymes are highly specific proteins which "speed up" chemical reactions in living cells. More than 20 kinds of enzymes carry out cellular respiration! If you also recall that membranes within organelles often sequence enzymes for efficiency, as in chloroplasts for photosynthesis, you will not be surprised that a specific organelle, the **mitochondrion** (**Figure** 5.6), is also a necessary condition of cellular respiration - at least in eukaryotes.

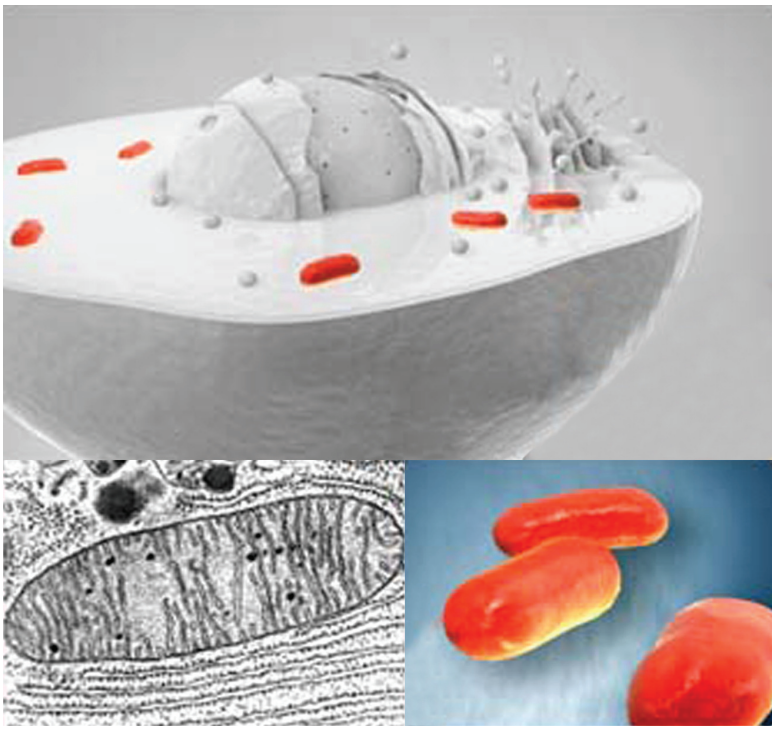


Figure 5.6: Mitochondria are membranous organelles which sequence enzyme and electron carrier molecules to make cellular respiration highly efficient. (13)

Within each eukaryotic cell, the membranes of 1000-2000 mitochondria sequence enzymes and electron carriers and compartmentalize ions so that cellular respiration proceeds efficiently. Mitochondria, like chloroplasts, contain their own DNA and ribosomes and resemble certain bacteria. The endosymbiotic theory holds that mitochondria, too, were once independently living prokaryotes. Larger prokaryotes engulfed (or enslaved) these smaller aerobic cells, forming eukaryotic cells. Many prokaryotes today can perform cellular respiration; perhaps they and mitochondria have common ancestors. Their expertise in generating ATP made mitochondria highly valued symbionts.

Including these necessary conditions and balancing numbers of atoms on both sides of the arrow, our final equation for the overall process of cellular respiration is:

$$6O_2 + \underset{\text{stored chemical energy, deliverable}}{C_6H_{12}O_6} + 38ADP + 38P_i \xrightarrow[\text{mitochondria}]{\text{enzymes}} \underset{\text{stored chemical energy, usable}}{38ATP} + 6CO_2 + 6H_2O$$

In words, cellular respiration uses oxygen gas to break apart the carbon-hydrogen bonds in glucose and release their energy to build 38 molecules of ATP. Most of this process occurs within the mitochondria of the cell. Carbon dioxide and water are waste products. This is similar to burning, in which oxygen breaks the carbon-hydrogen bonds in a fuel and releases their chemical energy as heat and light. Again, carbon dioxide and water are waste.

If you have studied the process of photosynthesis, you've probably already noticed its similarity to the process of cellular respiration. Both are processes within the cell which make chemical energy available for life. Photosynthesis transforms light energy into chemical energy stored in glucose, and cellular respiration releases the energy from glucose to build ATP, which does the work of life. Moreover, photosynthesis reactants CO_2 and H_2O are products of cellular respiration. And the reactants of respiration, $C_6H_{12}O_6$ and O_2, are the products of photosynthesis. This interdependence is the basis of the carbon-oxygen cycle (**Figure** 5.7), which connects producers to consumers and their environment. At first glance, the cycle merely seems to show mitochondria undoing what chloroplasts do; but the cycle's energy transformations power all the diversity, beauty, and mystery of life.

An excellent animation demonstrating cellular respiration can be found at the following web site:

- http://videos.howstuffworks.com/hsw/10323-matter-and-energy-glycolysis-and-cellular
  htm

Glycolysis: A Universal and Ancient Pathway for Making ATP

When was the last time you enjoyed yogurt on your breakfast cereal, or had a tetanus shot? These experiences may appear unconnected, but both relate to bacteria which do not use

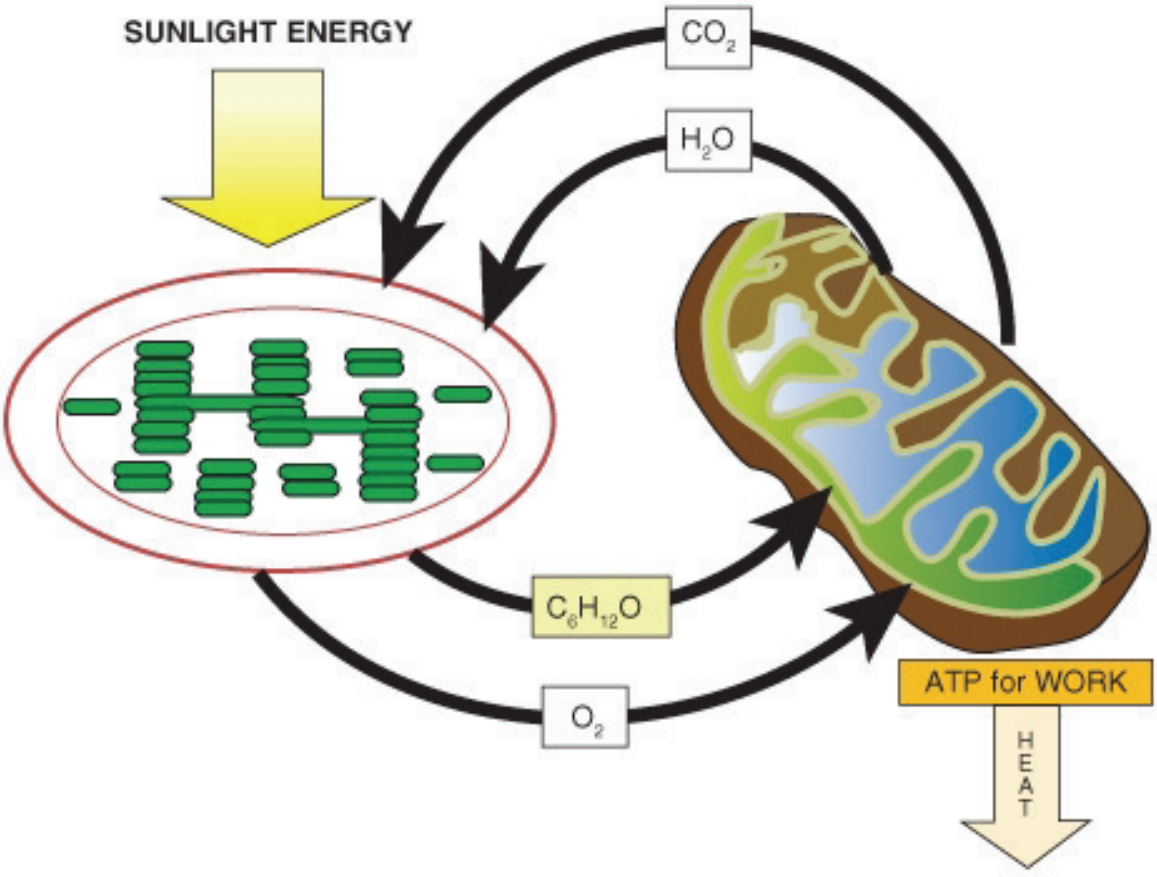


Figure 5.7: Photosynthesis in the chloroplast and cellular respiration in the mitochondrion show the interdependence of producers and consumers, the flow of energy from sunlight to heat, and the cycling of carbon and oxygen between living world and environment. (19)

oxygen to make ATP. In fact, tetanus bacteria cannot survive if oxygen is present. However, *Lactobacillus acidophilus* (bacteria which make yogurt) and *Clostridium tetani* (bacteria which cause tetanus or lockjaw) share with nearly all organisms the first stage of cellular respiration, glycolysis (**Figure** 5.8). Because glycolysis is universal, whereas aerobic (oxygen-requiring) cellular respiration is not, most biologists consider it to be the most fundamental and primitive pathway for making ATP.

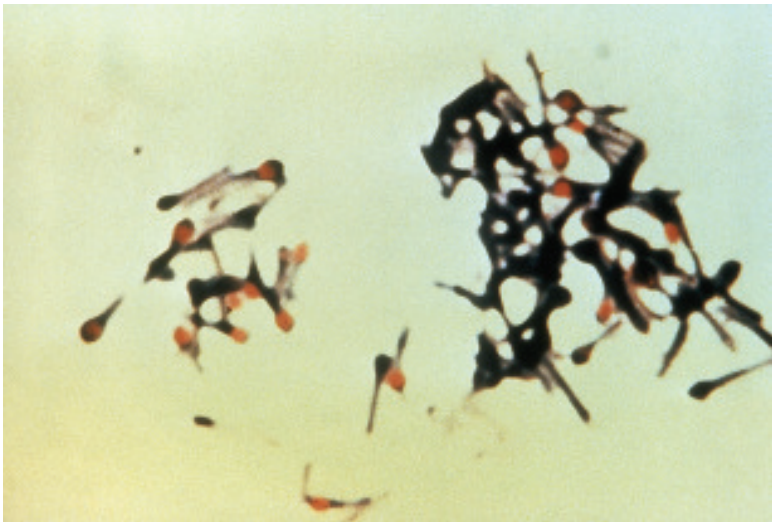


Figure 5.8: *Clostridium tetani* bacteria are obligate anaerobes, which cannot grow in the presence of oxygen and use a variation of glycolysis to make ATP. Because they can grow in deep puncture wounds and secrete a toxin, which can cause muscle spasms, seizures, and death, most people receive tetanus vaccinations at least every ten years throughout life. (9)

Return to the overall equation for cellular respiration:

$$\underset{\text{stored chemical energy, deliverable}}{C_6H_{12}O_6} + 6O_2 + 38ADP + 38P_i \xrightarrow[\text{mitochondria}]{\text{enzymes}} \underset{\text{stored chemical energy, usable}}{38ATP} + 6CO_2 + 6H_2O$$

Like photosynthesis, the process represented by this equation is actually many small, individual chemical reactions. We grouped the reactions of photosynthesis into two stages, the light reactions and the Calvin Cycle. We will divide the reactions of cellular respiration into three stages: glycolysis, the Krebs Cycle, and the electron transport chain (**Figure** 5.9). In this section, we will explore Stage 1, glycolysis - the oldest and most widespread pathway for making ATP. Before diving into the details, we must note that this first stage of cellular respiration is unique among the three stages: it does not require oxygen, and it does not take place in the mitochondrion. The chemical reactions of glycolysis occur without oxygen in the **cytosol** of the cell (**Figure** 5.10).

The name for Stage 1 clearly indicates what happens during that stage: *glyco-* refers to glucose, and *-lysis* means "splitting." In glycolysis, within the cytosol of the cell, a minimum of eight different enzymes break apart glucose into two 3-carbon molecules. The energy

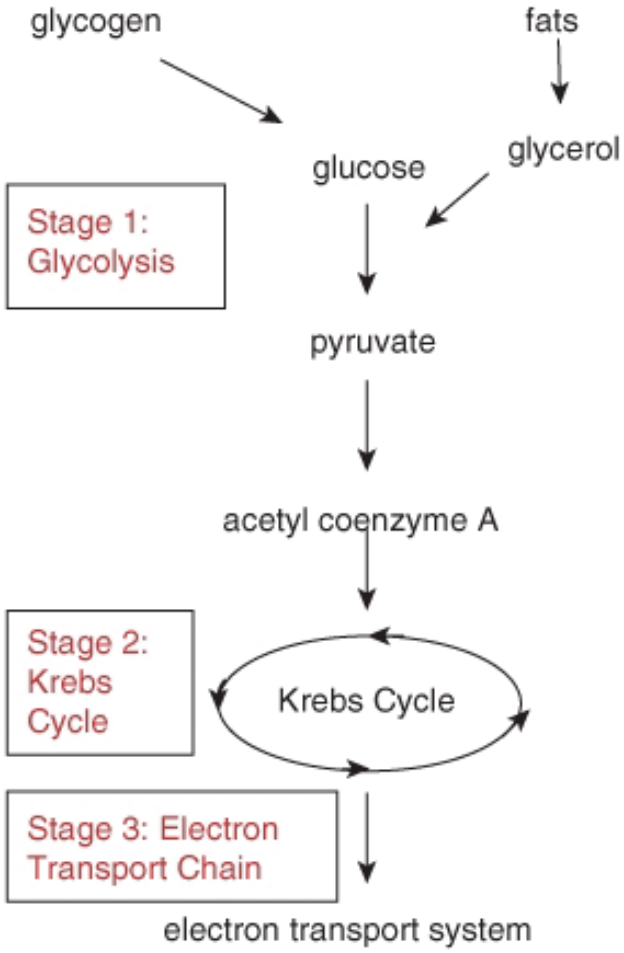


Figure 5.9: The many steps in the process of aerobic cellular respiration can be divided into three stages. The first stage, glycolysis, produces ATP without oxygen. Because this part of the cellular respiration pathway is universal, biologists consider it the oldest segment. Note that **glycogen** and fats can also enter the glycolysis pathway. (23)

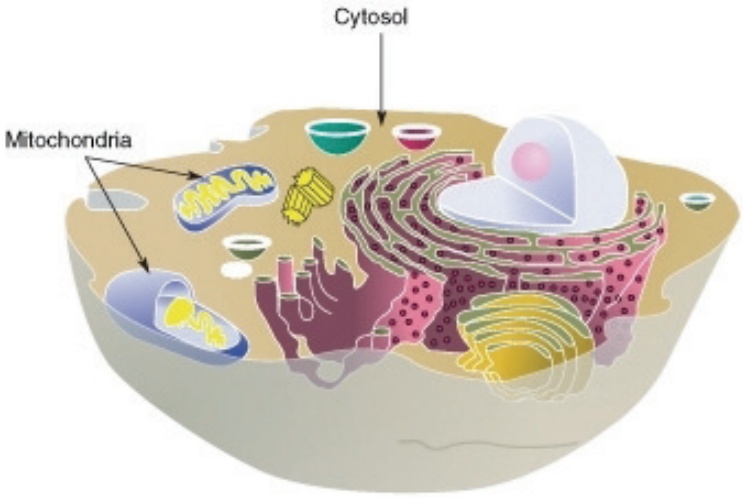


Figure 5.10: Glycolysis, unlike the latter two stages of cellular respiration, takes place without oxygen in the cytosol of the cell. For many organisms, aerobic respiration continues with the Krebs cycle and the electron transport chain in the mitochondria. (7)

released in breaking those bonds is transferred to carrier molecules, ATP and NADH. **NADH** temporarily holds small amounts of energy which can be used later to build ATP. The 3-carbon product of glycolysis is pyruvate, or pyruvic acid (**Figure** 5.11). Overall, glycolysis can be represented as shown below:

$$C_6H_{12}O_6 + 2NAD^+ + 2P_i + 2ADP \rightarrow 2\ \text{pyruvate} + 2NADH + 2ATP$$

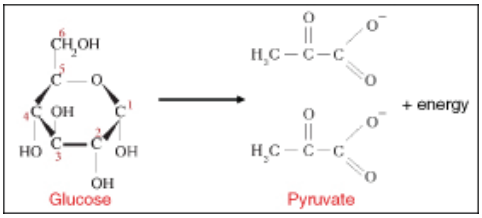


Figure 5.11: Glycolysis breaks the 6-carbon molecule glucose into two 3-carbon pyruvate molecules, releasing some of the chemical energy which had been stored in glucose. (10)

However, even this equation is deceiving. Just the splitting of glucose requires many steps, each transferring or capturing small amounts of energy. Individual steps appear in **Figure** 5.12. Studying the pathway in detail reveals that cells must "spend" or "invest" two ATP in order to begin the process of breaking glucose apart. Note that the phosphates produced by breaking apart ATP join with glucose, making it unstable and more likely to break apart. Later steps harness the energy released when glucose splits, and use it to build "hot hydrogens" (NAD^+ is reduced to NADH) and ATP (ADP + P_i $\longrightarrow$ ATP). If you count the

ATP produced, you will find a net yield of two ATP per glucose (4 produced – 2 spent). Remember to double the second set of reactions to account for the two 3-carbon molecules which follow that pathway! The "hot hydrogens" can power other metabolic pathways, or in many organisms, provide energy for further ATP synthesis.

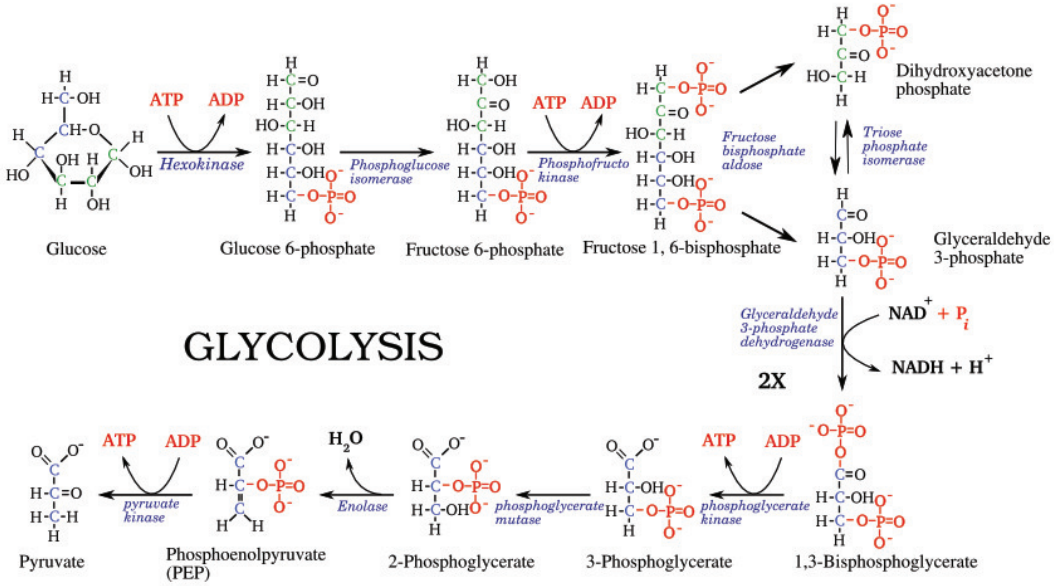


Figure 5.12: This detailed diagram demonstrates that glycolysis "costs" 2 ATP, but harnesses enough energy from breaking bonds in glucose to produce 4 ATP and 2 pairs of "hot hydrogens" (NADH + H^+). Note the multiplier (2X) required for the 3-carbon steps. (24)

To summarize: In the cytosol of the cell, glycolysis transfers some of the chemical energy stored in one molecule of glucose to two molecules of ATP and two NADH. This makes (some of) the energy in glucose, a universal fuel molecule for cells, available to use in cellular work - moving organelles, transporting molecules across membranes, or building large organic molecules.

Although glycolysis is universal, pathways leading away from glycolysis vary among species depending on the availability of oxygen. If oxygen is unavailable, pyruvate may be converted

to lactic acid or ethanol and carbon dioxide in order to regenerate NAD^+, ending anaerobic respiration. **Anaerobic** respiration is also called fermentation, which we will discuss in a later section.

If oxygen is present, pyruvate enters the mitochondria for further breakdown, releasing far more energy and producing many more molecules of ATP in the latter two stages of aerobic respiration - the Krebs cycle and electron transport chain. We will explore these, too, in a later section.

Lesson Summary

- Most organisms need oxygen for a single purpose: to release energy from food for use by cells.
- Cellular respiration is a series of chemical reactions which transfer energy from glucose (deliverable or fuel energy) to ATP (usable energy).
- Analyzing a campfire can clarify your understanding of cellular respiration. A campfire breaks chemical bonds in wood, releasing stored energy as light and heat; respiration breaks chemical bonds in glucose, releasing stored energy and transferring some to 38 ATP; some energy is lost as heat.
- This equation summarizes the process of cellular respiration:

$$6O_2 + \underbrace{C_6H_{12}O_6}_{\text{stored chemical energy, deliverable}} + 38ADP + 38P_i \xrightarrow[\text{mitochondria}]{\text{enzymes}} \underbrace{38ATP}_{\text{stored chemical energy, usable}} + 6CO_2 + 6H_2O$$

- In eukaryotic cells, organelles called mitochondria sequence enzymes and electron carriers and compartmentalize ions so that cellular respiration proceeds efficiently.
- Cellular respiration, in many ways the opposite of photosynthesis, shows the interdependence of producers and consumers. Combined, the two equations demonstrate how energy flows and the carbon and oxygen cycle between organisms and environment.
- The process of cellular respiration is actually many separate reactions, which can be divided into three stages: glycolysis, the Krebs Cycle, and the electron transport chain.

Review Questions

1. Why do nearly all organisms die without a constant supply of oxygen?
2. What source of energy do cells use to build ATP by cellular respiration?
3. Compare the purpose and energy content of glucose to the function and energy content of ATP; in other words, why do organisms need both kinds of energy-rich molecules?
4. Compare the process of burning gasoline in your automobile's engine to the process of cellular respiration in terms of reactants, products, and necessary conditions.

5. Write out the chemical reaction which summarizes the overall process of cellular respiration, first in symbols as a chemical equation, and then in words in a complete sentence.
6. In what eukaryote organelle does cellular respiration take place? Does this mean that prokaryotes cannot carry out the entire process of cellular respiration? Explain.
7. Compare and contrast cellular respiration and photosynthesis.
8. Diagram the carbon-oxygen cycle which connects producers, consumers, and their environment. (P = producer, C = consumer).
9. List the three stages of cellular respiration, and contrast the first stage with the other two in terms of distribution throughout the living world, location within the cell, and use of oxygen.
10. Summarize the overall process of glycolysis, following both carbon atoms and chemical energy.

Further Reading / Supplemental Links

- Martin Hoagland, Bert Dodson, and Judith Hauck, *Exploring the Way Life Works: The Science of Biology.* Jones and Bartlett Publishers, Inc., 2001. Chapter 3: "Energy – Light to Life," pp. 87-138.
- Diana C. Linden and Roberta Pollack, "Chart of Important metabolic products." In Biology 130 Introduction to Cellular Biochemistry Lectures, Occidental College, last updated 21 October 2000. Available on the web at: http://departments.oxy.edu/biology/bio130/lectures_2000/metabolic_products.htm
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- M.J. Farabee, 1992, 1994, 1997, 1999, 2000, 2001, 2007. "Glycolysis, the Universal Process." Biobook, Estrella Mountain Community College, last modified 2007. Available on the web at: http://www.emc.maricopa.edu/faculty/farabee/BIOBK/BioBookGlyc.html.

Vocabulary

aerobic With oxygen, or living or occurring only in the presence of oxygen.

anaerobic Without oxygen; living or occurring in the absence of oxygen.

ATP Adenosine triphosphate; the universal energy "currency" for the cell; molecule which stores a usable amount of chemical energy.

cellular respiration The process which transfers chemical energy from glucose (a deliverable fuel molecule) to ATP (a usable energy-rich molecule).

cytosol The solution portion of a cell's cytoplasm, consisting of water, organic molecules and ions.

endosymbiotic theory The theory which states that chloroplasts and mitochondria originated as independent prokaryotic cells which were engulfed by larger prokaryotic cells to form the first eukaryotic cells.

glucose The carbohydrate product of photosynthesis; serves as the universal fuel for life.

glycogen Glucose molecules that have been chained together for energy storage; human muscle and liver cells store energy in this form.

glycolysis The process of splitting glucose" - stage 1 of aerobic cellular respiration and also the basis of anaerobic respiration; splits glucose into two 3-carbon pyruvates, producing 2 (net) ATP.

mitochondrion The "powerhouse" organelle in all eukaryotic cells where stages 2 (Krebs Cycle) and 3 (Electron Transport Chain) of aerobic respiration produce ATP.

NADH An electron carrier used to deliver energy to the electron transport chain of aerobic respiration.

symbiont An organism which lives in a close, mutually beneficial relationship with another organism.

Points to Consider

- In this lesson, you've learned that scientists consider glycolysis to be the oldest, or at least one of the oldest, pathways for making ATP. What might this say about earth's ancient atmosphere? Can you imagine steps or events that might have been involved in the later evolution of aerobic cellular respiration, which includes glycolysis?
- Prokaryotes can use either photosynthesis or cellular respiration – or both - to make ATP. Why do you think both processes evolved? Why not just photosynthesis? Which do you think came first in evolution? Why?
- This lesson compares cellular respiration to burning. What activities in your daily life use burning? What are some consequences of those activities, in terms of materials produced and energy used?

5.2 Lesson 5.2: Into the Mitochondrion: Making ATP with Oxygen

Lesson Objectives

- Relate the history of oxygen in the atmosphere to the evolution of photosynthesis, aerobic respiration, mitochondria, and life on earth.
- Describe the fate in eukaryotic cells of the pyruvate molecules produced by glycolysis if oxygen is present.
- Recognize that for most organisms, if oxygen is present, the products of glycolysis enter the mitochondria for stage 2 of cellular respiration - the Krebs Cycle.
- Trace carbon and hydrogen atoms through the Krebs Cycle.
- Analyze the importance of the Krebs Cycle to cellular respiration by following the pathway taken by chemical energy.
- Describe the structure of the mitochondrion, and identify the site of Krebs Cycle reactions.
- Recognize that electron transport chain is the third and final stage of aerobic cellular respiration.
- Describe how chemiosmotic gradients in mitochondria store energy to produce ATP.
- Identify the role of oxygen in making stored chemical-bond energy available to cells.
- Relate the structure of mitochondria to electron transport chain function and the production of ATP.

Introduction

Enticing clues - volcanic gases, vast iron ore sediments, and bubbles of ancient air trapped in amber – suggest dramatic changes during the history of earth's atmosphere. Correlating these clues with the fossil record leads to two major conclusions: that early life evolved in the absence of oxygen, and that oxygen first appeared between 2 and 3 billion years ago (**Figure** 5.13) because of photosynthesis by bluegreen bacteria (**Figure** 5.14). The chemistry of cellular respiration reflects this history. Its first stage, **glycolysis**, is universal and does not use oxygen.

Absolutely dependent on oxygen gas, we find it difficult to imagine that its appearance must have been disastrous for the anaerobic organisms that evolved in its absence. But oxygen is highly reactive, and at first, its effect on evolution was so negative that some have named this period the "oxygen catastrophe." However, as oxygen gradually formed a protective ozone layer, life rebounded. After the first organisms "discovered" how to use oxygen to their advantage – in ways we will explore in this chapter – the diversity of aerobic organisms exploded. According to the **endosymbiotic theory**, engulfing of some of these aerobic bacteria led to eukaryotic cells with mitochondria, and multicellularity followed. Today, we

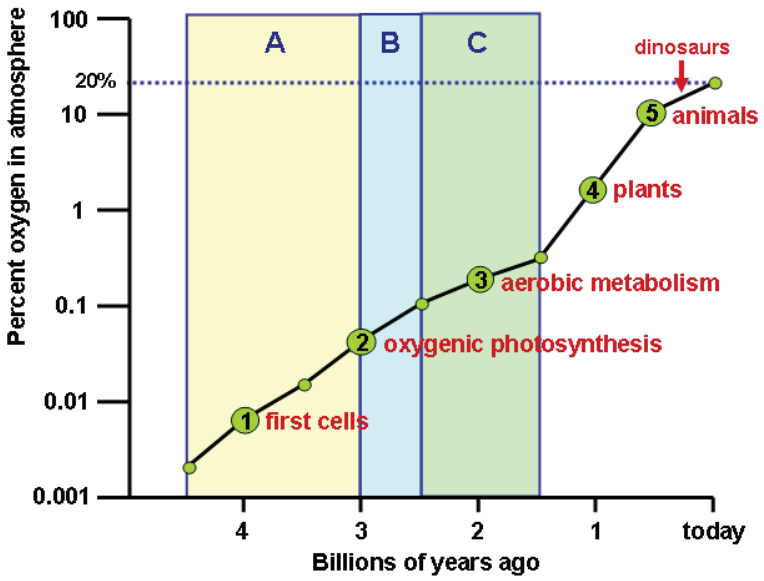

Figure 5.13: Oxygen has increased in the atmosphere throughout the history of the earth. Note the logarithmic scale, which indicates great increases after first photosynthesis and then land plants evolved. Related geological events: A = no oxidized iron; B = oxidized iron bands in seabed rock - evidence for O_2 in the oceans; C= oxidized iron bands on land and ozone layer formation- evidence for O_2 in the atmosphere. (12)

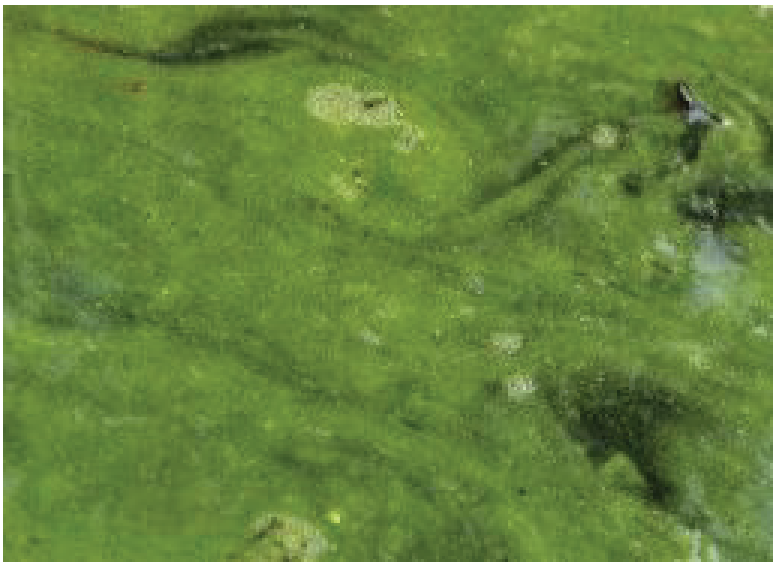

Figure 5.14: Bubbles of oxygen appear at the surface above a mat of bluegreen bacteria in a freshwater pond. Studies of the fossil record and earth's atmosphere suggest that life evolved before bacteria similar to these first added oxygen. (1)

live in an atmosphere which is 21% oxygen, and most of life follows glycolysis with the last two, aerobic stages of cellular respiration.

Recall the purpose of cellular respiration: to release energy from glucose to make **ATP** - the universal "currency" for cellular work. The following equation describes the overall process, although it summarizes many individual chemical reactions.

$$6O_2 + \underset{\text{stored chemical energy, deliverable}}{C_6H_{12}O_6} + 38ADP + 38P_i \xrightarrow{\text{enzymes, mitochondria}} \underset{\text{stored chemical energy, usable}}{38ATP} + 6CO_2 + 6H_2O$$

Once again, the first stage of this process, glycolysis, is ancient, universal, and anaerobic. In the cytoplasm of most cells, glycolysis breaks each 6-carbon molecule of glucose into two 3-carbon molecules of pyruvate. Chemical energy, which had been stored in the now broken bonds, is transferred to 2 ATP and 2 "hot hydrogens," **NADH**.

The fate of pyruvate depends on the species and the presence or absence of oxygen. If oxygen is present to drive subsequent reactions, pruvate enters the mitochondrion, where the **Krebs Cycle** (Stage 2) and electron transport chain (Stage 3) break it down and oxidize it completely to CO_2 and H_2O. The energy thus released builds many more ATP molecules, though of course some is lost as heat. Let's explore the details of how mitochondria use oxygen to make more ATP from glucose by aerobic respiration.

The Krebs Cycle: Capturing Energy from Pyruvate

Aerobic respiration begins with the entry of pyruvate (product of glycolysis) into the mitochondria. We will follow the six carbons of the original glucose molecule, so we will consider two 3-carbon pyruvates. The fate of pyruvate's energy and carbon atoms can be followed in the examples below:

1. Within the mitochondria, each pyruvate is broken apart and combined with a coenzyme known as CoA to form a 2-carbon molecule, Acetyl CoA, which can enter the Krebs Cycle. A single atom of carbon (per pyruvate) is "lost" as carbon dioxide. The energy released in this breakdown is captured in two "hot hydrogen" – NADH. See **Figure** 5.15. Fatty acids can also break down into Acetyl CoA. By this means, lipids, like carbohydrates, can be "burned" to make ATP using the Krebs Cycle.
2. The Krebs Cycle (**Figure** 5.16) begins by combining each Acetyl CoA with a four-carbon carrier molecule to make a 6-carbon molecule of citric acid (or citrate, its ionized form). For this reason, the Krebs Cycle, named for a scientist who worked out its details, is also called the Citric Acid Cycle.
3. The cycle carries citric acid through a series of chemical reactions which gradually release energy and capture it in several carrier molecules. For each Acetyl CoA which enters the cycle, 3 NAD+ are reduced to NADH, one molecule of FAD (yet another tem-

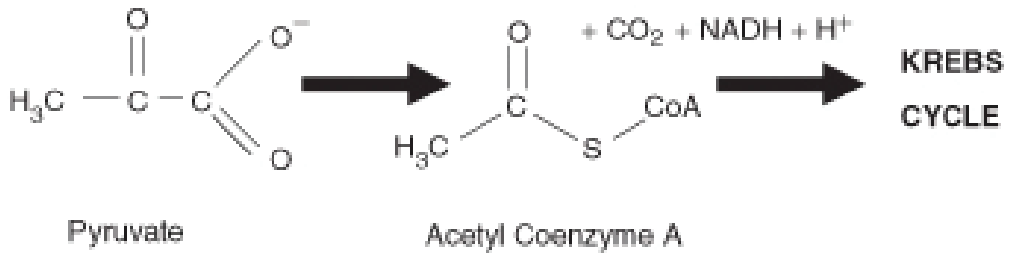

Figure 5.15: After glycolysis, two 3-carbon pyruvates enter the mitochondrion, where they are converted to two 2-carbon acetyl CoenzymeA (CoA) molecules. Acetyl CoA then enters the Krebs Cycle. Note that the carbons removed become carbon dioxide, accounting for two of the six such end products of glucose oxidation. The energy released by this breakdown is carried by "hot hydrogen." (8)

porary energy carrier we haven't met before) is reduced to $FADH_2$, and one molecule of ATP (actually a precursor, GTP) is made. Study **Figure** 5.16 to locate each of these energy-capturing events.

4. Note what happens to carbon atoms (black dots in **Figure** 5.16). For each 2-carbon Acetyl CoA which enters the cycle, two molecules of carbon dioxide are released - complete breakdown of the original 6-carbon glucose molecule. The final step regenerates the original 4-carbon molecule which began the cycle, so that another Acetyl CoA can enter.

In summary, the Krebs Cycle completes the breakdown of glucose which began with glycolysis. Its chemical reactions oxidize all six of the original carbon atoms to CO_2, and capture the energy released in 2 ATP, 6 NADH, and 2 $FADH_2$. These energy carriers join the 2 ATP and 2 NADH produced in glycolysis and the 2 NADH produced in the conversion of 2 pyruvates to 2 Acetyl CoA.

At the conclusion of the Krebs Cycle, glucose is completely broken down, yet only four ATP have been produced. Moreover, although oxygen is required to drive the Krebs Cycle, the cycle's chemical reactions do not themselves consume O_2. The conclusion of cellular respiration – its "grand finale!" – produces the majority of the ATP. The next section will explore the electron transport chain, where Stage 3 concludes aerobic cellular respiration.

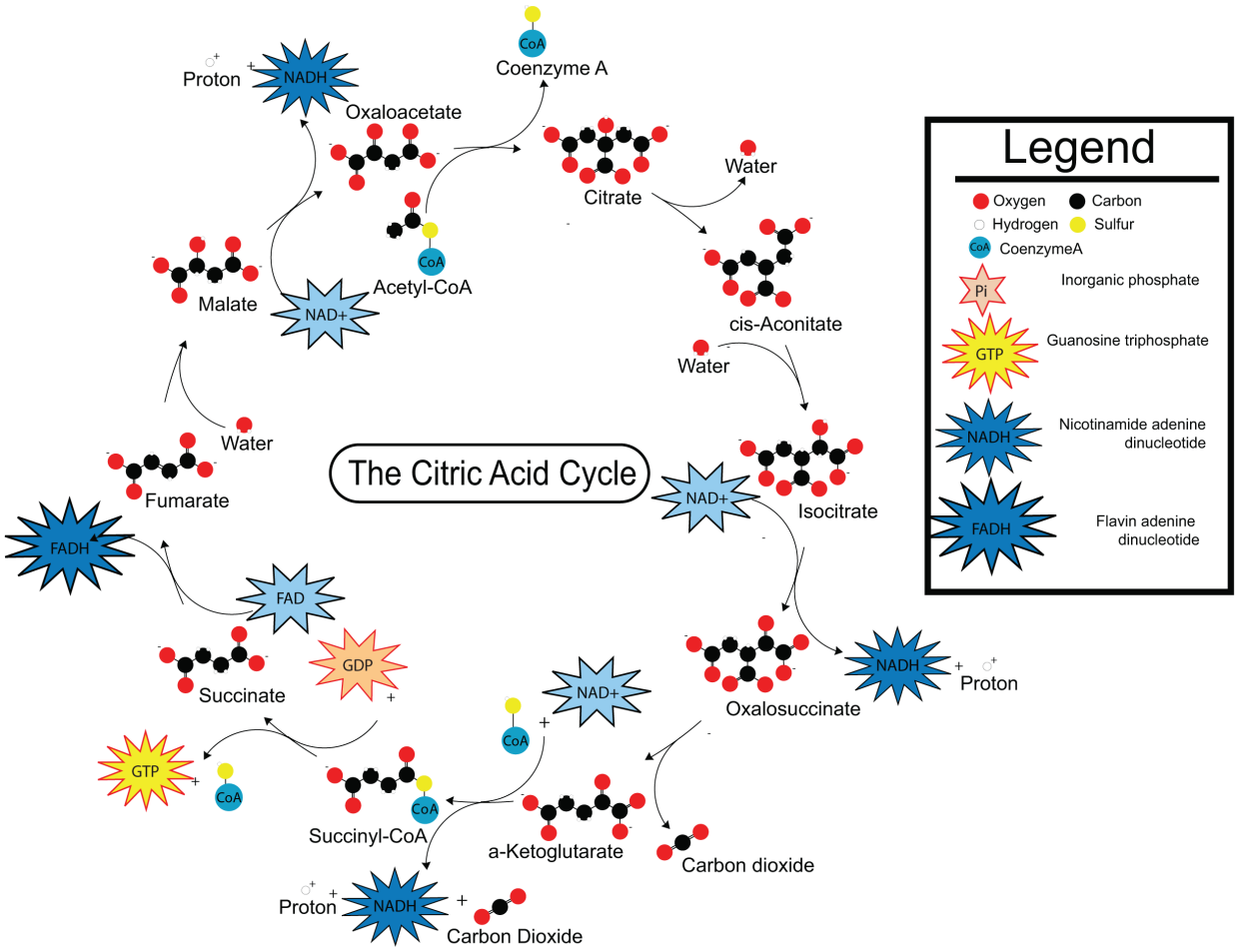

Figure 5.16: The Krebs or Citric Acid Cycle completes the breakdown of glucose begun in glycolysis. If oxygen is present, pyruvate enters the mitochondria and is converted to Acetyl CoA. Acetyl CoA enters the cycle by combining with 4-carbon oxaloacetate. Study the diagram to confirm that each turn of the cycle (two for each glucose) stores energy in 3 $NADH+H^+$, one $FADH_2$, and one ATP (from GTP), and releases 2 CO_2. (14)

Structure of the Mitochondrion: Key to Aerobic Respiration

As noted earlier, the aerobic phases of cellular respiration in eukaryotes occur within organelles called mitochondria. A detailed look at the structure of the **mitochondrion** (**Figure** 5.17) helps to explain its role in the last stage of respiration, the electron transport chain.

Two separate membranes form the mitochondrion. The inner membrane folds into **cristae** which divide the organelle into three compartments – **intermembrane space** (between outer and inner membranes), cristae space (formed by infoldings of the inner membrane), and matrix (within the inner membrane). The Krebs Cycle takes place within the matrix. The compartments are critical for the electron transport chain, as we'll see in the final section of this lesson. Glycolysis occurs in the cytoplasm of the cell, with the products of glycolysis entering the mitochondria to continue cellular respiration.

The Electron Transport Chain: ATP for Life in the Fast Lane

At the end of the Krebs Cycle, energy from the chemical bonds of glucose is stored in diverse energy carrier molecules: four ATP, but also two **$FADH_2$** and ten NADH. The primary task of the last stage of cellular respiration, the electron transport chain (ETC), is to transfer energy from these carriers to ATP, the "batteries" which power work within the cell.

Pathways for making ATP in stage 3 of aerobic respiration closely resemble the electron transport chains used in photosynthesis. In both ETCs, energy carrier molecules are arranged in sequence within a membrane so that energy-carrying electrons cascade from one to another, losing a little energy in each step. In both photosynthesis and aerobic respiration, the energy lost is harnessed to pump hydrogen ions into a compartment, creating an **electrochemical** or **chemiosmotic gradient** across the enclosing membrane. And in both processes, the energy stored in the chemiosmotic gradient is used to build ATP.

For aerobic respiration, the **electron transport chain** or "respiratory chain" is embedded in the inner membrane of the mitochondria (**Figure** 5.18). $FADH_2$ and NADH (produced in glycolysis and the Krebs Cycle) donate high-energy electrons to energy carrier molecules within the membrane. As they pass from one carrier to another, the energy they lose is used to pump hydrogen ions into the intermembrane space, creating an electrochemical gradient. Hydrogen ions flow "down" the gradient – from outer to inner compartment – through an ion channel/enzyme, **ATP synthase,** which transfer their energy to ATP. Note the paradox that it requires energy to create and maintain a concentration gradient of hydrogen ions that are then used by ATP synthase to create stored energy (ATP). In broad terms, it takes energy to make energy. Coupling the electron transport chain to ATP synthesis with a hydrogen ion gradient is chemiosmosis, first described by Nobel laureate Peter D. Mitchell.

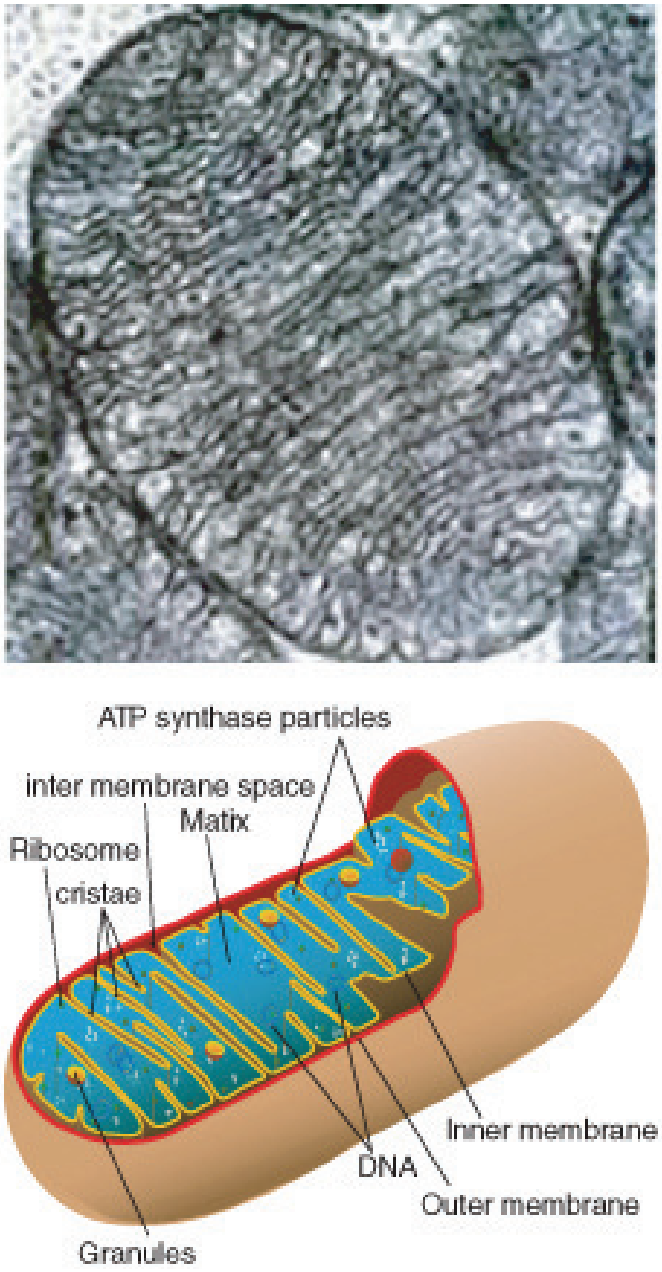

Figure 5.17: Mitochondria, organelles specialized to carry out aerobic respiration, contain an inner membrane folded into cristae, which form two separate kinds of compartments: inner membrane space and matrix. The Krebs Cycle takes place in the **matrix**. The electron transport chain is embedded in the inner membrane and uses both compartments to make ATP by **chemiosmosis**. (6)

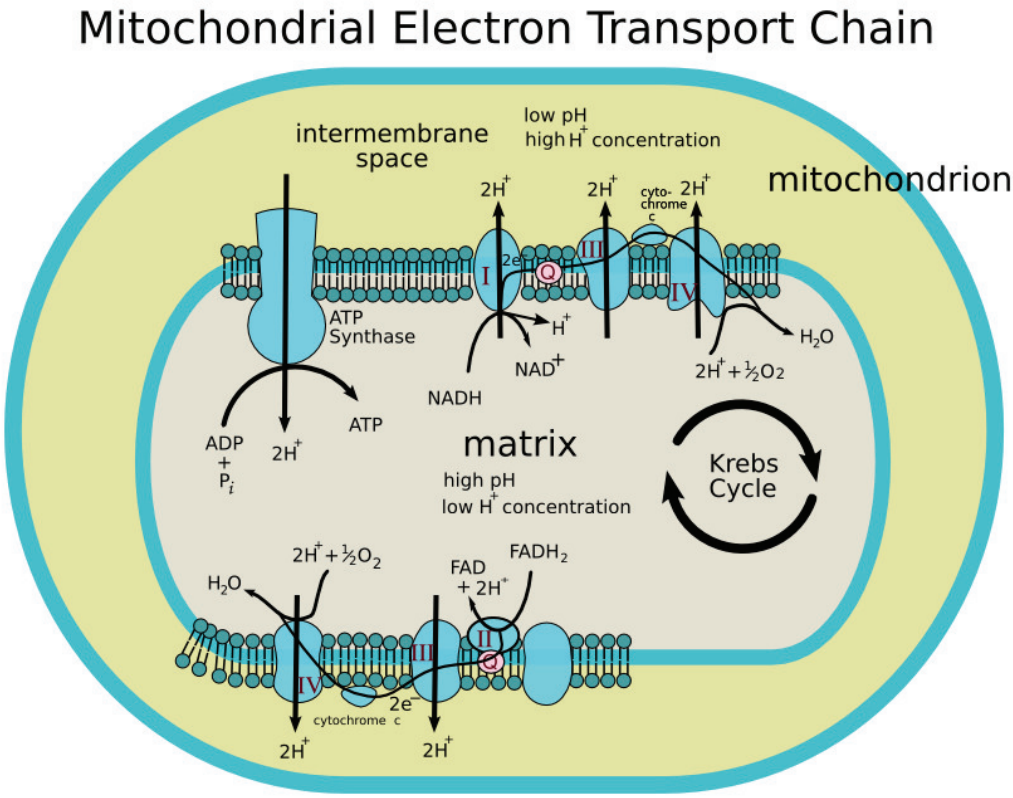

Figure 5.18: The third stage of photosynthesis uses the energy stored earlier in NADH and $FADH_2$ to make ATP. Electron transport chains embedded in the inner membrane capture high-energy electrons from the carrier molecules and use them to concentrate hydrogen ions in the intermembrane space. Hydrogen ions flow down their electrochemical gradient back into the matrix through channels which capture their energy to convert ADP to ATP. (21)

After passing through the ETC, low-energy electrons and low-energy hydrogen ions combine with oxygen to form water. Thus, oxygen's role is to drive the entire set of ATP-producing reactions within the mitochondrion by accepting "spent" hydrogens. Oxygen is the final electron acceptor; no part of the process - from the Krebs Cycle through electron transport chain – can happen without oxygen.

The electron transport chain can convert the energy from one glucose molecule's worth of $FADH_2$ and $NADH+H^+$ into as many as 34 ATP. When the four ATP produced in glycolysis and the Krebs Cycle are added, the total fits the overall equation for aerobic cellular respiration:

$$\underset{\text{stored chemical energy, deliverable}}{6O_2 + C_6H_{12}O_6} + 38ADP + 38P_i \longrightarrow \underset{\text{stored chemical energy, usable}}{38ATP} + 6CO_2 + 6H_2O$$

Aerobic respiration is complete. If oxygen is available, cellular respiration transfers the energy from one molecule of glucose to 38 molecules of ATP, releasing carbon dioxide and water as waste. "Deliverable" food energy has become energy which can be used for work within the cell – transport within the cell, pumping ions and molecules across membranes, and building large organic molecules. Can you see how this could lead to "life in the fast lane" compared to anaerobic respiration (glycolysis alone)?

Lesson Summary

Introduction to Aerobic Respiration:

- Oxygen produced by the first photosynthetic organisms was probably toxic to the anaerobic life forms which then populated the earth, but later organisms evolved a way to harness the power of oxygen to make ATP. This new pathway was aerobic respiration.
- In eukaryotic cells, if oxygen is present, the pyruvate molecules produced by glycolysis in the cytoplasm enter the mitochondria for further breakdown and energy release.

The Krebs Cycle harnesses the energy which remains in pyruvate after glycolysis.

- For most organisms, if oxygen is present, the products of glycolysis enter the mitochondria for stage 2 of cellular respiration - the Krebs cycle.
- In the mitochondrion, 3-carbon pyruvate combines with Coenzyme A to form 2-carbon Acetyl CoA and CO_2, storing released energy in NADH.
- Acetyl CoA enters the Krebs Cycle by combining with a 4-carbon molecule to form citric acid.
- The Krebs Cycle removes energy from citric acid in small steps, storing it in diverse energy carrier molecules: ATP, NADH and $FADH_2$.

- The Krebs Cycle produces two molecules of CO_2 per Acetyl CoA, completing the breakdown of glucose.

Mitochondria are organelles whose membranes are specialized for aerobic respiration.

- The matrix of the mitochondria is the site of Krebs Cycle reactions.
- The electron transport chain and most ATP synthesis rely on the compartments created by the inner membrane of the mitochondria.

The third and final stage of aerobic cellular respiration, the electron transport chain, accounts for most of the ATP.

- Stage 3 transfers the energy from NADH and $FADH_2$ to make ATP.
- High-energy electrons from these two energy carriers pass along electron acceptors embedded in the inner membrane of the mitochondria.
- As the electrons flow, the electron acceptors capture small amounts of energy to pump hydrogen ions out into the intermembrane space.
- These concentrated hydrogen ions store potential energy as an electrochemical gradient.
- Hydrogen ions flow back into the inner membrane space through channel proteins, which use their energy to build ATP. This is chemiosmosis.
- The ETC coupled with the hydrogen ion flow can build 34 ATP per glucose molecule.
- When ATP from glycolysis and the Krebs Cycle are added, a total of 38 ATP result from aerobic respiration of one molecule of glucose.

Summary Animations

- Interactive animation depicting the steps of cellular respiration.

http://www.uwmc.uwc.edu/biology/respiration/cellresp.html

- Animation detailing the steps of electron transport chain.

http://vcell.ndsu.edu/animations/etc/movie-flash.htm

- Animation detailing the H^+ concentration gradient and ATP Synthase.

http://vcell.ndsu.edu/animations/atpgradient/movie-flash.htm

Review Questions

1. Explain why the appearance of oxygen in the atmosphere between two and three billions of years ago was both "good news and bad news" for life on Earth.
2. In eukaryotic cells when oxygen is present, what is the fate of the pyruvate produced in glycolysis?
3. Trace the six carbon atoms originally from glucose through the Krebs Cycle.
4. Trace the flow of energy from the pyruvates produced in glycolysis through the Krebs Cycle.
5. Describe the structure of the mitochondrion, and identify the sites of the Krebs Cycle and the Electron Transport Chain.
6. Summarize the overall task of Stage 3 of aerobic respiration.
7. List the steps in stage 3 which produce ATP.
8. Name the three stages of aerobic cellular respiration. Then write the overall equation, and identify which stage:
    - uses each reactant
    - requires each necessary condition and
    - produces each product.
9. Explain the principle of chemiosmosis.
10. Predict the main idea of the next lesson by comparing the energy available to anaerobic organisms, which use just glycolysis to make ATP, to the energy available to aerobic organisms, which use all three stages of cellular respiration to make ATP.

Further Reading / Supplemental Links

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- Graham Kent, "An animation of the Tricarboxylic Acid Cycle." Biology 231 Cell Biology Laboratory, October 2004. Available on the web at: http://www.science.smith.edu/departments/Biology/Bio231/krebs.html.
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- Gabe Simon & Dr. Jeff Brodsky, "Citric Acid Cycle." Bioscience 1820 Interactive Pathways Study Guide, 2003.
- http://www.pitt.edu/AFShome/j/b/jbrodsky/public/html/1820/tca.htm

Vocabulary

ATP Adenosine triphosphate; the universal energy "currency" for the cell; molecule which stores a usable amount of chemical energy.

ATP synthase Ion channel and enzyme complex that chemically bonds a phosphate group to ADP, making ATP as H^+ ions flow through the ion channel.

chemiosmosis Process in cellular respiration or photosynthesis which produces ATP using the energy of hydrogen ions diffusing from high concentration to low.

chemiosmotic gradient In cellular respiration or photosynthesis, a difference in concentration of hydrogen ions across a membrane within the mitochondrion or chloroplast set up using energy from an electron transport chain.

cristae The space formed by infoldings of the inner membrane within the mitochondrian.

electrochemical gradient A difference in both electrical charge and chemical concentration across a membrane.

electron transport chain (ETC) A series of electron-carrying molecules which accept and pass along energy-carrying electrons in small steps, allowing the energy lost at each transfer to be captured for storage or work.

endosymbiotic theory The theory which states that chloroplasts and mitochondria originated as independent prokaryotic cells which were engulfed by larger prokaryotic cells to form the first eukaryotic cells.

$FADH_2$ An electron carrier used to deliver energy to the electron transport chain of aerobic respiration.

glycolysis The process of "splitting glucose" - stage 1 of aerobic cellular respiration and also the basis of anaerobic respiration; splits glucose into two 3-carbon pyruvates, producing 2 (net) ATP.

Krebs Cycle Stage 2 of aerobic cellular respiration; a series of chemical reactions which completes the breakdown of glucose begun in stage 1, releasing more chemical energy and producing carbon dioxide; also called the Citric Acid Cycle.

intermembrane space The space between the outer and inner membranes of the mitochondrian.

matrix The space within the inner membrane of the mitochondrian.

mitochondrion The "powerhouse" organelle in all eukaryotic cells where stages 2 (Krebs Cycle) and 3 (Electron Transport Chain) of aerobic respiration produce ATP.

NADH An electron carrier used to deliver energy to the electron transport chain of aerobic respiration.

Points to Consider

- According to the endosymbiotic theory, although some prokaryotes evolved aerobic respiration, eukaryotes took the short-cut of engulfing these prokaryotes rather than "re-inventing the wheel." The benefits to the "host" cells are obvious. What might have been some of the benefits to the prokaryote?
- Cycles, electron transport chains, and chemiosmosis are common to both photosynthesis and cellular respiration. Why do you think they're found in both energy pathways?

5.3 Lesson 5.3: Anaerobic Respiration: ATP, New Fuels, and Yogurt without Oxygen

Lesson Objectives

- Distinguish between obligate aerobes, obligate anaerobes, and facultative anaerobes.
- Explain that, in the absence of oxygen fermentation reactions must regenerate NAD+ in order for glycolysis to continue making ATP.
- Discuss how your muscles continue to work for you even when your respiratory and cardiovascular system can no longer keep up a continuous supply of oxygen.

- Identify yourself as "sprinter" or "endurance runner" and predict the type of muscle fiber (red or white) which predominates in your body.
- Describe how bacteria, including those we employ to make yogurt, make ATP in the absence of oxygen.
- Compare and contrast alcoholic and lactic acid fermentation pathways.
- Outline the process used to produce fuel from corn.
- Explain how we employ anaerobic organisms to make bread, beer, and wine.
- Compare the energy efficiency of aerobic cellular respiration to that of fermentation.
- List the advantages of anaerobic over aerobic respiration.
- Explain why vertebrate muscles use both aerobic and anaerobic pathways to make ATP.

Introduction

After the photosynthetic "oxygen catastrophe" challenged life between 2.5 and 3 billion years ago, evolution rebounded with biochemical pathways to harness and protect against oxygen's power. Today, most organisms use O_2 in aerobic respiration to produce ATP. Almost all animals, most fungi, and some bacteria are **obligate aerobes**, which require oxygen. Some plants and fungi and many bacteria retain the ability to make ATP without oxygen. These **facultative anaerobes** use ancient anaerobic pathways when oxygen is limited. A few bacteria remain as **obligate anaerobes**, which die in the presence of oxygen and depend on only the first (anaerobic) stage of cellular respiration.

Aerobic and anaerobic pathways diverge after glycolysis splits glucose into two molecules of pyruvate:

$$C_6H_{12}O_6 + 2NAD^+ + 2P_i + 2ADP \rightarrow 2\ \text{pyruvate} + 2NADH + 2ATP$$

Pyruvate still contains a great deal of chemical energy. If oxygen is present, pyruvate enters the mitochondria for complete breakdown by the Krebs Cycle and electron transport chain. If oxygen is not present, cells must transform pyruvate to regenerate NAD+ in order to continue making ATP. Two different pathways accomplish this with rather famous products: lactic acid and ethyl alcohol (**Figure** 5.19). Making ATP in the absence of oxygen by glycolysis alone is known as fermentation. Therefore, these two pathways are called **lactic acid fermentation** and **alcoholic fermentation**. If you lack interest in organisms, such as yeast and bacteria, which have "stuck with" the anaerobic tradition, the products of these chemical reactions may still intrigue you. Fermentation makes bread, yogurt, beer, wine, and some new biofuels. In addition, some of your body's cells are facultative anaerobes, retaining one of these ancient pathways for short-term, emergency use.

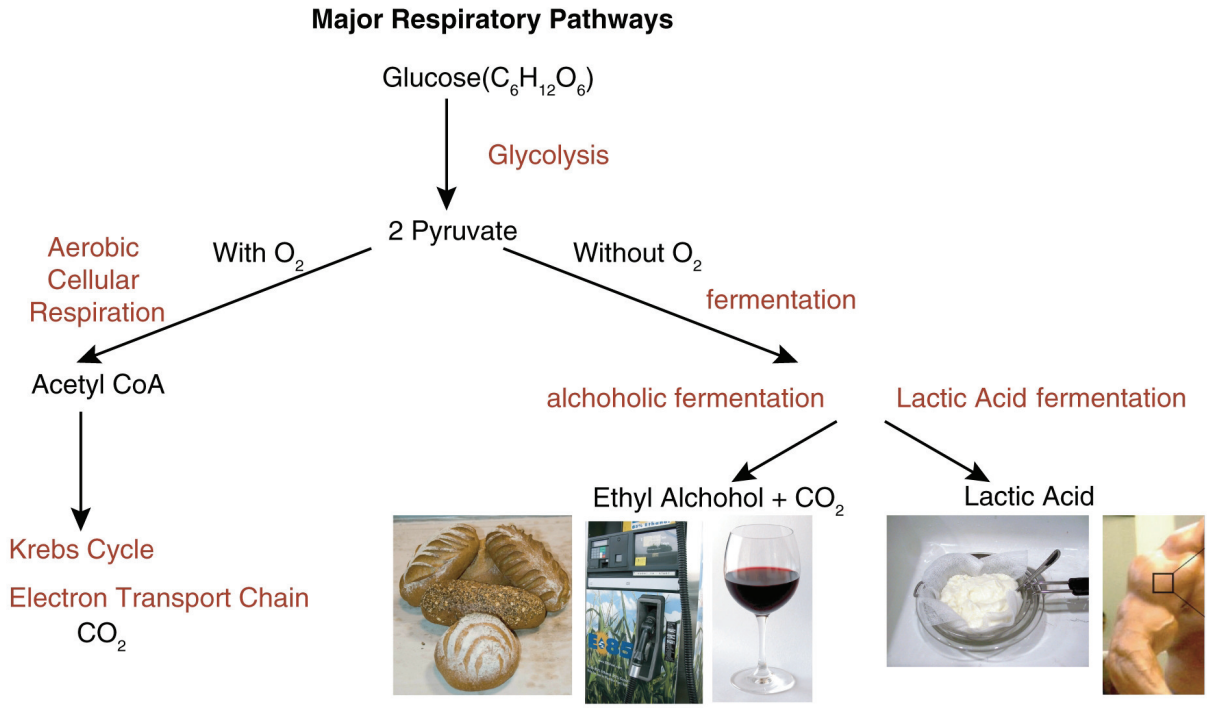


Figure 5.19: Anaerobic and aerobic respiration share the glycolysis pathway. If oxygen is not present, fermentation may take place, producing lactic acid or ethyl alcohol and carbon dioxide. Products of fermentation still contain chemical energy, and are used widely to make foods and fuels. (11)

Lactic Acid Fermentation: Muscle Cells and Yogurt

For chicken or turkey dinners, do you prefer light meat or dark? Do you consider yourself a sprinter, or a distance runner? (**Figure** 5.20)

Figure 5.20: Light meat or dark? Sprinting or endurance? Muscle cells know two ways of making ATP – aerobic and anaerobic respiration. (3)

Are Drumsticks and Athletic Prowess Related?

Yes! Muscle color reflects its specialization for aerobic or anaerobic metabolism. Although humans are obligate aerobes, our muscle cells have not given up on ancient pathways which allow them to keep producing ATP quickly when oxygen runs low. The difference is more pronounced in chickens and grouse (**Figure** 5.21), which stand around all day on their legs. For long periods of time, they carry out aerobic respiration in their "specialized-for-endurance" red muscles. If you have ever hunted grouse, you know that these birds "flush" with great speed over short distances. Such "sprinting" flight depends on anaerobic respiration in the white cells of breast and wing muscle. No human muscle is all red or all white, but chances are, if you excel at running short distances or at weight lifting, you have more white glycolytic fibers in your leg muscles. If you run marathons, you probably have more red oxidative fibers.

You probably were not aware that muscle cells "ferment." **Lactic acid fermentation** is the type of anaerobic respiration carried out by yogurt bacteria (*Lactobacillus* and others) and by your own muscle cells when you work them hard and fast. Converting pyruvate to 3-carbon lactic acid (see **Figure** below) regenerates NAD+ so that glycolysis can continue to make ATP in low-oxygen conditions.

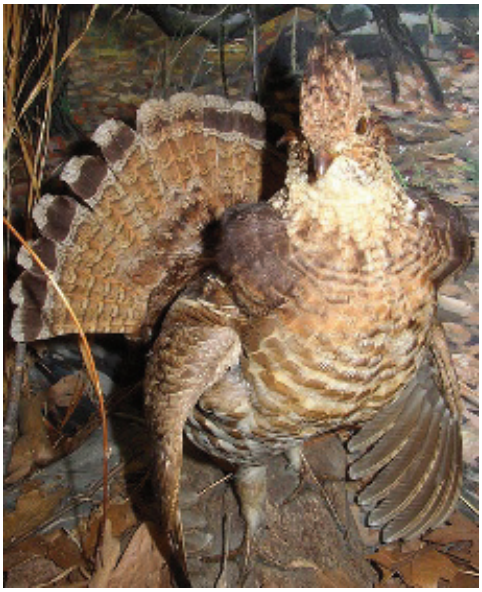
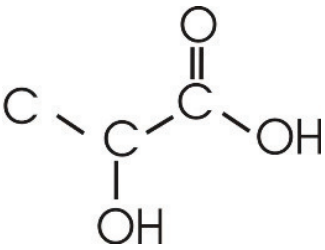


Figure 5.21: Ruffed grouse use anaerobic respiration (lactic acid fermentation) in wing and breast muscles for quick bursts of speed to escape from predators (and hunters!). (5)



$$C_3H_3O_3 \text{ (pyruvate)} + NADH \rightarrow C_3H_6O_3 \text{ (lactic acid)} + NAD^+$$

For *Lactobacillus*bacteria, the acid resulting from fermentation kills bacterial competitors in buttermilk, yogurt, and some cottage cheese. The benefits extend to humans who enjoy these foods, as well (**Figure** 5.22).

You may have noticed this type of fermentation in your own muscles, because muscle fatigue and pain are associated with lactic acid. Keep this in mind, however, as we discuss a second type of fermentation, which produces alcohol. Imagine what would happen as you ran a race if muscle cells conducted alcoholic rather than lactic acid fermentation!

Alcoholic Fermentation: A "New" Source of Energy?

Have you fueled your car with corn? You have, if you bought gas within the city of Portland, Oregon. Portland was the first city to require that all gasoline sold within the city limits

Figure 5.22: *Lactobacillus* bacteria use the same type of anaerobic respiration as our muscle cells. Lactic acid reduces competition from other bacteria, and flavors yogurt, as well! (4)

contain at least 10% ethanol. By mid-2006, nearly 6 million "flex-fuel" vehicles – which can use gasoline blends up to 85% ethanol (E85 – **Figure** 5.23) were traveling US roads. This "new" industry employs an "old" crew of yeast and bacteria to make ethanol by an even older biochemical pathway – **alcoholic fermentation**. Many people consider "renewable" biofuels such as ethanol a partial solution to the declining availability of "nonrenewable" fossil fuels. Although controversy still surrounds the true efficiency of producing fuel from corn, ethanol is creeping into the world fuel resource picture (**Figure** 5.24).

Figure 5.23: Ethanol provides up to 85% of the energy needs of new "fuel-flex" cars. Although its energy efficiency is still controversial, ethanol from corn or cellulose appears to be more "renewable" than fossil fuels. (22)

You are probably most familiar with the term "fermentation" in terms of alcoholic beverages. You may not have considered that the process is actually a chemical reaction certain bacteria and yeasts use to make ATP. Like lactic acid fermentation, alcoholic fermentation processes pyruvate one step further in order to regenerate NAD+ so that glycolysis can continue to make ATP. In this form of anaerobic respiration, pyruvate is broken down into ethyl alcohol and carbon dioxide:

$$\mathbf{C_3H_3O_3\ (pyruvate) + NADH \rightarrow C_2H_5OH\ (ethyl\ alcohol) + CO_2 + NAD^+}$$

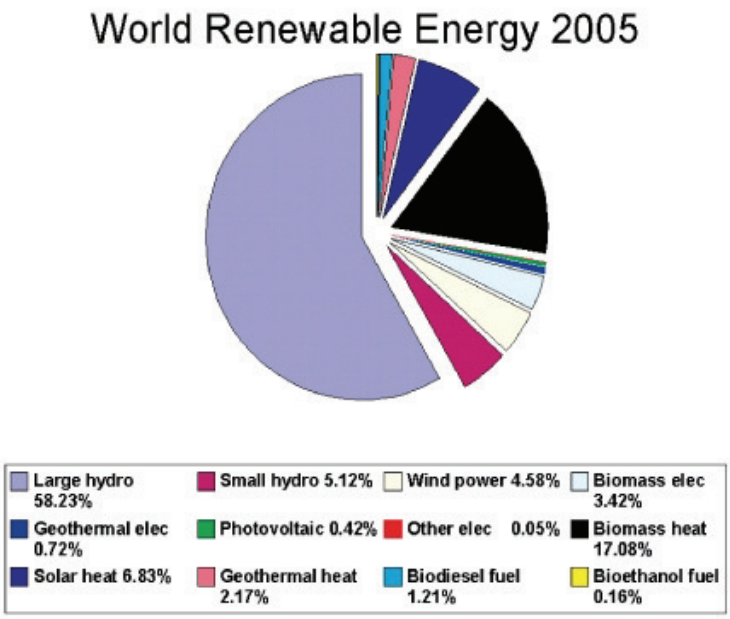


Figure 5.24: One of the newest kids on the block, ethanol from corn or cellulose is produced by yeasts through alcoholic fermentation – an anaerobic type of respiration. (25)

We have domesticated yeast (**Figures** 5.25 and **Figure** 5.26) to carry out this type of anaerobic respiration for many commercial purposes. When you make bread, you employ the yeast to make the bread "rise" by producing bubbles of carbon dioxide gas. Why do you suppose that eating bread does not intoxicate you?

Brewers of beer and wine use yeast to add alcohol to beverages. Traditional varieties of yeast not only make but also limit the quantity of alcohol in these beverages, because above 18% by volume, alcohol becomes toxic to the yeast itself! We have recently developed new strains of yeast which can tolerate up to 25% alcohol by volume. These are used primarily in the production of ethanol fuel.

Human use of alcoholic fermentation depends on the chemical energy remaining in pyruvate after glycolysis. Transforming pyruvate does not add ATP to that produced in glycolysis, and for anaerobic organisms, this is the end of the ATP-producing line. All types of anaerobic respiration yield only 2 ATP per glucose. In the next section, we will compare the advantages and disadvantages of aerobic and anaerobic respiration.

Aerobic vs. Anaerobic Respiration: A Comparison

As aerobes in a world of **aerobic** organisms, we tend to consider aerobic respiration "better" than **fermentation**. In some ways, it is. However, anaerobic respiration has persisted far longer on this planet, through major changes in atmosphere and life. There must be value

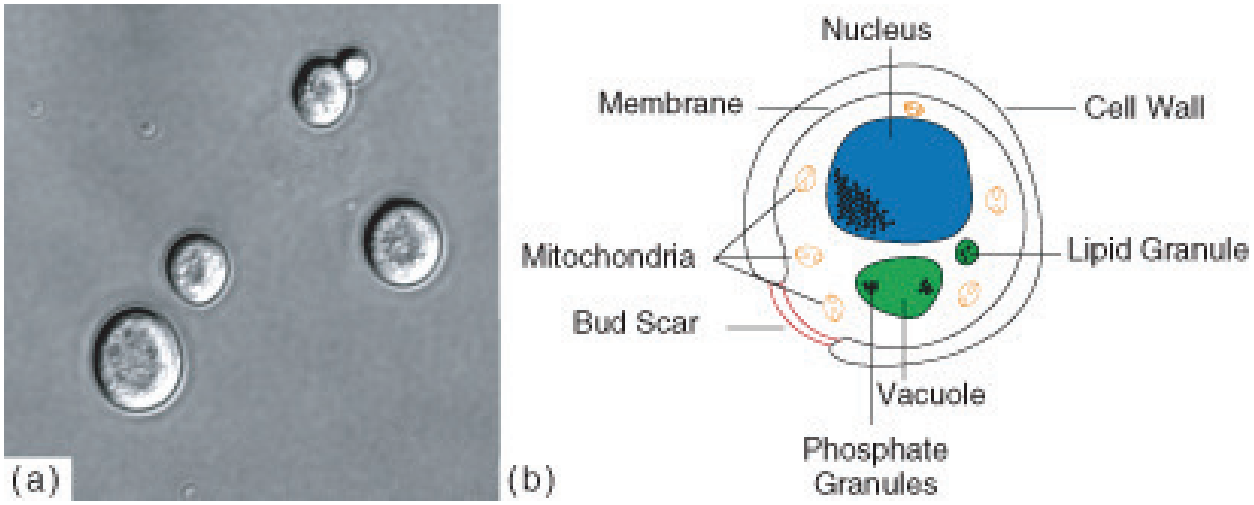


Figure 5.25: Yeasts are facultative anaerobes, which means that in the absence of oxygen, they use alcoholic fermentation to produce ethyl alcohol and carbon dioxide. Both products are important commercially. (17)

Figure 5.26: We employ yeasts to use their anaerobic talents to help bread rise (via bubbles of CO2) and grapes ferment (adding ethanol). (26)

in this alternative way of making ATP. In this last section, we will compare the advantages and disadvantages of these two types of respiration.

A major argument in favor of aerobic over anaerobic respiration is overall energy production. Without oxygen, organisms can only break 6-carbon glucose into two 3-carbon molecules. As we saw earlier, glycolysis releases only enough energy to produce two (net) ATP per molecule of glucose. In contrast, aerobic respiration breaks glucose all the way down to CO_2, producing up to 38 ATP. Membrane transport costs can reduce this theoretical yield, but aerobic respiration consistently produces at least 15 times as much ATP as anaerobic respiration. This vast increase in energy production probably explains why aerobic organisms have come to dominate life on earth. It may also explain how organisms were able to increase in size, adding multicellularity and great diversity.

However, anaerobic pathways persist, and a few obligate anaerobes have survived over 2 billion years beyond the evolution of aerobic respiration. What are the advantages of fermentation?

One advantage is available to organisms occupying the few anoxic (lacking oxygen) niches remaining on earth. Oxygen remains the highly reactive, toxic gas which caused the "Oxygen Catastrophe." Aerobic organisms have merely learned a few tricks – enzymes and antioxidants - to protect themselves. Organisms living in anoxic niches do not run the risk of oxygen exposure, so they do not need to spend energy to build these elaborate chemicals.

Individual cells which experience anoxic conditions face greater challenges. We mentioned earlier that muscle cells "still remember" anaerobic respiration, using lactic acid fermentation to make ATP in low-oxygen conditions. Brain cells do not "remember", and consequently cannot make any ATP without oxygen. This explains why death follows for most humans who endure more than four minutes without oxygen.

Variation in muscle cells gives further insight into some benefits of anaerobic respiration. In vertebrate muscles, lactic acid fermentation allows muscles to produce ATP quickly during short bursts of strenuous activity. Muscle cells specialized for this type of activity show differences in structure as well as chemistry. Red muscle fibers are "dark" because they have a rich blood supply for a steady supply of oxygen, and a protein, myoglobin, which holds extra oxygen. They also contain more mitochondria, the organelle in which the Krebs cycle and electron transport chain conclude aerobic respiration. White muscle cells are "light" because they lack the rich blood supply, have fewer mitochondria, and store glycogen rather than oxygen. When you eat dark meat, you are eating endurance muscle. When you eat white meat, you are eating muscle built for sprinting.

Each type of muscle fiber has advantages and disadvantages, which reflect their differing biochemical pathways. Aerobic respiration in red muscles produces a great deal of ATP from far less glucose - but slowly, over a long time. Anaerobic respiration in white muscles produces ATP rapidly for quick bursts of speed, but a predator who continues pursuit may eventually catch a white-muscled prey.

In summary, aerobic and anaerobic respiration each have advantages under specific conditions. Aerobic respiration produces far more ATP, but risks exposure to oxygen toxicity. Anaerobic respiration is less energy-efficient, but allows survival in habitats which lack oxygen. Within the human body, both are important to muscle function. Muscle cells specialized for aerobic respiration provide endurance, and those specialized for lactic acid fermentation support short but intense energy expenditures. Both ways of making ATP play critical roles in life on earth.

Lesson Summary

- In the two to three billion years since photosynthesis added oxygen to earth's atmosphere, life has become mostly aerobic. Some organisms and types of cells retain the older, anaerobic pathways for making ATP; these pathways comprise anaerobic respiration or fermentation.
- Obligate aerobes require oxygen to make ATP. Obligate anaerobes cannot survive in the presence of oxygen, so they occupy only anoxic habitats. Facultative anaerobes make ATP with oxygen, but if oxygen levels become low, they can use fermentation.
- Some bacteria, including those we employ to make yogurt, make ATP using lactic acid fermentation; the acid may help reduce competition from other bacteria. Muscle cells can continue to produce ATP when O_2 runs low using lactic acid fermentation, but muscle fatigue and pain may result.
- Red muscle fibers use mostly aerobic respiration to make ATP for endurance tasks; white muscle fibers use mostly lactic acid fermentation to make ATP quickly for short, intense activities. Human muscles contain a mixture of red and white fibers, but genetics may give sprinters more white fibers, and marathoners more red.
- Both alcoholic and lactic acid fermentation pathways change pyruvate in order to continue producing ATP by glycolysis.
- Ethanol produced by bacteria through alcoholic fermentation of corn (and perhaps other fuels in the near future) may provide a more renewable fuel for vehicles than the fossil fuels upon which we currently depend. We employ yeasts to help make bread through alcoholic fermentation; as they produce carbon dioxide, the bread dough rises. We employ anaerobic organisms to make beer and wine through alcoholic fermentation; the alcohol content is limited to 18% by volume because levels above that are toxic to these organisms.
- Aerobic respiration is far more energy-efficient than anaerobic respiration. Aerobic processes produce up to 38 ATP per glucose. Anaerobic processes yield only 2 ATP per glucose.

Review Questions

1. Classify your own cells as obligate aerobes, obligate anaerobes, or facultative anaerobes, and explain your reasoning. (Although these terms usually apply to whole organisms, assume they can also apply to individual cells within your body).
2. Identify yourself as a "sprinter" or an "endurance runner" and predict the type of muscle fiber (red or white) which predominates in your body. Explain your reasoning.
3. Construct a chart which compares alcoholic to lactic acid fermentation, considering at least three different features.
4. Outline the process used to produce fuel from corn and explain why some consider this fuel "renewable" and preferable to fossil fuels. Research the pros and cons of this fuel.
5. Explain how fermentation is used to make bread.
6. If two species of bacteria – one using aerobic respiration and the other using anaerobic respiration - were competing for the same source of glucose in the same environment, which one would out-compete the other? Explain why.
7. Human cells cannot carry out alcoholic fermentation, yet we use it for many purposes. Analyze its importance to human life.
8. Explain why both types of fermentation must change pyruvic acid, even though no energy is gained in this conversion.
9. Indicate the maximum alcohol content of wine and beer, and explain the reason for this limit.
10. Construct a chart comparing aerobic to anaerobic respiration using at least 5 characteristics.

Further Reading / Supplemental Links

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Vocabulary

aerobic With oxygen, or living or occurring only in the presence of oxygen.

alcoholic fermentation The process for making ATP in the absence of oxygen, by converting glucose to ethanol and carbon dioxide.

anaerobic Without oxygen; living or occurring in the absence of oxygen.

facultative anaerobe An organism which can respire aerobically when oxygen is present, but is also capable of fermentation when oxygen levels are low.

glycolysis The process of "splitting glucose" - stage 1 of aerobic cellular respiration and also the basis of anaerobic respiration; splits glucose into two 3-carbon pyruvates, producing 2 (net) ATP.

lactic acid fermentation The process for making ATP in the absence of oxygen by converting glucose to lactic acid.

obligate aerobe An organism which requires oxygen for cellular respiration.

obligate anaerobe An organism which uses anaerobic respiration, and dies in the presence of oxygen.

Points to Consider

- Humans seem to harness anaerobic respiration much more than aerobic respiration to create useful products, such as foods or fuels. Use your understanding of the two processes to explain why this makes sense.
- Some controversy exists over whether or not ethanol produced by fermentation of corn is an efficient and wise way to produce fuel. Can you think of some reasons, pro and/or con?
- How might the wing muscles of birds which migrate long distances compare to those of birds which do not migrate? Why do you suppose human muscles are mixtures of red and white fibers, rather than specialized, as in many birds?

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