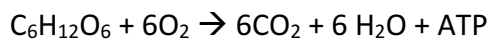


A closer look at cellular respiration

Name: _____ Date: _____ Period: _____



Glucose + oxygen \rightarrow (enzymes) \rightarrow carbon dioxide + water + energy

Through natural selection, such processes evolved in the first organisms. The simplest processes for converting food to usable energy are remarkably similar in all living organisms. Organisms that are as different as bacterial cells and humans have nearly identical processes for producing ATP. How do organisms convert food energy into energy that cells use easily? Let's follow the path of a glucose molecule to see how and where a cell harvests its potential energy. Remember, specific enzymes control every chemical reaction in cellular respiration.

The process begins in the cytoplasm. Glucose in the cytoplasm can go through glycolysis. This process does not require oxygen (see figure 8.25). A glucose molecule has six carbon atoms. It is quite stable. That is, the bonds holding its atoms together are not easily broken. Because of this stability, the cell uses a small amount of energy to begin the glucose-splitting reactions. It takes energy from two ATP molecules. The reaction splits each ATP into one stable ADP (Adenosine diphosphate) molecule and one phosphate (P) molecule.

Glycolysis breaks glucose down to two molecules that have three carbon atoms each.

Enzymes rearrange the atoms in these molecules to form two molecules of pyruvate. Glycolysis produces a small amount of ATP. Most of the energy of the original glucose molecule, however, remains in the two pyruvate molecules. Glycolysis may be followed by a pathway that does not require oxygen (Figure 8.26). This is the only way that some bacteria and archaea access the energy they need. But many organisms proceed to the next two stages of cellular respiration.

In addition to the ATP, glycolysis produces two molecules of NADH (nicotinamide adenine dinucleotide with a hydrogen atom). NADH is an example of a loaded electron shuttle. Some of the energy from the glucose molecule transfers to these electron shuttles. Cells sometimes use energy directly from loaded electron shuttles to do work.

The pyruvate molecules now enter the second stage of cellular respiration, the Krebs cycle. The Krebs cycle is a stage of aerobic respiration that involves many enzymes and molecular rearrangements. These reactions release most of the remaining energy in pyruvate. The reactions occur in the cell

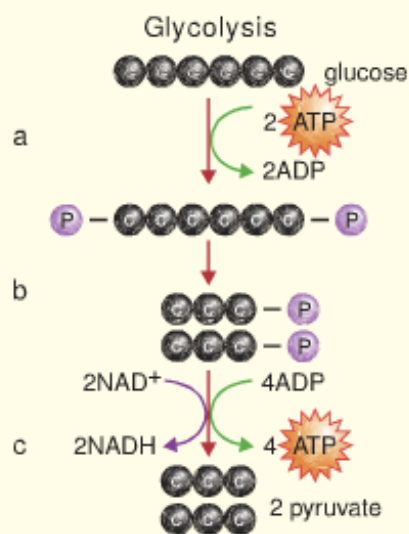


Figure 8.25 A molecular view of glycolysis. In glycolysis, glucose is broken down to two molecules of pyruvate. This takes place in many enzyme-catalyzed steps, illustrated by each red arrow. (a) The energy from some ATP is needed to begin the glycolysis reactions. Two ATP molecules each transfer a phosphate to glucose. (b) The glucose molecule is then broken down into two molecules that contain three carbons each. (c) In later steps, carbon atoms are rearranged to form pyruvate and ATP, and loaded electron shuttles (in this case, NADH) are produced.

compartments called *mitochondria* (see figure 8.27). Because the Krebs cycle only operates when oxygen is available, it is a part of aerobic respiration.

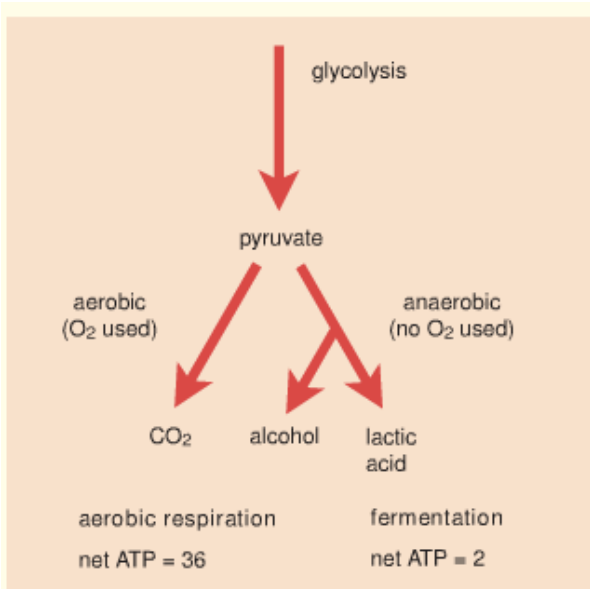
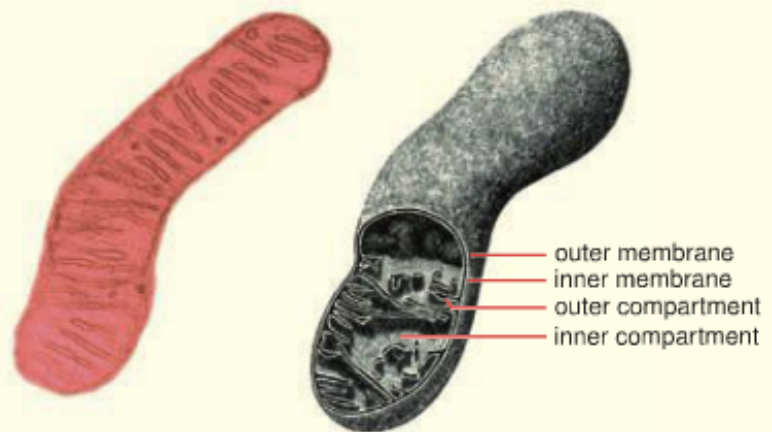


Figure 8.26 Aerobic and anaerobic energy release. When oxygen is present, pyruvate enters the Krebs cycle. The carbon in pyruvate is converted into carbon dioxide. Electron shuttle molecules transport electrons to the electron transport system. This system produces much ATP. In the absence of oxygen, pyruvate can be converted into alcohol or lactic acid through fermentation. What are the advantages of each process?

Figure 8.27 A mitochondrion. The reactions of aerobic respiration take place in this cellular organelle. Each mitochondrion has two membranes, an inner and an outer. The highly folded inner membrane forms the inner compartment. The space between the two membranes forms the outer compartment. The enzymes involved in the oxygen-requiring steps of cellular respiration are located inside the mitochondrion.



In preparation for the Krebs cycle enzymes convert pyruvate into a 2-carbon molecule. This process releases a molecule of carbon dioxide. Next, the 2-carbon molecule combines with a 4-carbon molecule and is carried through a cycle of reactions (figure 8.28). At the end of the cycle, carbon dioxide, a small amount of ATP, and several more loaded electron shuttles are formed. What do you think is released from the body as a result of these reactions? As with all transformations of energy, heat is produced. In humans, the circulatory system transports the carbon dioxide that was produced to the lungs. You exhale the gas as a waste product.

By the end of the first two stages of cellular respiration, the energy from glucose has been converted into energy in a few ATP molecules, loaded electron shuttles, and heat. Next, the energy in the loaded electron shuttles is converted into many more ATP molecules. This takes place in the third

stage of cellular respiration, the electron transport system. Figure 8. 29 outlines the electron transport system.

The electron transport system consists of a series of electron carrier molecules (different from the electron shuttles). These carrier molecules are embedded in the inner membrane of a mitochondrion. The electron shuttles deliver their high-energy electrons to the system. The electrons are passed to the chain of electron carrier molecules. As the electrons move from one carrier to the next, they release energy. Some of the energy pumps protons (H^+) across the inner membrane of the mitochondrion. The protons accumulate in the outer compartment of the mitochondrion. This results in a higher concentration of protons in the outer compartment than on the inside (a concentration gradient).

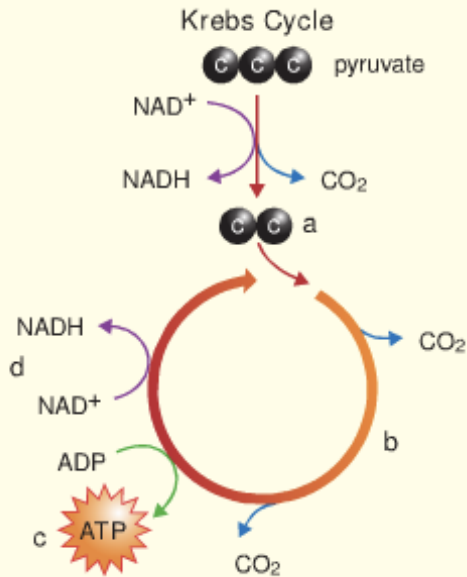
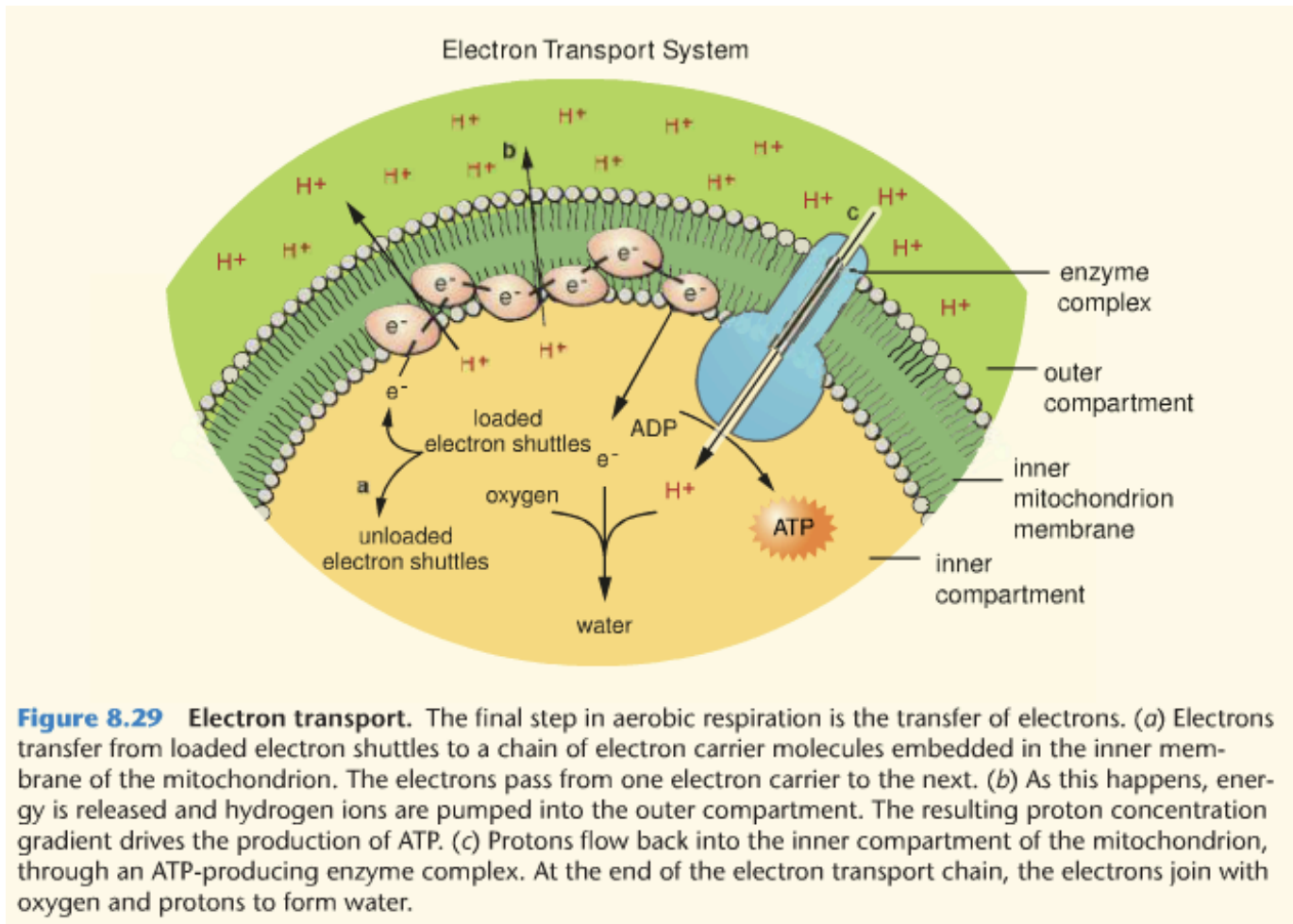


Figure 8.28 The Krebs cycle. In preparation for the Krebs cycle, each pyruvate molecule produced by glycolysis is converted into a 2-carbon molecule. Many enzyme-catalyzed reactions occur that release two molecules of carbon dioxide and ATP. In addition, loaded electron shuttles (NADH) are produced at three different points in the cycle.



A concentration gradient is a source of potential energy. The protons diffuse down the concentration gradient into the inner compartment. To diffuse into the inner compartment, the protons can only pass through an enzyme complex located in the membrane. The enzyme complex works much like a waterwheel. Waterwheels are sometimes used to transfer the energy of a flowing stream to a wheel used to grind wheat. In the electron transport system, the energy from the flow of protons through the enzyme complex is used to produce ATP. ATP is the ultimate product of cellular respiration. Carbon dioxide, water, and heat are by-products that we release when we exhale (Figure 8. 31). ATP can serve as the energetic push that starts many chemical reactions in the cell.

But where do the electrons from the electron transport system go? At the end of the electron transport system, the electrons are accepted by oxygen molecules. The oxygen then reacts with hydrogen to form water. Imagine what would happen if there were no oxygen present for use in the electron transport system. What would build up, and what would happen to the body? You breathe because you need oxygen to keep the electron transport system and all its transformations of energy going. Humans, as well as other animals, plants, fungi, protists, and many prokaryotes, require oxygen for their survival. Transformations of energy are necessary for life.

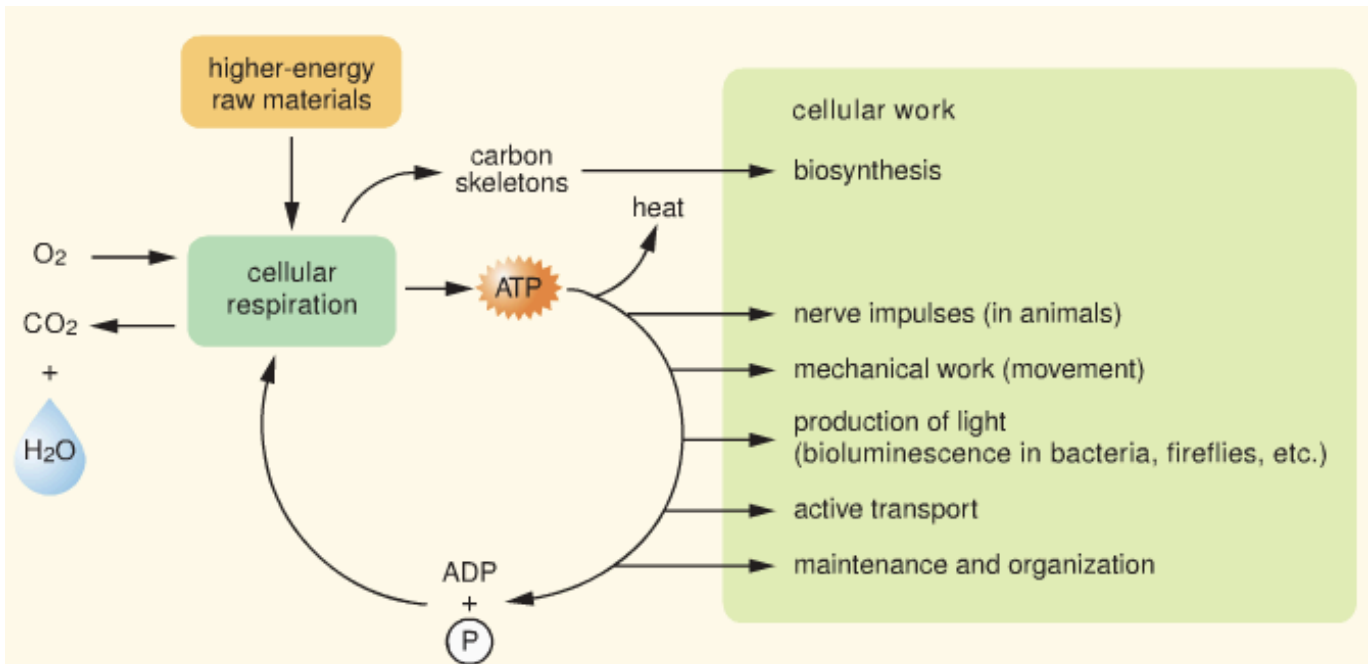
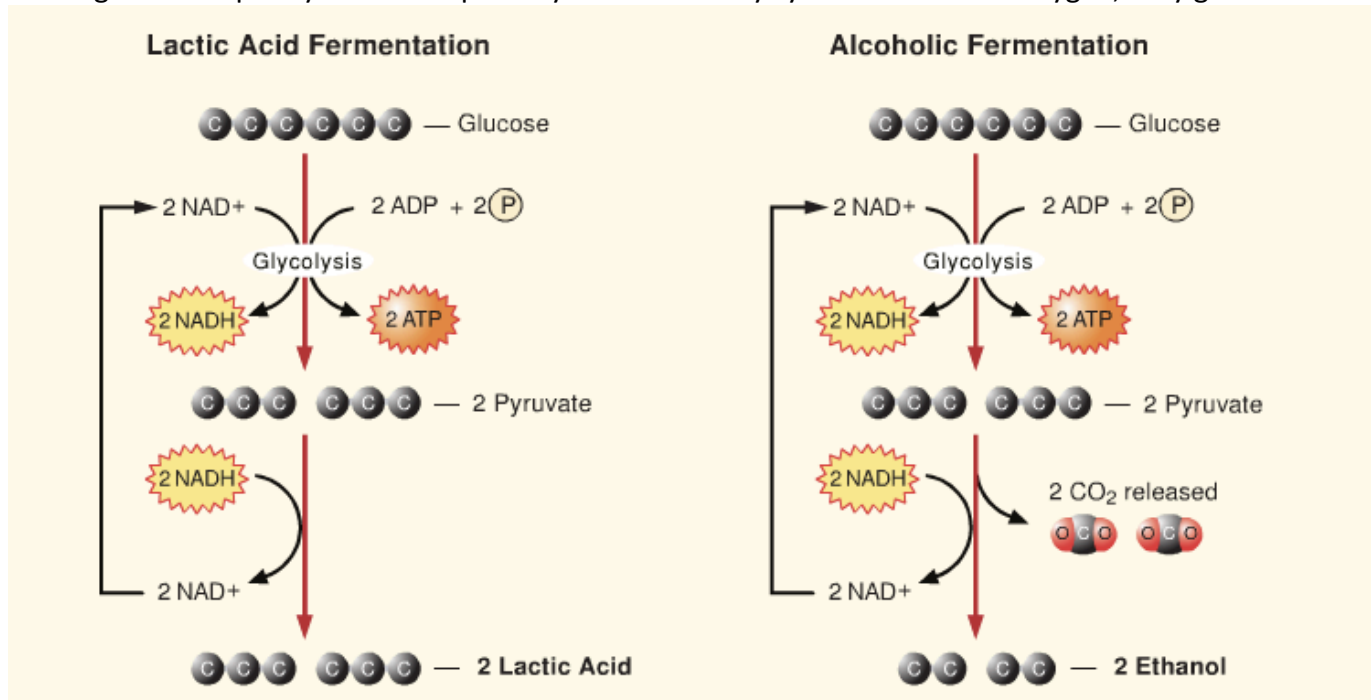


Figure 8.31 Products of cellular respiration. Cellular respiration breaks down sugars and other compounds. The products include carbon skeletons, which are used in biosynthesis, and ATP, which provides energy for work in cells. Heat and water are also produced. What kind of energy transformations occur in cellular respiration?

In the absence of oxygen, the electron transport shuttles (NADH) still need to get rid of their electrons so they can go back to work. This process is called “fermentation” and can happen in two ways: lactic acid fermentation or alcohol fermentation, see the figure below. When our muscles are burning ATP too quickly for our respiratory and circulatory systems to deliver Oxygen, they go into



anaerobic respiration (without oxygen) and produce lactic acid. This is one of the things that makes muscles sore after bursts of intense activity (note: hours later, your muscles have flushed out the lactic

acid and any soreness the day or two after intense activity is due to “microtears” in your muscle fibers. It is repairing these “microtears” that makes your body stronger!).

Baking Bread

When we bake bread, the yeast (a fungus) we put in undergoes respiration. The CO₂ that comes out during anaerobic respiration by yeast pushes out at the dough around it, causing the dough to rise (and the holes in the baked bread). Each yeast cell causes its own air pocket! The alcohol gets evaporated during the baking process, so we are not consuming alcohol when we eat bread.

Questions:

1. Fill out the following table:

Stage of cellular respiration	Glycolysis	Krebs Cycle	Electron Transport System
Cellular location			
Energy going in (chemical and/or ATP)			
What happens to the energy			
Energy coming out			

2. How does the overall process of cellular respiration release energy in a controlled way?

3. Why is it more efficient for organisms to use aerobic respiration than anaerobic respiration?

4. Why is it useful for organisms to use anaerobic respiration if they do not have access to Oxygen?